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Meta-analysis of crop responses to conservation agriculture in sub-Saharan Africa

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Front cover photo

Daimoniz Miondo is one of 800 farmers in Dowa District, Malawi, who have adopted conservation agriculture in recent years. Photo credit T. Samson/International Maize and Wheat Improvement Center (CIMMYT).

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Abbreviations and acronyms

CA	Conservation Agriculture
CT	Conventional Tillage
CV	Coefficient of Variation
FAO	Food and Agriculture Organization of the United Nations
LSD	Least Significant difference
NT	No-tillage without mulch and rotation
NTM	No-tillage with mulch application
NTR	No-tillage with mulch and rotation
SD	Standard Deviations
SE	Standard Error of the Mean
SSA	sub-Saharan Africa
WMD	Weighted Mean Difference

Executive summary

Conservation agriculture involves reduced or no-tillage, permanent soil cover and crop rotations to enhance soil fertility and crop yields. Conservation agriculture practices are increasingly promoted on smallholder farms in sub-Saharan Africa as a means to overcome continuing poor-profitability and soil degradation. In recent years a growing number of studies have been carried out in sub-Saharan Africa comparing conservation agriculture practices to conventional tillage-based practices. These studies have been conducted under a range of conditions (climate, soil, management, cropping system) gaining variable results on crop yield responses. The aim of this study is to compare and combine the results from different conservation agriculture experiments using meta-analysis in the hope of identifying patterns among study results, sources of disagreement among those results, or interesting relationships that may come to light in the context of the different studies.

The results of this meta-analysis show that reduced or no-tillage without mulch and/or crop rotation leads to depressed crop yields compared to conventional farmers' practices based on tillage. In contrast, crop grain yields were higher overall in no-tillage treatments in comparison to conventional tillage-based practices, when mulch was applied whether or not in combination with crop rotations. These outcomes suggest that for farmers to benefit from conservation agriculture they should be able to keep their crop residues as mulch on the soil surface. Additionally, crop rotation should be an integral component of their farming practice, which implies the change from continuous mono-cropping systems towards rotation systems that include different crops and preferably legumes. These two components of conservation agriculture are, however, for many smallholder farmers in sub-Saharan Africa the bottlenecks to adopting the approach. Crop residues have several other uses on the farm, in particular as feed for livestock. Legumes or other non-cereal crops in many cases gain limited interest, as ready markets for sale are often not available. Another important management factor with respect to the successful implementation of conservation agriculture practices is the use of chemical fertilizer. The results of this study demonstrate a clear response of crop yields to conservation agriculture with high nitrogen fertilizer application, and much less with low nitrogen fertilization. Crop yields are generally low in sub-Saharan Africa and organic residues in short supply. The use of fertilizer to enhance crop productivity and organic residue availability is essential for smallholder farmers to engage in conservation agriculture. Our study did not differentiate a rainfall regime as being better for successful implementation of conservation agriculture, as most of the published studies used in the meta-analysis did not report on rainfall distribution within the season. Considering the seasonal rainfall distribution would, however, help in assessing conservation agriculture practices for their resilience to future climate change.

1. Introduction

Conservation agriculture (CA) is advocated by many agricultural development actors and by the Food and Agriculture Organization of the United Nations (FAO) as a means to overcome continuous poor-profitability and soil degradation on smallholder farms in sub-Saharan Africa (SSA). The practice of CA involves minimal soil disturbance, retention of crop residues as mulch on the soil surface and the use of crop rotations and/or associations (FAO 2014).Worldwide, CA has increasingly been endorsed as a cropping practice for mitigating and adapting to climate change (Kassam et al. 2009, IPCC 2014). Conservation agriculture has the potential to sequester soil carbon, especially when it leads to increased crop biomass production via double cropping (two crops per year), thereby contributing to climate change mitigation (e.g. Corbeels et al. 2006). The beneficial effects of mulching with crop residues on the soil water balance (through reduced water runoff and soil evaporation) may enhance adaptation to future climate change, when rainfall is projected to decrease and become more unreliable (Scopel et al. 2004; Thierfelder and Wall 2010).

In recent years a growing number of studies have been carried out comparing the practices of CA to conventional tillage (CT)-based practices in SSA. The studies have been conducted under a range of conditions (climate, soil, management, cropping system). In general, the effects of CA on crop yield compared to CT in these studies are diverse, which makes it difficult to draw general conclusions. The fact that CA is not a single component technology but is based on three principles dictates that the effects on crop yield and yield stability are complex. A better understanding is required of which principles and related practices, including their interactions, contribute to desired effects on crop productivity. This is all the more important, given that in SSA farmers often face challenges with adopting all principles of CA as a package (Giller et al. 2009).

The aim of this study is to contrast and combine results from different CA experiments in the hope of identifying patterns among study results, sources of disagreement among those results, or interesting relationships that may come to light in the context of the different studies. A meta-analysis of the existing data can thus help in better understanding crop responses to CA and in identifying the agro-ecological and management conditions that favour positive crop responses to CA practices in SSA. This latter can contribute to better targeting investments with CA development and research. This study is a first attempt to analyse crop yield responses to CA in various agro-ecologies and climate conditions of SSA.

2. Materials and methods

The study consists of a literature and data review with the help of key experts working on CA in SSA. A meta-analysis was conducted to compare and integrate the results of multiple studies and to draw general patterns.

2.1. Literature search

Data was collected from scientific literature on the effects of tillage and crop residue management on crop yields in SSA through the end of April 2013. A comprehensive literature search was conducted for peer-reviewed publications using the online database ISI Web of Science (Thomson Reuters, New York, NY, USA) and Google Scholar (Google Inc., Mountain View, CA, USA). The literature search used the following keywords and their combinations: no-tillage, reduced tillage, conservation agriculture, minimum tillage, rotation, grain yield, rainfed, Africa, crop residues, mulch and fertilizer application. Key experts and authors were contacted for additional information and clarification on retrieved papers. Studies had to meet the following defined basic selection criteria to be included in the meta-analysis. First, field experiments that report on crop yields from a conventional tillage-based treatment (control) compared with crop yields from a CA-based treatment, where at least the effect of no-tillage is tested. Second, the experiments are conducted in SSA under rainfed field conditions. Third, the means, standard deviations or standard errors and samples sizes of annual crop yields are directly reported or can be calculated from the reported data. Fourth, data from the same experiment but reported in more than one publication are not repeated and fifth, the publication with the most complete dataset is used. 120 papers were retrieved from the literature search, 49 of the papers only had Africa mentioned in the abstract, introduction or in the reference list, 20 of the papers were on conservation agriculture in SSA but there were no reports on crop yield, 5 of the papers retrieved were on irrigated conservation agriculture in SSA. Five of the papers satisfied 3 of the basic criteria but error means were difficult to retrieve from the papers and so they were not included in the final dataset. In total, 41 papers were selected for the final dataset with 61 independent study sites (Table 1).

2.2. Building the database

Data was extracted from the selected 41 papers into a database template which was formulated in accordance to the objectives of the study and the requirements of meta-analysis. The categories used in the template included: rainfall, soil texture, yield, amount of mulch, type of mulch, experimental site, type crop, duration of experiment, CA type, CT type, standard deviations (SD of treatments, treatment means and number of replicates (n)). Standard deviations were hardly reported in the papers (5 out of 41 papers), rather standard error of the mean (SE), coefficient of variation (CV, %), and least significant difference (LSD) were reported. Standard deviation was calculated from the SE and CV and LSD. The LSD for some studies was estimated from the mean values presented in the papers by taking the smallest difference between the mean values of treatments that was still significant.

2.3. Meta-analysis treatments and calculations

Meta-analysis helps to quantitatively combine and analyse experimental results reported by other authors and to estimate overall effect. In this study we determined the effect of tillage and residue management on crop yield. The CT treatment was set as a control to compare with CA treatments. Factors used as covariates for the response of crop grain yield to tillage management included: seasonal rainfall, soil texture, and nitrogen input. Seasonal rainfall was categorized into low (<600 mm), medium (600-1000 mm), high (>1000 mm), nitrogen fertilizer input was categorized into low (< 100 kg ha^{-1}) and high (≥ 100kg ha^{-1}) and soil texture was categorized based on the categories: clayey soil, sandy soil, and loamy soil.

Data needed for the meta-analysis include: treatment mean, standard deviation, and number of replicates. In meta-analysis, continuous or measured variables are often expressed as ‘weighted mean difference (WMD)’ and for ease of understanding and making inference, mean differences were used for the analysis. Yield differences between treatment and control were used. In order to determine the overall effect estimates and to evaluate constancy of treatment effect across studies, mean differences were weighted. Individual studies were weighted by the reciprocal of the estimated variance. Different models used in meta-analysis to calculate effect size often give different results and interpretations. In this analysis, the random effect model was the most appropriate in calculating the effect size as it takes care of both within and between study variance. In addition, the random model can be broadened to include relevant covariates, which would reduce the heterogeneity and allow for more specific remedial suggestions. For the significance test of the overall mean effect, a mean effect size was significantly different from 0 if its 95% confidence interval did not overlap zero. The StatsDirect statistical software, version 2.7.2 Copyright© 1990-2008 (StatsDirect, Ltd.,Cheshire, UK) was used to perform the effect size meta-analysis.

Table 1. Selected studies for the meta-analysis

Reference	Country	Crop	Treatment	Soil texture	N application (kg ha^{-1})	Rainfall (mm)
Agbede & Ojeniyi (2009)	Nigeria	sorghum	CP, NT, NTM	sandy loam	0	375 866 410
Agboola (1981)	Nigeria	maize	CP, NTM	sandy loam	120	1250 950 960 1500
Anazodo et al. (1991)	Nigeria	maize	CP, NTM	loamy sand	0	1067 567 1200 1033 1000
Araya et al. (2011)	Ethiopia	wheat/tef	CP, NTM	clay	100	263 365 545
Araya et al. (2012)	Ethiopia	wheat/grass pea/hanfets	CP, NTR	clay	100	455 412 313 428 343 402
Baudron et al. (2012)	Zimbabwe	cotton/sorghum	CP, NT, NTM	sandy clay loam, sandy loam, loamy sand	0	845 850 600
Dusserre et al. (2012)	Madagascar	rice	CP, NTM	clay	79	1332 1080 1533
Enfors et al. (2011)	Tanzania	maize	CP, NTM	sandy loam	0	165 326 163 549 244
Erkossa et al. (2006)	Ethiopia	wheat/lentil/tef	CP, NTR	clay	0	541 1051 767 702 908
Gill & Aulakh (1990)	Zambia	wheat	CP, NTM	clay	113, 110, 87	923 1275 1364
Gill et al. (1992)	Zambia	maize	CP, NT, NTM	clay	110	1009 687
Habtegebrial et al. (2007)	Ethiopia	tef	CP, NT	clay loam	0	415 442 718

Table 1. continued

Reference	Country	Crop	Treatment	Soil texture	N application (kg ha^{-1})	Rainfall (mm)
Ike (1986)	Nigeria	maize/cotton	CP, NT	sandy loam	99	
Khatibu et al. (1984)	Zanzibar	maize/cowpea/ sorghum	CP, NTM	sandy clay loam	30, 60	400
Kihara et al. (2011)	Kenya	maize	CP, NT, NTM	sandy clay loam	60	245 285 825 374
Lal (1986)	Nigeria	maize	CP, NT, NTM	sand	100	604 604 637 615 581
Lal (1995)	Nigeria	maize	CP, NTM	sand	120	604 637 615 581 681 936 714 723
Mashingaidze et al. (2012)	Zimbabwe	cotton/sorghum	CP, NT, NTM	sandy clay loam	0	630 600
Materechera & Mloza-Banda (1997)	Malawi	maize	CP, NT	sandy clay loam	40	1084 839 647
Mbagwu (1990)	Nigeria	maize	CP, NT, NTM	sandy clay loam	0, 60, 120, 240	
Mesfine et al. (2005)	Ethiopia	sorghum	CP, NTM	silty clay loam	41	580
Mupangwa et al. (2007)	Zimbabwe	maize	CP, NTM	clay, loam, sand	50	290 910 280 790
Mupangwa et al. (2012)	Zimbabwe	maize/cowpea/ sorghum	CP, NT, NTM	clay loam	20	465 364 465 364
Naudin et al. (2010)	Cameroon	sorghum, maize	CP, NT, NTM	clay, loam, sand	0	
Nguyen (1987)	Cameroon	maize	CP, NT, NTM	loamy sand	0, 60, 120,	1390 1490
Ngwira et al. (2012)	Malawi	maize	CP, NTM	loamy sand	69	680 580 590
Obalum et al. (2011)	Nigeria	sorghum	CP, NT, NTM	sandy loam	0	855 1051
Ojeniyi (1993)	Nigeria	maize	CP, NT	sandy loam	0	
Oicha et al. (2010)	Ethiopia	tef	CP, NT	clay	50	
Olaoye (2002)	Nigeria	cowpea	CP, NT	sand	0	
Osuji (1984)	Nigeria	maize	CP, NTM	sandy loam	150	846 604

Table 1. continued

Reference	Country	Crop	Treatment	Soil texture	N application (kg ha^{-1})	Rainfall (mm)
Paul et al. (2013)	Kenya	maize, sorghum	CP, NTM	clay	60	625 988
Saito et al. (2010)	Benin	rice	CP, NT	loamy sand	0	1017
Shemdoe et al. (2009)	Tanzania	sorghum	CP, NTM	loamy sand	0	920 660
Sissoko et al. (2013)	Mali	cotton	CP, NTM	sandy silt	46	1230 1323
Thierfelder & Wall (2012)	Zimbabwe	maize, soybean	CP, NTM	sand, clay, loamy sand	115, 80, 103.5	393 870 412
Thierfelder et al. (2012)	Zimbabwe	maize, cowpea	CP, NTR	sandy loam, clay loam	80	785 791 550
Thierfelder et al. (2013c)	Zambia	maize	CP, NTM	sandy loam	0	1099 764 851 671 822
Thierfelder et al. (2013b)	Malawi, Mozambique, Zimbabwe, Zambia	maize	CP, NT, NTM	sandy, sandy clay loam, clay loam, sandy loam	69, 58, 81,109	855 960 1000 600
Thierfelder et al. (2013a)	Malawi	maize	CP, NTM	sandy loam, loamy sand, sandy clay, loam	0	
Tulema et al. (2008)	Ethiopia	tef	CP, NT	clay	60, 40, 21	670 763
Vogel (1993)	Zimbabwe	maize	CP, NTM	sand	24, 16	905 739 415 343

NT = no-till, CP = conventional plough, NTM = no-till + mulch, NTR = no-till + mulch and rotation

3. Results and discussion

3.1. Summary statistics of weighted mean difference

The results of the summary statistics of weighted mean differences of crop grain yields between CT and no-tillage without mulch and rotation (NT), no-tillage with mulch application (NTM) and no-tillage with mulch and rotation (NTR) are shown in Figure 1. NTM had the largest range with the largest positive mean (378 kg ha^{-1}) followed by NT with a negative mean (- 24 kg ha^{-1}) and then NTR with a positive mean (142 kg ha^{-1}). As illustrated by the various outliers, there is a large difference in crop grain yields among the CA treatments considered across the cropping situations and regions included in this study. NT had a negative overall effect on crop yields compared to the control. NTM and NTR both had positive overall effects on crop yields compared to the control. These results are comparable with those from a meta-analysis of maize yield responses to CA under sub-humid and semi-arid conditions worldwide (Rusinamhodzi et al. 2011) that also showed positive yield responses for NTR, but negative responses for NTM. In a meta-analysis published by Nyamangara et al. (2014) crop yields with planting basins (with/without mulch and with/without rotation) were superior to CT in 59% of the experiments, with an overall significant effect, but yields with the CA practice using a ripper (with/without mulch and with/without rotation) were not significantly different from those under CT.

3.2. Effects of no-tillage on crop grain yield

There was a change in the weighted mean difference of crop grain yields between NT and CT practices with time. When NT is practiced over a period of time less than 3 years the overall effect in terms of yield benefit is positive (88 kg ha^{-1}) compared with CT (Table 2, Figure 2). According to Kassam et al. (2009) minimum soil disturbance through no-tillage or reduced tillage ensures: 1) a favourable proportion of respiration gases in the rooting-zone; 2) moderate organic matter oxidation; 3) good porosity for water movement, and 4) limits re-exposure of weed seeds and their germination. All these factors may enhance crop growth and final grain yield. The opposite occurs when NT is practiced over a period of more than 3 years, with an overall negative effect (-227 kg ha^{-1}). This result indicates that in the longer term no-tillage without crop residue mulching triggers

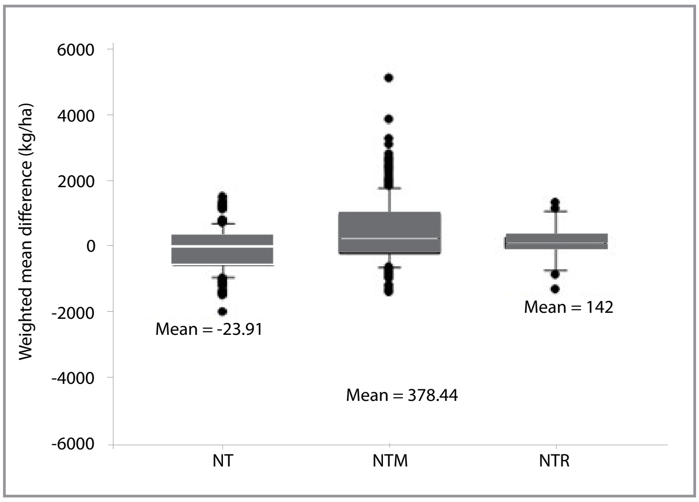

Figure 1. Weighted mean difference in crop grain yield of the treatments used in the meta-analysis. The middle lines represent the median values with upper and lower 25th percentiles. The outliers indicate extreme crop gains and/losses which deviates from the normally distributed range. NT = no-tillage/reduced tillage, NTM = no-tillage with mulch and NTR = no-tillage with mulch and rotation.

Table 2. Weighted mean difference in crop grain yield between CA and CT practices according different classes

Treatments	Weighted mean difference (kg ha^{-1})	
No-tillage ≤ 3 years	87.76	(36.62, 138.91)*
No-tillage > 3 years	-226.77	(-366.07, -87.46)*
No-tillage with mulch ≤ 3 years	294.21	(217.03, 371.39)*
No-tillage with mulch > 3 years	487.14	(380.62, 593.67)*
No-tillage with mulch and rotation	165.61	(25.74, 305.48)*
Seasonal rainfall < 600 mm	143.32	(88.98, 197.67)*
Seasonal rainfall 600 – 1000 mm	160.99	(80.78, 241.20)*
Seasonal rainfall > 1000 mm	348.44	(120.21, 576.67) *
Nitrogen fertilizer input<100 kg ha^{-1}	85.52	(-33.50, 204.55)
Nitrogen fertilizer input ≥ 100 kg ha^{-1}	390.62	(243.39, 537.85)*
Loamy soil texture	299.33	(257.92, 340.73)*
Sandy soil texture	71.26	(-65.78, 208.29)
Clayey soil texture	44.69	(-95.04, 184.42)

Values reported are weighted mean differences between CA and CT treatments with the 95% confidence intervals in parentheses. Confidence intervals that do not overlap with zero were considered significantly different (*).

negative impacts on crop production, which may be mainly due to a soil compaction or soil surface crusting (Baudron et al. 2012). A previous meta-analysis of worldwide tillage studies on maize under rainfed conditions (Rusinamhodzi et al. 2011) also reported lower yields under NT compared to CT during the first 10 years of the experiments. Govaerts et al. (2008) conducted a long-term study (1997-2005) assessing the effects of CA under rainfed conditions on crop performance and soil quality in contrasting environments in Mexico. They reported an overall yield reduction of 55% in crop grain yield under NT compared with CT. Reduction in yields was attributed to low soil aggregate stability, high soil penetration resistance, surface soil slaking, and high water runoff.

3.3. Effect of no-tillage with mulch on crop grain yield

Weighted mean differences of crop grain yield between NTM and CT tended to be higher when mulching is practiced over a longer period of time: 294 kg ha^{-1} for less than 3 years versus 487 kg ha^{-1} for more than 3 years (Table 2, Figure 3). The positive yield response under NTM indicates that mulch application is a major factor influencing the success of CA systems. Obtaining sufficient surface cover with crop residues in SSA by small-scale farmers is, however, very

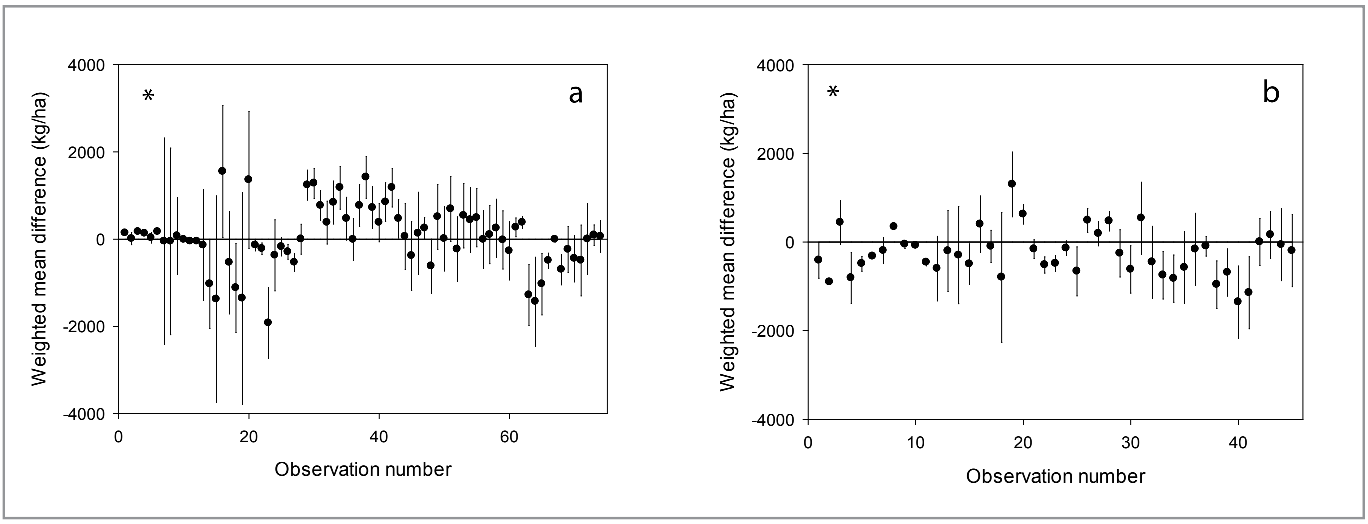

Figure 2. Weighted mean differences in crop grain yield in a) no-tillage/ reduced tillage without mulch and rotation (NT) compared with conventional tillage practiced for a period of less than 3 years; b) no-tillage/ reduced tillage without mulch and rotation compared with conventional tillage practiced for a period of more than 3 years. Error bars represent 95% confidence intervals. Significant difference of the overall effect size of NT is denoted by *.

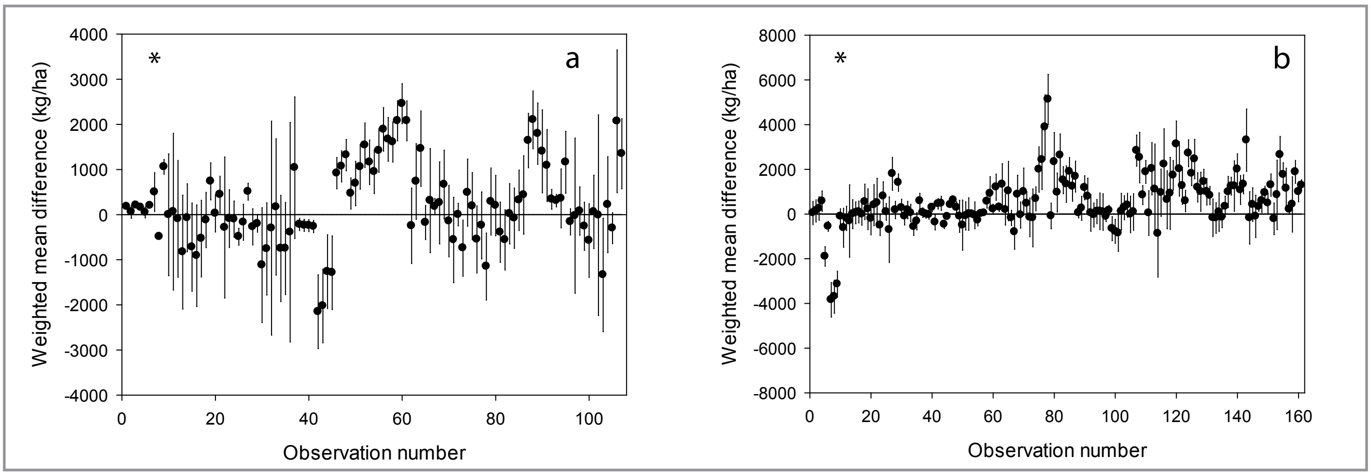

Figure 3. Weighted mean differences in crop grain yield in a) no-tillage/ reduced tillage with mulch and without rotation (NTM) compared with conventional tillage practiced for a period of less than 3 years; b) no-tillage/reduced tillage with mulch and without rotation compared with conventional tillage practiced for a period of more than 3 years. Error bars represent 95% confidence intervals. Significant difference of the overall effect size of NTM is denoted by *.

difficult to achieve owing to the multiple usage of crop residues, especially as fodder for livestock (Giller et al. 2009). Mulching is known to have a positive short-term effect on crop growth and productivity through increased soil water conservation (e.g. Scopel et al. 2004), and a positive long-term effect through enhancing soil carbon levels (e.g. Corbeels et al. 2006) and soil fertility in general (e.g. Govaerts et al. 2007). These results are, however, in contrast with those of Rusinamhodzi et al. (2011) and Nyamangara et al. (2014). Rusinamhodzi et al. (2011) found in their meta-analysis no effects of NTM on maize grain yields in the first 10 years of the experiments, and even negative effects later on. Similarly, Nyamangara et al. (2014) found in their meta-analysis for Zimbabwe no overall effect of mulching on crop yields.

3.4. Effect of no-tillage with mulch and rotation on crop grain yield

The weighted mean difference between CT and NTR was 166 kg ha^{-1} (Table 2, Figure 4). In about 90% of the studies, where crop rotation was practiced, maize was cultivated in rotation with a grain legume. Higher crop grain yield observed under NTR relative to CT can be attributed to combined effects of multiple factors like increased nitrogen inputs from biological nitrogen fixation in the case of legumes, enhanced water infiltration, increases of soil carbon and macro-faunal activity leading to better soil structure, and suppression of crop specific pests (e.g. Thierfelder et al. 2013). The results from this analysis are comparable to those reported by Rusinamhodzi et al. (2011) who showed significant maize grain yield increases under NTR with maize-legume rotation in their meta-analysis. However, these yield increases were only after about 10 years of NTR. Yield results from a long term tillage trial conducted by CIMMYT in El Batán, Mexico from 1997-2005 showed an increase in maize and wheat yields of 21% and 10%, respectively under NTR compared with CT (Govaerts et al. 2008). The results suggests that rotation should be an integral component of farmers' cropping practices and thus, for the full benefits of CA to be achieved farmers in SSA need to move from continuous mono cropping to associations and rotations that include crops of different types and preferably legumes. However, unless there is a ready market for the grain, smallholder farmers in SSA tend to grow grain legumes on a small proportion of their farm land, certainly not sufficient to provide a rotation across the farm (Giller et al. 2009).

3.5. Effect of seasonal rainfall

Overall, crop grain yields were 143, 161 and 348 kg ha^{-1} higher under CA compared to CT when growing season rainfall was < 600 mm, 600-1000 mm and > 1000 mm, respectively (Table 2, Figure 5). About 80% of the studies which reported significant yield increases under medium and higher growing season rainfall were on maize with the remaining 20% on the other crops, such as tef and rice. The significant yield increase with CA under high growing season rainfall (Figure 5b and 5c) may be due to the high level of variability in rainfall during the growing season, with occurrence of dry spells. The lower yields under CA highlighted in Figure 5c under high rainfall were reported by Anazodo et al. (1991), with mean maize grain yields of 1780 and 5620 kg ha^{-1} in 1984 under CA and CT respectively with growing season rainfall of 1200 mm and 650 and 4350 kg ha^{-1} in 1985 under CA and CT respectively with growing season rainfall of 1033 mm. In addition, the same study reported maize grain yield of 490 kg ha^{-1} under CA compared to 3630 kg ha^{-1} under CT with growing season rainfall of 1000 mm on a loamy sand (Figure 5b). The results from our meta-analysis are in contrast with findings from Rusinamhodzi et al. (2011) who found that maize yield was higher with CA practices when mean annual precipitation was below 600 mm and lower when mean annual precipitation was above 1000 mm. Also Nyamangara et al. (2014) found that a high rainfall regime (500–800 mm) resulted in lower weighted mean differences between CA and CT than a low rainfall regime (300–500 mm).The poor performance of crop grain yield under CA compared to CT under high rainfall conditions is often attributed to aeration problems resulting from waterlogging (Anazodo et al. 1991).

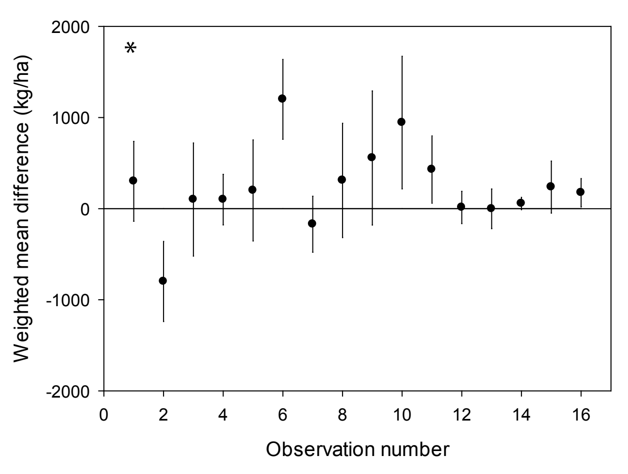

Figure 4. Weighted mean differences in crop grain yield in no-tillage/ reduced tillage with mulch and rotation (NTR) treatments compared with conventional tillage practice. Error bars represent 95% confidence intervals. Significant difference of the overall effect size of NTR is denoted by *.

3.6. Effect of soil texture

Crop grain yields on sandy and clay soils under CA were not significantly different from yields under CT (Table 2, Figure 6). The weighted mean differences were 72 and 45 kg ha^{-1} for the sandy and clay soils, respectively. In contrast, on loamy soils crop yields under CA treatments were overall significantly higher than that of CT, as indicated by the weighted mean difference of 299 kg ha^{-1}. Dickey et al. (1983) and Kapusta et al. (1996) reported a reduction of crop yields when CA is practiced on poorly drained soils. In our study, the outlier mean differences of crop grain yields on sandy soil texture (Figure 6c) were reported by Anazodo et al. (1991) and attributed to high soil compaction, weed infestation and aeration problems associated with waterlogging. The meta-analysis by Rusinamhodzi et al. (2011) showed higher maize grain yields under CA relative to CT on loamy and sandy soils, but negative on clayey soils. In general, crop yields are mostly reduced under CA under conditions of high rainfall and poor soil drainage which results in waterlogging, a phenomenon which typically occurs on granitic sandy soils that contain subsoil layers with high amounts of clay (Thierfelder and Wall 2012; Thierfelder et al. 2012). The observed increase in crop grain yields under CA (Figure 6a) on loamy soils may be partly related to the good water infiltration rate in these soils (Lal 1976; Mahboubi et al. 1993). There are likely to be important interactions between soil texture and other soil properties, in particular soil organic carbon, determining crop yield responses to CA. However, lack of reported data on soil properties in several studies did not allow an analysis of these interactions.

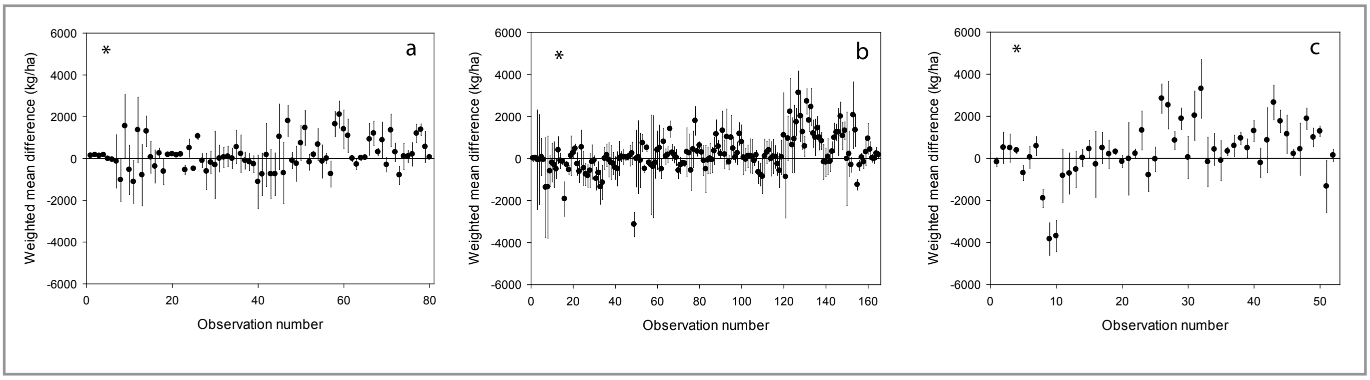

Figure 5. Weighted mean differences in crop grain yield in conservation agriculture practices (NT no-tillage/reduced tillage, NTM no-tillage with mulch, NTR no-tillage with mulch and rotation) compared with conventional tillage practices as affected by growing seasonal rainfall: a) <600mm ; b) 600 – 1000 mm; c) >1000mm. Error bars represent 95% confidence intervals. Significant difference of the effect size is denoted by *.

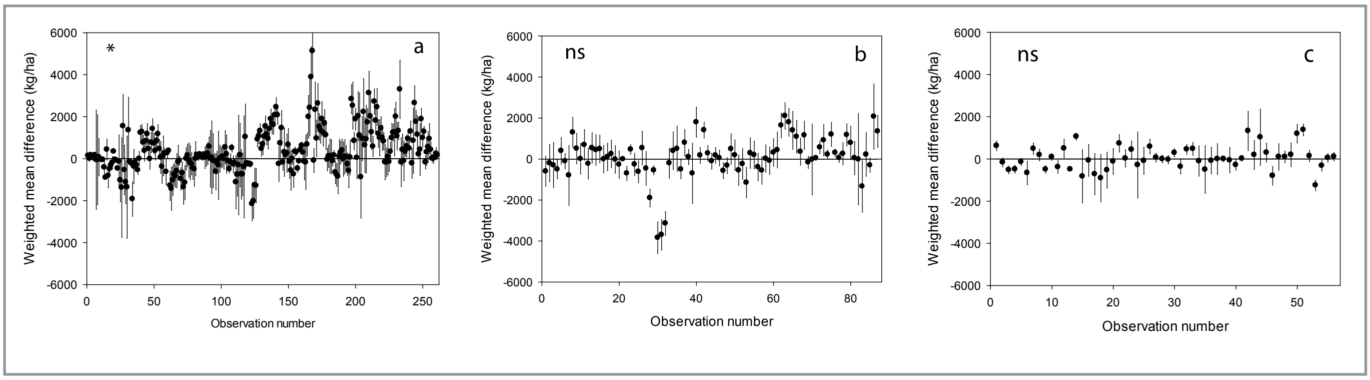

Figure 6. Weighted mean differences in crop grain yield in conservation agriculture practices (NT no-tillage/reduced tillage, NTM no-tillage with mulch, NTR no-tillage with mulch and rotation) compared with conventional tillage practiced as affected by soil texture: a) loamy soil, b) clayey soil, c) sandy soil. Error bars represent 95% confidence intervals. Significant difference of the effect size is denoted by *; ns denotes no significant difference.

3.7. Effect of nitrogen fertilizer application

Weighted mean differences in grain yields were significantly higher (391 kg ha^{-1}) than zero when nitrogen fertilizer input was higher than 100 kg ha^{-1}, but not (85 kg ha^{-1}) when N fertilization was lower than 100 kg ha^{-1} (Table 2, Figure 7). Studies reporting increases in crop grain yields under CA with low nitrogen fertilizer input are limited. A meta-analysis of tillage studies performed by Rusinamhodzi et al. (2011) in sub-humid and semi-arid regions showed lower maize grain yields under CA than under CT with low nitrogen input (<100 kg N ha^{-1}), and higher yields under CA compared to CT with high nitrogen input (≥ 100 kg N ha^{-1}). These results indicate that for crop yield to increase under CA, farmers need to increase their fertilizer application. The average fertilizer application rate by smallholder farmers in Africa is 8 kg ha^{-1} which implies that the fertilizer categories used in this meta-analysis are very high and do not reflect the application rate by farmers in SSA. Appropriate use of fertilizer is necessary in SSA for increasing crop productivity and the availability of crop residues for mulching (Vanlauwe et al. 2013). Nyamangara et al. (2014) found that the application of 10–30 kg ha^{-1} N (micro-dose range) resulted in a higher crop yield response to planting basins than zero nitrogen application.

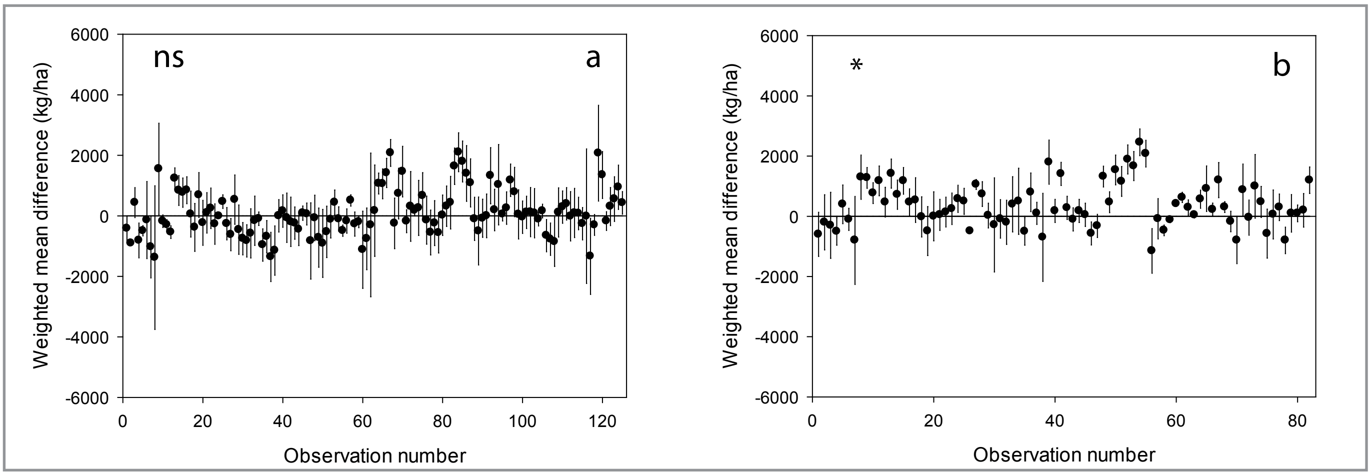

Figure 7. Weighted mean differences in crop grain yield in conservation agriculture practices (NT no-tillage/reduced tillage, NTM no-tillage with mulch, NTR no-tillage with mulch and rotation) compared with conventional tillage practiced as affected by nitrogen fertilization: a) low nitrogen fertilizer input of < 100kg N ha^{-1}; b) high nitrogen fertilizer input of ≥ 100 kg N ha^{-1}. Error bars represent 95% confidence intervals. Significant difference of the effect size is denoted by *; ns denotes no significant difference.

4. Conclusions

The meta-analysis of CA studies in SSA showed that crop grain yields are significantly higher in no-tillage treatments when mulch was applied and/or rotations were practiced in comparison to only no-tillage/reduced tillage without mulch and/rotation. These results suggest that for farmers to benefit from CA they should be able to keep their crop residues as mulch on the soil surface. Additionally, rotation should be an integral component of their cropping practice. These two components of CA are, however, for many smallholder farmers in SSA the bottlenecks to adopting CA. Crop residues have several other uses on the farm, in particular as feed for livestock. In many cases, legumes or other non-cereal crops gain limited interest, as ready markets for sale are often not available. A clear response of crop yield to CA with N fertilizer application leads to the conclusion that farmer ability to use fertilizer in sufficient quantities and correct proportions is needed for CA. In general, the use of fertilizer is necessary in SSA to enhance crop productivity and organic residue availability for mulching. Our study did not differentiate a rainfall regime as being better for successful implementation of CA. On the other hand, the analysis suggests that CA works better on loamy soils compared to sandy or clay soils.

In our study we encountered problems with access to treatment means and standard deviations for some of the reported CA experiments in the peer-reviewed literature. Relatively few papers reported on the effects of all three CA principles on crop yield, giving less attention to the principle of crop rotations/associations. This pleas for a more coherent approach to design CA research between research institutions at a continental and even global scale, addressing thematic and geographic research gaps and data completeness of field experiments. Ongoing and future empirical studies must report a minimum dataset encompassing valid statistical measures and comprehensive intervention descriptions that enable standardization and systematic approaches in quantitative syntheses. This minimum dataset should include an array of descriptive and measured information; a good example of a minimum dataset is given by Brouder and Gomez-McPherson (2014). Data sharing and open access should also be practiced to allow further informative analyses of existing data.

Most of the published studies used in the meta-analysis did not report on rainfall distribution within the season. Considering the seasonal rainfall distribution would, however, help in assessing CA practices for their resilience to future climate change with increased rainfall variability. The potential benefits from the practice of CA on the soil water balance has been the foundation for advocating CA as a technology to cope with a changing climate with erratic rainfall (Kassam et al. 2009). This potential has been theoretically shown in a crop growth modeling analysis for a case study in Zimbabwe (Corbeels et al. 2014). Model predictions suggest that 30% yield reductions in maize production under CT as a result of changing climate (15% less rainfall with 15% more within-season variability and higher temperatures of +1.1°C on average) in sub-humid southern Africa could be compensated by adopting no-tillage with mulching. The results of our meta-analysis, however, do not show a better performance of CA under dryer rainfall regimes compared to wetter regimes. On the other hand, a worthwhile point to mention with respect to (climate) risks for smallholder farmers is the finding from this meta-analysis that there is less variation in weighted mean difference in no-tillage systems with rotations compared to the other systems without rotation, which suggests more crop yield stability with the use of crop rotations.

A further analysis of the data is needed using linear-mixed models in order to better understand the relative importance of the different factors (climate, soil and management) and their interactions on explaining the variation in crop yield under CA compared to CT.

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Conservation agriculture practices are increasingly promoted on smallholder farms in sub-Saharan Africa as a means to overcome poor profitability and soil degradation. In recent years a growing number of studies have been carried out in sub-Saharan Africa comparing conservation agriculture practices to conventional tillage-based practices. This meta-analysis compares and combines the results of these studies. It aims to identify patterns, sources of disagreement, or interesting relationships that may come to light in the context of the different studies.

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