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Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research

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ABSTRACT

Improved agricultural productivity using conservation farming (CF) systems based on non-inversion tillage methods, have predominantly originated from farming systems in sub-humid to humid regions where water is not a key limiting factor for crop growth. This paper presents evidence of increased yields and improved water productivity using conservation farming in semi-arid and dry sub-humid locations in Ethiopia, Kenya, Tanzania and Zambia. Results are based on on-farm farmer and research managed experiments during the period 1999–2003. Grain yield of maize (*Zea mays* L.) and tef (*Eragrostis Tef* (Zucc)) from conventional (inversion) tillage are compared with CF with and without fertilizer. Rain water productivity (WP_{rain}) is assessed for the locations, treatments and seasons. Results indicate significantly higher yields ($p < 0.05$) for CF+ fertilizer treatments over conventional treatments in most locations, increasing from 1.2 to 2 t ha^{-1} with 20–120% for maize. For tef in Ethiopian locations, the yield gains nearly doubled from 0.5–0.7 to 1.1 t ha^{-1} for "best bet" CF+ fertilizer. WP_{rain} improved for CF+ fertilizer treatments with WP gains of 4500–6500 m^3 rainwater per t maize grain yield in the lower yield range from 0 to 2.5 t ha^{-1}. This is explained by the large current unproductive water losses in the on-farm water balance. There was a tendency of improved WP_{rain} in drier locations, which can be explained by the water harvesting effect obtained in the CF treatments. The experiences from East and Southern Africa presented in this paper indicate that for smallholder farmers in savannah agro-ecosystems, conservation farming first and foremost constitutes a water harvesting strategy. It is thus a non-inversion tillage strategy for *in situ* moisture conservation, rather than solely aimed at minimum tillage with mulch cover. Challenges for the future adoption of CF in sub-Saharan Africa include how to improve farmer awareness of CF benefits, and how to efficiently incorporate green manure/cover crops and manage weeds.

1. Introduction

To achieve the UN millennium development goals (MDGs) of halving the proportion of poor and hungry in the world by 2015 (compared to 1990) (UN, 2006), will require no less than a green revolution in sub-Saharan Africa (SSA) where the largest challenge of undernourishment and poverty prevail. At least a doubling of agricultural yields is required over the coming decades (SEI, 2005) in economies where a majority of the populations depend on smallholder rainfed farming for their livelihoods. A major challenge is to reverse trends of soil fertility depletion and soil desiccation. Approximately 65% of agricultural land in SSA is subject to degradation (UNEP/ISRIC, 1991; GEF, 2003), which contributes to the low yield levels experienced by farmers, generally oscillating around 1 t ha^{-1} for major staple grains (Rockström and Falkenmark, 2000). Conway (1997) pointed out that now a green–green revolution is required, which compared to

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the 1st green revolution in Asia, focuses more strongly on environmental sustainability of soil, crop and water resources. Falkenmark and Rockström (2004) concluded that in fact a triply green revolution is required, as the major hotspots in terms of food insecurity (sub-Saharan Africa, South Asia and parts of South-East Asia) also coincide with the world's savannahs. These are hydro-climatic regions subject to extreme rainfall variability, water scarcity and a large dependence on green water flows, i.e., soil moisture in the root zone from infiltrated rainfall that contributes evapotranspiration flow in rainfed farming systems.

A major driver behind land degradation causing low current yield levels is intensive soil preparation by hoe or plough combined with removal or burning of crop residues, leaving the soil exposed to climatic hazards such as rain, wind and sun (Benites, 1998; Derpsch, 1998). The process is particularly severe in the hot savannah zone.

Conservation farming (CF) systems,[1] particularly minimum and zero (no-till) tillage systems, have been developed and successfully adopted by farmers in particularly the US, countries in Latin America, Europe and certain parts of South Asia (e.g., the Indo-Gangetic basin), as a means to improve soil conservation, reduce labor and energy needs and in many cases also increase yield levels (Derpsch, 2001). Adoption among farmers in SSA has been limited, until recently concentrated to applied research efforts particularly in Ghana, South Africa, Zambia, and Zimbabwe (Benites et al., 1998). One reason for low momentum in SSA may be the traditionally narrow focus of CF on minimum and no-tillage systems that minimize disturbance of soil (FAO, 2001; Dumanksi et al., 2006). This has guided research to focus on minimum and zero tillage systems based on direct planting, strong emphasis on maintaining mulch, and often dependence on herbicides. Most soils in SSA suffer from poor physical and chemical properties, which combined with intensive rainfall events, make them particularly sensitive to crust formation (Casenave and Valentin, 1992; Gitau et al., 2006). In the savannah zone, practice of no-tillage systems is further impeded by hydrological conditions (a distinct dry season of 3–4 months in regions with bimodal rainfall and 7–9 months in regions with mono-modal rainfall, resulting limited room for mulch generating cover crops and intercropping) and socio-economic conditions (agro-pastoral communities with multiple and high demand for crop residues as fodder, fiber, fuel wood and construction materials in a biomass poor agro-ecosystem).

It has been suggested that there is a need to put stronger emphasis on water conservation aspects of CF (Twomlow and Bruneau, 2000; Fowler and Rockström, 2001; Rockström et al., 2001), which are critical in savannah agro-ecosystems. CF systems geared towards improved water management would be better adapted to resource limited smallholder farmers in rainfed, soil nutrient deficient and biomass poor agro-ecosystems (Comprehensive Assessment of Water Management in Agriculture, 2007).

This paper presents results from participatory on-farm experiments on conservation farming systems for smallholder farmers carried out over 3–4 years (1999–2003) in Ethiopia, Kenya, Tanzania and Zambia. Emphasis is on grain yield results and rain water productivity indices in order to assess the viability of different CF system options in water scarcity prone agro-ecosystems. The objectives of the research were two-fold: (1) to evaluate yield impacts of conservation farming and (2) to use the experience as a basis for the development of a conservation farming approach adapted to the physical, economic and social conditions among smallholder farmers in sub-Saharan Africa.

[1] In this paper the term conservation farming will be used, and considered equivalent to conservation tillage and conservation agriculture.

2. Materials and methods

2.1. Soil and water management in smallholder farmer systems in eastern and southern Africa

The on-farm trials on conservation farming systems were carried out in similar agro-ecological settings with common basic farming systems characteristics, even if implements, field operations and crops differed between countries. Farming is carried out in mixed crop-livestock production systems. Farm holdings are small, generally less than 5 ha cultivated land. Input of soil fertilization is low with negative nutrient budgets (Stoorvogel and Smaling, 1990) with very limited or inefficient use of in-organic fertilizers and insufficient organic fertilizers (Vanlauwe and Giller, 2006). Farmers in general practice animal drawn tillage, but some farmers, particularly poor and female headed households, practice manual hand-hoeing. Water is a key limiting growth factor together with poor nutrient status. Water limitation manifests itself through two main processes: (1) low actual soil water infiltration due to uneven temporal and spatial distribution of rainfall combined with soil crusting and (2) insufficient capacity by plants to utilize available soil moisture. Crop production is rainfed, cultivated during short 3–4 months rainy seasons with 300–700 mm of rainfall, and subject to frequent dry spells and droughts (Barron et al., 2003). Thus, water and nutrients alternate within a particular season as the key limiting growth factor. Soil and water management practices in the studied farming systems emphasize *in situ* soil and moisture conservation through terracing. The soil-bunded *Fanya Ju* (Kenya) and *Fanya Chini* (Tanzania) terraces have similar equivalents in farmers' fields in Ethiopia (more often using stone bunds) and in Zambia. While the degree of soil conservation varies in the region, and between farms within a region, experimental crop fields were consistently chosen among farmers who actively practice soil terracing. The reasons for selecting farms that already practice basic soil and water conservation were threefold. First, the objective was to investigate the potential of CF to raise yields on already reasonably well-managed farmland. Secondly, given that CF technologies are novel among farmers in the region, experienced farmers understanding the need for and practicing soil and water conservation were invited to participate in the experiment. Finally, despite basic practices of *in situ* moisture conservation, long-term yield levels remain low in the region, generally oscillating between 0.5 and 1 t ha^{-1} in the selected experimental areas (Rockström et al., 2007), and the aim was to explore whether CF has the potential of lifting crop systems to a new higher long-term productivity level.

Crop production is carried out within mixed farming systems in an agro-pastoral setting, where farmers strive to add organic fertilization from cattle, and where free post-harvest grazing is customary. Cover cropping is not practiced traditionally, and inter-cropping for green manure (mulching) is rare, due to farmers' fear of excessive competition for soil moisture. Termite activity, long dry seasons, and human export of crop residue, further adds to the rapid disappearance of mulch on the soils.

In Kenya, Tanzania and Zambia, the farming systems all include primarily animal drawn mouldboard ploughs, complemented by pitting using hand-hoes in certain locations. Maize (*Zea Mays* L.) is the predominant staple food crop. Rainy seasons are bi-modal in Kenya and Tanzania (with short summer rains between November and January, and long winter rains between March and July), while the experimental location in Eastern Zambia (Chipata) has a mono-modal rainfall pattern (rains from November to March). Despite the bi-modal rainfall patterns in Kenya and Tanzania, farmers in the semi-arid regions only erratically crop the long rains, which despite being longer (in time) are more unreliable (in distribution and depth).

In Ethiopia the farming system is also animal drawn, but here farmers use the traditional *maresha*, a wooden ard plough. The main staple food crop is tef (*Eragrostis tef* (Zucc.)) in most semi-arid regions of Ethiopia. Tef is a very small weed sensitive grain, and farmers generally plough up to five times before planting in order to secure an even and weed free planting bed (Temesgen, 2001; Gebregziabher et al., 2006). Tef is often complemented with maize cultivation, also using the *maresha* ard plough. While tef is always planted by broad-casting seeds, the maize seeds are usually planted in lines.

Ploughing in the region, both with the *maresha* and mouldboard plough, is generally shallow, carried out at depths between 12 and 15 cm. Further details on current crop, soil and water management practices at the experimental locations are provided in Supplement 1 (S1).

2.2. Experimental locations: climatic and soil conditions, seasonal rainfall

The on-farm experiments were carried out in Ethiopia, Kenya, Tanzania and Zambia over a period from 1999 to 2003. The trials were carried out in 8 different locations (Fig. 1) at 11 experimental sites, engaging varying numbers of farmers at each site. Each farm hosted one full experimental repetition, thus functioning as an experimental block. Experimental locations were primarily chosen in dry sub-humid and semi-arid savannah agro-ecosystems (Fig. 1, Supplement S2).

2.3. Experimental treatments and layouts: crops and tillage combinations

A systems approach to develop new CF-based production systems was adopted together with farmers. A shift from conventional (soil inversion) tillage to conservation tillage (non-inversion of soil), requires a simultaneous shift in weeding practices, timing of operations, and management of mulch, in order to successfully introduce a CF system, particularly if the system is to operate without use of herbicides.

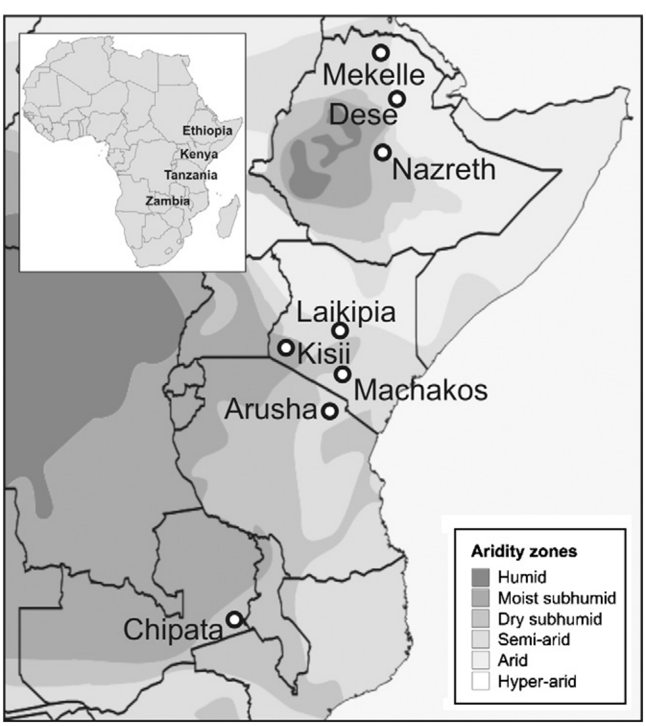

Fig. 1. Map with experimental locations of conservation farming trials in Ethiopia, Kenya, Tanzania and Zambia 1999–2003.

The following implement combinations were studied. In Ethiopia, special *maresha* adapted conservation farming implements were developed (Temesgen, 2000). These included a ripper tine combined with a wing-plow, or combined with ridging, and a sub-soiler, which was combined with the ripper (Table 1). The wing-plough, a flat shallow cutting (2–3 cm) sweep, was used prior to planting in order to enable a fine grained seed bed for the tef crop, as a substitute to the conventional primary ploughing. Added to these implements, a tie-maker for ridging was developed and used to further enhance moisture conservation. In Kenya, Tanzania and Zambia the basic CF implements used were the *magoye* ripper and the *palabana* sub-soiler developed by the IMAG Institute of Agricultural and Environmental Engineering, the Netherlands, and partners in Africa (IMAG, 1999). In Kenya, the *magoye* ripper was occasionally substituted by a locally manufactured ripper. The common objectives with these implements were to: (1) enable tillage to at least 15 cm for ripping and at least 25 cm for sub-soiling and (2) tillage was carried out in permanent planting lines only (for maize with 80 cm line spacing). The same ripping density was used for the tef crop in Ethiopia (while the wing-plough was used over the whole soil surface).

For each CF system practices were agreed with farmers on timing, weeding and mulching. Systematically, conservation farming was carried out prior to onset of rains, and whenever possible the maize crop was dry planted. Weeding was carried out manually, and for CF treatments farmers were encouraged to carry out an additional late season (3rd) weeding to reduce generation of weed seed. Farmers were encouraged to leave crop residue as mulch, and leguminous intercrops for mulching were introduced in Kenya and Tanzania (*Dolicos Lab lab* and cow pea). However, over the course of the experiments presented in this paper, neither mulch nor any significant cover crop was successfully achieved in any of the trials. Crop varieties were chosen by the farmers (generally hybrid maize and local tef varieties recommended by extension services).

The manual CF system consisted of digging planting pits with hand-hoe, to a depth exceeding 15 cm, with no soil disturbance in between pits.

All CF systems were compared with the current local practice (conventional ploughing) and combined with and without fertilization (except for the trials in Zambia) in order to enable the analysis of synergies between tillage and fertilization on yields.

For all experiments, levels of fertilization, choice of crop varieties, weeding practices, and planting and harvest times were the same for CF and conventional tillage (the control) systems. Table 1 summarizes the main experimental management treatments studied in the on-farm experiments.

The trials were designed using an action research approach. Workshops were held with farmers, where constraints in current farming practices were raised and where CF rationale and methods were presented and discussed. Based on these needs and opportunity assessments, CF production systems and experimental setups were designed. The participative approach resulted in different experimental designs at different locations, thus the number of treatments and seasons may be unbalanced. Each combination of tillage, timing, weeding, fertilization and crop choice was agreed in farmer groups, as was the set of comparative treatments. The trials were then laid out in researcher designed randomized blocks (generally with different farms functioning as blocks, while occasionally 2 blocks were located on one farm). All trials were managed by the farmers, following jointly agreed protocols. Experimental data used in this paper (yield and rainfall) were collected jointly under the guidance from the research team.

Table 1
Tillage treatments, fertilizers and crops at experimental locations.

Country, location	Crop	Fertilizer	Conservation farming treatments	Number experimental seasons	Remarks
Ethiopia					
Axum Wulinchity Melkaweba	Maize	Row spacing of 75 cm in CF plots. Seeds at 50 kg ha^{-1} in conventional, 30 kg ha^{-1} in CF treatments. Fertilizer DAP 100 kg ha^{-1} at planting	Conventional (w/o fertilizer) Ripper + wingplow (w/o fertilizer) Ripper + ridging + (w/o fertilizer) Ripper + subsoiling (w/o fertilizer)	4	Weeding by hand, or weeder
Axum Alamata Woldeya Wulinchity Melkaweba	Tef	Row spacing of 75 cm in CF plots. Seeds at 40 kg ha^{-1}. Fertilizer DAP 100 kg ha^{-1} at planting. In conventional plots, furrows at 2.5 m were done at planting to keep seeds at bay	Conventional (w/o fertilizer) Ripper + wingplow (w/o fertilizer) Ripper + ridging (w/o fertilizer) Ripper + subsoiling + fertilizer	5	Weeding by hand
Kenya					
Laikipia	Maize	Fertilizers applied 98 kg ha^{-1}. DAP 18 46 0, Top dressing with CAN	Conventional (w/o fertilizer) Ripping + fertilizer	3	Weeding by hand
Machakos	Maize	FYM and chemical fertilizers (DAP) applied at planting. Top dressing with CAN or Urea	Conventional Ripping + fertilizer Pitting + fertilizer	4	Two weedings by hand
Rachuonyo	Maize	Fertilizers are applied at the rates of 30 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}. Farm yard manure (FYM) applied at 10 t ha^{-1}. P_2O_5 was applied when planting while N is applied as top-dressing	Conventional Ripper + fertilizer Ridging + fertilizer Pitting + fertilizer	7	Two weedings Magoye ripper used with oxen
Tanzania					
Arusha, Arumeru	Maize	Conventional spacing 50 cm × 50 cm, CF treatments 75 cm × 30 cm, pitting 80 cm × 80 cm. Fertilizer manure (farmers own) 3 t ha^{-1}, N (Urea) 110 kg ha^{-1}, P (rock phosphate) 45 kg ha^{-1}	Conventional (w/o fertilizer) Ripping (w/o fertilizer) Ripping + fertilizer + covercrop Pitting + fertilizer	4	Magoye ripper used with oxen
Zambia					
Chipata	Maize	Fertilizer 'D' (10% N, 20% P, 10% K) as basal at planting and urea (N 40%) as top-dressing. Plant density: 40,000 plants ha^{-1}	Conventional Ripping + fertilizer Basins + fertilizer	2	Magoye ripper used with oxen. Weeding (3 times) by hand

Each year, yield results were analyzed and evaluated in joint farmer–researcher workshops using an iterative learning framework, which resulted in certain adaptation of treatments and experimental management.

2.4. Statistical evaluation

The SAS Systems V. 8.02 (SAS Institute Inc.) was used for statistical evaluation and treatment effects. For each country experimental plot data per season was used for datasets from Ethiopia, Tanzania and Zambia. Models using the parameters year, season, location, farm, tillage treatment, fertilizer treatment and plant density were used. Only significant differences between means of treatments of parameters tillage and fertilizer are reported here. Significance levels of differences of paired means are indicated at $p < 0.05$ as one asterisk (*), at $p < 0.01$ with (**), and $p < 0.001$ with (***).

3. Results

3.1. Yield results

3.1.1. Ethiopia

Ripping with ridging and fertilizer yielded on average 1780 kg ha^{-1}, improving maize grain yields with 40% over conventional practice using *maresha* and no fertilizer which gave an average yield of 1260 kg ha^{-1} ($p < 0.001$) (Table 2). Also conservation farming practices using ripper with wing-plough and fertilizer (1610 kg ha^{-1}) resulted in significantly higher yield than conventional practice with *maresha* and no fertilizer ($p < 0.01$). Neither improved tillage system alone (without fertilizer), nor fertilizer application only (without conservation farming practice) showed any significant improved maize yields over conventional use of *maresha* with no fertilizer at the experimental locations.

For tef, conventional *maresha* tillage without fertilizer resulted in the lowest yield with an average of 540 kg ha^{-1} (Table 3), which corresponds to the yield level experienced by many poor rural households in Ethiopia. Combined conservation agricultural practices (ridging, sub-soiling or reduced tillage with *maresha* and wing plough) with fertilizer resulted in almost doubled grain yield (average tef grain yield of 1076, 1044 and 1040 kg ha^{-1}, respectively) compared to conventional use of *maresha* and no fertilizer ($p < 0.001$). Conservation agricultural practices with no added fertilizer increased grain yields with 20–50% to 640 and 780 kg ha^{-1} for ripping + wing plough and ripper + ridging as compared to conventional non-fertilized tillage using *maresha*, although not statistically significant ($p > 0.05$). However, adding fertilizer to current conventional tillage system resulted in higher yield (average 940 kg ha^{-1}) than improved tillage with no added fertilizer. Ripping combined with ridging and wing-plough resulted in similar average yield levels (1080 and 1040 kg ha^{-1}, respectively).

3.1.2. Kenya

In Kenya, at the three locations where the CF experiments were carried out, only seasonal data on average yield levels for each treatment were available for each location (i.e., not yield data at plot level). Data on mean grain yields were collected for 7 experimental seasons at Rachuonyo location. Maize grain yields varied from a lowest yield of 0.9 t ha^{-1} for conventional ploughing (control) during short rains 2002 to highest average of 4.3 t ha^{-1} in ripper + fertilizer treatment long rains 2002. Highest average yield per season of 2.5 t ha^{-1} was achieved with ripping combined with fertilizer compared to conventional tillage practice of 2.0 t ha^{-1}.

Table 2
Average maize grain yields and standard errors for conservation farming experiments in Ethiopia 1999–2003.

Treatment	Fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*	Non-fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*
Ripping + ridging	1775 (111)^{a}	32	1462 (133)^{bc}	19
Ripping + wing-plough	1609 (128)^{ab}	19	1403 (179)^{bc}	9
Ripping + subsoiling	1540 (127)^{abc}	25	1266 (141)^{bc}	19
Conventional/Maresha	1458 (100)^{bc}	32	1258 (131)^{c}	18

* Significantly different at $p < 0.05$. Statistically significant differences between treatments (at $p < 0.05$) for *a* over *b* and *c*, and for *b* over *c*.

Table 3
Average tef grain yields and standard errors for conservation farming experiments in Ethiopia 1999–2003.

Treatment	Fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*	Non-fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*
Ripping + ridging	1076 (61)^{a}	27	771 (102)^{cd}	10
Ripping + wingplough	1044 (67)^{a}	59	641 (123)^{d}	5
Ripping + subsoiling	1040 (45)^{ab}	31	–	–
Conventional/Maresha	945 (46)^{bc}	64	539 (129)^{d}	5

* Significantly different at $p < 0.05$.

Pitting with fertilizer resulted in intermediate yields of maize with 2.2 t ha^{-1} per season. Overall, lowest yields were recorded in the ridged treatments, with slightly lower than conventional practice of 1.9 t ha^{-1} per season, which probably can be explained by water logging problems caused from ridging in the relatively wetter sub-humid Rachuonyo location.

At the more arid locations of Laikipia and Machakos, each site recorded complete crop failures in two out of three and four experimental seasons, respectively. At Laikipia, only long rains 2001 resulted in yields after 400 mm seasonal rainfall. Average seasonal yields ranged from 2.1 t ha^{-1} for conventional tillage with fertilizer to 3.7 t ha^{-1} for ripper with fertilizer. At the Machakos location, two seasons out of four resulted in yields less than 0.3 t ha^{-1}. Seasonal yields at the Machakos site varied from a minimum of 0 kg ha^{-1} harvested maize grains due to meteorological drought, up to more than 4 t ha^{-1} in all treatments for the short rains 2000/2001. The mean seasonal yield (4 seasons) indicates best performance in ripping + fertilized treatments with 2.0 t ha^{-1} per season whilst conventional mean yield was 1.6 t ha^{-1}. Lowest mean yield was recorded for pitting (pick axe) + fertilizer with mean yield 1.2 t ha^{-1} per season.

3.1.3. Tanzania

CF practices combining improved rainwater infiltration through ripping with fertilizer proved superior over fertilized conventional ploughing practices at the two Tanzanian locations. The conservation farming practice with ripping and fertilizer (RF) resulted in highest mean grain yield of maize of 3390 kg ha^{-1} per season from 1999 to 2002 (Table 4). The ripper + fertilizer combination more than doubled maize grain yields compared to conventional tillage systems (C) with average yields of 1550 kg ha^{-1} (significantly different at $p < 0.0001$). Combining ripping and fertilizer application with a cover crop had little effect on yield over the 3 years of experiments. A slightly lowered yield was experienced (3050 kg ha^{-1}) compared to the RF without cover crop (3390 kg ha^{-1}), which may be attributed to higher competition for soil moisture with a cover crop. Similarly, pitting + fertilizer (PF) also resulted in a similar yield level as the animal drawn CF treatments, with an average yield of 3050 kg ha^{-1}. Between treatments with ripping only (R), conventional practice with added fertilizer (CF) and conventional practice (C), average yields were non-significantly different over the period, despite difference of 700 kg ha^{-1} between lowest and highest average yield.

Although planting density differed between the tested tillage systems, this did not affect average yields. Treatments with lowest planting density (PF) and highest planting density (RF, RFCC, R) had significantly higher average yields over conventional systems (C, CF) with intermediate planting densities.

At the Tanzanian sites, the conservation farming practices (ripping and pitting) combined with fertilization, resulted in significantly increased (1.5–2.2 times higher) yields compared to conventional ploughing with fertilization.

3.1.4. Zambia

The CF treatments in eastern Zambia resulted in significantly higher maize grain yields ($p < 0.001$) compared to farmer's conventional practices (Table 5). There were no differences between the two tested CF practices of ridging + fertilizer and basin + fertilizer application. As can be seen from the Zambian results, the trials were conducted in a highly productive savannah agro-ecosystem, where even the control yields exceeded the CF yields in the experiments in Ethiopia, Kenya and Tanzania.

A regional summary of the yield results from the four countries show a systematic coherence, where conservation farming practices, particularly when combined with fertilization, resulted in higher average crop yields compared to conventional ploughing with and without fertilization (Fig. 2). The highest yield performing CF practice increased grain yields with 20–120% over current conventional tillage practices for the different experimental conditions presented here. The Tanzanian and Zambian locations improved yields with >100% for ripper + fertilizer and pitting + fertilizer as compared to conventional ploughing and no (or marginal) fertilizer addition. Less yield gains were recorded at the Ethiopian and Kenyan experimental sites. However, at the Kenyan and Ethiopian locations studies of labor input and cost-benefits showed other benefits than yields alone (Temesgen, 2001).

3.2. Rain water productivity

There was no clear correlation between rainfall and yield, neither for different locations, nor for tillage system. This is probably a reflection of the poor correlation between high rainfall totals and (for the crop) good rainfall distribution in semi-arid and dry sub-humid tropical environments. To test the *in situ* moisture conservation capacity of CF practices the relative yield increase from CF was instead plotted against rainfall, which resulted in an interesting trend (Fig. 3). As seen from Fig. 3 there is a tendency of a higher relative yield increase when adopting CF practices for drier rainy seasons, as compared to wetter seasons in the data presented. It is only during rainy seasons receiving >350 mm of rainfall that CF systems increase yields with <100% compared to conventional ploughing. This indicates that conservation farming in savannah agro-ecosystems may foremost function as a water

Table 4
Average yield of maize grains with conservation farming practices at Tanzanian experiments long rains 1999–2002.

Treatment	Fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*	Non-fertilized, mean yield (S.E.)* (kg ha^{-1})	*n*
Ripping + cover crop	3096 (214)^{a}	46	–	–
Ripping	3393 (214)^{a}	46	1946 (214)^{b}	46
Pitting	3051 (214)^{a}	46	–	–
Conventional	2200 (220)^{b}	44	1556 (220)^{b}	44

* Significantly different at $p < 0.05$.

Table 5
Average maize grain yield of Zambian experiments with conservation farming practices 2 seasons 2000/2001 and 2001/2002.

Treatment	Mean yield (S.E.)* (kg ha^{-1})	n
Ripping + fertilizer	6845 (277)[a]	66
Basin + fertilizer	6660 (277)[a]	66
Conventional	3153 (277)[b]	66

* Significantly different at $p < 0.05$.

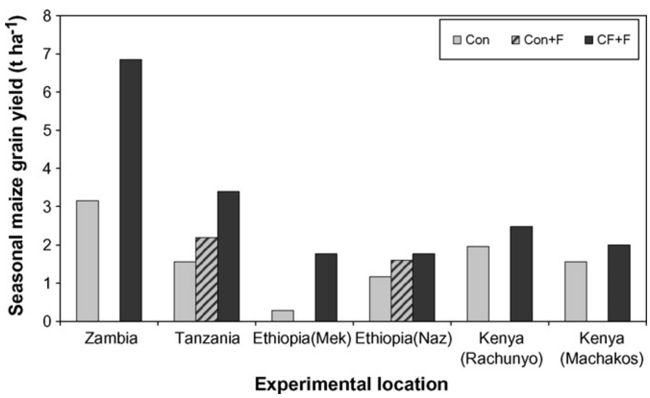

Fig. 2. Regional summary of average crop yields in Ethiopia, Kenya, Tanzania and Zambia, for animal drawn CF practices (ripping) with fertilization, compared to conventional ploughing with and without fertilization.

harvesting system, concentrating rainfall to the root zone. In the cases presented here, the highest yield difference occurs during rainy seasons with low rainfall, which generally also correspond to rainy seasons with poor rainfall distribution. CF then has the ability to maximize rainfall infiltration, which enables the crop to bridge short periods of dry spell.

Rain water productivity (WP_{rain}) (seasonal rainfall per ton grain yield, $m^3 t^{-1}$) improved with increased yield in all locations. Furthermore, the largest gain of WP_{rain} is for the yield increases between 0 and 2.5 t ha^{-1}. For yields >2.5 t ha^{-1} the WP_{rain} improvement with increased yield is marginal, which is an indication of the large relative improvement of crop water productivity that occurs when raising productivity in low-yielding production systems (explained by the reduction in non-productive water flows). This relationship, of exponential improvement of water productivity when improving agricultural water management in low-yielding farming systems, has recently been confirmed from several experiments (Comprehensive Assessment of Water Management in Agriculture, 2007). In Kenya, there is no clear tillage effect on the WP_{rain} (Fig. 4). However, in the semi-arid trials in Tanzania there is a tendency of improved WP_{rain} for conservation farming practices compared to conventional ploughing (Fig. 5).

The Ethiopian experiments show lower overall maize yields per hectare with corresponding high (equal to inefficient) WP_{rain} (Fig. 6a). There is a tendency of fertilized treatments having improved gains in WP_{rain} as compared to non-fertilized treatments. There are no clear effects of tillage, which is in line with the yield statistics above. The low tef yield levels, never exceeding 1.5 t ha^{-1} at any site in any season, resulted in consistently worse (i.e., higher volume of water requires per unit grain) WP_{rain} than anywhere else (Fig. 6b). However, the relative improvement of WP_{rain} is high for tef, sometimes halving the rain use, when fertilizer is added to any tested tillage system.

Rain water productivity (WP_{rain}) for 'best' CF practices at different country data sets, showed absolute average gains from

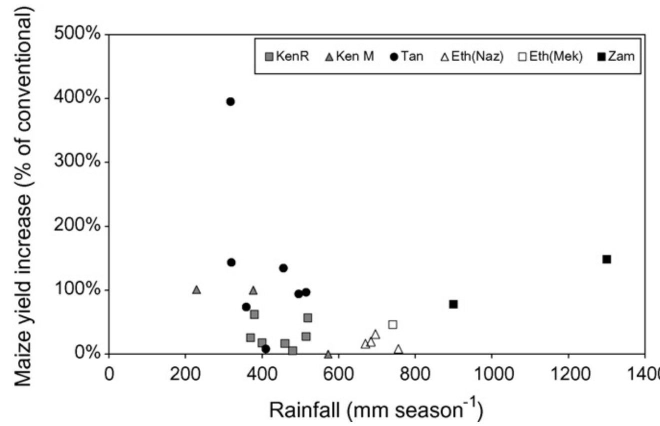

Fig. 3. Maize yield increase of the highest yielding CF system compared to conventional ploughing as a function of seasonal rainfall, for the data from Kenya, Tanzania and Ethiopia.

500 to 1500 m^3 per produced ton maize grain. The lowest WP_{rain} improvements for CF practices were observed in the Kenya-Rachunyo data, and largest WP_{rain} gains were obtained at the Ethiopian and Tanzanian experiments with more than 1000 $m^3 t^{-1}$ rainwater savings (on average) when practicing CF as compared to conventional tillage systems.

As seen from Fig. 7, yield improvements from CF systems result in a simultaneous improvement in rain water productivity. For water scarce semi-arid regions this is important, not only in terms of improving water availability for agriculture but also in terms of reducing pressure on water demands downstream. The results (Fig. 7) indicate a win-win situation with yield increases ranging from 20 to 120% over conventional tillage practice whilst rain water productivity improved with 10–50%.

4. Conclusions and discussion

4.1. Yield impacts

This paper has presented, what so far, is the most comprehensive analysis of yield effects of conservation farming practices in African semi-arid and dry sub-humid savannah agro-ecosystems. The results show a consistent yield increase for CF practices over conventional practices over time (1999–2003) and in the region (for trials in Kenya, Tanzania, Ethiopia and Zambia). Yields

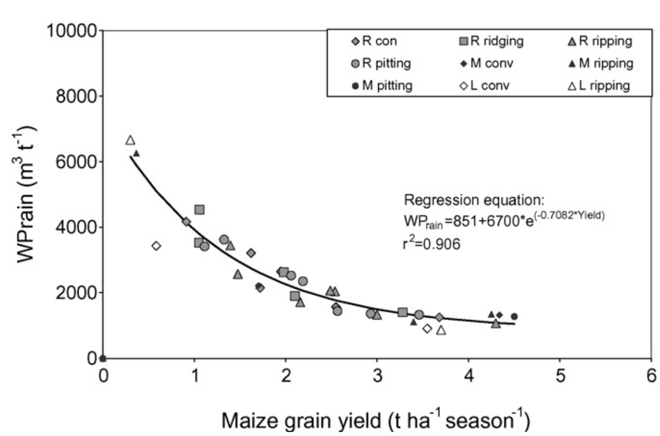

Fig. 4. Rain water productivity (WP_{rain}) for seasonal maize grain yields at conservation tillage experiments in Rachunyo (R), Machakos (M) and Laikipia (L), Kenya 1999–2003.

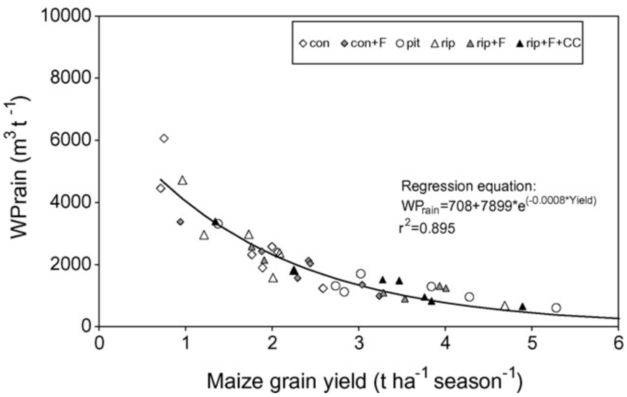

Fig. 5. Rain water productivity (WP_{rain}) for seasonal maize grain yields at conservation tillage experiments in Arusha and Arumeru, Tanzania 1999–2002. Conventional tillage (con), fertilized (F), and tillage using ripper (rip), pitting (pit) and combinations with cover crops (CC) are compared for each season and location.

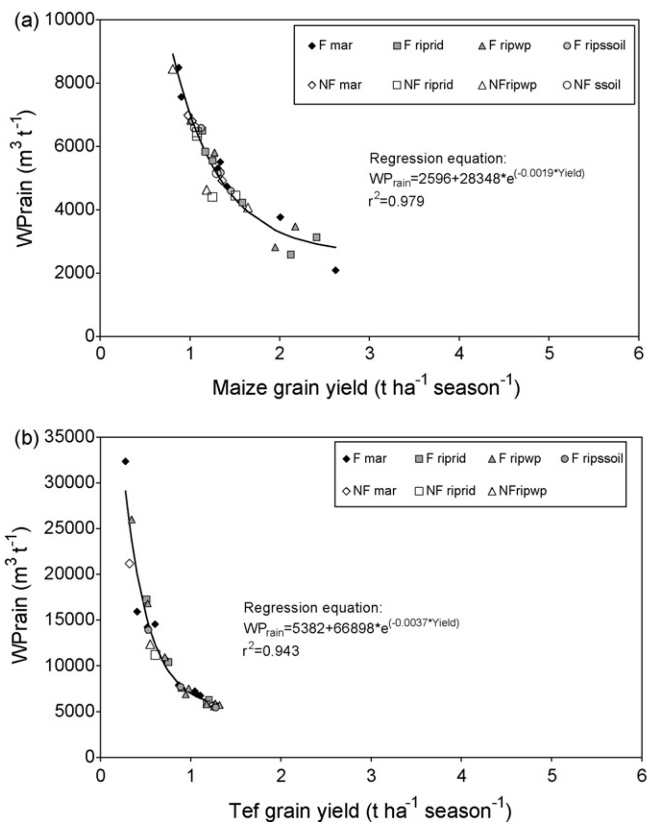

Fig. 6. (a) Rain water productivity (WP_{rain}) for seasonal maize grain yields at conservation tillage experiments in Ethiopia 1999–2003. F is fertilized and NF is non-fertilized treatments. Tillage with maresha (mar), ripper + ridging (riprid), ripper + winged plough (rip + wp) and ripper and sub-soiling (ripssoil) are compared for different seasons and locations. (b) Rain water productivity (WP_{rain}) for seasonal tef grain yields at conservation tillage experiments in Ethiopia 1999–2003. F is fertilized and NF is non-fertilized treatments. Tillage with *maresha* (mar), ripper + ridging (riprid), ripper + winged plough (rip + wp) and ripper and sub-soiling (ripssoil) are compared for different seasons and locations.

increased on average with 20–120% for maize. The yield improvements for tef, a very small grained Ethiopian cereal, were 35–100%. There is furthermore an indication to suggest that the yield improvement increases with lower rainfall, i.e., the effect of CF seems higher for rainy seasons with poor rainfall compared to seasons with adequate rainfall. More research is required to

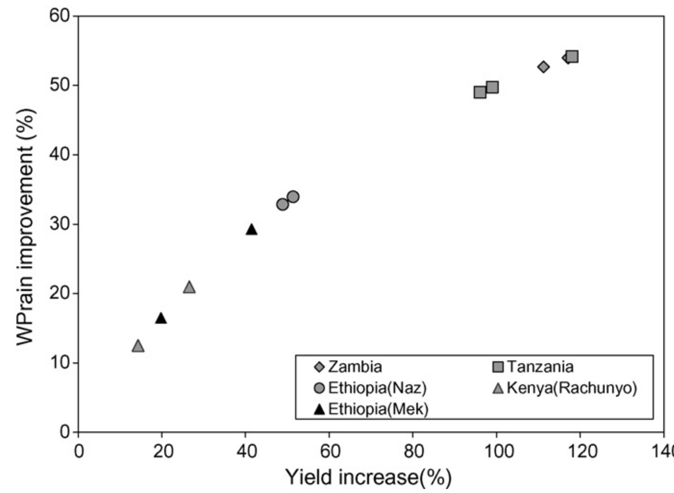

Fig. 7. Rain water productivity (WP_{rain}) improvement (%) for best CF practices compared to conventional practice versus yield increase (%) for all experimental sites in Ethiopia, Kenya, Tanzania and Zambia 1999–2002.

confirm this relationship, which would be important for farmers in the savannah zone, as their concern primarily is how to deal with the risk of yield reductions due to water scarcity.

It is worth noting the extreme yield increase in CF treatments over conventional in the Zambian location. The increase cannot be fully explained by the data collected. Probable explanations are the combination of extremely good rainfall (well above long-term average), good soil properties, the use of improved seed in CF treatments, resulting in high yield levels. The large difference compared to the control may be explained by the extremely low fertilizer and manure applications in the conventional practice.

4.2. Widening the scope for conservation farming in sub-Saharan Africa

There is very limited evidence of yield improvements from conservation farming practices in semi-arid and dry sub-humid smallholder savannah agro-ecosystems. On the other hand there is ample evidence of yield and soil improvements from humid tropical and temperate agro-ecosystems (e.g., Rasmussen, 1999; Diaz-Zorita et al., 2002; Bronick and Lal, 2005), where primarily minimum and zero-tillage practices are applied. These are farming environments with higher rainfall and longer rainy seasons, which permit easier cultivation of cover crops. In Pakistan, ripping systems for wheat have shown significant yield improvements and large scale adoption among farmers (Hobbs et al., 2000), also in drier areas, but these remain wetter in a hydro-climatic sense thanks to a cooler climate. In semi-arid sub-Saharan Africa documented success with CF practices remains limited and scattered, largely in relation to certain development projects, in e.g., Tanzania and Zambia (Rockström and Jonsson, 1999), even though significant success has been reported from commercial farms (Oldreive, 1993). CF success in Africa remains concentrated to more humid environments, in e.g., Ghana and Uganda (Ekboir et al., 2002). Generally, researchers insist that a prerequisite for success with CF practices is to maintain 30% mulch cover on the soil throughout the year. Furthermore, the aim is minimum disturbance of the soil, i.e., that the aim is zero-tillage (Erenstein, 2003). As shown by Okwach and Simiyu (1999) on crust prone soils with low organic matter, which is very common in savannahs, zero tillage may result in higher surface runoff, lower rainfall infiltration and subsequently lower yield levels. Mulching is difficult (but not impossible) to achieve in savannah agro-ecosystems, due to competition for soil moisture, free grazing traditions, high prevalence of agro-pastoral communities, and high dependence on biomass as fuel, fodder and construction material. The experimental results presented in this paper were undertaken predominantly under these conditions (for Ethiopia, Kenya except Rachuonyo, and Tanzania). Still, in our experiments, yields of maize and tef could be improved significantly through non-inversion conservation farming practices, where little or no permanent mulching through cover cropping or crop residues were achieved. The reasons for yield improvements were two-fold: (1) the water harvesting effect of conservation farming (where the soil was opened in the planting lines deeper than the ploughing depth) and (2) the soil fertility effect (of concentration of fertilizer along ripped and sub-soiled planting lines). For agro-ecosystems subject to frequent water scarcity, with short concentrated rainy seasons and soils sensitive to crusting, conservation farming becomes more a practice of wise tillage than minimum tillage. The core objective of the farmer becomes to harvest rainfall to the root zone rather than minimum disturbance of the soil.

The findings in this paper suggest that a widening of the scope of conservation farming is required, particularly for water-limited savannah agro-ecosystems, which does not delimit CF to practices of minimum non-inversion with mulch, but rather emphasizes the use of non-inversion tillage practices to maximize long-term soil and water productivity while reducing labor and costs. This puts the focus on the strategic role of non-inversion tillage as a water management practice, as pointed out by Stroosnijder (2003), and goes in line with the advancements of conservation farming systems in Africa by the African Conservation Tillage Network (ACT).

4.3. Integrated water and soil fertility effects

The results in this paper indicate a positive moisture conservation effect of conservation farming. At the same time, they also point at the need to combine CF with soil fertility management in order to generate a higher yield response. Similar water efficiency gains have been summarized for CF systems with cereals in USA (Hatfield et al., 2001). Farmers participating in the trials clearly stated the positive *in situ* moisture conservation effects of CF. However, they also expressed the positive effect of CF on soil fertility management. Tilling along permanent planting lines facilitated spot application of fertilizer along the planting lines, thereby concentrating soil nutrients close to the crop. The results from both Tanzania and Ethiopia, where CF was tested with and without fertilization, clearly show that the soil moisture effect alone (through CF) will not result in significant yield increase, as will not soil fertility improvements alone (ploughing with fertilization). Instead it is only when the two are combined that a full yield effect is experienced. At present fertilizer use is extremely low in sub-Saharan Africa, amounting merely to 9.5 kg ha^{-1} per year on average (Sachs et al., 2004), which results in hampered crop growth and inefficient water utilization.

4.4. Labor and weed management

For all trials labor requirements were also monitored and discussed with farmers. Labor needs for tillage reduced with at least 50%, while weeding needs increased with up to 30%. Overall, farmers were very satisfied with the reduction in labor, and particularly the reduction in animal traction requirements. Weed management was a problem, and is an area in need of further improvements. It should also be added though, that these trials did not go on for a long enough period (4 years only in this case) to enable a gradual reduction in weed pressure from CF. Reviews of multiple long-term conservation farming experiments from humid and temperate regions point towards a shift in weed populations towards more perennial types in reduced tillage systems as compared to conventional tillage (Moyer et al., 1994; Locke et al., 2002). However, pesticide use does not need to increase in reduced tillage as compared to conventional tillage systems if appropriate crop rotation and management is combined.

4.5. Potential for farmer adoption

Shifting from conventional ploughing to conservation farming is a major step, both financially and in terms of perceptions, for smallholder farmers. To facilitate the adoption of conservation farming is a large challenge for agricultural development as past experiences have not generated any general guidance on how and why adoption occurs (Knowler and Bradshaw, 2007). The action research approach adopted in this experiment, where farmers were involved in identifying problems and solutions, as well as designing the production systems, assessing results, and adapting the system, proved to be important in order to raise farmers' interest and commitment. In all countries the experiments were also carried out closely with extension services and local rural development partners. This enabled the research trials to be conducted closely to partners involved in dissemination of farm management approaches. Even today, five years after the finalisation of the on-farm trials, farmers who pioneered these experiments continue to practice and disseminate among fellow farmers the successful conservation farming systems. To facilitate the adoption of conservation farming is a major challenge agricultural development. Issues ahead concern development of capacity building materials, training of extension officers and development of markets for CF implements.

4.6. Experimental limitations and future issues

The action research nature of the experimental results presented in this paper naturally means that the experimental design, management of the trials and the gathering of data, varied slightly between locations and over time. Overall, the implications of this variation were to weaken the yield analysis by increasing the standard deviations of the data sets. Despite this weakness, yield improvements of CF practices were observed in the analysis. The Tanzanian experiments include the most complete set of data over the longest period of time (8–10 farmers over 4 years). This is important to note, as the Tanzanian trials also resulted in large and persistent yield improvements through CF. However, it is also important to add that the farming system in Arusha and Arumeru, where the Tanzanian trials were carried out, is particularly subject to soil compaction from decades of ploughing. The presented data indicate that more knowledge is needed to design of conservation farming systems, and to fully understand under which conditions they may contribute to long-term productivity increase in savannah agro-ecosystems of Eastern and Southern Africa. Long-term well-monitored field research sites are needed to evaluate slow changing soil physical, chemical and biological changes as well as estimate socio-economic and management factors.

Even though this paper suggests that CF can work in water scarcity prone farming systems without full mulch cover, it is beyond doubt a very important component that needs to be addressed even on the savannah. Successful trials have been carried out on cover crops and mulch farming also in more water scarce environments (Brunner et al., 1998), and farmers try to incorporate leguminous intercrops whenever possible. This is an area in need of future research in order to reduce weed pressure, improve soil fertility and moisture conservation. The results presented here are in this sense encouraging, even without the important positive productivity enhancing effects of mulch and cover crops, yields were improved with conservation farming. This suggests an even higher potential to improve yields further.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.still.2008.09.013.

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