Conservation Farming – A strategy for improved agricultural and water productivity among small-holder farmers in drought prone environments

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ABSTRACT

Water is a primary limiting factor for crop growth in semi-arid and dry sub-humid savannah agro-ecosystems, but not necessarily due to low seasonal rainfall but rather due to poor distribution of rainfall and large losses of water in the on-farm crop water balance. Conservation farming (CF), which aims at maximising rainfall infiltration, water holding capacity and crop water uptake capacity, is an effective *in-situ* water harvesting strategy for small-holder farmers in drought and dry-spell prone savannas. In this paper on-farm farmer driven trials on tractor based, animal drawn and manually based conservation farming systems are presented. As shown from trials in semi-arid regions of Tanzania, Madagascar and Sudan yield differences between conservation farming and conventional ploughing were significant and largest during the driest years – an indication of the water harvesting effect. The largest yield increase was realised when water harvesting through conservation farming was combined with soil fertility management, resulting in an average yield increase exceeding 200 % compared to current local practices. Rainwater productivity increased substantially from 3,800 m3/ton required for the conventionally ploughed system compared to on average 1,500 m3/ton for maize under conservation farming. The paper further discusses the challenges of achieving wider adoption of CF practices, and the wider advantages in terms of labour saving, which is particularly important in the region at present due to the HIV-AIDs pandemic.

Key words: Water harvesting, rainwater productivity, conservation farming, semi-arid, dry spell, drought.

INTRODUCTION

The frequent crop failures and yield reductions due to drought observed in the last years in many parts of Africa are not just a consequence of climatic variability but to a large extent a consequence of land degradation due to inappropriate agricultural practices. Land degradation, reducing rainfall infiltration, crop water availability and crop water uptake capacity, leads to agricultural droughts, where the crop suffers from water scarcity despite adequate amounts of rainfall. Agricultural droughts can often, unlike meteorological droughts, be managed through integrated soil and water management practices that focus on maximising crop water access and uptake. Conservation tillage systems, which have in common non-inversion of soil with the purpose of harvesting water and building soil quality, can together with improved soil nutrient management result in substantially improved yields by mitigating droughts and dry spells.

One of the most important natural resources is soil, especially agricultural soil. The resource soil can fulfil its functions, however, only in the presence of another precious resource, water, in particular rainwater. There are close interactions between these resources, as only a healthy soil can take up and store sufficient amounts of rainwater and make it available to plants over a prolonged period. These interactions between soil, water and plants (crops) are influenced by human activities and in many cases disturbed. Soil quality (soil structure, soil organic matter, soil life) is lowered in most cases by tillage operations, soils degrade and the ability to take up and store rainwater suffers. A great percentage (>50) of rainwater is lost by run-off and evaporation and crops suffer from water stress already after a few days without rain.

Food security and poverty reduction, main objectives of all development efforts, can only be achieved, if sustainable land and soil management practices are applied on a large scale. This calls for a drastic change, first of all of tillage practices. Tropical soils should be disturbed as little as possible and protected by a cover of mulch or crops (wherever possible by cover crops) the greatest part of the year. Ploughing and intensive hoeing should be replaced by ripping, direct planting or pitting. These conservation farming techniques, complemented by breaking of hardpans, contribute to a better water infiltration and reduce losses of precious rainwater by run-off. Conservation farming is therefore integrated soil and water management. It is an *in-situ* water harvesting strategy.

Semi-arid and dry sub-humid regions constitute some 40 % of the arable lands in SSA, and host some 40 % of the population. Rainfall is highly erratic, with large spatial and temporal variability, resulting in frequent periods of particularly dry-spells. The correct ecological term for these regions is savannah.

Water is the major limiting factor in savannahs, even on soils with a poor nutrient status, which means that the increase of rainwater productivity needs to gain priority before the application of mineral fertilizers. Importantly though, it is more often the poor distribution of rainfall over time that causes water scarcity, than low overall rainfall. This is not always well understood, and in the normal jargon these regions are generally denoted "drylands”. However, they are not all that dry (generally receiving at least 600 mm of rainfall). There is generally enough water, but it is there at the wrong time and such a large proportion is lost to the crop as evaporation and runoff. This indicates a window of opportunity to improve yield levels through improved water management..

The objective of this paper is to give evidence that conservation farming in sub-Saharan Africa (SSA) is an important water harvesting strategy with beneficial impact on yields in water scarcity prone semi-arid and dry sub-humid areas.

RAINWATER – PRODUCTIVITY

Dry spell mitigation

Rainfed farming in savannah agro-ecosystems is a highly risky business due to the extreme temporal and spatial variability of the rainfall. Rain is generally concentrated to one or two short rainy seasons, followed by distinct dry seasons exceeding 6 months of the year. The high rainfall variability results in a high risk of occurrence of meteorological droughts - here defined as a cumulative rainfall below the minimum crop water requirement to produce a crop (i.e., resulting in complete crop failure - in general when seasonal rainfall < 250 mm). Statistically meteorological droughts occur between 1 - 2 seasons in a decade. They are difficult, if not impossible to manage (there is simply no freshwater resource to manage) and form a natural part of the savannah reality. More importantly therefore, is to focus on meteorological dry spells - short periods of 2 - 4 weeks of no rainfall, resulting in crop growth reduction. If occurring during stress sensitive growth stages such as flowering, a severe dry spell can result in complete crop failure. As shown by Barron et al (in press) dry spells are very common in savannah farming systems, occurring almost every rainy season. Meteorological dry spells are manageable, but generally require management practices such as storage water harvesting systems for supplemental irrigation (SIWI, 2001). Importantly though, is that crop water stress may increase dramatically as a result of poor land management. Water stress causing dry spells and agricultural droughts are caused not primarily by low rainfall but due to poor rainfall partitioning resulting in large losses of water (from the perspective of the cultivated crop) in the water balance (as evaporation, runoff and drainage).

Water balance analyses from rainfed farming systems in savannah environments of sub-Saharan Africa indicate that only some 15 – 30 % of rainfall on average is used for productive crop growth (Rockström, 1999). On smallholder farms subject to land degradation, both in form of structural degradation impeding rainfall infiltration, water holding capacity and plant water uptake potential and in terms of soil fertility decline, less than 10 % of the rainfall takes the productive flow path as crop transpiration (Rockström et al., 1998). Yield levels in such degraded farming systems, which are systematically subject to management induced dry spells, oscillate around 0.5 - 1 ton grain per hectare. This is the common yield level generally observed among smallholder farming in Eastern and Southern Africa. It suggests (i) that there is a large management induced crop water scarcity and (ii) that there is a large potential of upgrading rainfed savannah farming through improved soil and water management.

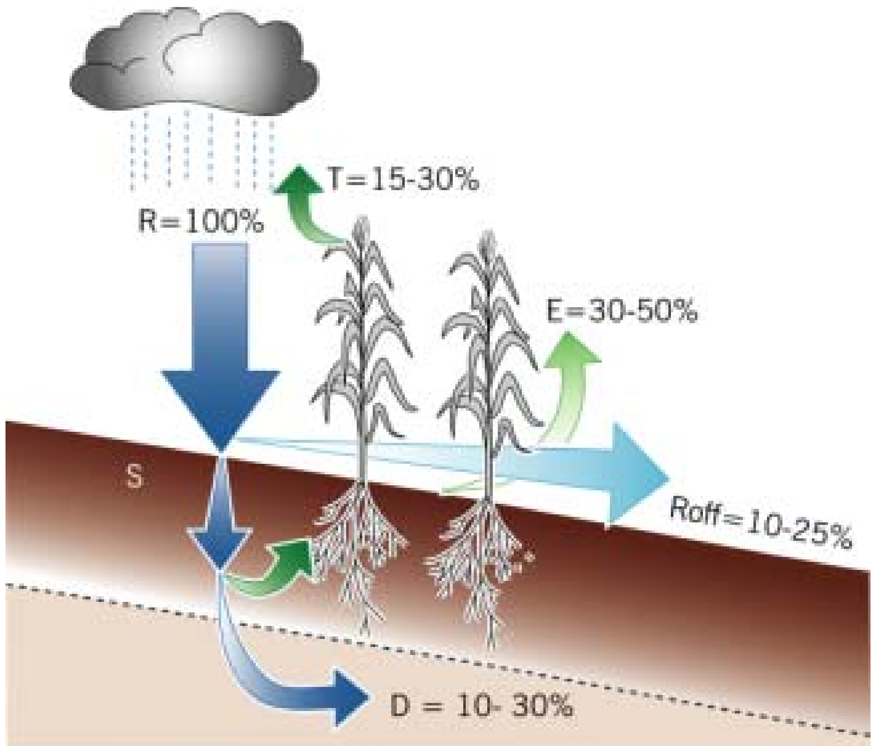

Figure 1. Rainfall partitioning in the semi-arid tropics in Sub-Saharan Africa.

Conservation farming – a water harvesting strategy

Conservation farming aims at reversing a persistent trend in many production systems of reduced infiltration capacity of soils due to compaction and crust formation and reduced water holding capacity due to oxidation of organic materials (due to excessive turning of the soil). From this perspective conservation tillage is a form of water harvesting, where runoff is impeded and soil water is stored in the root zone of the crop. This means that conservation tillage constitutes a very interesting approach to achieve improvements in water productivity and "crop per drop" increases, in line with the newly launched global dialogue on water for food and environmental security (Anonymous, 2001).

We know that for large parts of the developing world subject to rapid population growth yield levels of staple foods need to at least double over the next generation in order to at least keep pace with population growth. We also know that a majority of these countries are hosted in savannah environments. Generally it is assumed that water requirements increase linearly with increased food production, i.e., that a doubling of yields would result in a doubling of crop water use. Empirical research shows that water requirements range in the order of 1,000 – 3,000 m^3/ton grain (Falkenmark and Rockström, 1993), which explains why agriculture is the world's largest direct water using sector. However, there is strong evidence showing that water productivity can be improved (i.e., improvement in the amount of crop produced per drop of water) through management (Rockström et al., 2003).

Two key factors need to be improved in order to increase water productivity in agriculture:

- Increased crop water availability (through improved rainfall infiltration and water holding capacity, reduced soil evaporation losses through minimum or no-tillage and soil cover)
- Increased crop water uptake capacity (improved root depth and canopy development in order to maximise productive transpiration flow).

An aim of conservation tillage is to improve both these key water productivity enhancing factors. One major goal with conservation tillage is to change the partitioning of rainfall in favour of infiltration, soil moisture storage and plant water uptake. Rockström and Falkenmark (2000) have in a recent study shown that a doubling and in many cases even a quadrupling of crop yields in African savannahs is feasible from a hydrological perspective if such measures are accomplished.

Rainwater productivity can be increased further by timely farm operations such as timely planting and weeding. Planting is often delayed up to several weeks due to tillage operations. Adoption of reduced or no-tillage systems permit farmers to plant directly after the onset of the rains, thus exploiting the entire rainy season. Timely weeding is as important, as weeds compete for water. A permanent ground cover by crop residues and cover crops suppresses weed growth and reduces the labour requirements for weeding.

FARMER EXPERIENCES WITH CONSERVATION FARMING IN TANZANIA

Approach and Methodology

Farmer designed conservation tillage trials have been carried out since 1998 in semi-arid and dry-sub-humid (rainfall depth averaging 700 – 1000 mm yr^{-1}) parts of Arusha and Arumeru districts, North-western Tanzania. The trials included 8 – 10 farmers each year, in three villages; Sakila (sub-humid), Ngorobob and Mkonoo (semi-arid). The basic tillage implements involved are; ox and tractor drawn sub-soilers, ox-drawn Magoye ripper, and hand-hoe.

The trials included four principal production systems; (1) ripper/sub-soiler, (2) a ripped broad-bed system, (3) a manual pitting system and (4) the conventional ploughing system. These four systems were then combined and site-adapted regarding (i) inter-cropping (lab-lab or cowpea depending on location), (ii) fertilisation (manure, Mijingu rock-phosphate, and Urea), (iii) traction (oxen or tractor), (iv) crop rotation, (v) crop varieties. The main crop in all experiments is maize (*Zea mays*). Common to all sites was the use of a standard plant density of 80 x 30 cm, and the fertilisation (for all treatments expect the non-fertilised control). The experiment was a randomised block design with two repetitions per farm-site (i.e., two blocks with 6 treatments each). Each production system was repeated 16 – 20 times each rainy season (the variation explained by the varying number of farmers involved in the trials each rainy season).

Sub-soiling was carried out either with tractor or with an ox-drawn sub-soiler (developed by IMAG-DLO in Zambia, IMAG, 1999). Sub-soiling was carried out during the dry season to a depth of 40-50 cm for tractor sub-soiling and to 25-35 cm with the ox-drawn sub-soiler. The sub-soiling was then followed by ripping, which was done to establish permanent planting lines, along the contour at 75 cm spacing.

The pitting system was very similar to the *zai*-pitting found in the Sahel. A hand hoe was used to dig planting holes with a dimension of roughly 20x20x20 cm. Most important was that the depth exceeded the conventional ploughing depth (which in this region is 12-13 cm).

The conventional system (control) was similar in all locations, based on the post-onset ploughing with mouldboard plough. All conservation tillage treatments were dry planted, and crop residue was left on the fields as mulch (except for maize leaves, which were taken for fodder). Weeding control was done manually, following the normal practices in the area. However, one additional weeding operation was carried out after harvest in order to reduce weed infestation from weed seeding.

The trials started effectively with the long rains (March to June/July) of 1999. Despite a bimodal rainfall pattern, the short rains (generally from mid-October to January) are so poorly distributed with low cumulative rainfall, that most farmers do not even attempt to cultivate rainfed crops. The trials have been ongoing for 4 years, and in this paper yield data from the long rains of 1999-2002 are presented.

Yield Results

Table 1 shows the average yield results from the long rains 1999 - 2002 for the 8 - 10 participating farmers for each year. The average conventional ploughed maize yield is 1.3 t ha^{-1}, which is a factor 3 lower than the ripper treatments (yielding on average 3.8 – 4.0 t ha^{-1}).

Table 1. Maize grain yield of farmer trials in Tanzania for long rains 1999-2002 (4 rainy seasons). Treatment effects are shown compared to C (Control; conventional mouldboard ploughing without fertiliser application = farmer's current practice) and compared to C+FERT (conventional mouldboard ploughing including fertiliser application equal to the fertilisation of the CT treatments). Ripp = Magoye ripper, Ripp + CC = Magoye Ripper plus lab-lab cover crop, Ripp – Fert = Magoye ripper without fertiliser application, Pitting = manual hand-hoeing of planting pits plus fertilisation.

Treatment	N	Average Yield	SD	Treatment Effect - CONTROL	Treatment Effect C+FERT	Multiplyer	
		(kg/ha)	(kg/ha)	Sign.		Control	Control + Fertiliser
Ripp	39	3874	1781	0.0000 ***	0.0023 ***	2.4	1.4
Ripp+CC	39	3633	1809	0.0000 ***	0.0000 ***	2.2	1.3
Ripp-Fert	27	2539	1513	0.0024 **	0.4727	1.6	0.9
Pitting	39	3523	1515	0.0000 ***	0.0198 *	2.2	1.3
C+FERT	39	2783	1217	0.0000 ***	0.0000 ***	1.7	1.0
C	41	1621	885				

Conservation farming systems yielded on average 2.2 – 2.4 times higher yields than the present conventional practice based on mouldboard ploughing. This large and persistent difference can be attributed to the combined effect of improved water (through conservation tillage) and soil fertility management (through spot application of fertiliser and manure). The water effect of conservation tillage can be assessed by comparing the ripped system with the control receiving fertiliser, which resulted in a significant yield increase on average of 40 %. The soil fertility effect alone is indicated by the 70 % yield increase between the control with and without fertiliser application. It is interesting to note that addressing water alone – i.e., by adopting conservation farming without soil fertility management (represented by Ripp -Fert) results in roughly the same yield level as if the farmer addresses soil fertility alone (represented by conventional + Fert). This suggests two important issues. First that water is not necessarily the only, and often not even the major limiting factor for crop growth even in this semi-arid savannah environment. Secondly, it clearly shows that it is only when combining water and soil fertility management that a synergy effect is achieved, manifested in large yield level increases.

Similar results have been achieved in semi-arid Babati district, Tanzania, where tractor sub-soiling of maize resulted in an immediate (first season) 2.8 time increase in maize yields during the favourable rains 95/96 (from 1.7 to 4.8 t ha^{-1} for fertilised maize and 1.3 – 3.7 t ha^{-1} for non fertilised maize) and a 25 % increase in yields during a drought season (short rains 96/97) (Rockstrom and Jonsson, 1999).

The results of on-farm trials with subsoiling, cover crops and minimum-tillage, conducted in the neighbouring Hanang and Karatu districts confirm these findings. Yields of maize and wheat could be more than doubled during three consecutive years (1999-2001). The highest increment was observed in the dry year 1999, where the annual rainfall was only 233 mm and 451 mm compared to an annual average of 800 mm, and crops failed completely on conventionally tilled fields in Karatu district (TFSC/SARI 2000,2001 and 2002).

YIELD AND WATER PRODUCTIVITY

Rainwater productivity

The animal drawn ripper based conservation farming system resulted in increased rainwater productivity (an average WP_R of 2.400 m^3/ton compared to 3,800 m^3/ton for the conventional (non-fertilised) farmers' practice). According to the farmers participating in the trials, conservation farming resulted in practically zero surface runoff. This suggests that the reduction in water consumption per unit crop under CT is a result of a reduction on soil evaporation and/or deep percolation. Rainwater productivity was increased by fertilizer application in both systems (conventional = 1,750 m^3/ton; ripping = 1,400 m^3/ton) Using cover crops instead of fertiliser in ripped fields gave similar results as conventional farming with fertiliser (1,600 m^3/ton versus 1,750 m^3/ton). Data suggest a synergistic effect of rainwater harvesting and fertiliser application, indicating that fertiliser use efficiency is increased by conservation farming (i.e. improved soil moisture status)

The sub-soiling trials discussed above in Babati district in Western Tanzania using tractor drawn subsoiling and ripping, resulted in similar water productivity improvements (Fig. 2). A reduction in surface runoff and improved root water uptake, resulted, over a period of seven years, in a progressive improvement of WP_R from an average of 1.5 kg grain per mm of rainfall (6,600 m^3/ton grain) in the 1980s (based on conventional disc ploughing by tractor) to approximately 4.5 kg grain per mm of rainfall (2,500 m^3/ton) in the mid to late 1990s after adoption of deep tillage and non-inversion technologies (adapted from Rockström and Jonsson, 1999).

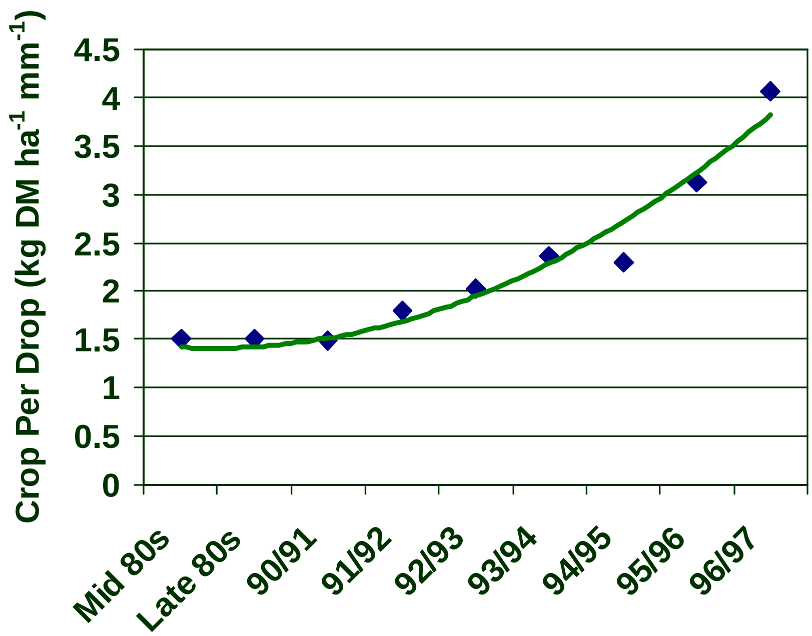

Figure 2: Development of rainwater use efficiency (kg DM grain mm^{-1} ha^{-1}) of maize in Babati District, Tanzania, before introduction of conservation tillage (Mid 80s to 90/91) compared to after introduction of conservation tillage (91/92 onwards) (Rockström, 2001).

FARMER EXPERIENCES WITH CONSERVATION FARMING IN MADAGASCAR

In Madagascar the French research organisation CIRAD is working since 1994 on the development of direct planting practices for smallholder farmers. Objective is to maintain soil fertility, prevent soil erosion and increase yields of food crops and produce also forage for livestock (cattle). Key issue is the maintenance of a permanent soil cover by crop residues and relay cropping of forage plants (oats,etc.) or associations with permanent species like *Desmodium uncinatum* or *Trifolium semipilosum*, Kikuyu grass or *Pennisetum clandestinum*. Crop yields, labour productivity and household incomes could be increased significantly with a steady upward trend.

Figure 3 shows data of on-farm trials of 6 successive years. Data are derived from 3 different regions in the semi-arid parts of the Madagascar highlands; three on-farm plots (=repetitions) were installed in 2 different sites in each region, in total 18 on-farm plots. Soils are sandy alfisols ("sols ferrugineux tropicaux) with 70 % sand and, 15 % clay. Annual rainfall varied between 480 and 850 mm. By stopping ploughing and direct planting bean yields could be raised from 200-400kg/ha to 800–1,700 kg/ha in unfertilised plots and from 400-600 kg/ha to 1,800–2,000 kg/ha in fertilised plots. The rainwater productivity was simultaneously raised from 0,1-0,2 kg of grain per m³ of water to 0,38 kg maize grains and 0,58 kg of maize and cowpea grains (intercropping).

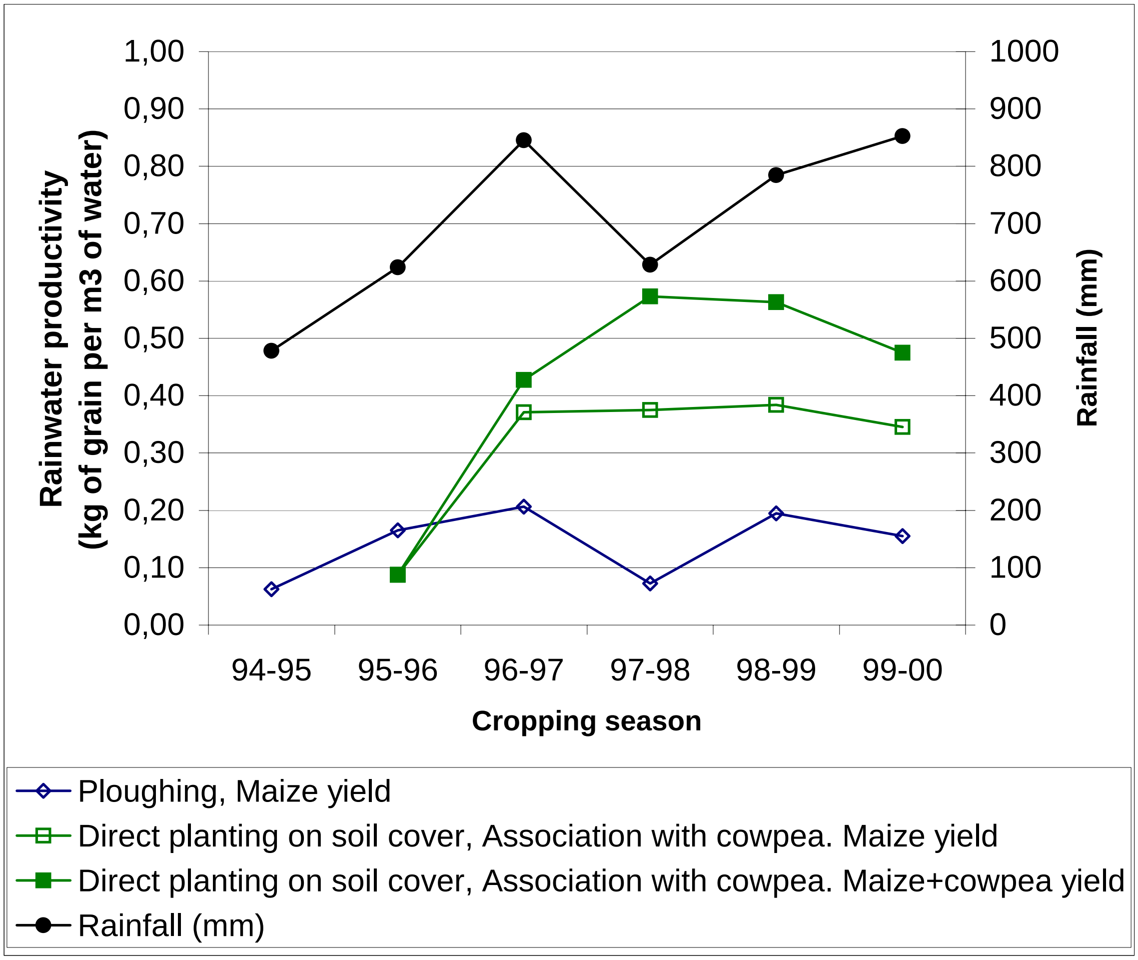

Figure 3:
Development of rainwater productivity under direct planting through soil cover in Tulear, Highlands of Madagascar.

DEVELOPING RAINWATER HARVESTING TECHNIQUES IN THE KORDOFAN PROVINCE OF SUDAN

In Sudan food security in dryland agriculture is threatened by low average rainfall and frequent droughts. Due to population growth more and more traditional pastureland is used for cropping. The National Agricultural Research Institute conducts since 1998 on-farm trials with rainwater harvesting methods in the Kordofan province, with the objective to increase yields and reduce the risk of crop failure due to drought. The land is almost flat with gradients of 1 %, only. Soils are sandy to sandy clay loams. Rainfalls are erratic, with annual means varying between and 140 and 624 mm (1998 – 2002). Prolonged dry spells during the cropping season are frequent.
Traditionally farmers till or better scratch the land only superficially with hand tools. The main crops are sorghum, millet, watermelon and groundnut. With the first rains the soil surface gets crusted, resulting in run-off and high losses of precious rainwater.
The rainwater harvesting techniques tested consists of parallel earth bunds, about 40 cm high, and build in 10 m distance. The upper half of the strip in between bunds serves as run-off area, the lower half is planted with Sorghum. The sorghum is planted in ripped (by a chisel or tine) rows, outlets for excess water are placed to ensure even water distribution, while cowpea or groundnuts and Roselle are planted on the inner side of the earth bunds (soil protection and additional source of food and income). With this simple technique sorghum yields can be tripled to quadrupled in normal years, and total crop failure can be prevented in dry years (Figure 4). The rainwater productivity is a rough estimate, based on total rainfall in the growing season and crop yields.

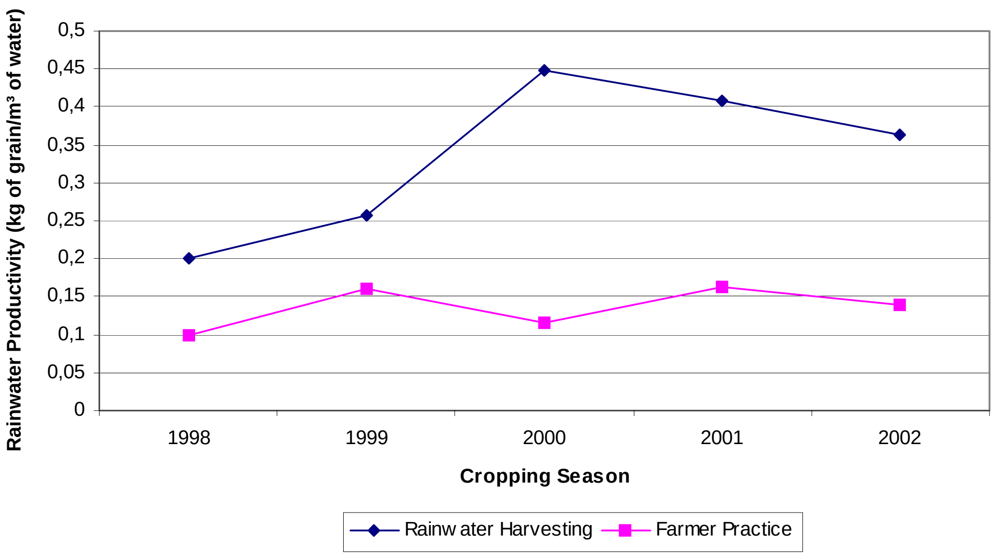

Figure 4: Impact of rainwater harvesting on sorghum yields in Obeid, Kordofan province, Sudan. Data from researcher managed on-farm trials 1998-2002. “Farmer practice” refers only to tillage not to other management aspects, which equal those of

"Rainwater harvesting". Data of farmer practice 1998 and 2002 interpolated. Complete crop failure due to drought in 2002 (Alfadni, pers. comm.).

CONCLUSIONS AND DISCUSSION

Conservation farming or tillage systems are not new and have during the last decades been adopted at large scale in several countries in Latin America, in parts of Asia, and in North America. Common to this wide adoption is that most success and adoption has been experienced in relatively wetter hydro-climatic zones, with limited success in drier, savannah agro-ecosystems. This paper addresses the water harvesting advantages of conservation farming systems, which forms an entry point to conservation farming development in relatively drier savannah environments. Interestingly, commercial farmers in semi-arid and dry sub-humid regions of, e.g., Tanzania and Zimbabwe, have adopted conservation tillage practices, resulting not only in higher and more stable yields but also significantly reduced labour and fuel needs (Oldreive, 1993). Only very limited adoption has been experienced among smallholder farmers in savannah agro-ecosystems.

On-farm trials in savannah agro-ecosystems among smallholder farmers in Tanzania show that yield levels of maize can be effectively more than doubled over consecutive years with varying rainfall levels, through the adoption of conservation farming practices. A cornerstone in these practices is the *in-situ* water harvesting effect of ripping and sub-soiling, which instead of turning the soil at shallow depth (as done by ploughing) opens a deep planting furrow, which effectively collects rainwater.

Mouldboard ploughing is still perceived among farmers, extension agents, development officers and most researchers, as a *sine-qua-non* in every crop producing system. The very notion of abandoning the plough in favour of various techniques of reduced tillage was initially not easy to convey. Disbelief was, however, rapidly turned into a strong local ownership of the adaptive process of designing site-specific conservation farming systems. This highlights two important issues; (1) that farmers understand their local water balance and the causes behind plant water stress despite adequate rainfall, and (2) that farmers are open-minded and prepared to ditch the most fundamental component of their land use practice – the plough – if they can see the benefits in doing so.

Rainwater productivity is increased by a soil cover of crop residues and covercrops. This is however difficult to achieve in dry savannahs, where rainy seasons are followed by long dry seasons, biomass growth is overall low, and livestock and humans compete for the use of post-harvest biomass remaining in the fields. A challenge in savannah regions is, therefore, to develop integrated crop-livestock production systems. This requires further research and development activities together farming communities.

Conservation farming systems provide farmers with an effective tool to maximise rainfall infiltration into the soil and to build up water holding capacity and crop water access. They do not provide farmers with a solution to mitigate dry spells, even though the length of dry spells and its effects can be reduced somewhat thanks to an increase in soil moisture availability. An interesting, unexplored avenue is to integrate conservation farming practices as a form of *in-situ* water harvesting with external water harvesting systems where runoff water upstream from cropland is harvested and stored for supplemental irrigation. Together, such practices could enable farmers to increase and stabilise food production, and thus improve rural livelihoods on the long term.

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