

Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanz...

Hodson Makurira


Agricultural Water Management

Cite this paper

Downloaded from [Academia.edu](#) 

[Get the citation in MLA, APA, or Chicago styles](#)

Related papers

[Download a PDF Pack](#) of the best related papers 



[Effect of minimum tillage and mulching on maize \(Zea mays L.\) yield and water content of cla...](#)

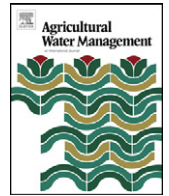
Walter Mupangwa

[Measuring and simulating maize \(Zea mays L.\) yield responses to reduced tillage and mulching under ...](#)

Walter Mupangwa

[Effect of Conservation Agriculture on Maize Yield in the Semi-Arid Areas of Zimbabwe](#)

Walter Mupangwa



Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanzania

Elin Enfors^{a,c,*}, Jennie Barron^{b,c}, Hodson Makurira^d, Johan Rockström^{b,c}, Siza Tumbo^e

^a Department of Systems Ecology, Stockholm University, Sweden

^b Stockholm Environment Institute (SEI), Sweden

^c Stockholm Resilience Center, Stockholm University, Sweden

^d Department of Civil Engineering, University of Zimbabwe, Zimbabwe

^e Soil Water Management Research Group, Sokoine University of Agriculture, Tanzania

ARTICLE INFO

Article history:

Available online 7 April 2010

Keywords:

Conservation tillage

Ripping

Agricultural droughts

In situ water harvesting

Maize yields

Soil health

Short- and long-term effects

Tanzania

ABSTRACT

Yield levels in smallholder farming systems in semi-arid sub-Saharan Africa are generally low. Water shortage in the root zone during critical crop development stages is a fundamental constraining factor. While there is ample evidence to show that conservation tillage can promote soil health, it has recently been suggested that the main benefit in semi-arid farming systems may in fact be an *in situ* water harvesting effect. In this paper we present the result from an on-farm conservation tillage experiment (combining ripping with mulch and manure application) that was carried out in North Eastern Tanzania from 2005 to 2008. Special attention was given to the effects of the tested treatment on the capacity of the soil to retain moisture. The tested conservation treatment only had a clear yield increasing effect during one of the six experimental seasons (maize grain yields increased by 41%, and biomass by 65%), and this was a season that received exceptional amounts of rainfall (549 mm). While the other seasons provided mixed results, there seemed to be an increasing yield gap between the conservation tillage treatment and the control towards the end of the experiment, and cumulatively the yield increased with 17%. Regarding soil system changes, small but significant effects on chemical and microbiological properties, but not on physical properties, were observed. This raises questions about the suggested water harvesting effect and its potential to contribute to stabilized yield levels under semi-arid conditions. We conclude that, at least in a shorter time perspective, the tested type of conservation tillage seems to boost productivity during already good seasons, rather than stabilize harvests during poor rainfall seasons. Highlighting the challenges involved in upgrading these farming systems, we discuss the potential contribution of conservation tillage towards improved water availability in the crop root zone in a longer term perspective.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The productivity of the smallholder farming systems that constitute the main livelihood source in sub-Saharan Africa is low (Sanchez, 2002; Conway and Toenniessen, 2003; Diao et al., 2007), with yield levels in the semi-arid and dry sub-humid regions averaging some 20–50% below what is achievable (Falkenmark and Rockström, 2004). Although this is a complex problem, linked to a number of biophysical and socio-economic factors (Reynolds et al., 2007), water shortage in the root zone during critical crop development stages is a fundamental issue (cf. Slegers and Stroosnijder,

2008). This is the result of a highly variable rainfall regime, leading to frequent dry-spells (Barron et al., 2003), in combination with large un-productive flows in the field water balance (Rockström and Falkenmark, 2000). The latter is related to climatic factors, to soil characteristics, and to land management. As the rain typically falls as high intensity storms in these climates, run-off rates are high and infiltration rates low, and high temperatures lead to high evaporation rates (Rockstrom, 1999). Further, conventional tillage by ploughing (and to a lesser extent hand hoeing) often cause crusting, compaction, and loss of structural stability in vulnerable dryland soils, leading to inefficient use of the water that is left (Mrabet, 2002; Roldan et al., 2003).

Over the past decades, conservation tillage (CT) has been promoted as a way to maintain and build up soil structure and fertility in tropical agro-ecosystems (Benites et al., 1998; Bolliger et al., 2006; Hobbs et al., 2008). CT includes a range of technologies aiming to conserve soil and water resources in the field, by minimizing

* Corresponding author at: Department of Systems Ecology/Kräftan, Stockholm University, SE-106 91 Stockholm, Sweden. Tel.: +46 073 707 86 20; fax: +46 08 15 84 17.

E-mail address: elin@ecology.su.se (E. Enfors).

soil disturbance and by maintaining a permanent organic soil cover (Steiner, 2002). In contrast to conventional tillage (with hand hoe or plough) the soil is not inverted when preparing the land in CT systems, and all or part of the plant residues are left on the field after harvesting (Fowler and Rockstrom, 2001). While there is an abundance of field studies that support the beneficial impact on soil health (for examples on chemical, physical and biological properties, see e.g. Lal, 1997b; Roldan et al., 2003; Brevault et al., 2007), it has more recently been suggested that the main benefit of CT systems in water scarce tropical environments in fact is an *in situ* water harvesting effect (McHugh et al., 2007; Rockström et al., 2009).

There are three main processes that potentially could promote such an effect, related to CT induced changes in the partitioning points of the field water balance. First, the increased surface roughness created by the soil structure and cover in CT systems slows down water flows, thereby increasing infiltration (Fowler and Rockstrom, 2001; Gicheru et al., 2004; Zhang et al., 2007; Knapen et al., 2008). The soil cover also minimizes the impact of raindrops; making the soil surface less prone to sealing and crusting, further promoting infiltration. Second, a permanent soil cover reduces evaporation, leaving more water in the soil (Fowler and Rockstrom, 2001). Third, organic matter levels build up under CT, both as plant residues remain on the field and as organic matter is not oxidized to the same degree when the soil is not inverted, improving the soil's aggregate stability and potentially also its capacity to retain moisture (see e.g. Zibilske et al., 2002; Roldan et al., 2003; Lal, 2006; Nyamadzawo et al., 2008). The absence of intensive tillage that pulverizes the soil, also improves the structural stability over time (Machado and Silva, 2001; Mrabet, 2002), forming more macropores (Kay and VandenBygaart, 2002; Zhang et al., 2007), which further would enhance the capacity of the soil to store water. Consequently, CT has the potential to shift the field water balance in a way that increases water availability in the root zone.

While this makes sense in theory, there is still limited systematic evidence for water-related CT benefits in smallholder systems in semi-arid and dry sub-humid SSA. Although the effects on infiltration and evaporation are better understood (see Rockström et al., 2009), the understanding of the degree to which the water holding capacity of the soil could be ameliorated is rather poor. Representing a resilient system property, the latter is however crucial for the system's ability to bridge dry-spells. Here we present the result from a participatory on-farm conservation tillage experiment that was carried out in semi-arid Tanzania from 2005 to 2008. Yields were measured for six consecutive seasons, and changes in bulk density, available water holding capacity, and soil organic matter (SOM) levels were studied to evaluate the effects of the tested conservation treatment, which combined ripping with mulch- and manure application, on the capacity of the soil to retain moisture. A range of other chemical and biological soil variables was also monitored to assess the overall soil system effects of the tested CT treatment.

2. Methodology

2.1. Site description

The Makanya catchment, which covers 320 km², lies wedged between two mountain ridges in the South Pare Mountains, Tanzania (Fig. 1a). The catchment area has a total population of about 35,000 people, primarily relying on small-scale rainfed farming, which is non-mechanized and involves little external inputs. The dominating crop is maize, and regionally harvests average just above 1 t/ha (FAO, 2008). The climate is semi-arid, and the rain pattern is bimodal, with a longer rainy season, locally referred to as *Masika*, between March and June and a shorter rainy season,

locally referred to as *Vuli*, between October and December. Average annual rainfall at Same, where the nearest meteorological station with a long-term data record is located (4°04'16"S, 37°44'10"E), is 562 mm. However, the rainfall variability is high both within and between years, intra-seasonal dry-spells constituting a major problem for local farmers (Barron et al., 2003; Enfors and Gordon, 2007). High potential evaporation, high run-off rates, and low water holding capacity of the soil further reduces the availability of water for crop production (Fig. 1b) (Makurira et al., 2007). Other limiting factors include poor soil fertility (most of the soils are Ferralsols), insect pests, and lack of labour and farm implements.

2.2. Experimental design

The participatory on-farm experiment, in which maize (*Zea Mays*) was grown under different treatments, was set up as a split-plot block design, with six experimental blocks at three different farms located mid-slope in the Makanya catchment. The blocks represented a range of typical environmental conditions in a semi-arid smallholder farming setting. The experiment ran for six consecutive seasons, from *Masika* 2005 to *Vuli* 2007/2008 (hereafter referred to as M05, V05/06, M06, V06/07 etc.).

Each experimental block contained four 10 m × 10 m treatment plots; one control plot cultivated with hand hoe (C); one plot cultivated with hand hoe, which was covered by a mulch from maize residues + a grown cover crop (to reduce evaporation and promote organic matter levels) and got inputs of locally available farmyard manure (to promote organic matter and nutrient levels) (CM); one plot cultivated with ripper (R); and one conservation tillage plot cultivated with ripper, but with mulch and manure (as above) (RM) (Table 1). In addition to these treatments, a fifth treatment plot (SI) was set up adjacent to one of the blocks (I2). Managed as a RM-plot but with supplemental irrigation from a rainwater harvesting system that diverts water from an external catchment via a gully to the plot, this was included to assess the combined effect on yields from conservation tillage and supplemental irrigation. The SI plot was set up during the second experimental season (V05/06). The particular experimental set-up, including the participatory aspects as well as the diversity of field sites and the tested treatments, was chosen to make sure that results arising from the experiment would be applicable and meaningful in a semi-arid smallholder farming systems context. Fig. 2 illustrates the layout of blocks and plots. The characteristics of the blocks are described in Table 2.

2.3. Experimental management

All farming operations in the experiment, such as land preparation, weeding, and pest management, were done by the three respective farmers. To ensure comparability of the results they followed the same protocol for these operations. Harvesting, as well as other on-farm measurements, was conducted in a participatory manner. Land preparation was done before the on-set of the rains, practicing dry planting as recommended by local extension services. The ripper lines, which were approximately 5–7 cm broad and 20–30 cm deep, were placed perpendicular to the slope of the field, with a spacing of 75 cm. The same ripper lines were used in R and RM plots every season to ensure maximum infiltration and maximum benefit of the manure, as well as to ensure that the soil in between the ripper tracks was left undisturbed throughout the experiment. Oxen were used for traction of the ripper. The maize was planted with a spacing of 30 cm between plants in R and RM plots, and with 50 cm between planting pits in C and CM plots, using three seeds per hill in all plots. To ensure comparability between the plots within each block, plant density was adjusted by thinning after germination. Seed varieties were chosen in consultation with the local farmers; who opted for TMV-1 during the two first sea-

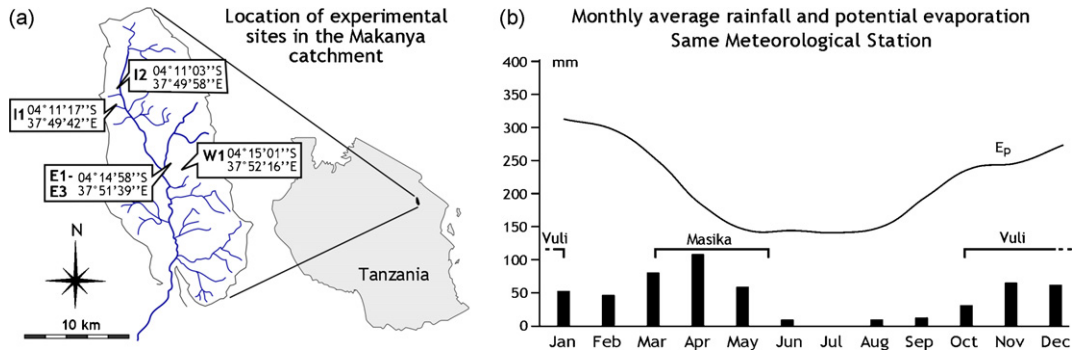


Fig. 1. (a and b) The experimental site. (a) The location of the Makanya catchment in North Eastern Tanzania as well as the location of the experimental sites in the catchment. (b) The relation between average monthly rainfall and potential evaporation in the area.

Table 1
Description of the treatments.

Plot	Treatment
C (control)	Conventional tillage with hand hoe, complete soil inversion to 15 cm depth, planting pits formed No inputs
CM	Conventional tillage with hand hoe, complete soil inversion to 15 cm depth, planting pits formed Seasonal application of farmyard manure in planting pits (5 t/ha wet weight, where the dry weight on average contains 1.1% N; 0.024% P; 0.6% K ^a) Soil surface covered by mulch, consisting of maize residues and a planted leguminous cover crop (Lablab beans during <i>Masika</i> seasons and Cowpeas during <i>Vuli</i> seasons)
R	Deep tillage to 20–30 cm using Magoye ripper without wings (see e.g. Baudeon et al., 2007). Ripper lines arranged perpendicular to the slope of the field, 5–7 cm wide and at a spacing of 75 cm, soil between ripper lines undisturbed (~80% of surface) No inputs
RM	Deep tillage to 20–30 cm using Magoye ripper without wings. Ripper lines arranged perpendicular to the slope of the field, 5–7 cm wide and at a spacing of 75 cm, soil between ripper lines undisturbed (~80% of surface) Seasonal application of farmyard manure in ripper lines (5 t/ha wet weight, on average containing 1.1% N; 0.024% P; and 16% OM) Soil surface covered by mulch, consisting of maize residues and a planted leguminous cover crop (Lablab beans during <i>Masika</i> seasons and Cowpeas during <i>Vuli</i> seasons)

^a The data is based on measurements from three seasons only, and the numbers should therefore be seen as an indication of the quality of the manure rather than as absolute values.

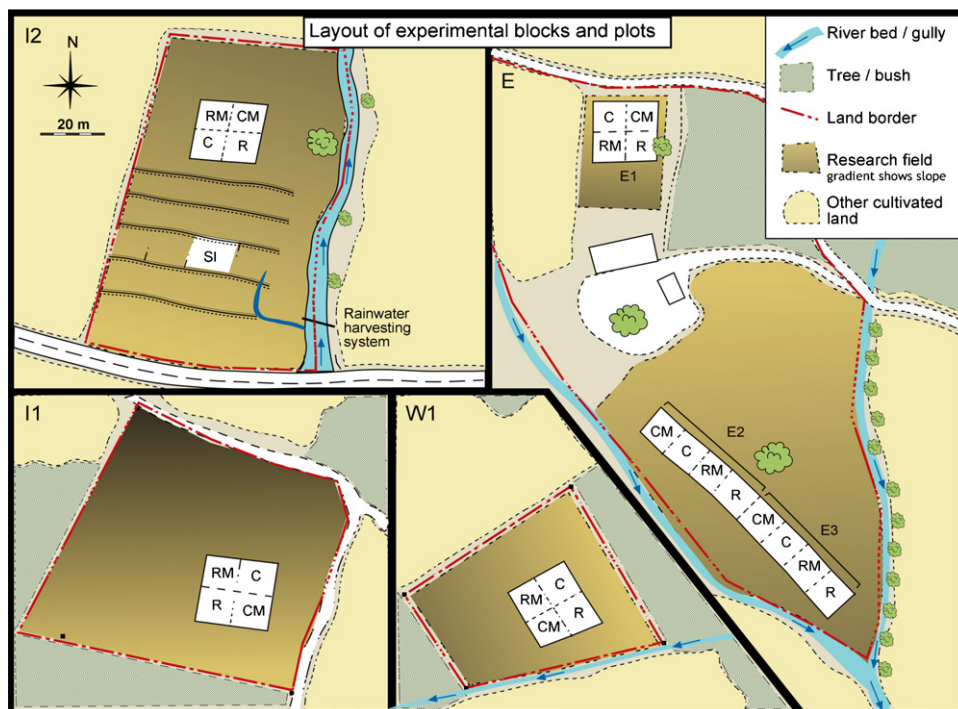


Fig. 2. The experimental set-up. The figure illustrates the location of the experimental blocks in the landscape and the layout of plots in the various blocks.

Table 2
Description of the experimental blocks.

	Soil classification (FAO)	Description	Farming history
I1	Ferric Cambisol	Relatively deep loam/sandy clay loam (>2 m), moderate slope (5%), surrounded by bush-land	In (bush-) fallow during the past 50 years, land cleared for the experiment
I2/SI	Rhodic Ferralsol	Moderately deep sandy clay loam (>1.5 m), moderate slope (4%), located near valley bottom	Continuously cultivated with maize and beans for at least 25 years, ploughed since 1997
E1	Rhodic Ferralsol	Shallow sandy clay loam (<50 cm) with lots of stones through out profile, moderate slope (5%)	Has been cultivated one season per year with maize, cassava and beans for at least two generations, occasional SI
E2	Rhodic Ferralsol	Moderately deep (>1.5 m) sandy loam, gently sloping (2%), located next to large gully	Has been cultivated one season per year with maize, cassava and beans for at least two generations, occasional SI
E3	Rhodic Ferralsol	Moderately deep (>1.5 m) sandy loam, with stones throughout soil profile, gently sloping (2%), located next to large gully	Has been cultivated one season per year with maize, cassava and beans for at least two generations, occasional SI
W1	Rhodic Ferralsol	Moderately deep loam/sandy clay loam (>1.5 m), steep slope (13%), stones through profile, crust prone surface with rills, on hill side	Cleared in 1997, cultivated for 3 years with maize, sorghum and pumpkin, in fallow from year 2000 until the start of the experiment

sons, and Kito for the remaining seasons. The cover crop, consisting of lablab beans and cowpeas, was planted between the ripper lines in the RM plots, and between the planting pits in the CM plots. To avoid competition over water during the sensitive establishment stage, the legumes were planted once the maize had reached 30 cm height. Local varieties of lablab and cowpeas were used. In addition to providing soil cover, these crops also gave the farmers an additional income source. The plots were weeded manually twice per season. Pests were controlled continuously. All residues were left on CM and RM plots after harvesting, whereas C and R plots were completely cleared. While we aimed at having at least 30% of the soil covered by mulch at all times, in reality this varied both between seasons and over the season from around 20% up to 100%.

2.4. Measurements

Before the first experimental season (in February 2005) soil sampling was conducted to determine baseline data for all experimental plots including soil types, and a range of chemical and physical properties. Composite samples at three depths (0–10 cm, 20–30 cm and 40–50 cm) were used for the analysis of particle size, pH, N (total, NH_4^+ , NO_3^-), P (total and available), organic matter, CEC, exchangeable bases, electric conductivity, and micronutrients. Core samples were taken, with three replicates at three depths (0–10 cm, 20–30 cm and 40–50 cm), for the analysis of bulk density, porosity, and available water holding capacity (defined as the difference in soil water content between field capacity and wilting point). The same soil sampling and analysis, adding an assessment of the microbiological activity (basal respiration, microbial biomass and N-mineralization), was repeated after the last experimental season (in February 2008). RM plots were sampled both between (RM_1), and within the ripper lines (RM_2). Seasonal on-farm measurements included nutrient content in the manure, biomass development, harvest (total wet weight, grain dry weight, 1000-grains weight), and daily rainfall.

2.5. Data analysis

Variation in dry grain yield and total aboveground dry biomass was analyzed using a two-way ANOVA for (a) each season, testing block and treatment effects and (b) each block, testing season and treatment effects. Where significant treatment differences were found, *t*-tests were used in a post hoc analysis to evaluate how the treatments differed from the control. To meet the criteria for the ANOVA analysis the data was log-transformed, which reduced the rainfall-induced differences in yield levels between seasons.

Variation in organic matter, bulk density, available water holding capacity, total nitrogen, mineralizable nitrogen, and microbial biomass and respiration was analyzed in the same way, among the soil samples from the initial and final sampling events respectively, testing for block, season, and treatment effects. Where significant treatment effects were found, *t*-tests were conducted as above. We did not directly compare the initial and final data sets since the two soil sampling batches could not be analyzed at the same laboratory. Thus, we report on the relation between the treatments plots in the final measurements as compared to how they related to each other in the initial measurements. This reflects the type of effect (and relative magnitude) that CT has on the soil system, as compared to conventional tillage, rather than the absolute magnitude of soil system change during the experiment. For grain yield, biomass and soil analyses the significance levels $p < 0.05$ (*) and $p < 0.01$ (**) are used.

3. Results

3.1. Yield effects

Both cumulative rainfall and rainfall distribution differed substantially between the experimental seasons. M05, V05/06, and M07 were low rainfall seasons, receiving less than 165 mm. During V05/06 only 99 mm of rain fell, and most crops in the area, including those on the experimental plots, failed completely. Two seasons, M06 and V07/08, received 250–350 mm, which is about the long-term seasonal average for the area. V06/07 was exceptionally good in terms of rainfall, with 549 mm. Fig. 3 shows a timeline for each experimental season, indicating the rainfall distribution as well as the timing of major crop management events.

The variable rainfall led to large differences in grain yield and biomass between the seasons, and all blocks, showed significant seasonal effects. The variation was high within seasons too, and there was a significant block effect in all seasons, except for M06. Table 3a and b shows the average grain yield and biomass per treatment for each season.

Since the first two experimental seasons were severely affected by drought, the cover crop did not develop and only few crop residues were available, which meant that no proper soil cover was achieved during these seasons. Consequently, starting M06, the conservation treatment had not yet been properly functioning. Interestingly, although the rainfall level only was slightly above the average, this season showed dramatically different results. Yield levels were high and relatively uniform throughout the experiment, averaging just above 2 t/ha. This homogeneity is likely explained by the low residual treatment effects from proceeding seasons, in com-

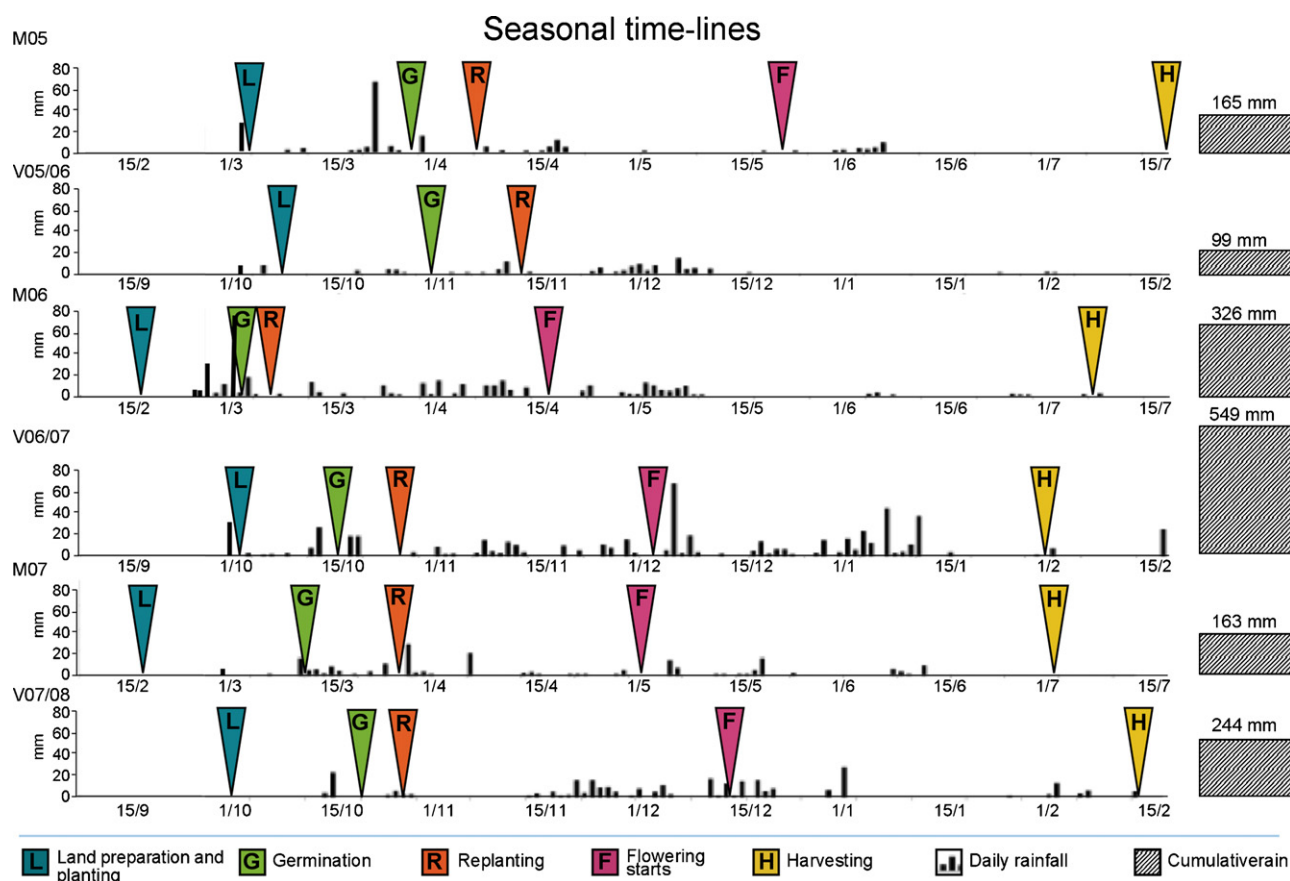


Fig. 3. Time-lines for the experimental seasons. The figure shows rainfall distribution and cumulative rainfall between planting and harvesting for all experimental seasons. It also shows the timing of major events during the growing season, such as land preparation and planting, flowering, and harvesting.

bination with a close to ideal rainfall distribution after that the first rain of the season (measuring 80 mm) had saturated the soil profile and averaged out potential tillage differences. It is interesting to note the large difference in harvest between M06 and V07/08, averaging around 2300 kg ha⁻¹ and 700 kg ha⁻¹ respectively (Table 3a). While the difference in cumulative rainfall only was 82 mm, the rainfall dynamics and distribution varied distinctively (see Fig. 3). The poorly defined on-set and the long dryspell during the estab-

lishment phase in V07/08 probably accounted for the large yield gap.

The only season that resulted in a clear treatment effect was the high rainfall season V06/07 (Table 3a and b). Both grain yield and biomass were significantly higher for the RM treatment, averaging at 2934/10572 kg ha⁻¹, than for the control, averaging at 2075/6412 kg ha⁻¹ ($p = 0.011$; 0.002). This translates to a grain yield improvement of 41% and a biomass improvement of 65%. With an

Table 3

(a and b) Average grain yield (a) and biomass yield (b) per treatment and season, including standard errors. There is a large variation in yields both between and within seasons. Especially the first two yielding seasons provide mixed results. Only V06/07 show a clear treatment effect for both yield and biomass. During the subsequent seasons there seems to be a tendency towards a treatment effect, in terms of improved productivity on RM plots. */**marks treatments that significantly differed from the control.

(a)	M05 ^a (kg ha ⁻¹)		V05/06 (kg ha ⁻¹)		M06 (kg ha ⁻¹)		V06/07 (kg ha ⁻¹)		M07 ^b (kg ha ⁻¹)		V07/08 ^c (kg ha ⁻¹)	
	Grain	S.E.	Grain	S.E.	Grain	S.E.	Grain	S.E.	Grain	S.E.	Grain	S.E.
C	321	99	0	–	2584	314	2075	583	392	194	512	232
CM	257	139	0	–	2295	173	2388	286	493	178	737	328
R	215	141	0	–	1969	403	1763	440	204	106	511	201
RM	310	204	0	–	2390	233	2934*	270	489	116	957	422
Prob. for no effect	0.82		NA		0.24		0.01		0.11		0.33	
(b)	M05 ^a (kg ha ⁻¹)		V05/06 (kg ha ⁻¹)		M06 (kg ha ⁻¹)		V06/07 (kg ha ⁻¹)		M07 ^b (kg ha ⁻¹)		V07/08 ^c (kg ha ⁻¹)	
	Biom.	S.E.	Biom.	S.E.	Biom.	S.E.	Biom.	S.E.	Biom.	S.E.	Biom.	S.E.
C	1709	425	0	–	6583	501	6412	1741	1457	472	1941	225
CM	1644	382	0	–	5674	340	8529*	1256	1915	559	2372	334
R	1345	452	0	–	5076	796	7012	1817	1080	335	1921	154
RM	1994	834	0	–	6292	529	10572**	1153	2337	517	3114*	434
Prob. for no effect	0.46		NA		0.26		0.01		0.26		0.02	

^a Block E3 is excluded due to complete crop failure.

^b Block E1 and E3 are excluded due to complete crop failure.

^c Block E3 is excluded due to crop failure, W1 excluded due to external disturbance.

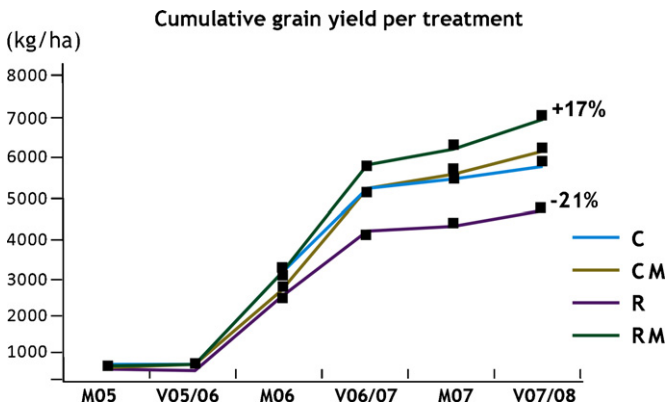


Fig. 4. Cumulative yield. The figure illustrates the cumulative yield per treatment (in kg ha^{-1}), across all blocks, as the experiment proceeds. Overall, 17% more maize was harvested from the RM treatment plots as compared with the control. The R treatment plots yielded 21% less than the control. CM plots performed very similarly to the control.

average biomass harvest of 8529 kg ha^{-1} , the CM treatment also yielded significantly better than the control ($p=0.034$), but no clear effect was seen on grain yield.

While the differences in rainfall between seasons make it difficult to discern any clear trends, there is a tendency towards a more pronounced treatment effect, in terms of RM treatments yielding better than the control, as the experiment progressed after V06/07 (Table 3a and b). During M07, which only received 163 mm of rain, there was a tendency towards an effect on grain yield ($p=0.11$, see Table 3a), and to a lesser extent on biomass (Table 3b). During V07/08, which received about the average amount of rainfall although it was poorly distributed, there was a significant effect on biomass yield ($p=0.02$, Table 3b), but the effect on grain yield was less clear (Table 3a). The CM treatment showed a similar trend (in relation to C and R), albeit the yield gap is smaller. Somewhat surprisingly, the average R treatment yielded less than the other treatments throughout the experiment. Although the first two yielding seasons (M05 and M06) provided mixed results due to reasons discussed above, these differences were also seen when looking at cumulative grain yield per treatment for the whole experiment (Fig. 4). Overall, 17% more grain was harvested from the RM plots as compared to the control, whereas R plots yielded 21% less. Taken as a whole, the CM plots performed very similar to the control, although the yield gap seemed to increase towards the end of the experiment.

No significant treatment effects were found within the individual blocks. However, when including the supplemental irrigation treatment in the analysis, block I2 showed a clear trend towards a treatment effect in terms of grain yield ($p=0.096$). Although it should be noted that this is based on data from only three seasons¹ (M06, M07, and V07/08), the difference was large. During M06 the SI plot yielded 4800 kg ha^{-1} as compared to the control (in the same block) at 3142 kg ha^{-1} , during M07 it yielded 1205 kg ha^{-1} as compared to the control at 907 kg ha^{-1} , and during V07/08 it yielded 3463 kg ha^{-1} as compared to the control at 838 kg ha^{-1} . This translates to an average yield improvement of 94%.

¹ There is only reliable data for the SI treatment from these seasons since this plot was set up one season later than the other plots, which was a meteorological drought that resulted in complete crop failure, and since the plot was disturbed during V06/07.

3.2. Effects on soil properties

Data from all six experimental blocks at both sampling events confirm that the soil quality in the area is poor, with low organic matter content, very low levels of total nitrogen, and limited capacity to retain moisture. While there were no significant differences between the treatment plots when setting up the experiment (data not shown since no tendencies towards a difference were seen), the analysis of the data from the final soil sampling revealed significant treatment effects in selected soil chemical and microbial characteristics (Tables 4 and 5). These were most pronounced in the 0–10 cm layer, but to some extent also visible at 20–30 cm soil depth.

Regarding chemical properties, SOM content showed a statistically significant increase in the top soil from an average of 1.38% in C treatments to an average of 1.62% in RM treatments (RM₂, Table 4). The CM treatment had an average of 1.56%, suggesting that the additional organic matter input of mulch and manure altered this treatment too, although somewhat slower. While the change in overall stocks of organic matter is not statistically significant, the measurements suggest that SOM increased in RM and CM treatments as compared to the control (17.8 and 17.1 vs. 15.9 kg m^{-3}), confirming the carbon sequestration effect. As expected, the nitrogen content shows similar trends. The N_{tot} levels in RM₂ top soil samples, averaging at 0.107%, were significantly higher than those in C samples, which averaged at 0.082%. The CM treatment was intermediate, with an average 0.095%. The R treatment had lower levels of both SOM and N_{tot} than all other treatments, corresponding to the low yields obtained from this treatment.

No clear treatment effects could be identified in the proxies for soil physical characteristics (Table 4). Top soil bulk density measurements from the ripper lines of RM plots (averaging at 1.39 g cm^{-3}) provided the overall lowest values, indicating that the management regime of permanent ripper lines in combination with continuous organic matter inputs may improve porosity, as compared to conventional management. However, the differences were very small and the change not statistically significant. Moreover, the potential density change is not reflected in the available water holding capacity, which displayed large within treatment variations and no significant treatment effects. Similar results were reported by Lal (1997a) from a long-term conservation tillage experiment in Nigeria.

While no treatment effect was seen on microbial biomass-C, the respiration in the 0–10 cm layer doubled from $175 \mu\text{g CO}_2 \text{ g}^{-1}$ in the C samples to $356 \mu\text{g CO}_2 \text{ g}^{-1}$ in the RM₂ samples (Table 5). This is somewhat surprising, since it suggests that the increased substrate availability merely promotes activity in the already existing microbiological community rather than stimulating its growth. Data from a previous study by Hällén (2007), conducted on the same experimental fields² during V06/07, both showed significant increases in respiration rates and in the amount microbial biomass-C for the RM treatment as compared with the control, suggesting that conservation tillage with mulch actually promotes both microbiological proliferation and activity. The same study also presented strong indications that the RM treatment conferred changes in the composition of the microbial community.

4. Discussion

4.1. Short-term and long-term system changes

Overall, the tested conservation tillage treatment yielded close to 20% more than the conventional management strategy. Return-

² Excluding E2 and E3, but including I2 SI.

Table 4

Effects on soil chemical and physical properties. The table shows average content of organic matter, total nitrogen, bulk density and available water holding capacity (AWHC) at 0–10 cm, and average stocks of organic matter in the sampled soil profile (0–50 cm), per treatment in the final soil sampling. */** marks treatments that significantly differed from the control.

	Soil organic matter (%)	Total nitrogen (%)	Bulk density (g cc ⁻¹)	AWHC (%)	Stocks of SOM (kg m ⁻³)
C	1.38	0.082	1.44	11.6	15.9
CM	1.56	0.095	1.43	12.0	17.1
R	1.25	0.072	1.50	11.5	15.6
RM ₁	1.43	0.089	1.46	12.1	16.9
RM ₂	1.62*	0.107**	1.39	11.3	17.8
Probability for no treatment effect	<i>p</i> = 0.02	<i>p</i> = 0.01	<i>p</i> = 0.28	<i>p</i> = 0.97	<i>P</i> = 0.20

ing to the hypothesis discussed in the introduction, does this mean that CT promotes *in situ* water harvesting in this type of faming systems? Considering that we neither saw a clear treatment effect during the low and intermediate rainfall seasons, nor did we see any positive impact on the soil physical variables that are key for the soil's capacity to retain water, the answer appears to be no. However, as deliberated in the discussion below, we suggest that the answer is more complex than what first appears.

The only season when the conservation tillage treatment had a clear impact on productivity was V06/07, which at 549 mm received well above the average amount of rainfall (the grain yield increased by 41%). A probable explanation is that the high water availability enabled better use of nutrients (that had been building up over the three previous yielding seasons) on RM treatment plots. However, had this been the entire explanation, the CM treatment plots would have performed equally well, which they did not. Consequently, the combination of ripping and application of mulch and/or manure promotes some kind of positive synergy effect, which is not obtained by only applying mulch and/or manure to a conventionally tilled field, and definitely not by only changing the tillage from hand hoeing to ripping, which was the poorest yielding treatment across all blocks and seasons (we return to this issue below). We lack data to determine exactly what constitutes the synergy effect, but there are several plausible explanations; e.g. that more water becomes available in the ripper lines through increasing infiltration, that root development improves with this type of tillage, and/or that ripping develop desirable but temporary effects on pore size distribution.

While both the grain yield and biomass results since V06/07 indicate that treatment effects may become more pronounced over time, the effect was not convincing during either of the subsequent seasons, which received low to average amounts of rainfall with poor distribution. Thus, the assumed *in situ* water harvesting was not sufficient to bridge dry-spells of the magnitude that occurred (see Fig. 3). Therefore we conclude that, at least in a shorter time perspective and under these soil and climate conditions, the tested type of conservation tillage may boost productivity during seasons that already are good (i.e. high and/or well distributed rainfall), rather than stabilize harvests and protect from crop failure during poor rainfall seasons. To bridge dry-spells sufficiently in this setting, and thereby stabilize yield levels, supplemental irrigation

Table 5

Effects on soil biological properties. The table shows average microbial biomass and respiration per treatment at the final soil sampling at the depth 0–10 cm. */** marks treatments that significantly differed from the control.

	Microbial biomass-C (mgC kg ⁻¹)	Respiration ^a (μg CO ₂ g ⁻¹)
C	123	175
CM	123	239
R	104	158
RM ₁	127	225
RM ₂	126	356**
Probability for no treatment effect	<i>p</i> = 0.25	<i>p</i> = 0.00...

^a Over an incubation period of 4 weeks.

appears to be needed. The results from the experimental SI-plot confirm this; with an average yield improvement of 94% during rainfall seasons in the 150–350 mm span.

The large difference in yield between M06 and M08 illustrate that this type of smallholder production systems operate on a thin line between failure and success, primarily due to how rainfall amounts play out in relation to the distribution (Fig. 5), as also outlined by e.g. Rockstrom et al. (2002). If the observed trend of an increasing yield gap between RM plots and control plots after M06 indeed reflects the development of a more pronounced treatment effect over time (that is mediated by a gradual improvement in the available water holding capacity), this type of conservation tillage may in a longer perspective have the potential to shift the breakpoint towards a lower rainfall level (Fig. 5). This would reduce the numbers of crop failures in the 200–300 mm span. The increased SOM levels on RM plots support this reasoning, as higher organic matter levels promote soil water retention (Brady, 1984). The lack of measured effects on bulk density and available water holding capacity, on the other hand, suggests that conservation tillage has limited effect on the measured soil physical properties, or alternatively, that it takes longer than six seasons for any measurable effects to develop. To properly evaluate this, data on other proxies for soil physical characteristics would have been needed, including for example continuous measurements of soil moisture content, pore size distribution, and root depth and distribution.

The overall poor performance of the R treatment, which gave about 20% less grain yield than the control, is interesting. There are several potential explanations for this. Either the assumed *in situ* water harvesting effect of conservation tillage mainly is created by the soil cover (decreasing evaporation and increasing infiltration), which means that it only comes into play when ripping is combined with organic matter inputs. Alternatively, although ripping may promote some kind of water harvesting effect in itself (mediated by e.g. better soil structure and water retention in the ripper

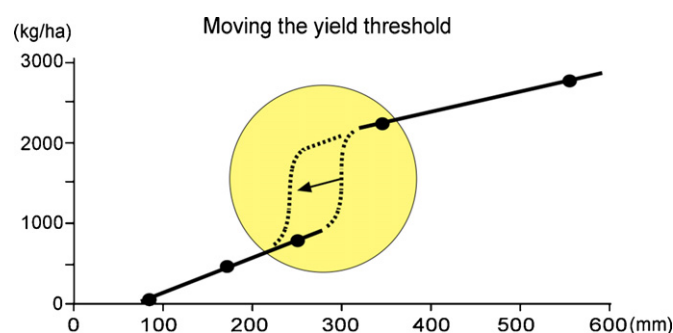


Fig. 5. Shifting the breakpoint. Small-scale farming systems in the semi-arid tropics operate on a thin line between failure and success. The breakpoint is determined by rainfall amounts in relation to rainfall distribution. If the conservation tillage treatment effect becomes more pronounced over time, due to a gradual improvement of the soil water holding capacity, CT could potentially shift the breakpoint towards a lower rainfall level, reducing the frequency of crop failures in the 200–300 mm span. (Yield data points are averages of all treatments per season)

lines) it cannot raise yields alone, since the crop faces an immediate nutrient stress as soon as the water demand is reasonably satisfied. Thus, water investments alone are unlikely to reap potential yield benefits unless coupled with improved nutrient management, since low soil fertility generally is an equally fundamental constraint in these systems (Twomlow et al., 2006; Rockström et al., 2007). Yet another explanation may be that ripping (without mulch and/or manure) on soils with low levels of SOM and poor structural stability only has a temporary positive impact on infiltration and/or water retention that does not last throughout the growing season (cf. Temesgen, 2007; Mupangwa et al., 2008). Most likely our results reflect a combination of these processes.

4.2. The challenge of making conservation tillage work

Although our results generate support for the argument that conservation tillage promotes soil health and improves yield levels over time, a crucial question is whether these changes are substantial enough, and occur at a time-scale relevant enough, to justify adoption among farmers. Conservation tillage implies considerable changes to conventional hand hoe based practices, and apart from the more technical constraints of accessing a ripper and trained oxen to pull it, we identified several challenges to adoption. Although the ripper treatment required less labour at land preparation, the labour needed for weeding increased (as also noted elsewhere, see e.g. Haggblade and Tembo, 2003). This is an issue of potential concern since proper weed management is crucial for the water availability in the soil profile (Twomlow and Bruneau, 2000). Another constraint became apparent after the high-yielding season V06/07. Due to inadequate post-harvest processing and storage capacity, the farmers lost most of their surplus from the conservation tillage plots due to outbreaks of storage pest and diseases. Without addressing this type of system-level constraints, which most likely will look different in different areas (Knowler and Bradshaw, 2007), adoption of conservation tillage techniques will probably remain limited in smallholder systems (Mupangwa et al., 2006).

Even so, the main challenge probably lies in making this type of technology function properly under semi-arid conditions, since it is difficult to increase the productivity enough to make a net return of organic matter to the soil possible (see Lal, 2004). First, a soil with an already low nutrient status will, without additional inputs (or with only smaller amounts of poor quality inputs), continue to produce low yields and little surplus biomass (Vanlauwe and Giller, 2006). Second, the temperature and rainfall regimes under which the semi-arid smallholder systems operate do not necessarily enhance the desired carbon sequestration, but may rather promote oxidization and decomposition of added organic matter (Thomas et al., 2007). Our results show that seasonal inputs of 5 t/ha manure plus cover crops and maize residues only gave a moderate increase in SOM over a 3-year period. Part of the explanation for this is likely the increasingly active microbiological community, counteracting the SOM build up (similar response to low quality organic matter inputs has been recorded in field trials in semi-arid West Africa, see Ouédraogo et al., 2007b). Thus, to add enough organic matter to the system to realize the suggested longer term effects on the soil water holding capacity, substantially more manure or manure with a higher nutrient content, and/or higher cover crop productivity, would be needed. This is challenging since it is difficult to achieve a good soil cover in these climates, since even the amounts of manure that were used in this experiment was difficult for the farmers to access, and since there are often competing needs for crop residues in smallholder systems (Baudeon et al., 2007; Chivenge et al., 2007; Lal, 2007). Given the closely coupled dynamics between organic matter and nitrogen in the soil, it may also be

necessary to complement the organic matter inputs by inorganic N in order to build up SOM stocks in semi-arid (N limited) farming systems (Ouédraogo et al., 2007a).

While our results demonstrate a moderate comparative advantage of the conservation tillage treatment already over the relatively short experimental period, the challenges outlined above likely mean that it takes many years to achieve the full benefits of conservation tillage in semi-arid smallholder systems.

5. Conclusions

In conclusion, the results from the 3-year (six seasons) on-farm conservation tillage experiment suggests that a slow yield increase is achieved when combining ripping with mulch and manure application in this type of semi-arid smallholder systems. Since the CT treatment (1) had the most evident impact on yield levels during a high rainfall season, (2) provided highly mixed results during the low to average rainfall seasons, and (3) did not seem to affect the monitored soil physical variables, the suggested *in situ* water harvesting effect, or at least its ability to stabilize yield levels under semi-arid conditions, appears limited in this time perspective. We therefore propose that the short-term benefit for farmers of this type of conservation tillage is a possibility to increase yields during seasons that already are good rather than a potential for minimizing risks from crop failure during poorer seasons. Question marks remain concerning how to achieve the net input of organic matter to the farming system needed to improve the soil's capacity to retain moisture, and there are several other system level constraints to large-scale adoption of conservation tillage among smallholders in semi-arid SSA. However, providing that these challenges can be handled, this type of technology may in a longer time perspective also provide a much needed opportunity to shift the critical threshold for crop failure towards lower rainfall levels and poorer distribution.

Acknowledgements

We are thankful to the farmers who provided us with land and invaluable help during these trials. We are also grateful to Dr. R. Ngatoluwa at SELIANI, Arusha, for assistance with soil classification, to Dr. K.P.C. Rao at ICRAF Soil and Plant Laboratory, Nairobi, for assistance with soil analysis, and to Dr. Vincent Chaplot at IRD/University of Kwa-Zulu Natal for valuable advice on soil analysis and interpretation. The work reported here was undertaken as part of the Smallholder System Innovations in Integrated Watershed Management (SSI) Program supported by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO), the Swedish International Development Cooperation Agency (Sida), the Netherlands Directorate-General of Development Cooperation (DGIS), the International Water Management Institute (IWMI), UNESCO-IHE Institute for Water Education, Sokoine University of Agriculture (SUA), Tanzania, University of Kwa-Zulu Natal (UKZN), South Africa and Stockholm University (SU), Sweden. FORMAS provided additional funding. The Soil-Water Management Research group (SWMRG) of SUA assisted with the implementation of field research.

References

- Barron, J., Rockstrom, J., Gichuki, F., Hatibu, N., 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology* 117, 23–37.
- Baudeon, F., Mwanza, H., Triomphe, B., Bwalya, M., 2007. Conservation Agriculture in Zambia: A Case Study of the Southern Province. African Conservation Tillage Network (ACT), CIRAD, FAO.
- Benites, J., Chuma, E., Fowler, R., Kienzie, J., Molapong, K., Manu, J., Nyagumbo, I., Steiner, K., van Veenhuizen, R. (Eds.), 1998. Conservation Tillage for Sustainable

- Agriculture. Proceedings from an International Workshop, Harare, Zimbabwe, 22–27 June 1998. Deutsche Gesellschaft, GTZ, Eschborn, Germany.
- Bolliger, A., Magid, J., Amado, T.J.C., Neto, F.S., Ribeiro, M.D.D., Calegari, A., Ralisch, R., de Neergaard, A., 2006. Taking stock of the Brazilian “zero-till revolution”: a review of landmark research and farmers’ practice. *Advances in Agronomy* 91, 47–110.
- Brady, N., 1984. *The Nature and Properties of Soils*, 9th ed. Macmillan Publishing, New York.
- Brevault, T., Bikay, S., Maldes, J.M., Naudin, K., 2007. Impact of a no-till with mulch soil management strategy on soil macrofauna communities in a cotton cropping system. *Soil & Tillage Research* 97, 140–149.
- 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 Research* 94, 328–337.
- Conway, G., Toenniessen, G., 2003. Science for African food security. *Science* 299, 1187–1188.
- Diao, X., Hazell, P., Resnick, D., Thurlow, J., 2007. The role of agriculture in development: implications for sub-Saharan Africa. IFPRI Research Report, 153.
- Enfors, E., Gordon, L., 2007. Analyzing resilience in dryland agro-ecosystems: a case study of the Makanya catchment in Tanzania over the past 50 years. *Land Degradation & Development* 18, 680–696.
- Falkenmark, M., Rockström, J., 2004. *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan Publications Ltd., London, UK.
- FAO, 2008. *Agro-MAPS: Global Spatial Database of Agricultural Land-Use Statistics*. FAO.
- Fowler, R., Rockstrom, J., 2001. Conservation tillage for sustainable agriculture – an agrarian revolution gathers momentum in Africa. *Soil & Tillage Research* 61, 93–107.
- Gicheru, P., Gachene, C., Mbuvi, J., Mare, E., 2004. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. *Soil & Tillage Research* 75, 173–184.
- Haggblade, S., Tembo, G., 2003. *Conservation Farming in Zambia*. International Food Policy Research Institute (IFPRI).
- Hällén, C., 2007. Effects of conservation management on soil microbiology in a Tanzanian agro-ecosystem. M.Sc. Thesis in Environmental Science, Lund University, Sweden.
- Hobbs, P., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B* 363, 543–555.
- Kay, B.D., VandenBygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. *Soil & Tillage Research* 66, 107–118.
- Knapen, A., Poesen, J., Govers, G., De Baets, S., 2008. The effect of conservation tillage on run-off erosivity and soil erodibility during concentrated flow. *Hydrological Processes* 22, 1479–1508.
- Knowler, D., Bradshaw, B., 2007. Farmers’ adoption of conservation agriculture: a review and synthesis of recent research. *Food Policy* 32, 25–48.
- Lal, R., 1997a. Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. I. Crop yield and soil physical properties. *Soil & Tillage Research* 42, 145–160.
- Lal, R., 1997b. Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. II. Soil chemical properties. *Soil & Tillage Research* 42, 161–174.
- Lal, R., 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* 123, 1–22.
- Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development* 17, 197–209.
- Lal, R., 2007. Constraints to adopting no-till farming in developing countries. *Soil & Tillage Research* 94, 1–3.
- Machado, P., Silva, C.A., 2001. Soil management under no-tillage systems in the tropics with special reference to Brazil. *Nutrient Cycling in Agroecosystems* 61, 119–130.
- Makurira, H., Savenije, H.H.G., Uhlenbrook, S., Rockstrom, J., Senzanje, A., 2007. Towards a better understanding of water partitioning processes for improved smallholder rainfed agricultural systems: a case study of Makanya catchment, Tanzania. *Physics and Chemistry of the Earth* 32, 1082–1089.
- McHugh, O.V., Steenhuis, T.S., Berihun, A., Fernandes, E.C.M., 2007. Performance of in situ rainwater conservation tillage techniques on dry spell mitigation and erosion control in the drought-prone North Wello zone of the Ethiopian highlands. *Soil & Tillage Research* 97, 19–36.
- Mrabet, R., 2002. Stratification of soil aggregation and organic matter under conservation tillage systems in Africa. *Soil & Tillage Research* 66, 119–128.
- Mupangwa, W., Love, D., Twomlow, S., 2006. Soil–water conservation and rainwater harvesting strategies in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C* 31, 893–900.
- Mupangwa, W., Twomlow, S., Walker, S., 2008. The influence of conservation tillage methods on soil water regimes in semi-arid southern Zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C* 33, 762–767.
- Nyamadzawo, G., Chikowo, R., Nyamugufata, P., Nyamangara, J., Giller, K., 2008. Soil organic carbon dynamics of improved fallow-maize rotation systems under conventional and no-tillage in Central Zimbabwe. *Nutrient Cycling in Agroecosystems* 81, 85–93.
- Ouedraogo, E., Brussaard, L., Stroosnijder, L., 2007a. Soil fauna and organic amendment interactions affect soil carbon and crop performance in semi-arid West Africa. *Biology and Fertility of Soils* 44, 343–351.
- Ouedraogo, E., Mando, A., Brussaard, L., Stroosnijder, L., 2007b. Tillage and fertility management effects on soil organic matter and sorghum yield in semi-arid West Africa. *Soil & Tillage Research* 94, 64–74.
- Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E., Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B., 2007. Global desertification: building a science for dryland development. *Science* 316, 847–851.
- Rockstrom, J., 1999. On-farm green water estimates as a tool for increased food production in water scarce regions. *Physics and Chemistry of the Earth Part B: Hydrology Oceans and Atmosphere* 24, 375–383.
- Rockstrom, J., Barron, J., Fox, P., 2002. Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth* 27, 949–959.
- Rockström, J., Falkenmark, M., 2000. Semiarid crop production from a hydrological perspective: gap between potential and actual yields. *Critical Reviews in Plant Sciences* 19, 319–346.
- Rockström, J., Hatibu, N., Oweis, T., Wani, S., Barron, J., Bruggeman, A., Farahani, J., Karlberg, L., Qiang, Z., 2007. Managing water in rainfed agriculture. In: Molden, D. (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan and International Water Management Institute (IWMI), London, UK, and Colombo, Sri Lanka.
- Rockström, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., Temesgen, M., Mawenya, L., Barron, J., Mutua, J., Damgaard-Larsen, S., 2009. Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. *Soil & Tillage Research* 103, 23–32.
- Roldan, A., Caravaca, F., Hernandez, M.T., Garcia, C., Sanchez-Brito, C., Velasquez, M., Tiscareno, M., 2003. No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico). *Soil & Tillage Research* 72, 65–73.
- Sanchez, P.A., 2002. Soil fertility and hunger in Africa. *Science* 295, 2019–2020.
- Slegers, M.F.W., Stroosnijder, L., 2008. Beyond the desertification narrative: a framework for agricultural drought in semi-arid East Africa. *Ambio* 37, 372–380.
- Steiner, K., 2002. *Conservation Tillage: Gateway to Food Security and Sustainable Rural Development*. African Conservation Tillage Network/GTZ.
- Temesgen, M., 2007. Conservation tillage systems and water productivity implications for smallholder farmers in semi-arid Ethiopia. Ph.D. Thesis from UNESCO-IHE and Delft University of Technology, Delft, The Netherlands.
- Thomas, G.A., Dalal, R.C., Standley, J., 2007. No-till effects on organic matter, pH, cation exchange capacity and nutrient distribution in a Luvisol in the semi-arid subtropics. *Soil & Tillage Research* 94, 295–304.
- Twomlow, S., Steyn, J., Du Preez, C., 2006. *Dryland farming in southern Africa*. Dryland Agriculture, Agronomy Monograph, No. 23, 2nd ed. American Society of Agronomy, Madison, Wisconsin (Chapter 19).
- Twomlow, S.J., Bruneau, P.M.C., 2000. The influence of tillage on semi-arid soil–water regimes in Zimbabwe. *Geoderma* 95, 33–51.
- Vanlauwe, B., Giller, K.E., 2006. Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 116, 34–46.
- Zhang, G.S., Chan, K.Y., Oates, A., Heenan, D.P., Huang, G.B., 2007. Relationship between soil structure and runoff/soil loss after 24 years of conservation tillage. *Soil & Tillage Research* 92, 122–128.
- Zibilske, L.M., Bradford, J.M., Smart, J.R., 2002. Conservation tillage induced changes in organic carbon, total nitrogen and available phosphorus in a semi-arid alkaline subtropical soil. *Soil & Tillage Research* 66, 153–163.