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One size does not fit all: Conservation farming success in Africa more dependent on management than on location

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ABSTRACT

Conservation agriculture practices have been successfully applied to improve crop yields in South America, but questions arose whether these practices can be successfully implemented in Africa. Here we show that a specific set of soil conservation practices called conservation farming (CF) using planting basins and hand hoes disseminated on 280 farms in Zambia on average failed to increase maize yields compared to traditional farming (TF). Average grain yield was low with 1.2 t ha^{-1}, but variation between farms was large with a variance of 32% for CF, ranging in individual farms from 0.02 to 2.8 t ha^{-1}. Yields on farms that declared to practice CF were more constrained by inappropriate management ($P < 0.001$ of multiple stepwise regression; 13% of total variability) such as lack of early planting and insufficient weeding (25% of total variability explained by management) than by site or climatic conditions. In contrast, yields under TF varied the most (26%) based on the amount and types of inputs. CF practices increased maize yields at rainfall below 1000 mm yr^{-1}, and in valley bottoms possibly due to the water-collecting properties of the planting basins, but decreased yields in lower slope and valley positions of higher rainfall regions above 1000 mm yr^{-1} likely due to waterlogging. Observed management constraints in comparison to site or soil conditions highlight the critical importance of training needed to make complex interventions such as CF successful in areas where means and infrastructure are insufficient to provide farmers with external inputs.

1. Introduction

The need to feed an ever increasing global population faces the challenge of improving crop productivity in the face of increasingly degraded soil resources, especially in the poorest regions of the world (Lal, 2006; Nellemann et al., 2009). A significant yield gap in Africa (Licker et al., 2010) suggests a considerable potential to improve agricultural productivity (Sanchez, 2002). The bemoaned failure of the green revolution in Africa (Ejeta, 2010; Evenson and Gollin, 2003) has stimulated global efforts to mitigate food insecurity (Annan, 2003; Godfray et al., 2010). Practices of soil conservation including reduced tillage and crop residue retention have been very successful in many parts of the world (Hobbs et al., 2008; Kassam et al., 2009). Major development initiatives see a combination of these soil conserving techniques under the term “conservation agriculture” as a significant pathway to achieving food security also in sub-Saharan Africa (Conway and Toenniessen, 2003; Sanchez and Swaminathan, 2005). However, significant questions remain whether similar successes can be replicated in sub-Saharan Africa (Erenstein et al., 2012; Giller et al., 2009; Knowler and Bradshaw, 2007; Rusinamhodzi et al., 2011; Nyamangara et al., 2013). Even though notable advances have been made (Marongwe et al., 2011; Thierfelder et al., 2013a), the adoption in Africa has been comparatively low compared to other regions (Kassam et al., 2009; Grabowski and Kerr, 2013). Given the small scale of many farms in Africa, it has been argued that the development and adoption of conservation agriculture approaches may follow different paths than in other regions (Gowing and Palmer, 2008) and therefore widespread adoption of conservation agriculture may not be likely (Baudron et al., 2012b).

Specifically, it is not fully clear what role site and soil conditions play in the success of conservation agriculture (Gowing and Palmer, 2008; Giller et al., 2009). Under what soil and climate conditions conservation agriculture is most successful is only supported by

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limited data (Johansen et al., 2012; Thierfelder et al., 2013a). This is important as a combination of soil properties and topographic features can explain, e.g. 60% or more of maize yield variability (Kravchenko and Bullock, 2000). On the other hand, implementing a set of basic management principles in conservation agriculture seems to be key to its success (Hobbs et al., 2008; Mazvimavi and Twomlow, 2009; Thierfelder et al., 2013a). Providing site-adapted management will help advance what many see as a promising management approach (Hobbs et al., 2008; Twomlow et al., 2008; Erenstein et al., 2012). Whether location or management are more important for improving crop yields with conservation agriculture is less obvious.

The objective of this study was to quantify maize (*Zea mays* L.) yields after dissemination of a specific set of conservation agriculture practices using basins dug with hand-hoes in comparison to traditional farming practices in Zambia. Specifically, we were interested in assessing the relative importance of site and soil conditions in comparison to management in determining crop yields for both farming approaches.

2. Materials and methods

2.1. Study sites

The experimental sites were located on an environmental gradient of 217 km in Lundazi, Mambwe and Mpika districts of Eastern and Northern provinces in Zambia within Universal Transverse Mercator (UTM) projection Zone 36S (11°51′ S to 13°30′ S latitude, 31°25′ E to 33°007′ E longitude; Supporting Fig. S1). Site elevations ranged from 500 to 1400 m above sea level with mean annual temperatures ranging between 10 °C and 35 °C (Supporting Table S1). Mean annual precipitation lies between 500 to 1400 mm with a unimodal distribution pattern from November to April spanning all climatic zones representative of so-called Miombo woodland ecosystems (Desanker et al., 1997). The inter-annual variability of rainfall is high and ranges from 26% to 50% for a 21-year measurement period (1985–2006; Lusaka Meteorological Station, unpubl. data). Miombo woodlands cover about 2.8 million km^2 or 42% of the 6.5 million km^2 of Angola, Malawi, Democratic Republic of Congo, Mozambique, Tanzania, Zimbabwe, and Zambia (Desanker et al., 1997). The area was chosen on a physiographic basis and is subdivided into three landscape agroecological zones (AEZ) (Chiwele and McKenzie, 1996) differentiated by rainfall pattern (Supporting Fig. S2) and soil type. Over 280 small-scale farmers with less than 2 ha of land, which were instructed in and declared themselves to have implemented conservation agriculture (the specific set of practices are described below) but maintained traditional agriculture practices on some portion of their farms, were selected (Supporting Fig. S1) from the three AEZs. Sites were stratified according to mean annual precipitation, landscape position and soil texture to ensure representation of the most important environmental characteristics.

In AEZ I soils have a higher pH and nutrient content than in other AEZs (Supporting Table S2) and are classified as Haplic Luvisols (FAO-UNESCO, 1988) in the Rift troughs and Haplic Solonetz (loamy and clayey soils with coarse to fine loam top soils) on flat land. The rainfall in this zone is early, erratic and low with a cumulative average of 796 mm during the cropping season (Supporting Fig. S2). AEZ II represents a degraded plateau with moderately leached clayey to sandy-loam soils classified as Haplic Luvisols, Haplic Acrisols and Haplic Lixisols, with an average cumulative rainfall of 900 mm. Soils in this zone have coarser texture, lower nutrient and carbon contents than the other two AEZs (Supporting Table S2). Soils in AEZ III are highly weathered and leached with clayey to loamy textures, and are classified as Haplic Acrisols, having low pH and cation exchange capacity (CEC) indicative of a mineralogy dominated by highly weathered clays. AEZ III has the greatest cumulative rainfall with a 21-year average of 1045 mm (Lusaka Meteorological Station, unpubl. data).

2.2. Experimental design and methods

Farms were identified in areas with a wide variability of rainfall gradient, terrain and soil texture that declared to implement both a set of specific conservation agriculture practices called conservation farming (CF), as instructed by extension services for all 3 years of implementation of which this study is the third year (described in Section 2.3), and traditional farming (TF) (paired plots in close proximity within less than 100 m distance). Soil texture and terrain variables were comparable across the rainfall gradient, but significantly varied within each AEZ (Supporting Table S1). The experimental design was a stratified random sampling with one treatment replicate per farm. Stratification was based on a three-level model to examine the effects of environmental variables, including (i) three AEZs as proxies for mean annual precipitation (MAP); (ii) five landscape positions, and (iii) three soil textures (fine, intermediate and coarse). Within each strata multiple farms were randomly identified in the landscape. This publication presents the second year of these data, being the third year CF was practiced on the studied farms. The farms were part of CF programs of the Community Markets for Conservation (COMACO) and Swedish International Development Agency (SIDA) which have been disseminating CF in the region for 3 and 5 years prior to this study, respectively.

Crop productivity of maize was determined as managed and practiced by farmers after instruction for all 3 years since introduction on the studied farms, and only yield and soil properties were quantified by researchers. The CF plots were demarcated on existing 1-year-old CF fields with maize as a previous crop while TF fields were demarcated on adjacent fields by the same farmer with the same cropping history prior to CF establishment. The choice of maize variety was made by farmers and was identical across an individual farm in order to obtain an unbiased measure of CF yields in comparison to TF. Maize was planted using four seeds per planting hole and thinned to three (Aagaard and Gibson, 2003a,b) at a rate of 20–25 kg seeds ha^{-1}. The planting hole (basin) dimension was 0.3 m by 0.15 m by 0.15 m, length by width by depth, respectively. The assessments were conducted during the rainy seasons of 2006/2007 and 2007/2008, but only the last season is presented here due to severe crop damage as a result of floods in early 2007. Demarcated plots had a dimension of 4.5 m by 3.5 m (15.75 m^2), and were planted in rows with a distance of 0.9 m between rows and 0.7 m within each row, and were randomly located within the field that the farmer had allocated to either CF or TF. One of each, CF and TF plots, were located on a single farm (without replicates per farm; farms served as replicates).

In addition to this pair of CF and TF plots, which were demarcated before the cropping season and maintained over 2 years, one additional pair of CF and TF was randomly identified on each farm at harvesting. This additional pair of plots was used to verify whether assignment of plots prior to the cropping season introduced an artifact through different management by the farmers. Farmers may unintentionally or intentionally change their practices depending on their perception of expected outcomes of a trial (Boughton et al., 1990). There were no significant ($P > 0.05$) yield differences found between random and pre-allocated plots (Supporting Table S3), confirming the validity of comparisons between CF and TF ($n = 85$ and 83, respectively, for comparison between random and pre-allocated plots for each management system). Any comparison between treatments was only made for those farms where both plots were available to avoid bias by unexplained interactions (missing data were caused for a variety of reasons including damage by animals), and stratification according to gender and fertilizer use were examined separately (the number of available replicates therefore varies for each pair-wise comparison and is indicated in the text and tables).

2.3. Field management

Farmers declared that they managed the fields according to the practices laid out for CF (Aagaard and Gibson, 2003a,b; Haggblade and Tembo, 2003) and were instructed by COMACO and SIDA in CF. The same technology was disseminated on over 70,000 farms across Zambia by the year 2002 by the Zambian National Farming Union (ZNFU; in following years additional conservation agriculture technologies were introduced and not necessarily reported separately) which established the Conservation Farming Unit (CFU) to adapt the hand hoe-basin system to local conditions and to actively promote CF among smallholders (Haggblade and Tembo, 2003). These specific conservation practices recommended and disseminated in Zambia under the term conservation farming include (i) completion of land preparation in the dry-season using minimum tillage systems and early planting; (ii) no burning but retention of crop residues; (iii) establishment of permanent planting stations using dug-out basins; (iv) early and continuous weeding; and (v) crop rotations including 30% nitrogen-fixing plants. The farmers followed the instructions given by the extension agencies COMACO and SIDA, which were harmonized and verified, but not enforced by the authors. The COMACO network of extension agents provided support in AEZ I and II, and SIDA together with the CFU in AEZ III. Actual management practices (which may have deviated from the instructions given) were recorded for both CF and TF, which included variety of maize planted, dates of planting, previous crops planted (rotation), harvesting and dates of weeding, as well as the type and amount of soil amendments (fertilizer, lime, compost, manure) and date applied. The design and position of the basins were not assessed separately. The size of the basins differed depending on the type of hoe used and the time when the basins were dug and were not harmonized between farms. Recommendations for fertilizer applications followed CFU basic guidelines of 125 kg ha^{-1} of Compound D (10:20:10 NPK; 13 kg N and K ha^{-1}, 25 kg P ha^{-1}) as basal fertilizer and 200 kg ha^{-1} of urea (46% N; 92 kg N ha^{-1}) as top dressing and were not differently prescribed for CF and TF, and no systematic difference in the actual amounts applied by farmers was found.

2.4. Sampling and analyses

Maize grain and stover yields were determined in all plots at harvest at physiological maturity. To avoid edge effects a net harvest area of 5.7 m^2 was established within the demarcated plot area (15.75 m^2). Fresh plant material was weighed and a representative subsample dried at 60 °C for 48–72 h and then re-weighed. An aliquot grain subsample of about 500 g was taken for moisture content determination using a PreAgro grain moisture tester (PreAgro 35 Oy Santasalo-Sohlberg, AB; Finland). Grain yield data were corrected to a moisture content of 15.5%. In those cases where cobs were missing from the subplot (removed by people or destroyed by elephants or other animals), the average weight of the grain per harvested cob for the remainder of the plot was multiplied by the measured plant density at harvest to obtain a corrected estimate of total grain yield (Ngoze et al., 2008). The geographic coordinates of the experimental area within each farm (four corners) were recorded with a handheld global positioning system (GPS; Garmin 72XL model, instrument precision of ±10 m) using Universal Transverse Mercator coordinate system and projection (UTM, Zone 36), WGS84 datum.

2.5. Field sample collection and laboratory analyses

For site characterization, actual rainfall was recorded daily during the cropping season using a separate rain gauge on each farm (Tru-Chek® Rain Gauge; farmers were trained to perform measurements with regular follow-up). Ten random topsoil samples from both CF and TF plots on each farm were taken to a depth of 0.15 m and pooled as a composite (only one composite sample per farm, avoiding the basins which had received inputs in previous years). Sub-samples from the bulked composite were air dried and passed through a 2-mm sieve. The samples were analyzed for pH (in KCl) at a w/v ratio of 1:2.5 using a glass electrode. Mehlich 3 soil extracts (Anderson and Ingram, 1993) were analyzed for available Ca, Mg, K, and P by Inductively Coupled Plasma Atomic Emission Mass spectrometry (ICP-MAS, Spectro Ciros, Spectro A.I. Inc., MA, USA).

To estimate cation retention independent of soil pH, potential cation exchange capacity (CEC_{pot}) was determined by quantifying NH_4 exchanged with 2 N KCl after saturating cation exchange sites with NH_4 acetate buffered at pH 7.0 (Anderson and Ingram, 1993; Hendershot et al., 1993), followed by colorimetric NH_4 analysis on a continuous flow analyzer (Technicon Auto Analyzer, Colorimeter; Technicon, NY, USA). Total soil C and N were determined by dry combustion. A subsample of 0.5 g of each soil sample was finely ground for 10 min with a ball mill (Retsch® MM301, Retsch Inc., Newtown, PA, USA). From the fine material a 20-mg sample was weighed into Sn capsules and analyzed for total C and N contents with a Europa ANCA-GSL CN auto-analyzer (PDZ Europa Ltd., Sandbach, UK).

Spatial analyses were in this study performed to evaluate the effect of field location at a landscape scale (rather than on a household scale). Digital elevation models (DEM) produced from the DEM Shuttle Radar Topographic Mission (SRTM; CGIAR-CSI) at 90-m resolution were used to derive slope gradient, slope aspect (direction of slope), slope position and slope curvatures (profile, plan, absolute) for each field. The SRTM-derived terrain parameters were computed using ArcGIS 9.3 in a standard 3 by 3 raster (grid-cell) neighborhood size of 90 by 90 m pixels. Slope gradients in arc degrees were obtained using the Spatial Analyst feature of Arc GIS (ESRI, Redlands, CA). This process uses a 3 by 3 raster neighborhood around the processing cell to calculate slope gradient values. The algorithm identifies the maximum rate of change in elevation from each cell to its neighbors, defined as the first-order derivative of the terrain (ESRI, 1996). The Topographic Position Index (TPI), the difference between the elevation at a cell and the average elevation in a neighborhood surrounding that cell, was calculated using topographic arc tools (Jenness, 2006). TPI was utilized to classify the slope position within each AEZ into slope position classes based on both extreme TPI values and the slope gradient. High TPI values are found near hilltops while low TPI values are found in valley bottoms and values near zero are either on flat ground or in mid slope positions. In order to classify small features such as streams and drainages, a small rectangular neighborhood was used. In this study, five slope positions were derived and coded as 1 valley; 2 lower slope; 3 flat slope; 4 middle slope; and 5 ridges. Slope curvature (absolute, profile and plan) was derived using the Spatial Analyst surface tool in Arc GIS (ESRI, Redlands, CA) and calculated using a 3 by 3 raster neighborhood. The values were classified as concave or convex based on positive or negative values (if $n > 0.1$, $-0.1 > n < 0.1$, $n < -0.1$). Zero values have no slope curvature. Curvature describes the acceleration or deceleration of water flow over a surface. For instance, in plan curvature negative curvature (if $n < -0.1$) corresponds to concave surfaces and flowing water tend to converge, while positive curvature (if $n > 0.1$) corresponds to convex surfaces or hills and flowing water will tend to diverge, and vice versa for profile curvature's positive and negative values. Here we use the value of absolute curvature which integrates profile and plan curvatures. Slope aspect (azimuth) was computed in units of arc-degrees, recoded through the cosine function from north, and classified into four degree categories: −1 represents south (135–225); −0.5 represents west (225–315); 0.5 east (45–135); and 0 north (315–450) after cosine transformation. For quantitative validation of the DEM terrain parameters, a value was calculated for the center of each plot from the measured four corners (Supporting Fig. S1).

2.6. Statistical methods

Statistical analysis was conducted using a three-level stratified model of rainfall as the main factor (as the three AEZ), slope position within AEZ, and soil type (texture) within slope position, whereby treatments (CF versus TF) were nested within farms. Analysis of variance (ANOVA) was calculated using JMP (SAS Institute Inc., Cary, NC) to test the null hypothesis of higher grain yields under CF than TF after verification of normality. Treatment means were separated using standard error of difference. The soil chemical and physical properties and site characteristics were used as environmental co-variates. Management practices were then correlated with yields. Correlation analyses were done to determine if any linear relationships existed between the co-variates and main as well as interaction effects. A principal component analysis (PCA) was carried out using JMP (SAS Institute Inc., Cary, NC) to investigate the site characteristics and to identify important soil and management practices to be used as inputs for further analyses.

Groups of soil properties, site characteristics and management practices from factors derived from PCA were considered mutually orthogonal, uncorrelated and successively explain the maximum residual variation (Sena et al., 2002). Factors with an eigenvalue ≥1 (Kaiser, 1960) that explained at least 5% of the variation in the data (Wander and Bollero, 1999) were retained for further analyses. Environmental co-variates and management practices with factor loadings >0.60 were selected to be included in each factor. If the loading coefficient was >0.60 in more than one factor, it was included in the factor having the highest coefficient value for that property. The retained factors were subjected to varimax rotation to redistribute the variance of significant factors and thereby maximize the relationships using SAS (SAS Institute, Cary, NC). Correlation coefficients were calculated between crop yield and soil variables, site characteristics or management variables.

Stepwise regression was employed to analyze the combined effect of all spatial and management characteristics on crop yield. Multiple regression analysis was performed using derived PCs as independent variables and average grain yield as the dependent variable at $P \leq 0.05$.

3. Results and discussion

3.1. Management effects on maize yields under CF

Average maize crop yields on farms that declared to practice CF did not increase compared to TF (Table 1), regardless of stratification by fertilizer use or gender ($P > 0.05$). Despite the low average grain yield of 1.2 t ha^{-1}, compared to the 2008 average for Africa of 1.9 t ha^{-1} (FAO, 2011), the variation between farms was large with a variance of 32% for CF, ranging in individual farms from 0.02 to 2.8 t ha^{-1}. This raises the question why crop yields spanned more than two orders of magnitude.

When looking at all the farms in aggregate, the core reasons for CF's failure to improve average maize yields in this study was inadequate implementation of CF management, particularly insufficient weeding and late planting (Table 2: PC1 for CF under management $P < 0.001$; Supporting Fig. S3), despite the fact that farmers received CF training and declared to practice CF. These factors accounted for 25% of the total variation in crop yield that could be explained by management (PC1 in Table 3; multiple regression yield = 1.164 + 0.097 PC2 Soil + 0.064 PC1 management − 0.077 PC3 management; $P < 0.001$, $R^2 = 0.13$; PC principal components as shown in Table 3). Finer soil texture correlating with higher soil carbon contents increased with greater yields under CF (but less for CF than TF, Fig. 1). A strong positive relationship between clay content and soil organic carbon content is well documented (Six et al., 2002) and only a weak indication exists from our factor analysis that differences in organic carbon were caused by differential management practices. In a separate study on a small set of farms in

Table 1
Maize yield under either traditional (TF) or conservation farming (CF) in three agroecological zones (AEZ, average rainfall in brackets from Chiwele and McKenzie (1996)) in Zambia (means followed by standard deviation in brackets; $n = 280$ for all sites; only sites considered for statistical comparison (and indicated as number of observations in the table) where both TF and CF were available on the same farm; however, identical conclusions can be drawn from the full data set).

Farming system	Grain yield (t ha^{-1})			
	AEZ I (796 mm)	AEZ II (900 mm)	AEZ III (1050 mm)	All sites
TF	1.40 (0.58)	0.97 (0.50)	1.65 (0.57)	1.15 (0.61)
CF	1.56 (0.52)	0.92 (0.51)	1.28 (0.50)	1.17 (0.57)
P value	0.22	0.55	0.04	0.77
LSD (0.05)	0.26	0.16	0.36	0.14
Observations	38	82	19	139

Table 2
Correlation coefficients between either CF or TF yield (all AEZs together) and principal components that represent either soil properties, site variables or management with significance level of $P \leq 0.05$ (principal components for soil properties and management in Tables 3 and 4; for site variables in Supporting Material).

	Principal components	TF (ns)	CF (ns)
Soil properties	PC1	0.004	0.05***
	PC2	−0.01	0.05**
	PC3	−0.01	−0.0002
	PC4	−0.01	−0.01
Site variables	PC1	−0.03	−0.0002
	PC2	0.06***	−0.01
Management	PC1	0.05**	−0.05**
	PC2	0.01	−0.002
	PC3	0.002	−0.004

ns, not significant.
*** $P < 0.001$.
** $P < 0.01$.

Table 3
Variable loading coefficients of management variables with principal components (PCs), the eigenvalues and proportion of principal components explaining crop yield under CF (factor loadings in bold are considered highly weighted).

Management variables	PC1	PC2	PC3	PC4
Date of planting	**0.857**	0.035	−0.195	0.228
First weeding	**0.858**	0.061	−0.103	−0.009
Second weeding	**0.835**	0.091	0.049	0.108
Third weeding	0.648	−0.006	0.351	−0.074
Soil amendment input date	0.260	−0.062	−0.785	0.211
Lime applied	−0.004	**0.952**	−0.030	0.036
Basal fertilizer applied	0.115	**0.713**	0.511	0.184
Manure applied	0.132	0.569	0.007	−0.473
Compost applied	−0.223	−0.002	0.061	−0.551
Top dressing applied	0.168	0.060	0.776	0.207
Crop rotation	−0.033	0.028	0.094	0.717
Proportion of variance explained (%)	2.76	1.76	1.67	1.23
Cumulative variance (%)	25.1	41.1	56.3	67.5
Eigenvalue (no dimension)	2.93	2.09	1.35	1.06

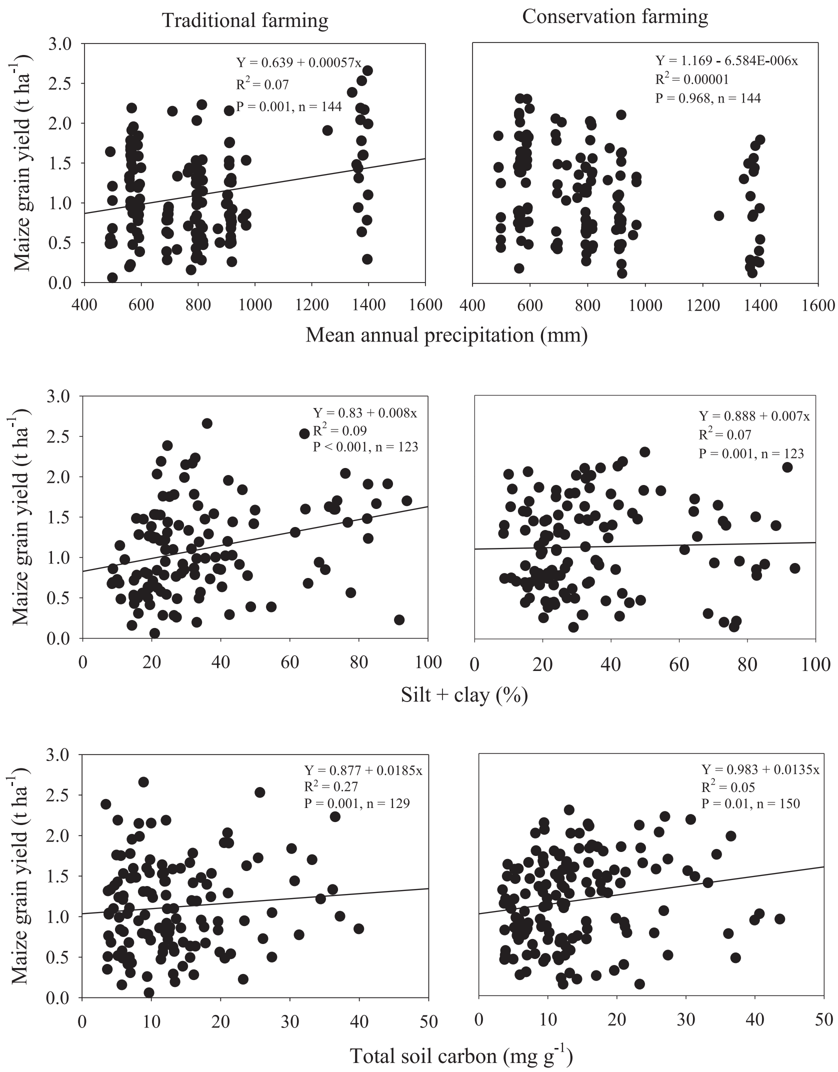

Fig. 1. Relationship between selected soil and site variables and crop yield under conservation and traditional farming in eastern Zambia.

the same area, however, paired sampling indicated greater topsoil organic carbon under CF than TF (Lewis et al., 2011).

Delayed planting and lack of appropriate weeding are well recognized as major determinants of crop success or failure (Haggblade and Tembo, 2003; Silwana and Lucas, 2002). Weeding is known to be especially critical under reduced tillage (Kayode and Ademiluyi, 2004; Tittonell et al., 2007; Mashingaidze et al., 2012) such as in the practice of CF. The well-known benefits of early planting is one of the strengths of CF, which allows planting well before the period that would be possible with TF (Haggblade and Tembo, 2003; Tittonell et al., 2007) resulting in significantly greater yields (Twomlow et al., 2009). Late planting and insufficient weeding may therefore explain the lack of positive yield responses with CF in the studied farms, despite the fact that the farmers received CF training and declared to practice CF. Failure to plant and weed appropriately and commensurate with CF instructions could be the result of a variety of factors including timely supply of fertilizers and labor bottlenecks (Giller et al., 2009; Umar et al., 2011), but the reasons were not studied further here.

3.2. Site effects on crop yields under CF

The practiced set of CF technologies in this region tended to improve crop productivity under low-rainfall conditions (AEZ I; Supporting Fig. S1), whereas a trend toward decreasing yields was observed under high-rainfall conditions (AEZ III; interaction between cropping system and AEZ $P = 0.036$; $P = 0.003$ for female farmers). A 10% increase in maize grain yield was also observed for female farmers in AEZ I by comparing CF with TF implemented in different but neighboring villages (Lewis et al., 2011). Even though these differences amounted on average to less than 0.4 t ha^{-1} and may therefore not be agronomically important compared to increases that are typically achievable by enhancing fertilizer use (Denning et al., 2009), it suggests opportunities for appropriately targeting site selection for the two different cropping systems. Changes of only 10–30%, albeit of rather low baseline yields, may still be important at a household level in areas with 94% food insecurity (Lewis et al., 2011). However, additional increases for a broader set of farmers are needed for sufficiently demonstrating the potential to increase food security by CF in the study region. In contrast, conservation agriculture practices without basins were found to be applicable to any investigated soil and under a broad range of climate in Zimbabwe (Thierfelder et al., 2013a) and was particularly effective for increasing infiltration (Thierfelder and Wall, 2012b; Thierfelder et al., 2012).

The implemented basins may have collected rainwater (as concluded by Rockström et al., 2009) and may have improved water availability in the drier regions, but were not needed or even deleterious in regions with adequate rainfall (Fig. 1) as also pointed out

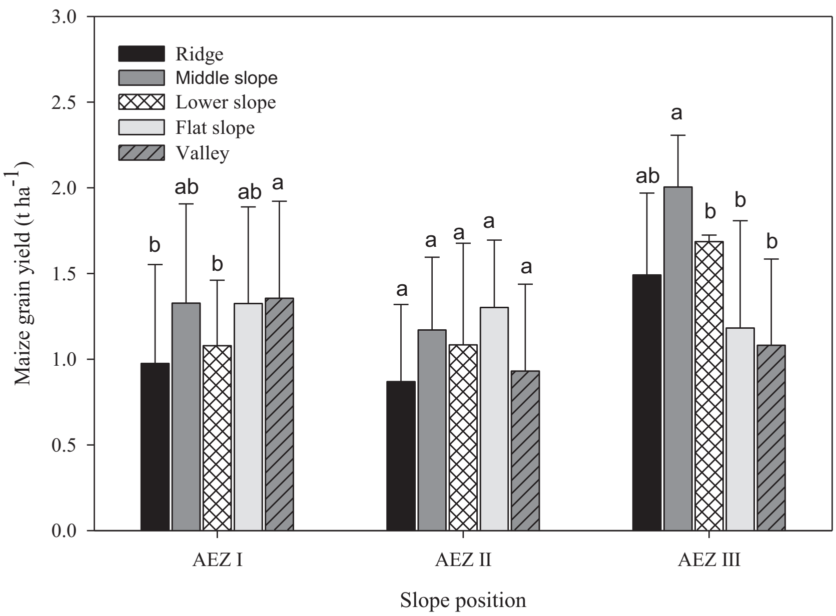

Fig. 2. Average maize grain yields of CF at different landscape positions (error bars represent standard deviations). Comparisons are done for each agroecological zone separately (bars with a different letter within a zone are significantly different from each other at $P < 0.05$).

by Baudron et al. (2007) for a qualitative survey in southern Zambia. Under a related conservation agriculture system in Zimbabwe, yield reductions were observed in very wet seasons on sandy soils due to waterlogging (Thierfelder and Wall, 2012a). These conclusions are also supported by our observations that yield by farmers that declared to practice CF were significantly ($P < 0.05$) greater in valley bottoms than on ridges for the dry region AEZ I, but were diminished ($P < 0.05$) in lower and middle slope positions compared to ridges for the wetter regions AEZ II and III (Fig. 2). The influence of elevation and slope gradient on yield is often reflected in water availability and this effect is more readily observed under extreme weather conditions (either wet or dry) and field topography (Kravchenko and Bullock, 2000). The basin technology of CF was therefore most beneficial below about 1000 mm mean annual rainfall in our study region. Benefits of CF through water harvesting by the basins was also concluded by Rockström et al. (2009) for their investigated sites in Kenya, Ethiopia, Tanzania and Zambia which for all but one site reported mean annual rainfall of less than 1000 mm. This is also the rainfall regime that most conservation agriculture has been promoted for in the study region. For significant yield increases, however, additions of fertilizers were needed in a study of 450 farms in Zimbabwe of which most received less than 1000 mm annual rainfall (Nyamangara et al., 2013).

3.3. Crop yield dependencies under TF

In contrast to CF, yields under TF were consequently greater with higher rainfall ($P < 0.001$; Fig. 1) but depended more on the amount of inorganic fertilizer and lime additions than on any other management practice (Table 2 with PC1 for lime, PC2 for top dressing and weeding, PC3 for compost as listed in Table 4). Specifically in AEZ III characterized by higher rainfall and lower chemical soil fertility, grain yields were greater ($P = 0.054$) with TF (1.7 t ha^{-1}) than CF (1.3 t ha^{-1}) when both received fertilizer ($n = 15$). Large and widespread yield increases were also documented with increased nutrient additions facilitated through fertilizer subsidies in Malawi (Denning et al., 2009) without primarily relying on CF technologies. Therefore, similar increases in fertilizer use will likely improve yields also throughout the Miombo woodlands of Zambia and neighboring countries. These may benefit from a combination with CF practices in a precision conservation agriculture framework (Twomlow et al., 2008).

Increasing fertilizer additions is a comparatively simple measure in terms of changes in management. However, the necessary distribution networks, timing of applications, and financial resources still pose significant challenges in Africa (Sanchez, 2002), and have historically combined to severely limit farmers' access to fertilizers, particularly in the Luangwa valley. On the other hand, CF management practices such as those originally propagated in Zambia require little external or financial resources, but are comparatively complex to implement (Tittonell et al., 2008; Wall, 2007). It has been suggested that transformative yield increases may only be achieved under more resource intensive cropping strategies with external inputs (Baudron et al., 2012a) and that also conservation agriculture relies on adequate inputs (Grabowski and Kerr, 2013; Nyamangara et al., 2013; Thierfelder et al., 2013a). The reason for the observed failure of CF dissemination to improve average maize productivity across a wide environmental gradient in our study may result more from the inability of the farmers to implement the entire technology package ("all or nothing") than from a lack of site adaptation, even though the tested basin system may not be appropriate at high rainfall. More attention to training for farmers and extension agents in proper implementation of CF management practices as well as attention to socio-economic situations

Table 4
Variable loading coefficients of management variables with principal components (PCs), the eigenvalues and proportion of principal components explaining crop yield under TF (factor loadings in bold are considered highly weighted).

Management variables	PC1	PC2	PC3
Basal fertilizer applied	0.757	0.414	−0.160
Lime applied	**0.929**	−0.099	−0.027
Manure applied	0.604	−0.016	0.171
Weeding date	−0.082	**0.819**	−0.035
Top dressing applied	0.173	**0.803**	−0.053
Compost applied	0.005	0.115	**0.902**
Date of planting	−0.061	0.333	−0.525
Proportion of variance explained (%)	1.84	1.62	1.15
Cumulative variance (%)	26.3	49.5	65.9
Eigenvalue (no dimension)	2.03	1.52	1.06

is required to evaluate the potential of CF in Africa (Tittonell et al., 2012; Thierfelder et al., 2012, 2013b), which is considerably more complex than comparatively simple recommendations of fertilizer inputs.

4. Conclusions

The study demonstrates the complexity of management and environment for making land use management decisions and provides guidance as to the strength of basin-based CF for lower rainfall regimes. This landscape-scale model may need to be complemented by a farm-scale model that takes account of past and present decisions that affect soil fertility at a household level. Appropriate management, particularly frequent weeding and early planting, was more important to the success of the tested CF management system than the choice of appropriate environment. In comparison, the amount of inorganic fertilizer additions was more critical to yield increases in conventional agriculture. Future research may need to address options for appropriate and cost-effective nutrient additions to improve yields.

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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.2013.08.006.

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