Dry spell mitigation to upgrade semi-arid rainfed agriculture:

Water harvesting and soil nutrient management
for smallholder maize cultivation in Machakos, Kenya

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Doctoral thesis in Natural Resource Management

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Abstract

Improvements in on-farm water and soil fertility management through water harvesting may prove key to up-grade smallholder farming systems in dry sub-humid and semi-arid sub-Sahara Africa (SSA). The currently experienced yield levels are usually less than 1 t ha^{-1}, i.e., 3-5 times lower than potential levels obtained by commercial farmers and researchers for similar agro-hydrological conditions. The low yield levels are ascribed to the poor crop water availability due to variable rainfall, losses in on-farm water balance and inherently low soil nutrient levels. To meet an increased food demand with less use of water and land in the region, requires farming systems that provide more yields per water unit and/or land area in the future. This thesis presents the results of a project on water harvesting system aiming to upgrade currently practised water management for maize (*Zea mays*, L.) in semi-arid SSA. The objectives were to a) quantify dry spell occurrence and potential impact in currently practised small-holder grain production systems, b) test agro-hydrological viability and compare maize yields in an on-farm experiment using combinations supplemental irrigation (SI) and fertilizers for maize, and c) estimate long-term changes in water balance and grain yields of a system with SI compared to farmers currently practised *in-situ* water harvesting. Water balance changes and crop growth were simulated in a 20-year perspective with models MAIZE1&2.

Dry spell analyses showed that potentially yield-limiting dry spells occur at least 75% of seasons for 2 locations in semi-arid East Africa during a 20-year period. Dry spell occurrence was more frequent for crop cultivated on soil with low water-holding capacity than on high water-holding capacity. The analysis indicated large on-farm water losses as deep percolation and run-off during seasons despite seasonal crop water deficits. An on-farm experiment was set up during 1998-2001 in Machakos district, semi-arid Kenya. Surface run-off was collected and stored in a 300m^3 earth dam. Gravity-fed supplemental irrigation was carried out to a maize field downstream of the dam. Combinations of no irrigation (NI), SI and 3 levels of N fertilizers (0, 30, 80 kg N ha^{-1}) were applied. Over 5 seasons with rainfall ranging from 200 to 550 mm, the crop with SI and low nitrogen fertilizer gave 40% higher yields (**) than the farmers' conventional *in-situ* water harvesting system. Adding only SI or only low nitrogen did not result in significantly different yields. Accounting for actual ability of a storage system and SI to mitigate dry spells, it was estimated that a farmer would make economic returns (after deduction of household consumption) between year 2-7 after investment in dam construction depending on dam sealant and labour cost used.

Simulating maize growth and site water balance in a system of maize with SI increased annual grain yield with 35 % as a result of timely applications of SI. Field water balance changes in actual evapotranspiration (ET_a) and deep percolation were insignificant with SI, although the absolute amount of ET_a increased with 30 mm y^{-1} for crop with SI compared to NI. The dam water balance showed 30% productive outtake as SI of harvested water. Large losses due to seepage and spill-flow occurred from the dam. Water productivity (WP, of ET_a) for maize with SI was on average 1 796 m^3 per ton grain, and for maize without SI 2 254 m^3 per ton grain, i.e, a decerase of WP with 25%. The water harvesting system for supplemental irrigation of maize was shown to be both biophysically and economically viable. However, adoption by farmers will depend on other factors, including investment capacity, know-how and legislative possibilities. Viability of increased water harvesting implementation in a catchment scale needs to be assessed so that other down-stream uses of water remains uncompromised.

Papers

I. Barron, J., Rockström, 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.*

II. Barron, J., Rockström, J., Gichuki, F. 1999. Rainwater management for dry spell mitigation in semi-arid Kenya. *East African Agriculture and Forestry Journal 65(1):57-69.*

III. Barron, J. Okwach, G. Run-off water harvesting for dry spell mitigation in maize (*Zea mays L.*): results from on-farm research in semi-arid Kenya. *(Submitted to Agricultural Water Management)*

IV. Fox, P., Rockström, J., Barron, J. Risk analysis and economic viability of water harvesting for supplemental irrigation in the Semi-arids. (*Accepted for publication in Agricultural Systems with minor revisions)*

V. Barron, J., Rockström, J., Stroosnijder, L., Modelling on-farm water balance effects of water harvesting system for *Zea mays* in semi-arid Kenya (*Manuscript*)

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Other related work:

Rockström, J., ***Barron, J***., Fox, P., 2003. Water productivity in rainfed agriculture: Challenges and opportunities for smallholder farmers in drought prone tropical agro-ecosystems. In 'Water productivity in agriculture: limits and opportunities for improvements' (Eds. J.W. Kijne, R. Barker, D. Molden), CABI, Wallingford, U.K.

Rockström, 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

Contents

1. Introduction

Water is a major limiting factor for crop growth in smallholder farming systems in semi-arid and dry sub-humid Africa. The climatic conditions with high atmospheric evaporative demand and highly variable rainfall in spatial and temporal scales make farming a risky business. As a result of variable rainfall, low fertilizer use and poor overall crop management, small-holder farmers' cereal yields are low at 1 t ha^{-1} or less (e.g., FAOStat, 2003; Rosengrant et al., 2002). Potential yields obtained by on-station or commercial farmers for similar conditions are 3-5 times higher. In a longer term perspective on a regional scale the effect is less ability to feed the population as yield growth stagnate or decrease over time (Pinstrup-Andersen et al., 1999). Future scenarios with high population growth (UN/Population Division, 2002) albeit not necessarily in agricultural production (Tiffen, 2003), marginally reduced poverty (FAO, 2003) and increasing demand of water and land for other societal and ecosystems uses (Falkenmark, 1997), put additional pressure on small-holder farmers to produce more with less resources. Better on-farm water management through rain water harvesting can prove to be an opportunity to upgrade current farming practices in these climate regions (Rockström, 2003). Less risk of crop failure due to crop water deficits may improve farmers' willingness and ability to further invest with fertilizers and other crop management strategies.

The UN Millenium Development Goals (see UN, 2004) aim to half the number of poor and food insecure by 2015. Of the 1 billion poor in the world today, 75% make their living in typical rural areas, dependant on smallholder farming for their livelihood. Agricultural productivity is a key to rural development in poverty-stricken regions (World Bank, 2003). Unlocking the potential of rainfed farming systems in regions subject to frequent environmental constraints such as dry spells and droughts should therefore be high-priority to achieve the Millenium Development Goals. This requires innovative and viable options on farm-scale without compromising land and water resources for other uses in landscape and society.

This thesis presents the results from an on-farm experiment using a rain water harvesting (RWH) system for dry spell mitigation in maize (*Zea mays*, L.). The overall objective was to test biophysical and socio-economical viability of a system that collect sheet and rill runoff, and store the collected water for use as SI to stabilize maize yields. With focus on innovative options to upgrade smallholder farming in tropical savannah agro-ecosystems, the underlying hypotheses were formulated as

- Dry spell occurrence in smallholder farming systems can explain the large yield gap between farmers and reported on-station yields
- Water lost on a field scale can be utilized as supplemental irrigation to mitigate dry spell effects and lead to increased biomass production
- Improved crop water status justifies addition of fertilizer to further stabilize yields
- Upgrading current farming system through SI and fertilizer can be viable and sustainable way to improve livelihood security for smallholder farming households in a long-term perspective

The research aimed to

- Assess current climatic limitations in terms of rainfall amounts and dry spell occurrences for maize growth and yields at the a semi-arid location, Eastern Africa (Paper I)
- Test technical viability on-farm of a rain-water harvesting system collecting runoff in an earth dam and using gravitational forces to irrigate for down hill located maize crop (Paper II, III)
- Measure on-farm water balance and yield effects of maize subject different combinations of SI and fertilizers during 5 rainfall seasons (Paper II, III)
- Estimate economical cost and benefit for small-holder farmer household to implement similar system with RWH stored for use as SI in maize crop (Paper IV)
- Simulate long-term on-farm water balance and yield effects for a system with water harvesting for SI at the site (Paper V)

The experiment was located in Mwala, Machakos District, semi-arid Kenya at two farmers' fields during 1998-2001. Surface run-off was collected and stored in an earth dam, subsequently used for supplemental irrigation (SI) of maize. Treatment of SI was combined with 3 different levels of nitrogen fertilizer. The on-farm agro-hydrological measurements were used as indata to simulations of maize growth and water balances with MAIZE1&2 models during a 20-year period. The thesis begins to presents the overall context of water and nutrient management in tropical savannah agro-eco systems with special focus on conditions in Machakos District, Kenya. The papers are briefly presented and discussed in relation to other work relevant to the results. Finally, some points are made for potential implementation of the results and further research in the area of rain water harvesting for tropical savannah agro-ecosystems.

2. Background

Rainfall in savannah agro-ecosystems

Approximately 60 % (excluding the hyper arid climate zones) of the African continent is classified as dry sub-humid or drier (UNEP, 1992; UNDP/ UNSO, 1999). These climatic zones roughly coincide with the so-called tropical savannah agro-ecosystems. An estimate of 40% of the SSA population lives in these regions (UNDP/ UNSO, 1999). Rainfed farming systems is a major source of food and income for many. Rainfall in tropical semi-arid and dry sub-humid climate zones is highly variable in spatial and temporal scales. Several studies of crop water balances in savannah agro-ecosystems have been undertaken on research stations and on-farm (e.g., Rockström & Falkenmark, 2000; Bennie & Hensley, 2001). In this thesis the water balance components will be discussed mainly on a field scale and on seasonal to decadal time-scales. The water balance equation for a unit land area can be written as

$$P + Irr + R_{on} = R_{off} + \left(E + I + T\right) + D + \Delta S \qquad (1)$$

Where P is rainfall, Irr is irrigation, R_{on} is run-on from adjacent up slope located land units, R_{off} is runoff into adjacent down slope located land units, E is evaporation, I is interception losses, T is transpiration losses, D stands for deep percolation, and ΔS represents change in water content in soil during time step. All units are normally in (m^3 m^{-2}) or mm. The term $(E + T + I)$ is referred to as the 'green water flow', i.e., the amounts of water used (or required) for production of biomass.

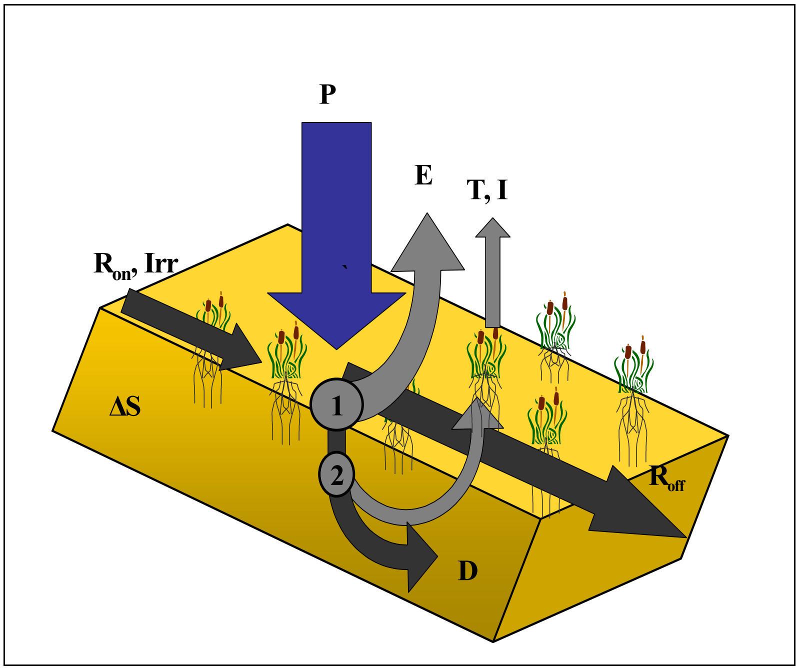

Figure 1: Water balance components in landscape unit with partitioning points 1) on soil surface, and 2) in the soil. The letters symbolizes the parameters of Eq 1): P=rainfall, E=evaporation, T,I=transpiration and interception respectively, R_{on}=run-on, Irr=irrigation, ΔS=change in soil water content, D=deep percolation, and R_{off}=runoff.

Some characteristics of field water balances in semi-arid tropics can be summarized as:

- Atmospheric demand (ET_p) is ranging from 1.5 to 10 times the annual average rainfall
- Rainfall is highly variable both in temporal and spatial scales, and increases in variability as long-term seasonal average decreases

- Rainfall falls during limited time (rain seasons) which are relatively short, 3-6 months
- Relatively small amounts of seasonal rainfall is used for biomass production (*T*)
- Large amounts of water are unproductive on a field scale (*E*, *D*, R_{off}) compared to transpiration losses

Long-term seasonal amount often range between 400-1000 mm concentrated to a limited period of 70-140 days. This is substantial amount of water, which hypothetically could produce 4000-10000 kg grain ha^{-1} if all water could be used effectively for transpiration. Crop water deficits are not so much due to lack of rainfall amounts, but rather due to poor distribution. When rain occurs, it is usually plenty, causing local floods, soil erosion and infrastructural damage (FAO, 2000b). As the rainfall for a semi-arid site often show skewed distributions of rainfall, the number of seasons which are above long-term average are usually fewer than the number below (Nicholson,1993; Sivakumar, 1992). An example of seasonal rainfall variations is shown in Fig. 2 for rainfall data collected in near Mwala, Machakos District; Kenya.

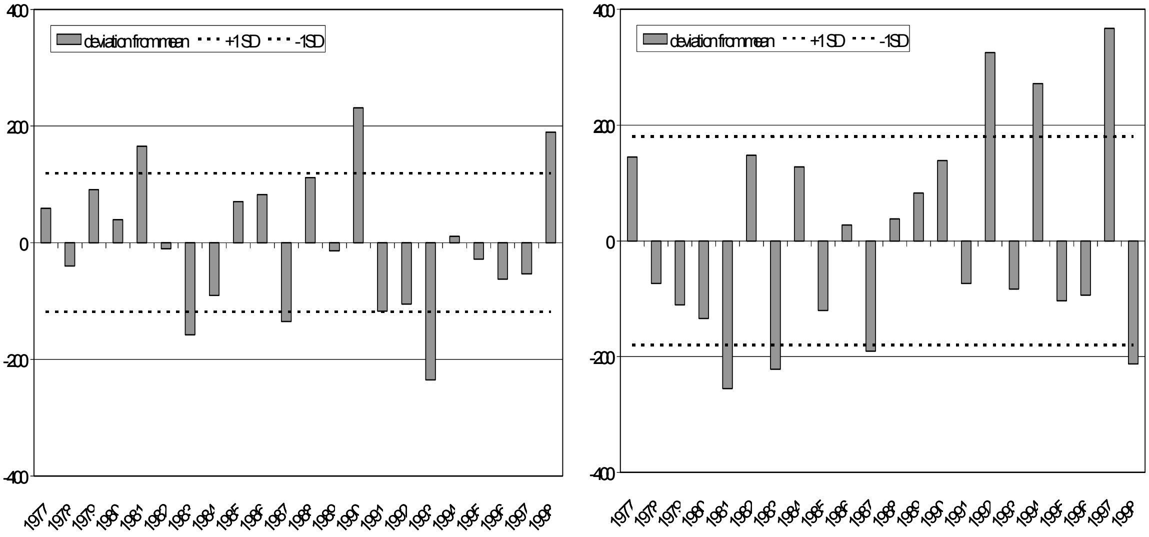

Figure 2: Chief Mbiuni Camp, Machakos District, Kenya seasonal rainfall deviations from long term mean during long rains= 323 mm(left) and short rains = 399 mm(right) during 1977-1998. Standard deviations from mean are indicated as lines.

Equally disrupting are droughts, when seasonal rainfall falls below a minimum requirements for maintenance of societal requirements (e.g., Agnew & Anderson, 1992; Glantz, 1994; UNDP/UNSO, 1999; Thompson, 1999). Meteorological droughts are often defined as seasons (years) with long term mean rainfall minus 1-1.5 standard deviation (e.g., Le Houérou, 1992; Downing et al., 1985; Williams & Balling, 1994). This typically occurs in 1 of 10 seasons in semi-arid SSA and result in complete crop failure (Stewart, 1988). An agricultural drought may occur with higher seasonal rainfall than a meteorological drought. But due to poor distribution within season and low crop water availability as losses (to the crop) of water as runoff and evaporation causing 'drought' in the root zone, result in crop failure. From an agricultural perspective it is unlikely that crop failure due to meteorological drought can be prevented, unless a system of full irrigation is applied. An agricultural drought may however be prevented through crop management practises, for example improved crop varieties, appropriate cropping systems, or better crop water availability through supplemental irrigation.

Uneven distribution incurs periods of dry spells within rainfall season. It is useful to distinguish between dry spell occurrence as a result of meteorological conditions, i.e., rainfall or no rainfall, or agricultural dry spell occurrence, which is linked to crop, soil and rainfall conditions at a site. It is worth noting that the bulk of analysis on occurrence of water stress has focused on the occurrence of meteorological droughts. A number of analyses for meteorological dry spell occurrence have been presented for different locations in SSA (Sivakumar, 1992; Sharma, 1995; Jimoh & Webster, 1996; Adiku et al., 1997; Mahoo et al., 1999; Ochola & Kerkides, 2003;). However, few analyses have been done on the occurrence of dry spells and management-related agricultural dry spells, their (potential) impact on crop growth, and their relative importance for risk management among farmers. In this thesis, Paper I presents an evaluation of dry spell occurrence and potential impact on maize growth in relation to water deficit for two sites in semi-arid Kenya and Tanzania. Similar data is also presented for a site in semi-arid Burkina Faso, which constitutes the basis of cost-benefit analysis in Paper IV.

In the future, dry sub-humid and semi-arid regions in SSA are expected to face water scarcity, i.e., insufficient amounts of water to meet population demand of food and development whilst maintaining eco-systems life supporting processes. Projections of population growth, water requirements for agriculture, societal needs and for maintenance of eco-systems services are increasingly competing for water quantities as well as water qualities (e.g., Kijne et al., 2003). It is being realised that more food has to be produced with less water, meaning higher water productivity (WP, kg grain or biomass per m^3 water) to meet demands. As water demand increases for non-agricultural uses, it is unlikely that future food requirements can be met by sole reliance on irrigated crop production. Today more than 90% of agricultural land in SSA is under rainfed production, producing more than 96% of cereals (Rosengrant et al., 2002). The challenge may be on how to improve rainfed agriculture by simultaneously improving rural livelihoods and water productivity (e.g., Rockström et al, 2003). Where are the greatest potentials for yield increases with the least resources?

Water, nutrients and maize yields in small-holder farming systems

Although water may be primarily limiting for agricultural production and crop growth (e.g., Voortman et al., 2003), the instant soil water is available nutrient deficiency will be the limiting factor. Obviously, the two states will alternate during the crop season and in the end determine final yields (e.g., Gregory et al., 1997). To further complicate matters different nutrients can alternate to limit growth in different stages in a situation were soil water is readily available (e.g., Penning de Vries, 1984). Lack of available soil nutrients and low input of fertilizers in smallholder farming systems in SSA have been thoroughly discussed elsewhere (e.g., Voortman et al., 2003; IFPRI, 1999; Stoorvogel et al., 1993; Smaling & Braun, 1996; Nadwa & Bekunda, 1998; Bationi et al., 1998). Although previous data on soil fertility status and the importance of organic matter status may have been overestimated (de Ridder et al, 2004; Sanginga et al., 2003) low yield levels persist with no additional in-put of nutrients. Several studies have showed the interaction of soil water and nutrients for semi-arid farming conditions (Klaij & Vachaud, 1992; Brouwer & Bouma , 1997; Rockström et al., 1999; Fox & Rockström, 2003) which emphasis the importance to secure water availability in order to improve crop nutrient uptake. A schematic figure (Fig. 3) can be used to illustrate the water-nutrient interactions.

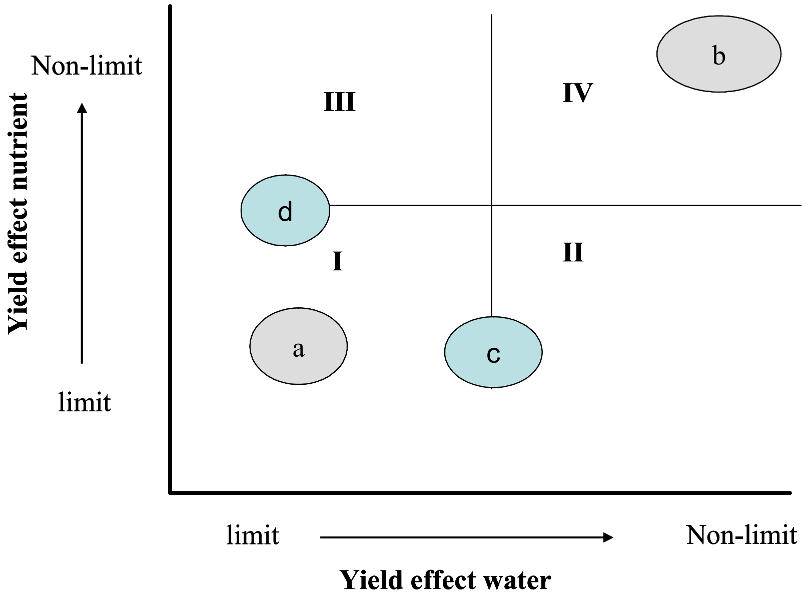

Figure 3: Conceptual matrix of yield effects due to water-nutrient limiting conditions in farming systems. Number I-IV refers to water-nutrient domains. Letter a) represents current practiced smallholder farming system with water and nutrient limiting yield levels, b) refers to potential achievable yield level for local conditions, c) represents improvement of a through e.g., water harvesting, d) represents a with improved nutrient status.

In this figure (also discussed in Paper V), decline in yields as a result of water limitations are on x-axis, and decline in yields as a result of nutrient limitations are on y-axis. Four different water-nutrient domains presents themselves: I) as in current rainfed small-holder farmer with limited input of nutrients for crop, II) as improved systems with better crop water availability through *in-situ* water harvesting, or other soil and water conservation strategies, III) improve yields by better nutrient management (as suggested by extensive research), and IV) as in a high-intensity system with combination of better water and nutrient management. Farmers current practised system with low (no) nutrient management and low water management result in low yields (a). The potential yield level refers to site and crop specific conditions (b). Farmers' experiences and research have shown that better soil water management (such as in-situ rain water harvesting) improve yields (c). Research has shown that better nutrient (fertilizer) management in farmers current practises improve yield levels (d). However, improved water combined with nutrient management does not necessarily shift yield levels to higher yield levels in line with b-d. It would be expected that over-all yields improve more than either c or d, due to synergistic effects of the combination of water and nutrient management.

The main cereal crop in savannah agro-ecosystems is maize (*Zea mays* L.) in Southern and Eastern Africa. Also in parts of West Africa maize is a major contributor to household diets (Carter, 1997; CIMMYT, 1999). Maize is favoured by farmers compared to more drought tolerant cereals such as millet or sorghum despite its sensitivity to water deficiency, in particular during flowering and grain filling. Maize was brought to the African continent during the 16th century but it has only been cultivated continuously on a larger scale for approximately 70 years. Today maize is grown on more than 70 % of total area of cereal cultivation in many countries in Southern and East Africa (CIMMYT, 1999). As maize is 'only' 70 years old, it is unlikely to find 'indigenous farming systems' not affected by external inputs such as information, technology, tools and possibly improved seeds, fertilizers and pesticides. Farmers have in the past and continue to adapt their farming systems to conditions both environmental and socio-economical change (e.g., Critchley, 2000; Tiffen et al., 1994; Niemeijer, 1996; Mortimore & Adams, 2001). Despite this yield levels are not increasing in step with population growth. Former agricultural systems may have been appropriate and sustainable when land was more abundant (such as fallow systems, slash and burn). With increased pressure on land and water for different uses, they may have to be abandoned and new strategies introduced. The overall aim to meet food demand should be to increase efficiency, i.e., produce more with less resources. In particular, this relates to improved on-farm water and nutrient management, but also for land area, labour input and other commodities in agricultural production. As an example for maize yield improvements, a recent study from USA reported that the yield increase from 1 t ha^{-1} in the 30s to todays' level of 7 t ha^{-1} mean yields is a result of combined plant breeding and agronomic management factors (Tollenaar & Lee, 2002). CIMMYT suggest that genetic improvement can account for 15-25% yield gap decrease, 15-25% can be achieved with better management of existing N and water resources, and the remaining yield gap can only be reduced through addition of both water and nutrients (CIMMYT, 1999, p. 26).

Farmers in tropical savannah SSA incorporate different technologies to improve *in-situ* water infiltration capacity. Examples are numerous soil conservation technologies such as terracing, mulching, contour bunds, ridging, semi-circular formations, living barriers, pitting, reduced tillage, etc. (e.g., Reij et al., 1996; Ellis-Jones & Tengberg, 2000; Hatibu, 2003). Improved strategies incorporating in-situ water harvesting together with fertility management are also suggested (e.g., Gicheru et al., 2003; Jensen et al., 2003). Although these structures improve soil infiltration and crop water availability, the efficiency for mitigation of dry spell effects may be limited depending on soils inherent water holding capacity. Examples of traditional irrigation systems exists usually practising flood irrigation /diversions of flood water (e.g., Adams & Watson, 2003; Tesfai & Stroosnijder, 2001). Water harvesting with storage component are much less common in SSA than for example in South Asia (SIWI, 2000; Sivanappan, 1997; Agrawal & Narain, 1997). There are also a few documented examples of run-off water harvesting with storage using water for supplemental irrigation combined with fertilizer (e.g., Fox & Rockström, 2003; Carter & Miller, 1991) although this type of systems have improved water productivity in e.g., Mediterranean climate (Oweis et al., 1999; Oweis & Hachum, 2003). Considering the amounts of runoff created in these environments, there appears to be a potential to better utilize surface runoff on a field scale. This includes a major shift in view on surface runoff as a '*problem*' causing soil erosion, to a manageable '*resource*' leading to yield stability and potential increase. The argument made here is that if water availability can be secured for a larger part of the crop season (than in current farming systems) the final yields would be increased. The yield stability with less risk for crop failure may also provide incentive to invest in other crop management practices that further improve yields. The potential gains are for the farmer higher yields and better livelihood security, and on a larger scale (catchment/regional), improved water productivity and improved food self-sufficiency.

3. Material and methods

Location and current farming system

The on-farm experimental site outside Mwala Town was located in Machakos District, Kenya (Fig. 4). The area is semi-arid with bi-modal rainfall pattern of 600-100 mm y^{-1} and ET_p ranging between 1200-1800 mm y^{-1} (Jaetzold & Schmidt, 1983). Long rains (LR) begin in March to May, and Short rains (SR) from mid-October to mid-Janyary (see also Paper I). The environmental history of Machakos District has been extensively documented and studied (Tiffen et al., 1994). Briefly, the farming is characterized by small-holding farms relying on maize intercropped with beans and pigeon peas for subsistence production. Livestock is usually kept as goats, indigenous cattle and poultry (Runkadema, 1984). As in many other part of SSA, population has grown at 2.5-3 % per annum during the last 50 years. This has increased demand for agricultural land, so that today farmers use approx. 1 -5 ha for an average household. In colonial times, Machakos was subject to much soil erosion problems (according to colonial administration). Therefore regulations for land management were imposed in order to reduce land degradation in the area. Post-colonial development has included large support to Machakos District agricultural extension service including soil conservation branch of Ministry of Agriculture (e.g., Pretty et al., 1995). Other factors improving land management has been ascribed to population increase and subsequent availability in labour as well as increased land value (Tiffen et al., 1994), and development of infrastructure, access to markets and wind fall of coffee during the 70s' (Zaal & Oostendorp, 2002). Today, most land in the district is terraced, and farmers are generally aware of the beneficial effects of soil conservation methods such as terracing, mulching, and run-off diversion techniques to maintain land productivity. Although such methods may improve soil water status as well as reduce soil erosion, farmers neighbouring the field experiment did not explicitly practice water conservation. In an interview study of 66 farmers in Masinga, Masii and Wamynyu locations in Machakos District, several issues concerning farm water management and dams were identified (Jurdell & Svensson, 1998):

- Farmers with dams (median dam size of 750 m^3) used water for domestic, livestock and crop production
- In crop production, most farmers irrigated so-called cash crops
- Dams tended to be located at the lowest part of farm, i.e., irrigation of above – located fields may be labour intensive
- The farmers with dams in the study tended to be comparatively better situated than farmers without dams
- Farmers without dams perceived dam construction as expensive and laborious
- 2/3rds of the dams were constructed manually

At the same time, farmers around the experimental site expressed much concern on water availability both for household and for crops. In another study on rainwater harvesting for food security for households in the Mwala Division (Duveskog, 2001) fresh water was identified as a major constraint both for domestic and for crop production. Available stream and shallow ground water is saline due to weathered bedrock in the area. Rainfall was perceived as erratic and poorly distributed. But few of the farmers (n=69) had dams or other water storage in their farm. Most households in the survey experienced food shortage during part of the year. The study estimated that on average, a farm household could produce its food during average rainfall years. During poor rainfall, food for own consumption would be limited.

On a national level, fertilizer consumption is increasing in Kenya. Data is not available on how the fertilizer is used, i.e., for what type of crops or farms. There are indications that the increase is due to increased use in high-potential areas and/or by commercial farmers rather than smallholder subsistence farmers (Jayne et al., 2003). The current practised farming systems may be efficient in the sense that soil erosion has decreased (e.g., quantitative loss). But due to limited input of nutrients, farmers tend to ‘mine’ the soil in a qualitative sense. It has been suggested that current farm household income is partly due to nutrient mining (de Jaeger et al., 2001). The lack of water bodies is another major restriction for future intensification of agriculture. Machakos District has few permanent rivers, and few developed ground water sources for water withdrawal to agriculture (Machakos District Development Plan, 1994). It is unlikely that agriculture can withdraw any significant amounts of fresh water for irrigation in the future.

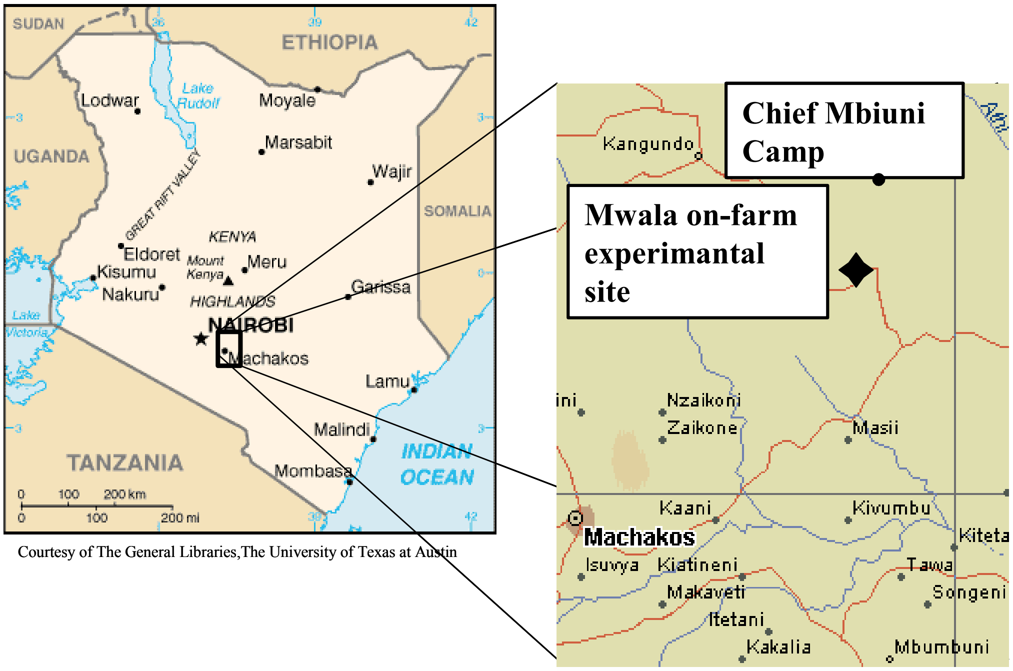

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Figure 4: Location the on-farm experimental site outside Mwala, Machakos District, Kenya.

Site description and agro-hydrological measurements (Paper II, III)

The site for on-farm supplemental irrigation of maize was located to two farmer's fields outside Mwala Town, Machakos District, Kenya (37°25'E, 1°20'S, approximately 1 200 m. a. s.). The site construction started in February 1998 and the agronomical experiments began long rains 1998 until end of short rains 2001. The site consisted of the upper catchment area with a hand-dug earth dam for collected run off, and a lower situated field on three terraces (see Paper III, Fig. 2). The runoff was collected partly from a 25–year old fallow of 7 250 m^2 (van Vliet, 1999) and partly from a larger catchment area of 19 700 m^2 which was believed to vary in size depending on rainfall amounts (Jansson, 2001). Irrigation was fed by gravitation to the field. On the field furrows were used to distribute water in plots. The soil in the experimental field was classified as a Chromic Cambisol in the upper terrace and as a Mollic Fluvisol in the lower terrace according to the FAO soil classification system (Dr Gicheru, *personal com.*). The textural analyses and soil water retention curves for the two profiles are presented in Fig. 5 and Fig.6.

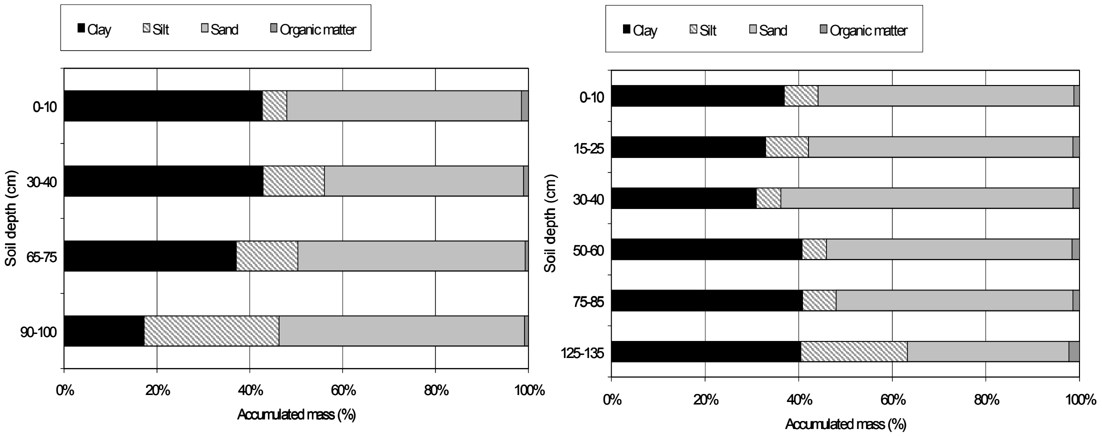

Figure 5: Textural composition for the sampled soil profiles on top terrace Block I (left), and lower terrace Block III-V (right).

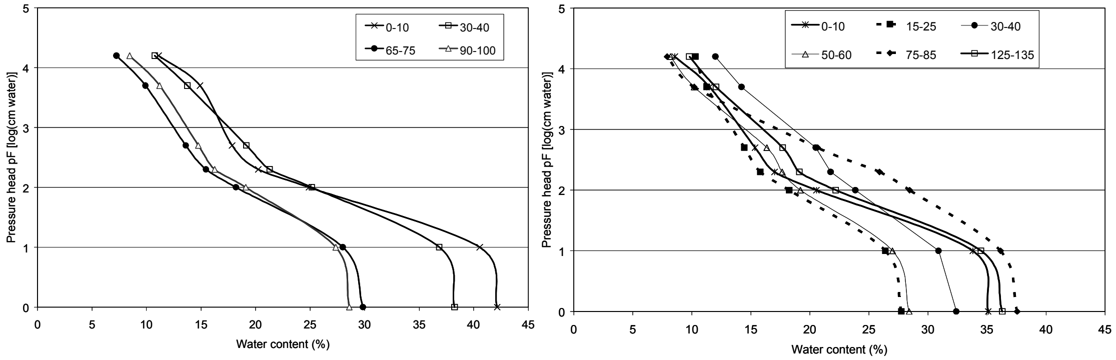

Figure 6: Water retention curves for the sampled soil profiles on top terrace Block I (left), and lower terrace Block III-V (right).

Treatments were randomly allocated to main plots of supplemental irrigation (SI) or no irrigation (NI). Within each sub-plot treatments of no (0 kg N ha^{-1}), low (30 kg N ha^{-1}) or high (80 kg N ha^{-1}) fertilizer dose was applied. Treatment NI 0 kg N ha^{-1} was taken to represent current farming practises. The treatments were replicated in 5 blocks (Fig. 7). The site conditions and experimental set-up is further described in Paper II and III.

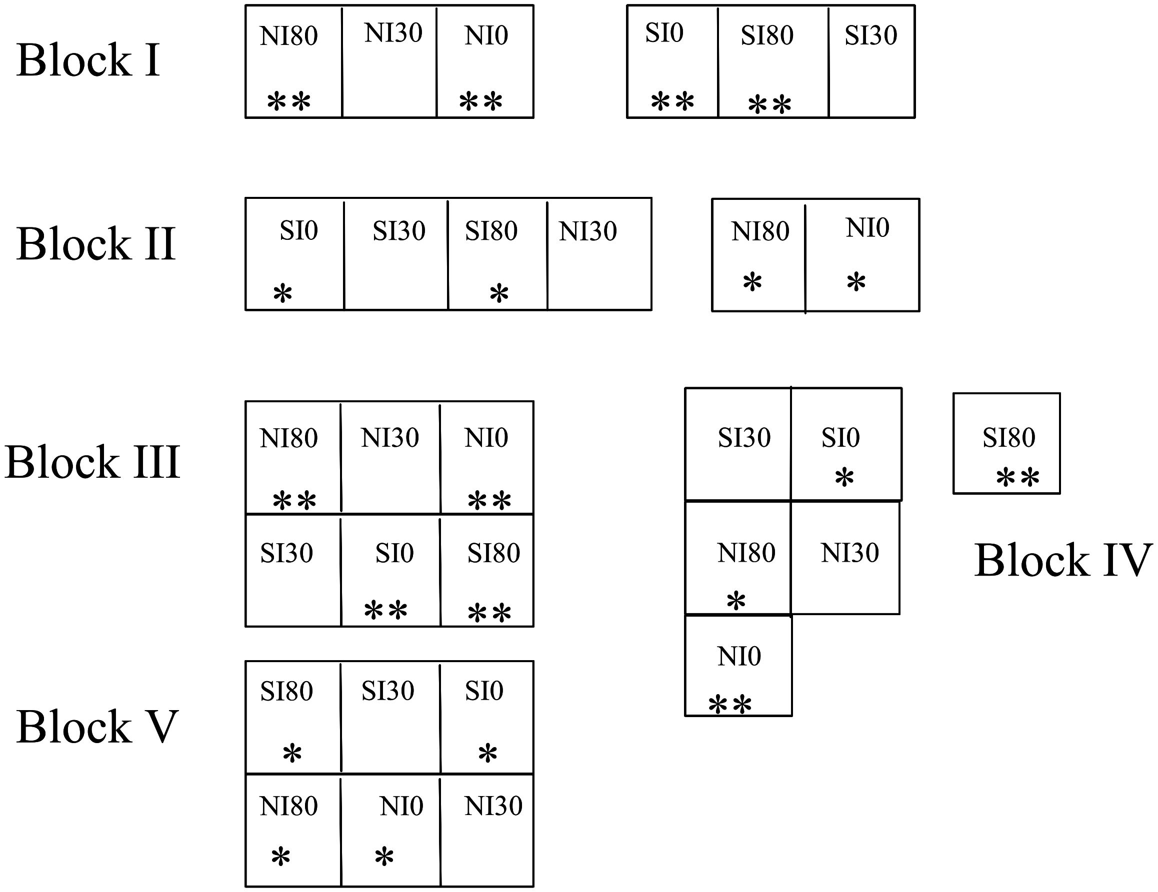

Figure 7: Experimental layout of treatments of supplemental irrigation and N fertilizer in maize at the Mwala site, 1998-2001.

The on-farm water balance components were measured directly or estimated indirectly from other measured parameters (Table 1). Crop production was measured during seasons through above-ground biomass sampling and leaf area index (LAI, $m^2 m^{-2}$) 4-5 times during crop season. Final total above ground biomass and final grain yield were measured for each plot. Root growth was estimated for two plots during LR00. Recorded seasonal rainfall, harvested dam water, SI applications and yields are further presented in Paper III.

Table 1: Description of measured and/or estimated water balance components for the Mwala field site 1998-2001

Water balance parameter	Measurement/estimate	Time interval for measurement	Data presented
Rainfall	Automatic rain gauge	15 minute reading with automatic storage	Paper III
	Manual rain gauge	Daily readings	
Potential evapo-transpiration	Automatic weather station used for estimate	15 minute reading with automatic storage	
Potential evaporation	A-pan (manual)	Daily readings	
Runoff	Dam water level (manual)	Daily reading	Paper III
	V-notch (automatic)	Continuous readings	Metto, 1999
	Infiltration measurements	LR98, LR00	van Vliet, 1999, Jansson, 2001
Irrigation	Manually measured at application using 1m^3 tanks	Based on farmers decision supported by soil moisture measurements	Paper III
Transpiration	Estimate from soil water uptake measured with a TDR and plant development (roots, LAI)	TDR measurements 0-160 cm soil depth twice a week during season Plants samples taken 4-6 times during season	Paper V
	Sap flow by heat pulse technique	During LR00, hourly readings	
Soil evaporation	Estimate from TDR measurements and soil physical characteristics	TDR as above Soil samples for soil characteristics taken once during project duration	Paper III
	Micro-lysimeters	Daily during LR00	Hannerz, 2001
Dam water evaporation	A-pan (as above)	Daily	Paper III
Soil water storage	TDR readings	TDR as above	Paper V
Deep percolation	Estimated from TDR readings	TDR as above	

Estimating dry spell occurrence (Paper I, IV)

In Paper I meteorological and agricultural dry spell analyses are presented for the Mwala site. The meteorological analysis is based on statistical evaluation of daily rainfall using a so-called Markov chain method. The second analysis used a simple crop-water model, the FAO-24 (Doorenbros & Pruitt, 1977; Allen et al., 1998) for maize on a sandy soil and a clay soil at two locations in typical semi-arid agricultural systems in East Africa. The effect of agricultural dry spell occurrence was also related to maize yield response.

A series of daily rainfall data was obtained 7 km north east of the experimental site for 1977-1998 at Chief Mbiuni Camp, Machakos District, Kenya (37^{o}24'E, 1^{o}15'S, approximately 1 200 m. a. s.). Climatic data to estimate potential evapotranspiration (ET_p) was obtained through the CLIMWAT database (Smith, 1993). The Kitui data set (38^{o}01'E, 1^{o}22'S, 1 090 m. a. s.) was used for ET_p calculations. Kitui is closely located geographically at a slightly lower altitude above sea level. The Kitui data set of ET_p also correlated reasonable well to 2 years A-pan measurements carried out at the Mwala site (Fig. 8).

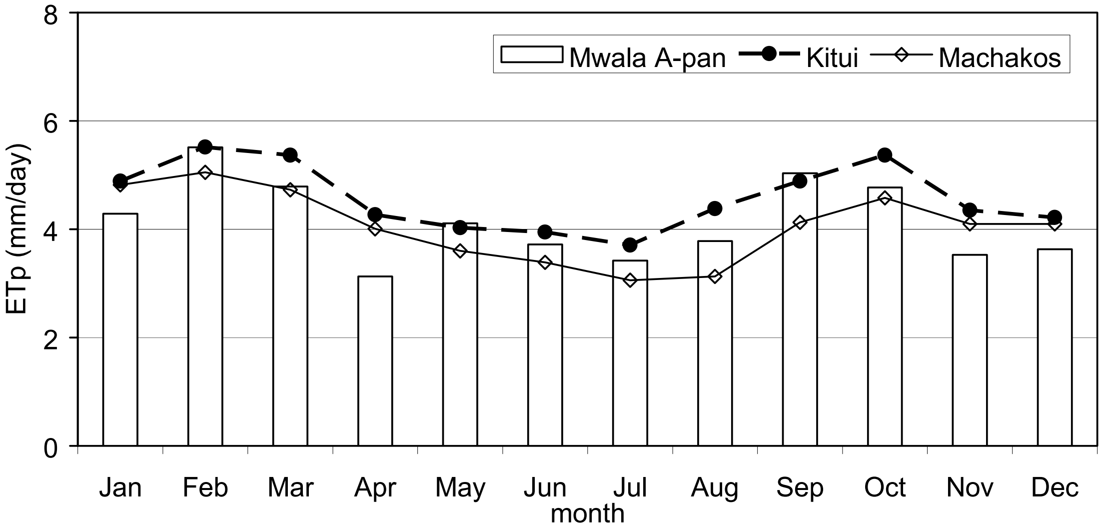

Figure 8: Comparison of mean daily potential evapotranspiration per month from A-pan measurements at the Mwala site 1998-2000 (corrected with factor 0.8), and data for Kitui and Machakos Town, CLIMWAT database (Smith, 1993).

The methods of meteorological and agricultural dry spell occurrence were also the base for yield predictions in the cost-benefit analysis (Paper IV). The methods were applied for the Golagou site, Burkina Faso, with supplemental irrigation of sorghum (Fox & Rockström, 2003).

Simulation of field water balance and maize yields (Paper V)

The data collected on-farm was used for simulation of water balance and maize growth (Paper V). Climatic indata was generated based on dry-wet day data measured at the Mwala experimental site. Rainfall data collected 7 km NE of the experimental site was used at Chief Mbiuni Camp (see Fig.4). The MAIZE1&2 (Stroosnijder & Kiepe, 1998) is based on the generic crop model SUCROS87 (Spitters et al., 1989), which has been used extensively in different climates and crop systems. The MAIZE1&2 models has been developed for tropical maize, and calibrated for Katumani Composite B grown in Machakos District, Kenya (Kiepe, 1995). The overall aim with the simulations was to compare the water balance for farmers current system with a system using water harvesting, storage and SI application of maize. Three main aspects were investigated: 1) can the system with water harvesting used as SI significantly increase yields through dry spell mitigation during a longer term, e.g., 20 years, 2) are the amounts of water re-routed from run-off to ET_a possible to determine, and 3) are there changes in water productivity (WP) due to use of SI?

4. Results

Dry spell occurrence & potential yield effect (Paper I, IV)

In Paper I the focus is on maize grown in semi-arid hydroclimate and it concludes that in a "best case" scenario, dry spell exceeding 10 days occurred in > 75 % of seasons during any crop development stage for sandy soils. A crop on clay soil experienced dry spells exceeding 10 days or more in 15-25 % of seasons during vegetative and flowering stage, and in 70-80 % of seasons during grain filling stage (except for Same location, Tanzania, were the values were lower during long rains). This showed that farmers can expect dry spells with a length that potentially damage the maize crop due to water deficit at least in three seasons of four, and possibly more than one such dry spell may occur, in particular on a sandy soil. The high occurrence of dry spells in the water budget analysis, which considers rainfall partitioning and soil water-holding capacity, is on average well in line with the estimated probabilities of occurrence determined through the use of Markov chain methods, which only captures meteorological dry spells. But in detail, the use of meteorological dry spell occurrence only would overestimate frequencies for a maize crop on clay soil, and underestimate dry spell frequencies for the same crop on a sandy soil. The high amount of dry spell frequencies can partly be explained by the fact that maize is a crop, which requires better water availability to produce to its potential. The water balance model was also used for a millet crop using the Chief Mbiuni Camp data set for long rains. The values are compared to the maize crop values (Paper I) in Table 2. In general, the millet crop utilized more of its potential as compared with the maize. In particular it seemed to do better on a sandy soil. Although the millet did not use much more rainfall (i.e., E_a/P was equal), it was closer to its maximum capacity (E_a/E_c was higher for millet than maize).

Table 2: Mean and standard deviation (in parenthesis) of E_a/P (%) and E_a/E_c (%) for a millet and a maize crop during long rains Chief Mbiuni Camp, Machakos District, Kenya (1977-1998)

	Millet		Maize	
	Clay	Sand	Clay	Sand
Ea/P (%)	63 (15)	39 (12)	64 (15)	35 (14)
Ea/Ec (%)	67 (16)	41 (13)	54 (14)	30 (10)

In Fig. 9, estimated crop water requirements for maize and millet are compared for the 20 seasons of long rains. The maximum seasonal crop water requirement (E_c) of millet is approximately 80 % of seasonal E_c of maize. Rainfall exceeded maize E_c in 8 seasons of 20, and 11 of 20 seasons for a millet crop. A millet crop would suffer less from water deficit, and subsequently have the potential to produce closer to its maximum yield level than a maize crop in this environment. I.e., the risk of low yield levels due to water deficit is expected to be more frequent and more severe for maize than millet. Although this analysis is very limited, it does indicate that farmers cultivating maize in the Mwala location are exposed to a higher risk of low yield levels than they would be if they cultivated a more drought tolerant species such as millet.

In Paper I, the water budget analysis resulted in quite substantial losses of water in regard to biomass production. The soil evaporation losses are not separated from the actual production losses of water (*T* + *I*) in the water balance. Individual seasons could loose 90-300 mm, in particular on a sandy soil where actual evapotranspiration (E_a) rarely exceed 50 % of potential crop eavpotranspiration (E_c). From a crop production point, there appears to be a potential for better water management in order to improve yield levels. Water was due to its natural uneven distribution not accessible during parts of growth stages, but on a seasonal basis there were excess. From a crop production point it should be of interest to better utilize the resource of water to reduce dry spell impact. Although the clay soil managed to 'bridge' dry spell occurrences much better than a sandy soil (Paper I, Table 3), further reduction in dry spell occurrence with yield impact would have to include external source of water, i.e., a system with supplemental irrigation.

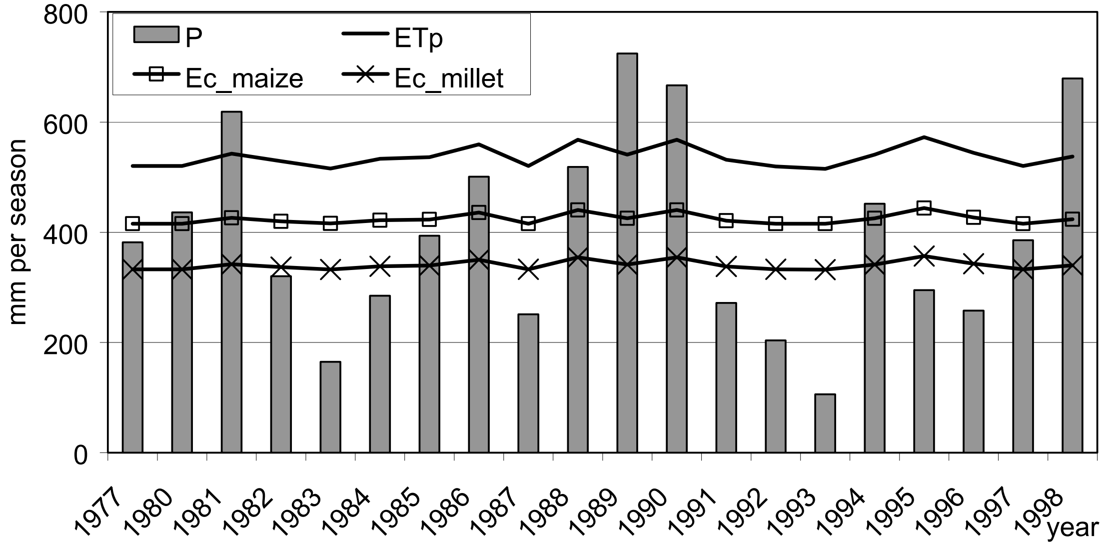

Figure 9: Comparison of potential evapotranspiration for millet (E_{c_millet}) and maize (E_{c_maize}) with seasonal rainfall and potential evapotranspiration (ET_p) for Mwala long rains 1977-1998.

The results from dry spell analysis at the Goulagou site, Burkina Faso (Paper IV) indicate that meteorological dry spell occurrence for the site was high during 1977-2000. Following the analysis in Paper I for daily rainfall 1977-2000, the minimum probability for dry spell >5 days was 0.2. During flowering and grain filling, probability of dry spell occurrence exceeding 10 days was 80%,i.e, a dry spell in 4 of 5 seasons. However, this grossly underestimated the agricultural dry spell occurrence of sorghum at the site (Table 3). The soil had extremely low water holding capacity, and as a result the crop experienced more dry spells than suggested by the Marchov chain method. During flowering and grain filling approximately 1/3-2/3 of days were classified as dry ($E_a<0.5E_c$) with potential yield-limiting impact.

Table 3: Agricultural and meteorological dry spell occurrences as % of total seasons for sorghum grown in Goulagou, Burkina Faso1977-2000 (Paper IV) based on methods in Paper I.

	Agricultural dry spell occurrence	Meteorological dry spell occurrence
Drought	9 %	9 %
Severe	41 %	32 %
Mild	36 %	36 %
No dry spell impact	14 %	23 %

The seasonal water balance shows that on average the sorghum crop had an E_a of 49 % of rainfall over the time period, corresponding to 61% of potential E_c (Fig. 10). The water not used for crop production was lost as surface runoff. This was also confirmed by field measurements of soil water contents at the site (Dr. Fox, *pers. comm.*). There appears to be scope for further water management measures as large losses of water occurs whilst the crop still suffers from dry spell occurrences on a seasonal basis.

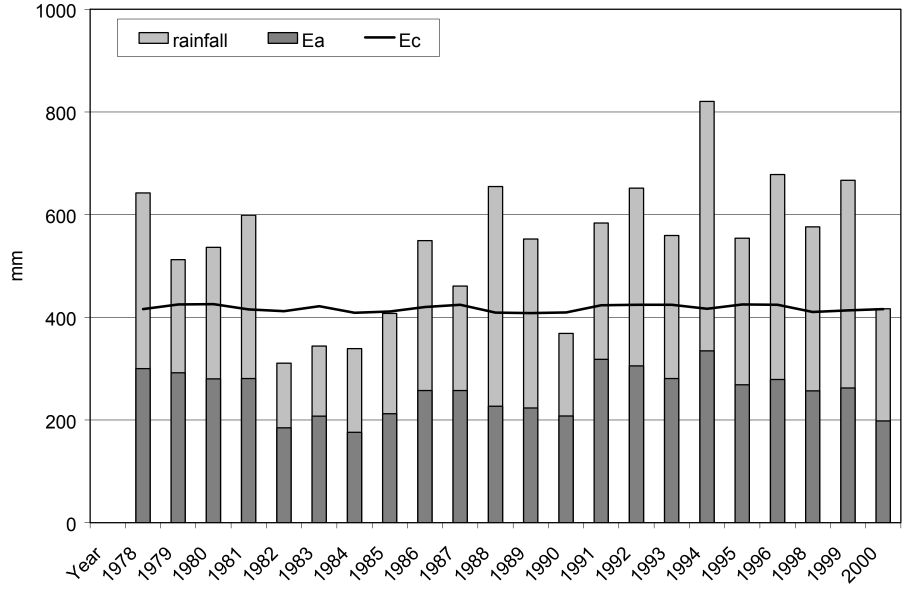

Figure 10: Seasonal actual crop evapotranspiration (E_a) compared to estimated potential crop evapotranspiration (E_c), and seasonal rainfall (P) for Goulagou, Burkina Faso1977-2000

Yields & agronomic results (Paper II, III)

The seasonal agro-hydrological conditions and measured biomass and grain yields from on-farm experiment at Mwala are presented in Paper II and III. Overall, the collection and storage of surface run-off functioned well over the experimental period. The hand-dug earth dam had to be sealed with rubber tarpaulin after the initial season proved that seepage losses were high due to the soil deep percolation capacity. The use of gravitational force for distribution of irrigation water also proved a viable technical solution. The treatment SI30 proved superior to all other treatments during the experimental period. There were no other significant differences between treatments. Within high rainfall seasons, NI treatments exceeded SI. The treatments of 80 or 30 kg N ha^{-1} yielded more than 0 kg N ha^{-1}. There was no additional yield effect for 80 kg N ha^{-1} compared to 30 kg N ha^{-1}. The seasons had different rainfall conditions from complete drought to extremely well distributions, and as an effect the yield results are highly variable. The statistical analyses showed that application of SI gave positive yield results when rainfall was poorly distributed (LR99, LR00). Effects of SI were negative during well-distributed rainfall seasons (SR99, SR00), possibly due to the late application of SI which prolonged crop drying. SI applications were not possible during the season with complete drought (SR98) due to inadequate amounts of harvested water in the dam. However, the treatment NI0 taken to represent farmers current practises, yielded above long-term average yields as reported by local extension services (Mwala Agricultural Office, *pers. comm.*) (Fig. 11). The average seasonal yield results show marginal effect of SI and/or improved fertilizer status on above-ground biomass yield. The effects of improved water availability and nutrient status through SI30 and SI80 over NI30 and NI80 were more apparent. However, there was no detectable increase in grain yield due to increased nutrient from 30 kg N ha^{-1} to 80 kg N ha^{-1} for the experimental period. It is also worth noting that farmers in the area experienced food shortages as a follow-on effect of a drought season. When SR 98 failed completely, there were no seeds, nor adequate labour for LR99. The crop failed partly due to poor rainfall and partly as a result of previous drought. As a consequence, many farmers suffered food and labour shortage also for SR99, which proved to be a good season. The harvest only reached ‘medium’ although rainfall could have resulted in ‘high’ yields. LR00 resulted in famine for many in the area and distribution of relief food as crops failed when 80% of seasonal rainfall was received during the 30 days following season on-set. Note that the crop with SI resulted in 1000-1600 kg grain ha-1 depending on fertilizer treatment (Paper III, Table 5).

Economic viability (Paper IV)

Paper IV presents a cost benefit estimate for the system with storage and use of SI for maize production at the Mwala field site. The underlying basis is the estimate of potential to mitigate dry spell occurrence. The results show that current farming systems are not sufficient to meet average household food demand for the conditions prevailing at the site. This has also been discussed by Duveskog (2001). Depending on how labour cost was estimated, the structure and system of SI and fertilizer was estimated to provide household food self-sufficiency and net income after 1-7 years. The most profitable estimate was for no labour cost and thin plastic sheeting as a sealant. The investment of a storage facility such as a 300 m^3 dam structure appears too costly for current investment a capacity of farmers. This points out the necessity to provide micro-schemes for farmers to enable investments without risk for investment losses due to failing rains.

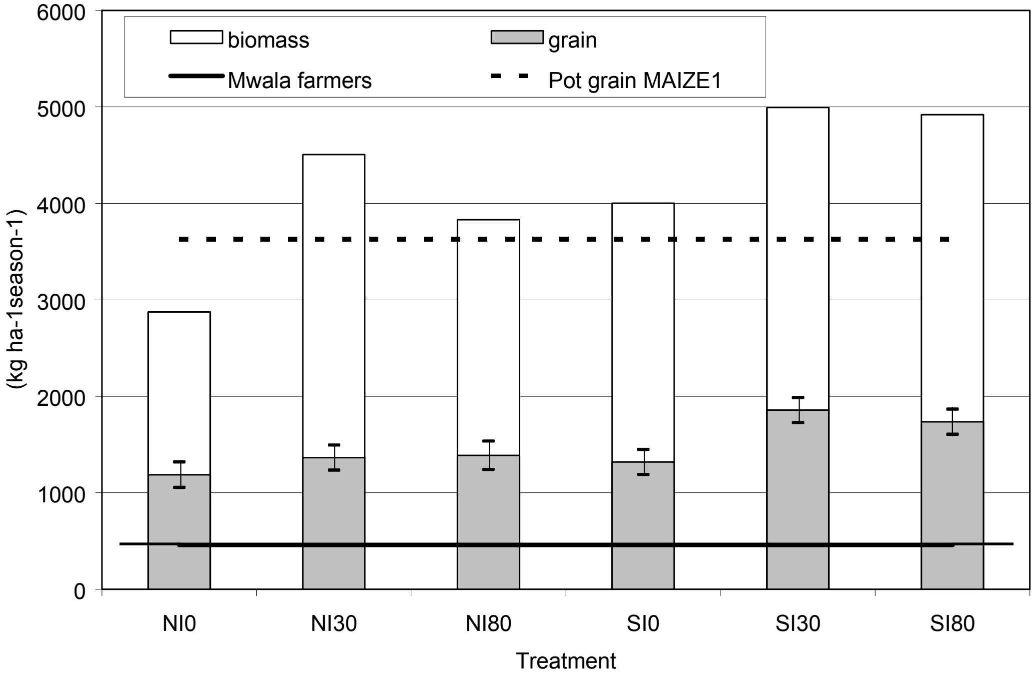

Figure 11: Average grain and biomass yields for supplemental irrigation (SI) or no irrigation (NI) during Mwala on-farm experimental seasons SR98-SR00. Long-term average maize yields as reported by local extension service and potential yield levels as simulated by MAIZE1 (Paper V) are indicated.

There are a few aspects that the cost-benefit analyses fail to reflect. The first is the multiple demand of water by farmers' households as described above. Water is not required only for crop growth in Mwala, but for a range of other uses. A dam would therefore have multiple benefits when the analysis only accounts for crop water use. The second is that when household fail in meeting own demand, food needs to be purchased with cash, which is often lacking in rural poor households. Thirdly, farmers expressed unwillingness to use SI for cereals in case water was available. They would rather apply water on crops of markets/cash production (Jurdell & Svensson, 1998; Duveskog, 2001). This may be due to the innovative character (i.e., there is no inherent 'know-how' among farmers of SI for maize) as well as the household demand for cash income. Despite the assumed low investment capacity of farmers, another storage facility for collecting run-off gained great interest among farmers. This was an underground tank of approximately 15 m^3 intended for garden/ cash crop irrigation. Farmers in the area of the experiment identified the low cost (ca 200US$), low external input of resources, and no land required to set aside for the construction needed (Oduor, 2003). It appears that it is not only a matter of investment capacity but also the know-how that is lacking to upgrade current practised water and fertility management.

Effects on water balance and maize yields (Paper V)

Paper V presents the simulated water balance of a system with *in-situ* water harvesting through terracing, and a system of run-off collection and use as SI. It shows that only 5% of total catchment rainfall was collected in the designed system annually (Fig. 12). Most of the collected water was lost as seepage or overflow when the dam was full. Approximately 33%, or 330 m^3 was applied as SI.

The application of SI did not alter field water balance significantly. The partitioning of P or P+SI into ET, D and R_{off} are of same size as percentage of total in-put of rainfall or rainfall and SI. Although the absolute amounts are higher for P+SI, most of the addition of SI was used by the crop as T (Fig. 13).

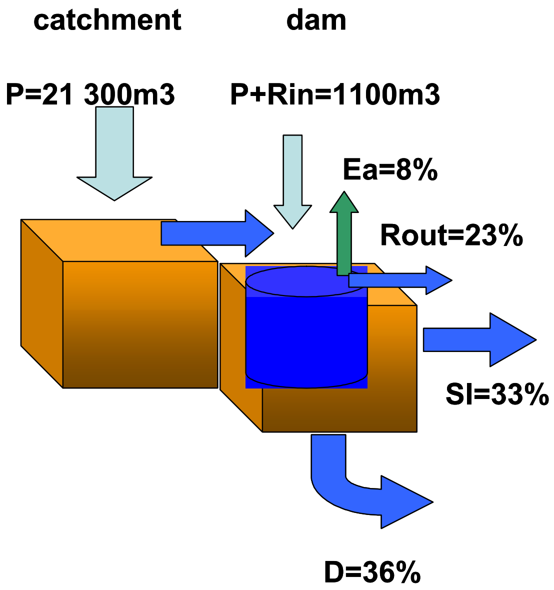

Figure 12: Water balance for run-off water harvesting and storage in dam for use as supplemental irrigation (SI).

However, even the limited application of SI had large yield effects as SI was supplied when the crop experienced water deficits in critical development stages (flowering and initial grain filling). The water productivity for NI WP_{ETa}= 2254 m^3 t^{-1} grain decreased to WP_{ETa}=1796 m^3 t^{-1} grain for SI over the simulated period. The decrease in WP_{ETa} is therefore largely explained by this yield gain due to timely application of SI, rather than increase in transpiration and reduced E and D flows. Two main conclusions can be made of the results in Paper V. On a farm scale, an appropriately sized dam can provide SI for a few timely occasions, which subsequently improve yield stability. On a catchment scale, gains in WP through timely applications of SI may maintain adequate water amounts for downstream uses, depending on local conditions. In the simulated case, very little additional water was lost through ET_a by application of SI. Most water either continued as spill flow (R_{off}) from the dam or as seepage (D), re-charging seasonal river below the crop field.

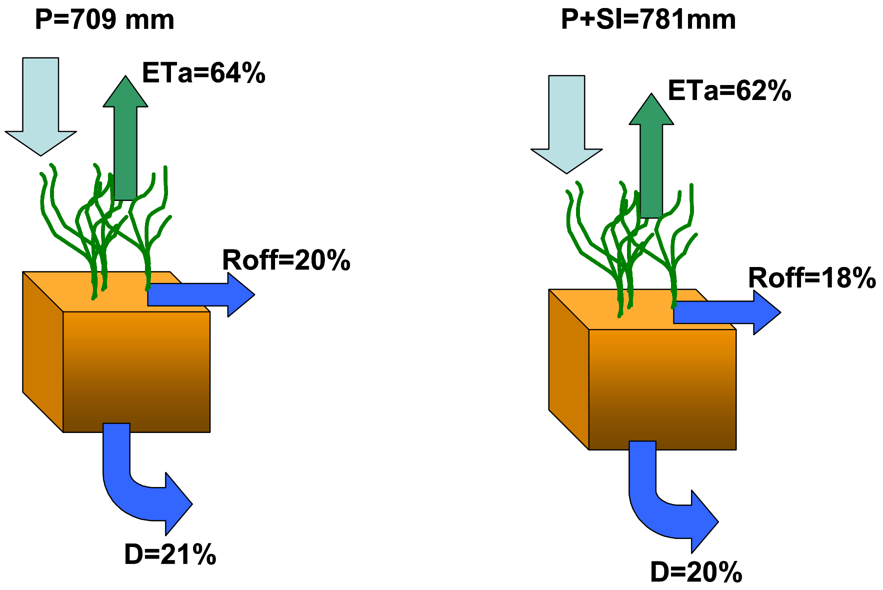

Figure 13: Water balance for in the field for non-irrigated maize (NI) and supplemental irrigated maize (SI) as simulated with MAIZE2 (Paper V).

5. Discussion

Dry spell analysis and agro-hydrological measurements on-farm

The results of the dry spell analysis in Paper I & IV give information on the need of dry spell mitigation for specific sites. The meteorological method provides general information of a site, readily comparable between different areas or regions (Stern et al, 1982; Dennett, 1987). However, for the on-farm management the agricultural dry spell analysis provides more useful knowledge. As an example, it resulted in different cost-benefit depending on if the soil at a certain rainfall domain is of high or low water holding capacity. This will determine the benefit of investment for the farmer, e.g., number of times dry spell effects can be mitigated with rain-water harvesting storage facility and use of SI. A dry spell analysis incorporating water balance of crop and soil conditions may therefore be a useful tool for a farmer and extension staff on decision – making whether to invest in different types of rain water harvesting as well as combinations with nutrient management strategies.

The on-farm experimental site was located on a soil with reasonably high water availability for crops. The farmer himself considered the land quite fertile with little need for external fertilizer in-put. Due to limited research funds, it was impossible to measure system nutrient flows in more detail. From the current results, it is difficult to explain why treatments with 80 kg N ha^{-1} yielded less than 30 kg N ha^{-1}. One explanation may be that water conditions were not optimal for crop uptake of high N dose (as discusesed in paper IV). Other explanations may be that additional N were lost through flushes at intense rainfall, lost due to volatilization as application was not incorporated into the soil. It may also be that the soil had other (micro) nutrinet deficits that limited further efficient use of N fertilizer. Even though the soil at the site was considered 'good farm land', the treatments of SI yielded more than NI combined with low fertilizer dose over the seasons. Applying a system with SI on a soil with lower water holding capacity would therefore prove even more beneficial in terms of yield stability. This was also the case for a similar experimental set-up at Goulagou, Burkina Faso (Fox & Rockström, 2003; Paper IV).

The results from the agro-hydrological measurements could have been improved if more measurements of actual transpiration were made. It was only manageable to measure through sap flow gauges during a limited period LR00 (Hannerz, 2001). These measurements provide valuable information on crop-water dynamics which are useful in simulation modelling work. Discussion on crop water productivity in the experiment would benefit from better estimates of ET_a over seasons with different rainfall regimes (see Paper III, Fig. 4).

The field site of the experiment had been cultivated for at least 25 years with little or no external supply of fertilizer. This was common practice in the area, although the farmers usually inter-cropped maize with nitrogen fixing plants such as beans. The site had been under *in-situ* rainwater harvesting, i.e., terraced during that time period. Although most farmers in the area practised terracing to prevent soil erosion rather than improve water infiltration, terracing is also increasing infiltration, thus increasing crop water availability as compared to non-terraced land. But *in-situ* water harvesting through terracing proved insufficient to cope with the extended dry spells during LR99 and LR00. The results with maize under SI suggest that to achieve more stable yields of maize in the area, *in-situ* rain water harvesting is insufficient. To upgrade the cropping system, it may prove economically option to invest solely in additional fertilizer combined with *in-situ* rain water harvesting for soils with high water holding capacity. In locations with less seasonal rainfall and/or less soil water holding capacity, maize yield increase will only be viable with a combination of more timely application of water for crop and fertilizer management.

Possibilities to develop more RWH and SI

The results from the on-farm experiment in Mwala suggest that at the site, rain-water harvesting with use of water as SI proved technically viable and improved yield levels over current practices. Farmers in the area also showed great interest, although they most likely would have used the water for other crops than maize. In the area, farmers have since the end of the field trial required assistance to develop their own on farm- water resources preferably by including different types of storage structures (Cherogony, *pers. comm.*; Ngigi, 2003). In Kenya, as in many other countries around the world, all water sources currently belong to the State and the use of source is regulated by the State. Water for household use does not need permit as long as it is withdrawn without any technical tools (including canals , pumps) and is withdrawn from a shallow well situated more than 100 yards from nearest water body (Huggins, 2002). This means that (in theory) a farmer would need a permit to construct a storage facility on his/her land to harvest surface run-off (Hartung & Patschull, 2001). Whether that actually takes place is unclear. For harvesting water in an *in-situ* harvesting structure such as terraces or a stilling dam would not require a permit.

Labour availability in the farm household has a large impact on production options. Current practised farming system is labour –intensive, especially as many practise hand-tillage (twice a year) and maintenance of terraces. Labour was also mentioned in the interview survey as a major constraint after water (Duveskog, 2001). In the described experiment, we did not explicitly look at labour requirement for irrigation. Farmers would be more attracted to systems that reduce labour per produced grain yield. As urbanisation and for example, the HIV/AIDS pandemic is expected to reduce labour further in agricultural production, the issue of labour requirement needs to be assessed in more detail. The viability of rain water harvesting for SI needs to be set in the context of rural livelihood and household vulnerability. Labour costs should be related to opportunity costs of labour (see Paper IV), which in poverty stricen rural areas genereally arae low. According to Fox (2003) a similar system with RWH and SI of sorghum reduce labour requirement to a third of the conventional practised system for the same grain yield produced. The reduced risk for crop failure and slow household food availability is an essential aspect of rain water harvesting, which may be difficult to value in a cost-benefit analysis. Adaptationa nd adoption analyses of rain water harvesting systems should therefore done in a systems context of participating development and local co-management to capture local perceptions and decision considerations.

The issue of scale

Although the rainfall characteristics and atmospheric evaporative demand pose constraints on farmers in tropical savannah SSA, there appears to be a realistic opportunity in RWH and SI systems. On a farm scale, SI and improved nutrient management improve yield stability, increase household food availability a/o net income. With improved crop water and nutrient management on a farm scale, WP gains are achieved on a catchment scale, i.e., more food produced per unit of water input. If this can be achieved several alternatives to the 'doom-and-gloom' scenario present itself:

- less water is needed to produce same amount of food, water can be utilised for other purposes
- less land may be required to sustain same yield output

The results from an upgraded production system in tropical savannah SSA is implemented and assesses on a farm/field scale. The consequences for down-stream users of several farmers implementing run-off water harvesting in a catchment are unpredictable. It is not possible to aggregate field scale data on water balance flows and partitioning to useful information on a catchment scale. Data on water balances for farming systems are available on field scale, but few published results on cathment scale. For management of land and water resources in a catcment scale, there appears to be a knowledge gap, partly due to the inability of scaling information. How can the relative abundant information on water and nutrient balances on farm scale be aggregated to useful information on catchment scale? What are the hydrological and subsequent environmental consequences of water balance partitioning changes due to farm practise alterations? How can cost-effective monitoring of environmental consequences be implemented?

6. Conclusions

The following conclusions can be made from the results presented here

- Upgrading rainfed small-holder farming systems in semi-arid tropics requires addressing occurrenceof extremely frequent dry spells through integrated water and soil fertility management. To realize a much required productivity increase in rainfed farming (based on green water flow), it needs to be integrated with irrigations (i.e., blue water flows) such as supplemental irrigation

- The natural occurrence of dry spells in tropical savannah agro-eco systems and the potential yield effect on cereals can be assessed for a given location to determine agro-meteorological conditions (Paper I). This may serve as guidance on appropriate soil and nutrient management systems on-farm including its potential profitability (Paper IV)

- The implementation of rainwater harvesting and storage system, using gravitational forces for water use a supplemental irrigation (SI) of maize was technically viable at a location in semi-arid Machakos District, Kenya (Paper II, III). Over 5 seasons with rainfall ranging from 200 to 550 mm, the crop with SI and low nitrogen fertilizer gave 40% higher yields (**) than farmers' conventional *in-situ* water harvesting system (Paper III). Adding only SI or only low nitrogen did not result in significantly different yields as compared to farmers' conventional practices (Paper III)

- Accounting for dry spell mitigation ability of a system with storage and SI, it was estimated that a farmer would make economic returns (after deduction of household consumption) between year 2-7 depending on dam sealant and labour cost used (Paper IV)

- Water productivity (m^3 water t^{-1} grain) improved with 25 % in a system of maize with SI compared to farmers conventional *in-situ* water harvesting due to timely applications of SI. Field water balance partitioning changes in transpiration, evaporation and deep percolation were insignificant with SI, although the absolute amount of ET_a increased with 30 mm y^{-1} for crop with SI compared to conventional system. The dam water balance showed small productive outtake as SI and large losses due to seepage, and spill-flow (Paper V).

To upgrade current farming system in tropical savannah agro-eco systems, improved water management combined with soil nutrient management is required. Rainfall exceeds crop water demand for most seasons, i.e., there appears to be no water scarcity but rather an issue of poor water distribution in time and space. For soil types with high water holding capacity it may suffice to improve soil water retention, e.g., *in-situ* water harvesting. On soils with low water holding capacity, only SI will improve dry spell mitigation as the soil fails to buffer crop water requirements. Securing crop water availability during critical growth stages minimise risk of crop failure, and stabilise yields over several seasons. Stabilised yields may be incentive for farmers to further invest in crop management and farm activities.

7. Acknowledgements

Very many helped in different ways towards the findings and content in this thesis. I hope most are mentioned here. I wish to acknowledge the collaboration of farmers and local community at the Mwala site, in particular to ‘mama’ Mrs. Kavula Muangi, Mr. Moki Muangi and family, and Mr. Peter ‘Liko’ Munuve and family who provided land for the experimental set-up. Field assistants Mr. Elijah Kamalu and Mr. Boniface Muli were invaluable in their contributions to this work, long hours in the field and translation of all our communication. Mr. Alex Oduor and Mr. R.K Cherogony assisted with much technical experience of soil water conservation and practical solutions at the site. Mr. Peter Kiio and family did yet another invaluable contribution by doing all manual readings every day, housing students and assistants in their home, and keeping an eye on things in general. Local and regional extension staff from Ministry of Agriculture and local administrative chiefs helped us and introduced us to the community.

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