Increasing the Productivity & Sustainability of Rainfed Cropping Systems of Poor Smallholder Farmers

Proceedings of the CGIAR Challenge Program on Water and Food International Workshop on Rainfed Cropping Systems

Editors : E. Humphreys & R.S. Bayot

CGIAR Challenge Program on
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Photo by R.S. Bayot

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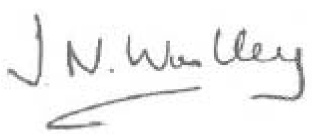
Foreword

The majority of the world's rural poor people depend on rainfed crop and livestock systems for their food and incomes. When the productivity of these systems is low, as is so often the case, food insecurity, impoverished livelihoods and land and water degradation often prevail. Yield and rainwater productivity are much lower than potential in many rainfed environments because the rain often falls in a relatively small number of large events, with dry spells and droughts in between. Furthermore, soil water holding capacity and fertility are often low, and many farmers grow old varieties with low drought (or other stress) tolerance. Rainfall variability and the frequency of extreme events are likely to increase in the future as a result of climate change.

Fortunately, there is high potential to increase land and water productivity in smallholder rainfed crop, livestock and crop-livestock systems through improved soil and water management and germplasm, as demonstrated by many of the projects of Phase 1 of the CGIAR Challenge Program on Water and Food (CPWF). In fact, a full 75% of the additional food needed to feed the world's population in the coming decades could be met simply by raising the production levels of rainfed farmers. Better use of water and other inputs are central to making this happen.

The CPWF seeks to increase the productivity of water for food and livelihoods, in a manner that is environmentally sustainable, socially acceptable and that alleviates poverty for all disadvantaged groups. During Phase 1 (2004-2008) of the CPWF there were projects in 9 benchmark river basins around the world, working across 5 major themes. The focus of Theme 1 was "Improving Crop Water Productivity", and this was a major theme for 14 Phase 1 projects. During Phase 2 (2009-2013) the CPWF will continue to work in 6 of the original benchmark river basins (Limpopo, Nile, Volta, Ganges, Mekong and Andean system), and the major topic for the 3 African basins will be "Improving Rainwater Management".

Thus it was very timely that in September 2008 CPWF held an international workshop on "Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers" at Tamale in northern Ghana. The workshop was organized by the CPWF Theme 1 Leader (Liz Humphreys) and Assistant Leader (Bing Bayot). The objectives of the workshop were to compile, review and synthesize findings from phase 1 projects focusing on increasing water productivity in rainfed cropping systems. The focus was on the use of in-field water harvesting and conservation strategies, supplementary irrigation, the application of crop models to study these systems, and scaling out – downstream consequences and strategies for achieving widespread adoption. The workshop also sought to develop recommendations for research priorities for the Improving Rainwater Management topic for phase 2. The 21 workshop papers presented in these proceedings, together with an overview which seeks to synthesize the main findings and recommendations, provide a timely stocktake of progress to date and future needs and opportunities.



Jonathan Woolley

Coordinator of the Challenge Program on Water and Food, 2003 to 2009

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Thank you very much

Liz Humphreys and Bing Bayot
Workshop Conveners

Increasing the productivity and sustainability of rainfed cropping systems of poor, smallholder farmers: overview of recent findings from the Challenge Program on Water and Food

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Abstract

The majority of the world's rural poor people depend on rainfed crop and livestock systems for their food and livelihoods. However, the productivity of these systems is often low, leading to hunger and poverty, and land and water degradation often prevail. As this review of the findings of many CGIAR Challenge Program on Water and Food and other projects shows, there are many well-known technical options to enable better use of rainwater and nutrients by crops. These include the use of improved varieties, improved fertilizer and agronomic management, in-field water harvesting, conservation agriculture, and supplementary irrigation from ground and surface water sources. For maximum benefit, integrated crop, nutrient, soil and water management is essential. However crop yield response to these technologies is variable, depending on site, cultural practices and seasonal conditions, affecting adoption by farmers. The challenges to achieving widespread adoption of the improved technologies include identifying the optimal or "best bet" technologies for local situations, taking into account the local agro-ecological and socio-economic conditions, plus institutional and policy factors at local to national levels. Systematic approaches, with detailed process monitoring, combined with the use of crop simulation models, are needed to develop generic guidelines to match technologies to agro-ecological conditions, together with analyses of risk in terms of productivity and profitability. The improved technologies must be used by very large numbers of poor farm families if they are to make a substantial difference to rural food security and quality of livelihoods. However, widespread uptake of technologies also requires good understanding of farmers' socio-economic conditions and perceptions, and the presence of enabling policies and institutional arrangements. These include investment in dissemination strategies, improvements in access to micro-credit and input and product markets, fertilizer subsidies, and

investment in infrastructure such as roads. Widespread adoption of technologies to increase land and water productivity of rainfed cropping systems will affect patterns and quality of runoff to surface water bodies, and deep drainage to groundwater systems, with possible consequences for downstream water users, including surface and groundwater dependent ecosystems. Therefore a focus on integrated land and water resources management is important, and this must be done across scales, from groups of small fields to communities, to sub-catchments and catchments, and ultimately to whole river basins. Unfortunately, this has not been adequately addressed.

Based on the findings of this review, five key recommendations are proposed to further progress the adaptation and adoption of improved technologies to improve food security and livelihoods of poor, rural smallholders. These are:

Recommendation 1 – systematic evaluations of water harvesting and conservation agriculture technologies, integrated with crop and nutrient management, and with good monitoring of crop and soil water dynamics to develop generic process understanding

Recommendation 2 – use of crop simulation modeling to inform the systematic evaluation in recommendation 1; this will also require significant investment in good data sets for model calibration and evaluation

Recommendation 3 – development and application of models and other approaches for assessing the impacts of widescale adoption of improved crop/water management technologies in farmers' fields at a range of scales from micro-catchment to basins

Recommendation 4 – longer term trials with the warrantage (inventory credit) system to assess its sustainability and impacts, and factors leading to successful implementation

Recommendation 5 – significant investment in understanding farmers' conditions and perceptions, and in the development of institutions and policies that enable widespread uptake of improved technologies by farmers, and that promote integrated land and water resources management. This should include policies that enable the tremendous potential for fertilizer to greatly increase production in Sub-Saharan Africa.

Key words

rain water harvesting, conservation agriculture, supplementary irrigation, fertilizer, Africa

Introduction

Rainfed cropping systems and poverty

The majority of the world's rural poor people depend on rainfed crop and livestock systems for their food and incomes (Peden et al. 2007; Rockström et al. 2007). When the productivity of these systems is low, as is so often the case, food insecurity, impoverished livelihoods, and land and water degradation often prevail. Over the past 50 years, expansion of land under rainfed agriculture has been a key driver of the degradation of ecosystem services (MEA 2005). Fortunately, there is great potential to increase the productivity of rainfed systems, and in ways that benefit the environment. This is true across a wide range of environments from arid and semi-arid temperate regions to the semi-arid and sub-humid tropics, as this paper will show.

The CPWF and improving rainwater management

In 2002 the Consultative Group on International Agricultural Research (CGIAR) Challenge Program on Water and Food (CPWF) launched a proposal to significantly increase the productivity of water used for agriculture (CPWF 2002). The implementation of research projects commenced in 2004, with "Improving Crop Water Productivity" as one of 5 themes, and this was the major theme for 14 of the Phase 1 (2004-2008) projects. A key element of these projects was to improve rainwater productivity, and some of their major achievements are summarized by Humphreys et al. (2008a), together with key research and adoption gaps, and future research priorities. In September 2008 the CPWF convened an international workshop on *"Increasing the productivity and sustainability of rainfed cropping systems of poor smallholder farmers"* at Tamale in northern Ghana. The objectives of the workshop were to share, review and synthesize findings of those CPWF Phase 1 projects targeting increased water productivity in rainfed cropping systems. The focus was on the use of in-field water harvesting and conservation strategies agriculture, supplementary irrigation, the application of crop models to study these systems, and scaling out in terms of both strategies for achieving widespread adoption and the downstream consequences of such levels of adoption. The workshop also sought to develop recommendations for future research priorities.

Outline of the proceedings

Twenty-one papers from members of 11 CPWF Phase 1 projects were prepared by the workshop participants for these proceedings. The papers are organized into four thematic sections, although many of the papers contain insights relevant to more than one theme.

Section 1 presents the findings of **in-field technologies** for increasing water productivity of rainfed cropping systems. The emphasis is on aspects of the three pillars of conservation agriculture (minimum tillage, mulching and crop rotation), applied in a wide range of environments from low rainfall temperate regions of the Yellow River Basin (<400-700 mm rainfall) to the semi-arid tropics of the Volta, Nile and Limpopo Basins (600-1,200 mm) to the steep slopes of the sub-humid tropics in Central America (1,200-1,500 mm).

Section 2 provides several examples of the evaluation and application of **crop models** for rainfed cropping and in-field rain water harvesting and conservation agriculture technologies, again in a range of environments in the Volta, Limpopo, Nile and Yellow River Basins. These papers are among the first published attempts to use crop models to simulate conservation agriculture technologies in general, and in these regions in particular. The case studies also include three quite different but instructive examples of the application of models to optimize the availability of scarce fresh water resources, to assess the profitability and riskiness of in-field technological options, and to identify the impacts of climate change and possible adaptation strategies.

Widespread adoption of technologies that improve crop productivity in farmers' fields in rainfed regions will affect components of the water balance, including runoff to surface water bodies, and deep drainage to ground waters. However, very little is known about how these effects will scale up at micro-catchment to Basin scales. **Section 3** of the proceedings thus provides three early examples of frameworks and models to **assess the downstream effects** of changing land use and management at sub-catchment and catchment scales.

Finally, **Section 4** presents five papers providing case studies of approaches to enhance the **adoption** of improved soil and water management technologies, and the resultant benefits to farm households in terms of crop productivity, food security and financial gain. Levels of adoption, constraints to adoption and potential approaches and interventions to facilitate adoption are also discussed.

Section 1. In-field technologies for increasing water productivity of rainfed cropping systems

One reason why rainfed systems have such great potential is that rainfall is often not as scarce as is commonly thought (Rockström et al. 2007). In the wetter semi-arid and dry sub-humid regions, total seasonal rainfall generally exceeds crop water needs. The distribution of rain over the cropping season is often more important than the total amount. Yield and rainwater productivity are much lower than potential in many rainfed environments because rain often falls in a small number of large events, with large runoff and erosion losses, and with long dry spells in between rains. The distribution of the rains over the growing period is often more important, with greater effects on yields, than the total quantity of rainfall. Furthermore, soil water holding capacity and soil fertility are often low, and many farmers grow local traditional varieties with low drought tolerance, without fertilizers or other inputs, using inferior technologies.

A range of in-field water harvesting and conservation agriculture technologies have been evaluated by CPWF projects and others in various rainfed environments and cropping systems in Africa, China, and Central America (Mupangwa et al. 2007; Bongani et al. 2009; Castro et al. 2009; Fatondji et al. 2009; Fosu et al. 2008; Kihara and Bationo 2009; Twomlow et al. 2009; Wall and Thierfelder 2009; Yan et al. 2009). The majority of these technologies involved adoption of at least one of the three principals of conservation agriculture – reduced or zero tillage, surface cover, and crop rotation. Notably, few studies involved adoption of all three principals, whereas there is evidence from intensive maize-wheat cropping systems in Mexico that failure to adopt all components (in that case no tillage in the absence of mulching) can result in declining system performance (Govaerts et al. 2007). In continuous maize in western Kenya, Kihara et al. (2009) also found a consistent trend for lower yields of maize with reduced tillage in the absence of residues (2 t ha^{-1}) than in the presence of residues over 6 seasons, but the differences were never significant. There was no such trend with conventional tillage. Twomlow et al. (2009) also reported lack of yield response to mulching in farmers' fields (straw levels up to 3 t ha^{-1}) and research station trials (straw levels up to 10 t ha^{-1}) in Zimbabwe. In contrast, Wall and Thierfelder (2009) found significant yield increases for maize and groundnut with 3 t/ha of mulch, in the drier environments of Macia and Chokwe, Mozambique. In continuous maize in the Yellow River Basin, Yan et al. (2009) found significant yield increases with maize straw retention in both conventionally tilled and non tilled treatments. The amounts of residues retained in China were much higher (6-7 t ha^{-1}) than in the African studies, and the residues remained in the field from the time of harvest of the previous crop, rather than being applied at or after sowing.

All three principals of conservation agriculture were tested in the relatively wet environments of western Kenya (rainfall 1,000-1,400 mm) (Kihara et al. 2009). Inclusion of a legume in a maize rotation resulted in similar maize yields without the need for N fertilizer, while rain water productivity of both the maize and soybean was unaffected by tillage method or residue retention, over 8 consecutive crops. On steep slopes in the sub-humid tropics, the Quesungal Slash and Mulch Agroforestry System (QSMAS) in Honduras also adopts all three principals of conservation agriculture (Castro et al. 2009). QSMAS is an indigenous production system which is being practiced by 6-7,000 resource-poor smallholders in south west Honduras in hilly to mountainous regions. Here annual rainfall is high (~1,400 mm), with very intense rainfall events at the start of the rainy season, but with a long dry season of up to 6 months and thus only one crop per year is feasible. In both the low and high rainfall situations, there were increases in available soil water and soil organic carbon or carbon sequestration in the mulched, no-till treatments in comparison with conventional tillage in bare soil (after removal or crop residues or slash and burning). Castro et al. (2009) also found that the QSMAS system had greatly reduced runoff and erosion losses, and a much lower global warming potential than the traditional slash and burn system. Crop water productivity was greatest in the young QSMAS systems (< 2 years old) where N fertilizers were used.

One of the most common technologies evaluated in Africa by the CPWF projects was "planting basins". Planting basin systems, with a variety of basin sizes and spacings, are practiced in various part of Africa under several names such as the Zai system in Mozambique, Mali and Burkina Faso, the Chololo system in Tanzania (Mati 2005), the Trus system in Sudan, and the Tassa system in Niger. Seeds are sown in the basins, often with small amounts of organic and/or inorganic fertilizers. The combined use of planting basins with the application of small doses of fertilizers directly to each plant (microdosing) is sometimes referred to as Precision Conservation Agriculture (PCA, Twomlow et al. 2009). The objectives of the basins are to reduce runoff and increase infiltration through breaking the surface crust and creation of a depression, and to increase soil fertility through reduction in erosion. Planting basins are a form of minimum tillage, as only a small area where the seeds are to be planted is cultivated. The technology is particularly suited to smallholder farmers without animal or mechanical draft power, as it is done using a hand hoe. The technology greatly increases labor requirement on a per hectare basis (Magombeyi and Taigbenu 2008), but this may or may not incur a cash cost depending on household labor availability. The preparation of the basins may be spread over the dry season, enabling timely planting due to reduced reliance on borrowed or hired draft animals, and the labor requirement declines with time (Twomlow et al. 2009). Furthermore, if use of the technology is associated with large productivity increases, the increased labor requirement may be offset by the fact that less land may needed for crop production, and with the additional benefit of reduced land area for weeding and other crop management activities. Planting on ridges and tied ridges (soil bunds spaced 1-2 m apart connecting the ridges to prevent runoff along the furrows) has also been quite widely evaluated in Sub-Saharan Africa by CPWF projects (Fosu et al. 2008; Mustafa et al. 2009) and others. Several reports from west and southern Africa show reduced runoff and/or reduced soil loss with a range of technologies including reduced and no till with mulching, and ridging across the slope (Agyare et al. 2008; Ncube et al. 2009; Wall and Thierfelder 2009).

The main objective of in-field rainwater harvesting and moisture conservation technologies in rainfed systems is to increase soil water availability for the crop, a result of increased infiltration and reduced soil evaporation. This was shown to be the case in a wide range of environments examined in the workshop papers, e.g. China (Nangia et al. 2009; Yan et al. 2009), Honduras (Castro et al. 2009), Mozambique (Momade 2006 in Ncube et al. 2009), Niger (Fatondji et al. 2009), S. Africa (Magombeyi, M.S. and Taigbenu 2008), Zambia (Wall and Thierfelder 2009), Zimbawe (Mupangwa 2009; Wall and Thierfelder 2009). In some situations the technologies resulted in higher yields, and in low rainfall years the technologies made the difference between no yield and some yield. However, increased soil water availability did not always translate into higher yield (Bongani et al. 2009; Wall and Thierfelder 2009; Yan et al. 2009), and in some situations the water conservation technologies led to loss of yield or water productivity (Bongani et al. 2009; Kihara et al. 2009; Yan et al. 2009). Lack of yield response to rainwater harvesting and moisture conservation can be a result of many factors, such as adequate and well-distributed rainfall on the one hand, and prolonged drought during critical stages on the other. The lack of response to increased soil water availability can also be due to many other factors including low soil fertility and poor crop management practices. Heavy rainfall, especially early in the season, can lead to greater waterlogging damage and yield loss with in-field rainwater harvesting and conservation, especially on clay soils. In some environments the soil temperature depression due to mulching can delay establishment and early growth, leading to loss of yield. The yield response to water harvesting and conservation technologies is variable within sites, largely as a result of variable rainfall across seasons. It is also variable across sites as a result of many factors including climate, soil physical properties, slope, crop/variety, soil fertility and agronomic management. The interactions among these factors have not been adequately investigated. There is a need for "process based experiments", with plausible hypotheses, to understand the mechanistic processes underlining the observed phenomena to develop the capability of predicting the optimum technologies for different agro-ecological situations. Simulation models (Section 2) greatly increase this predictive capability, but they must be developed and refined based on sound process understanding.

A common factor across the many locations where in-field rainwater harvesting and conservation agriculture technologies are being evaluated is the importance of improving soil fertility, especially nitrogen. Often, the yield or rain water productivity responses to fertilizer are much higher than the response to the rainwater harvesting technologies (e.g. Fosu et al. 2008; Kihara et al. 2009; Mustafa et al. 2009). Often the biggest benefit comes through a combination of improved soil fertility and water management, as in the case of the use of microdosing of N fertilizer on the yield of groundnuts in Mozambique (Wall and Thierfelder 2009), in some of the trials with tied ridges and N fertilizer in Ghana (Fosu et al. 2008), and with Zai pits and organic manures in Niger (Fatondji et al. 2009).

Supplementary irrigation

Only one paper in these proceedings examines the potential for supplementary irrigation to increase land and water productivity of rainfed cropping systems. Over three very different rainfall seasons (390-1,400 mm) in the Limpopo Basin, Magombeyi et al. (2009) found large yield responses to supplementary irrigation of maize, ranging from 67 to 314%, with the highest responses in the driest years. The amounts of supplementary irrigation to achieve these responses were relatively small – 110 mm in the driest year, and 50 mm in the wettest year. Crop water productivity (WP_{ET}) was increased more than 3-fold, from 0.11 to 0.35 kg $mm^{-1}ha^{-1}$ in the driest year, and by 50% (from 0.3 to 0.45 kg $mm^{-1}ha^{-1}$) in the wettest year. The significant response to a small amount of supplementary irrigation even in the wettest year reflects the erratic rainfall pattern typical of the semi-arid tropics, and the potential for supplementary irrigation to bridge long dry spells at critical stages. Supplementary irrigation can be practised without water harvesting structures where ground water or surface water resources are available. Water harvesting systems can also be constructed to provide a source of water for supplemental irrigation where sufficient rainfall flows as runoff. However, the results of Magombeyi et al. (2009) also demonstrated the potential for in-field rainwater harvesting – even in the lowest rainfall year (390 mm), runoff losses from the rainfed plots were large (100 mm).

The potential for supplementary irrigation was also investigated by a CPWF project in the semi-arid Karkeh River Basin (Tavakoli et al. 2008). As for in-field water harvesting/conservation, the biggest opportunities for increasing yield and water productivity occurred when supplemental irrigation (SI) was combined with N fertilizer and improved varieties. Use of a single supplementary irrigation (50 mm) to bring forward the start of the growing season by 2-4 weeks roughly doubled yields of wheat and barley by giving enough time for good crop establishment before the onset of winter frosts. While full supplementary irrigation to satisfy crop water requirements gave maximum yield, it required more irrigation water, and water productivity was maximized with a single irrigation. Applying one irrigation (100 mm) in spring also increased wheat grain yield by about one-third, but with much lower irrigation water productivity (0.9 kg m^{-3}) than for a single irrigation prior to sowing (3.4 kg m^{-3}). In water scarce situations, the timing of the supplementary irrigation is critical.

Section 2. Application of crop models to evaluate options for increasing water productivity in rainfed cropping systems

The above in-field water harvesting and conservation agriculture studies demonstrate the considerable potential to greatly increase land and water productivity using these technologies. The studies also demonstrate that the benefits of these technologies are maximized when they are used in combination with improved fertility and other management. However, the results also show that the technologies do not increase productivity in all situations - the effects are variable across sites and seasons, and there are complex interactions between a range of factors affecting crop response to the technologies. Clearly there is need for systematic evaluation of the technologies over a range of site (e.g. soil type, slope, cropping system), weather (especially rainfall) and agronomic management conditions. Detailed analysis of crop yields on the basis of long (more than 10 years) series of weather is crucial, especially to better understand risks, and also to better appreciate how farmers respond because of risks.

Good crop and soil monitoring are essential parts of such evaluations to generate good process understanding to help identify the agro-ecological and management conditions under which the technologies increase productivity. Gomez-MacPherson et al. (2009) provide a useful example of a relatively simple methodology for estimating whole of season crop water balance, but more detailed crop and soil water monitoring is needed for process understanding. Magombeyi et al. (2009) provide a good example of the use of soil water monitoring and knowledge of soil hydraulic properties to help understand water limitations to crop yield. However it is very costly, and in fact impossible, to properly evaluate all technologies of interest over all likely site, seasonal and agronomic conditions. Simulation models deal with many of these interactions and can be used to help identify the most promising technologies for different conditions, if properly calibrated and validated. Furthermore, crop models can be used to estimate important parameters that are too difficult to measure in the field, such as some of the components of the water balance and thus water productivity (e.g. evapotranspiration, WP_{ET}, deep drainage). Crop models can also be used to evaluate the riskiness of technology options by taking into account weather variability. The information generated by crop models can then be used in combination with economic, social and cultural factors to identify the best bet technology options taking into account the farming family situation for that location. The family situation includes their ability to take risks (many poor farming households cannot afford to take risks). The data generated by crop models, especially the water balance data, can also provide critical inputs for spatial scale models (e.g. catchment models), as in the framework proposed by Bongani et al. (2009).

However, before crop models can be used to help develop management guidelines, to inform decision making, or to provide inputs for spatial scale models, they must be calibrated and validated for the environment and types of applications of interest. There are few examples to date of the evaluation of crop models for rain water harvesting and conservation agriculture technologies for rainfed crops in the CPWF benchmark basins or similar environments. The papers in these proceedings present three early examples: an evaluation of DSSAT/CERES Millet v4.5 (Tsuji et al. 1994) for conventional tillage and in Zai pits on a very degraded soil in

Niger (Fatondji et al. 2009), evaluation of DSSAT/CERES Maize v4.5 with the new tillage/mulch module in Shanxi Province, China (Nangia et al. 2009), and evaluation of APSIM (Keating et al. 2003) for maize, groundnut and cowpea with conventional tillage in Limpopo Province, South Africa (Dimes and du Toit 2009). Kpongor et al. (2008) and MsCarthy et al. (2009) both evaluated DSSAT CERES Sorghum v3.5 and APSIM for sorghum in northern Ghana, as part of one of the CPWF projects. Performance of all models was generally good across a range of crop and soil water parameters including total biomass, grain yield and soil water content over time throughout the root zone. In fact, the ability to accurately simulate soil profile water changes over time was a highlight of the performance of the models in all three studies presented in these proceedings, giving confidence in their ability to simulate components of the water balance. In Niger, CERES Millet also performed well in predicting the crop response to manure application for both conventional tillage and Zai pits, but greatly over-predicted the response to the addition of millet residues (3 t ha^{-1}) to the Zai pits and the conventionally tilled treatment. Possible reasons included under-prediction of immobilization of nitrogen, and low phosphorus availability (the millet model in DSSAT v4.5 does not account for phosphorus limitations to growth). In Ghana, CERES Sorghum v3.5 also performed well in predicting crop response to N at rates from 0 to 120 kg N ha^{-1} (Kpongor et al. 2008), while APSIM performed well in predicting response to both nitrogen and phosphorus rates (McCarthy et al. 2009). In China, predicted yields of maize grown with tillage (with and without residues incorporated) and without tillage (with and without mulching) were within 3-12% of observed yields over two seasons (Nangia et al. 2009).

While performance of all models was encouraging, it is important to note that all the evaluations were done on data sets from the same experiments used to calibrate the models and/or to develop model inputs (except for the studies of Kpongor et al. [2008] and McCarthy et al. [2009]). Furthermore, there was a lack of measured input data for some of the key parameters at all sites, especially in relation to soil initial conditions and soil hydraulic properties. There needs to be significant investment in good data sets for model calibration and evaluation to capitalize on the predictive capacity of crop models in rainfed environments. Rigorous evaluation of models, using independent data sets (i.e. not the data sets used for calibration) is essential. Ideally, the determination of crop genetic coefficients should be based on results from several sowing dates and seasons.

The modeling papers include three instructive and quite different examples of the application of crop models to identify technologies to optimize crop water productivity.

(i) In the salt-affected coastal areas of Bangladesh, where there is traditionally only one crop each year (rice during the rainy season), the challenge is to intensify the cropping system by including an additional crop during the dry (boro) season. During the dry season, most of the fields lie fallow because the water in the rivers becomes too saline to use for irrigation part way through the cropping season. With the help of the ORYZA2000 model, Sharifullah et al. (2009) determined the area of boro rice that could be planted and grown through to maturity in a case study polder, by irrigating with fresh water stored in the canals and old river channels within the polder after the surrounding rivers became too saline. The stored water was taken from the river before it became too saline. They also used the model to identify the optimum planting date to maximize rice production, taking into account tradeoffs between the effect of planting date on yield and the amount of stored fresh water needed to finish off the crop. They found that about 15% of the polder rice area could be grown to maturity in 50% of years, and that the area could be increased to 40% if the canals were dredged. The work also implied that the potential cropped area could be increased further by the development of cold tolerant varieties, as these could be planted earlier, reducing the amount fresh water needed from the canal to grow the crop to maturity.

(ii) Dimes and du Toit (2009) used APSIM to predict the effects of climate change on crop productivity at Bulawayo, Zimbabwe. As expected, potential yields of all crops (sorghum, maize, groundnut and pigeon pea) were decreased (by about 7%) by reduced rainfall, but this was roughly offset by elevated carbon dioxide levels. Increased temperature had a much greater effect, reducing yields of all crops (except pigeon pea) by 16-30%, due to greatly reduced crop duration. Yields of pigeon pea were hardly affected as it has a much longer duration than the other crops. Importantly, the analysis suggested that adoption of longer duration germplasm would be the appropriate adaptation response for sorghum, maize and groundnuts. This is in contrast to much current thinking which points to the need to breed shorter duration cultivars to deal with assumed shorter growing periods and increased moisture stress under climate change. The shorter crop duration due to climate change resulted in higher residual soil water content at harvest, suggesting relay cropping as another adaptation opportunity to be investigated further. However, the most important observation made by Dimes and du Toit (2009) was that the impacts of climate change on yield pale into insignificance in comparison with the large impacts on yield which could be achieved by increasing the use of nitrogen fertilizers now (as well as under the expected future climate). This observation is consistent with the findings of many field studies evaluating the impacts of nitrogen fertilizer in sub-Saharan Africa (Fosu et al. 2008; Kihara et al. 2009; Mustafa et al. 2009; Wall and Thierfelder 2009). Yet the majority of smallholder farmers use no or little fertilizer - at the end of the 20th century, average fertilizer use in Africa was only 8 kg/ha, compared with around 100 kg/ha in Asia (Kelly et al. 2007 as cited in Denning et al. 2009).

(iii) To date, there have been few rigorous economic evaluations of the performance of technologies for increasing water productivity. At best, partial budgeting and gross margins have been used to compare technologies, and these analyses are based on the performance of the technologies over a very limited range of conditions and seasons. The analyses usually only take into account the value of the grain, and not the straw, which usually has a value as animal feed. Nor do most economic analyses consider the medium to long effects that technologies may have, such as build up in soil fertility and its effects on yield or input requirements, as in the approach used by Singh et al. (2008) for wheat direct drilled ("no till") into rice residues (in comparison with residue burning and tillage). The outputs of (validated) crop models can be used to provide probabilities of yield as inputs into economic assessments. Mustafa et al. (2009) used the results of field experiments comparing farmers' practice and a range of technologies and monthly rainfall to develop an empirically derived model (based on a Cobb-Douglas production function). The model was used to predict the yield of barley in the Eritrean highlands, as affected by seasonal conditions (monthly rainfall over 13 years). The predicted yields were used to determine crop water productivity and net returns, and to identify the most profitable agronomic practices and their associated levels of risk (variability). Compared with farmers' practice, all the treatments (N fertilizer, tied ridges, and weeding, used alone and in all possible combinations) increased grain yield and water productivity at all locations. However, only the treatments that included N fertilizer (alone, or in combination with rainwater harvesting or weeding) had higher average net returns than farmers' practice, at all three study locations.

Rainwater harvesting alone was less profitable than farmers' practice at all locations. Only two treatments, N fertilizer and N fertilizer plus weed control, were less risky (lower variability) than farmers' practice. The use of process crop models such as APSIM (Keating et al. 2003) and DSSAT (Tsuji 1994) in such an approach is highly desirable, as such models can be applied in a far wider range of situations than empirically derived production functions. The main need is that the models are capable of simulating the treatments of interest. Both the DSSAT and APSIM models simulate responses to water and N fertility, and APSIM has an intercropping module which can be used to simulate the response to weeds. When used in cropping system mode, both modeling platforms can be used to simulate long term effects of the technologies on some important properties such as soil organic C and N.

Section 3. Downstream impacts of increasing water productivity in rainfed cropping systems

Water management in rainfed cropping occurs in small fields on small farms of less than 5 ha (Rockstrom et al. 2007). Runoff, lateral sub-surface flows and deep drainage in farmers' fields may all be affected by changed management (section 2). Runoff and deep drainage water quality may also be affected by changes in crop management practices. Widespread adoption of rainwater harvesting, conservation agriculture, and improved management in general, may have substantial downstream impacts if they result in diverting significant amounts of rainwater or soil moisture from recharge (deep drainage to aquifers), and/or in diverting rainwater from one micro-catchment to another. Therefore the consequences of scaling out of technologies for increasing rainwater productivity on water flows and quality for downstream water users, including ecosystems, need to be considered at micro catchment, catchment and basin scales. This information is needed to inform land and water resources planning to optimize food production, poverty alleviation, and environmental sustainability.

Many approaches have been developed to model water flows at a range of spatial scales, and some of these are being tested in and adapted to catchments, sub-basin and basins in CPWF benchmark basins (see papers in Humphreys et al. 2008). These efforts include assessment of the impacts of changed land or water management in upper catchments of CPWF benchmark basins, but most of these focus on small to medium scale irrigation developments (e.g. van Giesen et al. 2008; Love et al. 2008; Kemp-Benedict et al. 2008). To date, the development and application of methodologies to predict the downstream impacts of widespread adoption of changed management at the farmer field scale has received inadequate attention. Two of the papers in these proceedings provide examples of modeling approaches to estimate the impacts of changed management in upper catchments on downstream flows (and sediment load in one case) (Awulachew and Tenaw 2009; Hessari et al. 2009). A third paper proposes a framework for systematically and comprehensively investigating the impacts of out-scaling in-field and ex-field rainwater harvesting (Ncube et al. 2009). The framework incorporates consideration of socio-economic factors in addition to crop yields and water flows.

Hessari et al. (2009) determined the potential area for supplementary irrigation in the upper Karkeh River Basin (KRB) based on slope classes and distance from streams (water sources). They used monthly flow and rainfall records over 30 years to develop rainfall-runoff relationships at the sub-basin scale. They combined this with a simple water balance in a GIS framework to assess the impacts of adoption of different supplementary irrigation strategies on monthly stream flow within each sub-basin, and the combined effect on flows into the Karkeh reservoir. The results indicated that implementation of supplementary irrigation would reduce flows by 9-15% in an average rainfall year, and by 5-10% under dry conditions.

Awulachew and Tenaw (2009) studied rainfall-runoff and sediment-runoff relations in the Gumera watershed in the Blue Nile River Basin, and calibrated and validated the SWAT model for this watershed against observed flows and sediment loads at the outlet of the watershed. The data showed that the peak sediment concentration preceded the peaks for rainfall and runoff, and that most of the sediment enters the river during the first three months of the rainy season, at a time when there are large areas of exposed soils due to cultivation and over-grazing during the dry season. The results also showed that both runoff and sedimentation can be reasonably simulated using the SWAT model, and the simulations predicted that the use of 5 and 10 m wide vegetation strips ("filters") reduced sedimentation by 52 and 74%, respectively.

Section 4. Adoption constraints and opportunities

The five papers in this section of the proceedings provide a range of experiences of adoption of improved technologies, and insights into factors constraining or facilitating adoption, in Sub-Saharan Africa (Agyare et al. 2009; Awulachew et al. 2009; Bediako 2009; Tabo et al. 2009a,b). Bediako (2009) presents six case studies, whose findings included: the importance of participatory research with farmers, in their fields, so that the recommendations are appropriate for farmer circumstances; the importance of involving extension workers in on-farm research with the farmers; and the need for strategies to provide cash loans to farmers. Constraints to adoption of technologies included lack of understanding by those introducing technologies of the constraints and opportunities faced by rural farmers, high fertilizer prices, inadequate and untimely supply of fertilizers, low levels of technology dissemination within the context of a relatively low level of investment in soils research, and lack of adequate training of farmers in new technologies. The multitude of NGOs controlling technology dissemination and competing with each other in northern Ghana, with little government supervision, was also noted as a problem.

Many of the CPWF Phase 1 crop water productivity projects recognized the need for knowledge and understanding of the farmers' circumstances (financial, assets, family labor, knowledge, information networks, market opportunities etc.) as critical considerations in the development of technologies suited to their circumstances. Farmer training is another important step to ensure the technologies are properly utilized. Many projects undertook quite comprehensive investigations using a range of methods including surveys and discussions groups. A good example of the conduct and application of a range of socio-economic studies in the development, evaluation and adoption of technologies for improving water productivity and livelihoods of farmers is those undertaken as part of CPWF PN10 'Coastal resource management for improved livelihoods') and its predecessor project (UK DfID CRF Project R7467C on Accelerating Poverty Elimination through Sustainable Resource Management in Coastal Lands Protected from Salinity Intrusion) in the Mekong delta (Hossain et al. 2006; Hoanh et al. 2006). However, how (or whether) this information has been used to help design appropriate technologies is less clear in most cases, as the findings of the surveys have often emerged well after the selection of technologies for development and evaluation was well underway. The findings of many of these socio-economic investigations are not readily available to date.

Participatory research was also a feature of many of the CPWF Phase 1 crop water productivity projects, with farmers, extensionists, national researchers and sometimes policy makers actively involved in various phases of the research. Participatory approaches were probably most developed in PN10 (above, Mondal et al. 2006), and in PN2 'Water productivity improvement in Eritrea', where all stakeholders (farmers, extension, local government, researchers, and Ministry representatives) were involved in research and planning, implementation, technology evaluation, selection of germplasm, and project evaluation. PN10 has clearly demonstrated that starting with a good understanding of the farmers' situation, and active participation of all stakeholders from farmers to policy makers and resource managers, can lead to significant adoption. Key ingredients are the development of improved technologies based on sound science, that are more profitable for farmers, and that lead to improved environmental management, and bureaucrats and policy makers that recognize the benefits of the technologies.

All papers in this section included consideration of profitability as a factor relevant to adoption. These included one paper focusing on technology adoption-poverty relationships in Ethiopia, where the current level of adoption of irrigation is only about 6% of potential (Awulachew et al. 2009). Awulachew et al. (2009) undertook a detailed analysis of the relationships between adoption of agricultural water management technologies and poverty in four regions in Ethiopia. The technologies consisted of various strategies of storing, conveying and applying water for irrigation by small holder farmers. Their analysis showed that the incidence, depth and severity of poverty were all significantly lower among users of the agricultural water management technologies. The users of technologies were 22% less poor than non-users, on average. The poverty reduction varied with the technology, and was greatest for users of deep wells (50%), followed by river diversion (32%) and micro dams (25%). However Awulachew et al. (2009) did not have the baseline data needed to determine whether the users were less poor because they used the technologies, or whether they were able to use the technologies because they were less poor. Notably, soil and water conservation strategies such as terraces and trash lines had no effect on poverty levels. In northern Ghana, where irrigation is also under-developed, a range of methods is also used by smallholder farmers to irrigate crops during the dry season, including small dams, dugouts, and pumping directly from the White Volta River (Agyare et al. 2009). Agyare et al. (2009) found that the mean return to labor for pump irrigation was more than twice the mean daily wage for labor at the time of the study.

Perhaps the most dramatic example of adoption of technologies by farmers among all the papers is the relatively high rates of adoption of Precision Conservation Agriculture (PCA – planting basins and microdosing) in Zimbabwe (Twomlow et al. 2009). Wide scale testing of PCA was conducted across multiple locations in southern Zimbabwe through relief and recovery programs, which provided the farmers with seed, fertilizer and technical support. Adoption increased rapidly from 4,700 households in 2004/5 to 50,000 households in 2007/8, and the area per farm increased from 0.1 to 0.3 ha. PCA was associated with average yield increases of 50 to 300%, the size of the increase depending on a range of factors including rainfall, soil type and fertility, and market access. Average gross margins per hectare of PCA were several-fold higher than gross margins of traditional farmer practice, and returns to labor were about double the returns for farmer practice. While these numbers seem large, the authors point out that the area under PCA is not yet large enough to create a marketable surplus. Whether the high levels of adoption will be sustained, and to what degree, when provision of free inputs is withdrawn, is a question for future study.

The low use of fertilizer in Africa despite the well-established large benefits requires a good understanding before it can be resolved. Pre-conditions of fertilizer use are that (i) the harvested crop can be sold for cash, which requires sufficient yield beyond subsistence and the presence of reliable markets, (ii) profitability - sufficiently high output/input ratios; in Africa, grain prices are relatively low and fertilizer prices are relatively high at the farm gate due to many things including expensive transport costs between producers and suppliers, and (iii) farming households need to be able to take the risk of losing the investment in fertilizer prior to harvest. All these conditions seem to be negative in large parts of semi-arid Africa. Therefore there is a renewed belief that the re-introduction of subsidies on fertilizers, on a large scale, is an important part of the solution (e.g. Denning et al. 2009; Vitousek et al. 2009; Morris et al 2007).

Fertilizer microdosing has been evaluated extensively with hundreds of farmers in several parts of West Africa over several years, including in CPWF projects (Tabo et al. 2009a). Overall grain yields and net returns were double those of traditional farmer practice. However adoption of improved technologies that involve additional inputs (such as fertilizers and seeds of improved varieties) requires the inputs to be affordable and readily available locally, at the right time, and in appropriate-sized packages (Simpungwe et al. 2008). Simpungwe et al. (2008) showed that farmers are more likely to try fertilizer if it is supplied in small, (more affordable) packages.

The warrantage or inventory credit scheme is a means of providing farmers with credit by allowing them to mortgage their grain at harvest time to secure a loan, and to avoid having to sell their grain at harvest time when prices are low (Tabo et al. 2009b). The system involves a secure storage for the grain, which is sold later when prices are higher. Ideally the farmers would use the loan to conduct income generating activities, and to buy inputs to improve their crop productivity in the following season. The system is run by farmer groups who are linked with decentralized financial systems, such as the "Caisse Populaire" in Burkina Faso, who provide micro credit. Storage facilities and input shops are built, and credit and savings schemes are established. Warrantage systems have been tested in West Africa over the past few years, with net financial benefits to the farmers wherever they have been practiced, and which probably explains the increasing farmer participation over time after these systems are introduced. Constraints to their implementation include lack of sufficient capital in the decentralized financial systems to grant loans and for supervising bodies to provide guarantees, lack of good linkages between farmers' organizations and lending bodies, lack of infrastructure for storage of grains, unavailability of fertilizers at the right times, inappropriate packaging of fertilizers (Simpungwe et al. 2008), and poor roads and thus movement of produce to markets and inputs to farmers. While results of initial trials of warrantage are promising in terms of farmer participation and financial benefits to farmers, results from longer term trials to assess their sustainability are needed. Whether the availability of credit and other benefits of the system really do lead to significantly increased adoption of improved crop production technologies is also yet to be demonstrated.

Conclusions and recommendations

There are many technical options to enable better use of rainwater by crops for poor, small holder farmers, including improved varieties, improved fertilizer and agronomic management, in-field water harvesting, conservation agriculture, and supplementary irrigation from ground and surface water sources. For maximum benefit, integrated crop, nutrient, soil and water management is essential. And the improved technologies must be used by very large numbers of poor farm families if they are to make a substantial difference to rural food security and quality of livelihoods. However, widespread uptake of technologies also requires the presence of enabling policies and institutional arrangements, such as investments in dissemination strategies, improvements in access to micro-credit and input and product markets, and investment in infrastructure such as roads. Widespread adoption of technologies to increase land and water productivity of rainfed cropping systems will affect patterns and quality of runoff to surface water bodies and deep drainage to groundwater systems, with possible consequences for downstream water users, including surface and groundwater dependent ecosystems. Therefore a focus on integrated land and water resources management is as important, and this must be done across scales, from groups of small fields to communities, to sub-catchments and catchments, and ultimately to whole river basins.

Soil and water conservation, and in-field water harvesting, are the logical entry points for improved water management in rainfed agriculture (Rockström et al. 2007). These strategies are often relatively cheap and can be applied anywhere, and should be optimized before water from external sources for supplementary irrigation is considered. Supplementary irrigation can bridge critical yield-reducing dry spells, stabilize yields, and greatly increase crop water productivity.

The yield response to water harvesting and conservation agriculture technologies is variable within sites, largely as a result of variable rainfall across seasons. It is also variable across sites as a result of many factors including climate, soil physical properties, slope, crop/variety, soil fertility and other agronomic management. There is therefore a need for:

Recommendation 1 – systematic evaluations of the technologies, which should include good monitoring of crop and soil water dynamics to increase process understanding and help identify generic knowledge; in particular, which technologies perform best under which conditions.

Recommendation 2 – Such analysis needs to be informed by the results of crop simulation modeling. The use of simulation models enables evaluation of technologies over the likely range of seasonal conditions, taking into account soil type and a range of management factors. Crop models also enable estimation of components of the water balance and crop water productivity, parameters which are extremely difficult to measure in the field. Models also allow analysis of risk, and tradeoffs between yield, water depletion, deep drainage, runoff etc. However, there needs to be **significant investment in good data sets for model calibration and evaluation and process understanding** to capitalize on the predictive capacity of crop models in rainfed environments. This is currently a major gap in poor, smallholder, rainfed cropping systems.

Widespread adoption of rainwater harvesting, conservation agriculture, and improved management in general in farmers' fields, may have substantial impacts on downstream surface and groundwater systems and those dependent on them, including wetlands and groundwater dependent ecosystems. Therefore

Recommendation 3 – models and other approaches for assessing these impacts at a range of scales from micro-catchment to basins are needed. A range of tools and approaches have been developed for estimating water and pollutant fluxes across a range of spatial scales. Some of these are in the process of being tested and adapted to catchments and sub-basins where rainfed cropping is an important land use. However, there have been few studies to date of the impacts of widespread adoption of conservation agriculture, in-field rainwater harvesting, and small scale ex-field water harvesting technologies on water, sediment and other pollutant fluxes, and their consequences for downstream people and ecosystems.

Achieving widespread adoption of improved technologies in rainfed cropping systems is a major challenge. Most or all of the technologies discussed above are not new, however determining which technology will be beneficial to which farmers, in terms of both productivity and profitability, needs to be systematically assessed taking into account local site conditions, farmer circumstances, social and cultural factors. Some of the major constraints to adoption of improved technologies include lack of availability of access to inputs, microfinance to purchase inputs, and output markets. The warrantage system was developed to address these constraints. While results of initial trials of warrantage are promising in terms of farmer participation and financial benefits to farmers,

Recommendation 4 – results from longer term trials with warrantage to assess their sustainability and impacts are needed, together with policy and institutional changes to increase access to microfinance, inputs and output markets. Whether the availability of credit and other benefits of the system really do lead to significantly increased adoption of improved crop production technologies is also yet to be demonstrated.

Recommendation 5 – significant investment in understanding farmers' conditions and perceptions, and in the development of institutions and policies that enable widespread uptake of improved technologies by farmers, and that promote integrated land and water resources management. This should include policies that enable the tremendous potential for fertilizer to greatly increase production in Sub-Saharan Africa.

There is great potential to increase the productivity and profitability of rainfed cropping systems of poor, smallholder farmers. However, this will require significant investment to fine tune the technologies to the local circumstances, to create an enabling environment for adoption, and to do this using an integrated approach for land and water management across a range of scales from micro-catchment to whole of river basin.

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SECTION 1

In field technologies for increasing water productivity of rainfed cropping systems

Some experiences with conservation agriculture in southern Africa

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Abstract

Conservation agriculture (CA) is a term used to describe agricultural systems that combine three basic principles: soil cover with crops and/or crop residues, minimal soil movement and crop rotation. One of the major benefits of CA is improved water use efficiency, whether this be from rainfall or irrigation, by increasing water infiltration rates and reducing evaporation. In rainfed systems the higher infiltration rates on CA fields generally result in less water run-off and less soil erosion. Data from trials in Zambia and Zimbabwe confirm the improved crop water balance under CA, although these do not always result in higher crop yields if moisture stress is not an important factor during the particular season. In on-farm trials in Zimbabwe, crop yields are generally increased by the CA practices and these increased yields represent greater rainfall use efficiency. CA practices have not been incorporated into trials managed under the Water and Food Challenge Programme PN1, but results from Mozambique do show positive effects of mulch (residue cover) on crop growth and yield.

Key words

mulch, water use efficiency, rainfed, basin planting, zero tillage

Introduction

At a recent meeting on Soil Quality in Rome[1] the more than 50 delegates agreed that "ample evidence now exists of the successes of CA (Conservation Agriculture) under many diverse agro-ecological conditions to justify a major investment of human and financial resources in catalysing a shift, whenever and wherever conditions permit it, from tillage-based production systems to those based on minimal soil disturbance, organic residue retention, and crop rotations and combinations." This statement clarifies that CA is not a technology, but a general description of varied agricultural systems based on three central pillars or principles. The ample evidence of the successes of CA is born out by the adoption of no-tillage agriculture on about 100 million hectares worldwide (Derpsch, 2008). Although no-tillage agriculture is not necessarily CA, the three principles of CA appear to be followed on a significant proportion of the area of no-tillage, although statistics are generally not available to define agricultural systems in such detail. Most of the area of no-tillage (and of CA) is on large, mechanised farms, but increasingly in many parts of the world there is adoption by smallholder farmers as techniques and technologies to apply the principles of CA are adapted

[1] "Investing in Sustainable Crop Intensification: The Case for Improving Soil Health". Technical Workshop, held at FAO headquarters (Rome), 22-24 July 2008.

to their particular circumstances (Wall, 2007), especially in Brazil, Paraguay, Ghana (Ekboir, 2002) and Zambia (Haggblade and Tembo, 2003). There are reports of much CA in China but it is difficult to get information on what constitutes these CA systems. However, there are at least 200,000 ha of potatoes seeded under CA conditions by simply placing the seed in the residues (Kaiyun Xie, CIP, personal communication). In the Indo-Gangetic Plains there are at least 1 million hectares of zero-tillage wheat, but the soils are intensively tilled for the rice crop, destroying any benefits to the soil accrued in the wheat season.

The spread of CA in different parts has been spurred by different benefits: in Brazil the main initial driver was overcoming erosion (Ekboir, 2002), in Bolivia it was the efficiency of use of machinery and reductions in fuel costs (Wall, 2002); in the Indo-Gangetic Plains the main initial driver of no-till wheat in the rice-wheat system was the ability to plant the wheat on time (Erenstein and Laxmi, 2008) although weed control and, later, costs savings have also been important drivers (Hobbs, 2007; Erenstein and Laxmi, 2008) . However, in numerous surveys of smallholder farmers the benefit most often cited is the reduction in the amount and drudgery of labour (e.g. Sorrensen et al., 1998; Ekboir et al., 2001) although, if herbicides are not used for weed control, labour requirements under CA may be high and onerous in the first years of adoption (Rockstrom et al., 2001). Also digging the basins in Conservation Farming systems being promoted in Zambia and Zimbabwe involves considerable initial labour although this may be spread over the dry season and declines with time (Haggblade and Tembo, 2003).

Nutrients and water are generally considered to be the most important factors limiting yields of the major crops on smallholder farms in southern Africa. Although total rainfall may be sufficient to achieve the yield potential of the area, as much as 75% of the rainfall may be lost to surface run-off and evaporation (Roskstrom, 1999). Results in other parts of the world have shown that CA practices result in greater water infiltration (and therefore less water run-off and erosion) and less evaporation of soil water. The studies reported here were designed to quantify some of these effects under conditions representative of two major production areas of southern Africa.

Materials and Methods

Researcher-managed "on-station" trials

Multi-season randomised block trials (four replications per site) comparing CA and conventional agriculture practices were established in 2004 at Henderson Research Station (HRS), Mashonaland Central Province, Zimbabwe (17.57ºS; 30.99ºE; 1136 m.a.s.l., mean annual rainfall 884 mm) and in 2005 at the Monze Farmer Training Center, Southern Province, Zambia (MFTC) (16.24ºS; 27.44ºE; 1103 m.a.s.l, mean annual rainfall 748 mm). Soils at HRS are sandy with Arenosols and Luvisols predominating, while at MFTC the predominant soils are clay loams classified as Lixisols (FAO, 1998). These trials are more fully described by Thierfelder and Wall (2008).

Rainfall during the crop season (October to April) was very high in 2005/06 at HRS (1096 mm) but lower and more evenly distributed in 2006/07 (534 mm). At MFTC the October-April rainfall was close to the annual mean in 2005/06 (734 mm) but lower in 2006/07 (551 mm). In neither year were there pronounced periods of moisture stress at either of the two sites.

A sub-set of three treatments from these trials is reported: the traditional farmers' practice consisting of shallow mouldboard ploughing with animal traction (MP) is compared to two CA treatments representing two major avenues of CA being promoted in the region. The first of these is a "basin" treatment, commonly called Conservation Farming (CF), with basins (holes) approximately 15cm x 15cm and 15cm deep dug manually on untilled soil during the winter period. All fertility inputs and the seed are placed in the basin, which is dug on exactly the same site each season. The second treatment is direct seeded (DS) into untilled soil with a Fitarelli animal traction direct seeder Model #12 (long beam) (http://www.fitarelli.com.br/), except at HRS in 2006 when it was planted with a manual jab-planter. With the direct seeder, fertilizer is dribbled into the same furrow as the seed, whereas with the jab planter it is placed separately alongside the seed.

Commercial maize hybrid varieties (SC627 in 2005/06 and SC635 in 2006/07 at HRS and SC513 at MFTC) were seeded at 44,000 seeds ha^{-1} in rows 90 cm apart at moderate fertilizer levels: 81-23-12 and 109-33-17 (N-P_2O_5-K_2O) at HRS and MFTC respectively. Crops were seeded as early as possible after the start of reliable rains: Nov 24 and 27 in 2005 and 2006 respectively at HRS and Dec 1, 2005, and Nov 23, 2006 at MFTC. Weeds were controlled by an application of 3 l ha^{-1} glyphosate at seeding, followed by hand-weeding as necessary.

Field monitoring

Infiltration and water runoff were measured (three replications per plot) in January of both years on all replications at both sites using a small rainfall simulator described by Amézquita et al. (1999). Simulated rainfall of 95 mm h^{-1} was applied to an area of 36cm x 44cm for 60 min and runoff measured on an area of 32.5cm x 40cm (0.13 m^2). The remainder of the water that did not run off was assumed to have entered the soil.

Soil moisture at 5, 15, 25, 35, 50 and 80 cm depth was monitored regularly (generally twice per week) during the cropping season using a capacitance probe (PR-2 probes from Delta-T Devices Ltd., UK) inserted into previously installed access tubes (3 access tubes per plot in 3 replicates). We report here the data from the 0-60 cm horizon.

Yield assessment

Cobs from twenty samples of 5 linear meters of row were harvested from each plot for yield analysis. Two cobs were taken from each sample, combined, threshed, the grain weighed and grain moisture measured immediately using a moisture tester (Dickey John MGT). Grain yield was then calculated on a per hectare basis at 12.5% moisture.

Statistical analysis

Data analysis was carried out using the commercial statistical package "Statistix 9" (Analytical Software). Yield data were analysed using the general Analysis of Variance routine, and infiltration and soil water content samples using the Descriptive Statistics routine to obtain the standard error of the mean.

"On-farm" demonstration sites

On-farm demonstration plots comparing two CA options with the conventional farmer land preparation practices, were initiated in each of two communities in Zimbabwe in 2004: one community in the Zimuto Communal Area of central Zimbabwe with extremely sandy soils (92-94% sand) and low rainfall (mean = 634mm) and one with clay-loam soils and higher average rainfall (mean approx. 880mm) near Shamva in the north-east of the country. One of the CA treatments is rip-line seeded with seed and fertilizer placed by hand in a narrow slot opened by a ripper tine attached to the plow frame after removal of the mouldboard shear, while the other is direct seeded using the Fitarelli seeder described above which dribbles fertilizer and seed into a furrow made by the machine. Demonstration plots have continued on the exact same area each season. The seven sites installed in Zimuto and six installed in Shamva each comprise a replication of a randomised block trial. Each replication is on a different farmer's field in the community and managed by a farmers' group with orientation from the local (Ministry of Agriculture and/or NGO) extension officer. All treatments and sites within the same community are seeded with the same variety and receive the same fertilizer application (47-23-12 [2004 and 2005] and 81-23-12 [2006 and 2007] in Zimuto and 81-23-12 in all years in Shamva). In Zimuto in 2005 and in Shamva in all seasons, 2.5 l ha^{-1} glyphosate was applied to half of the two CA treatments at seeding. All other weed control in these plots and in the farmers' check was done manually. As post-seeding weed control was uniform, grain yield data presented below is a mean from both the glyphosate treated and untreated areas.

At harvest, ten samples of 10 linear meters of row were harvested from each plot, and the cobs from each sample weighed. A subsample of two cobs was taken at random from each sample, weighed, shelled, weighed again and the moisture content measured (Dickey John MGT moisture meter) to allow correction of the cob yields to grain yields on a per hectare basis at 12.5% moisture.

Mozambique groundnut and maize on-farm trials

Trials under the Water and Food Challenge Programme Project 1 for the Limpopo Basin "Increased food security and income in the Limpopo Basin through integrated crop, water and soil fertility options and public-private partnerships" were conducted in the Macia and Chokwe Districts of Gaza Province of Mozambique in 2005/06 and 2006/07 to identify the principal factors that limit water productivity. Soils are extremely sandy and rainfall is low, and after the first season of the PN1 trials it was evident that maize was far too risky and that groundnuts were the most reliable annual crop, especially in the Macia District.

In the 2005/06 season one replication of a split-plot groundnut "Mother Trial" was harvested. This trial compared three varieties (main plots) with (3 t ha^{-1}) and without mulch and with and without a "micro-dose" N fertilizer application (20 kg/ha N) arranged as a 2 x 2 factorial. Also four "Baby Trials" from different farmer's fields where each consisted of one replication of the mulch and microdose 2 x 2 factorial were harvested. However, different varieties were used at different sites. These trials were analysed together as seven replications of a 2 x 2 factorial trial of mulch and microdose N fertilizer, where the effect of variety was confounded with site and replication. The mulch, generally of "thatching grass", was only applied after seeding, so any possible benefits of pre-season moisture storage with the mulch were not achieved in these trials.

A similar set of trials was conducted on maize in the 2005/06 season, and one replication of the Mother Trial with three varieties, and five replications (sites) of the 2 x 2 factorial mulch x microdose trial with different varieties at different sites were harvested. Again this was analysed as eight replications of a 2 x 2 factorial where varieties were confounded with replication and/or site.

In the 2006/07 season the Mother-Baby groundnut trials compared treatments with and without mulch (3 t ha^{-1} of thatching grass), two varieties (Nametil and Mamani), all with and without 20 kg ha^{-1} of nitrogen fertilizer as a starter fertilizer on these extremely sandy soils. Unfortunately only four Baby Trials survived the season, allowing just one complete replication. The only comparison that could be made with these Baby Trial results was the effect of mulch.

Results

On-station trials at HRS and MFTC

Infiltration rate

There were no significant differences between treatments in total water infiltration during the one hour of the simulated rainfall at HRS in early 2006. Infiltration in the basin treatment was surprisingly low in this season, possibly associated with significant soil movement during hand-hoe weeding. However, in the 2006/2007 season the total infiltration was significantly greater ($P \leq 0.01$) in the direct seeded treatment than in conventionally tilled treatment (Table 1) while infiltration in the basin treatment was intermediate. On average 24% more water infiltrated in the two CA treatments than in the tilled treatment in 2007, with 30% more water entering the soil in the direct seeded treatment than in the check. At MFTC water infiltration was significantly ($P \leq 0.10$) greater in the two CA treatments than in the conventionally tilled treatment in the first year of the trial (2005/2006) and in 2006/2007 this difference was more marked and more significant ($P \leq 0.01$). Averaged over the two CA treatments at this site, 68% more water entered the soil during the one hour of simulated rainfall than in the tilled treatment in 2007.

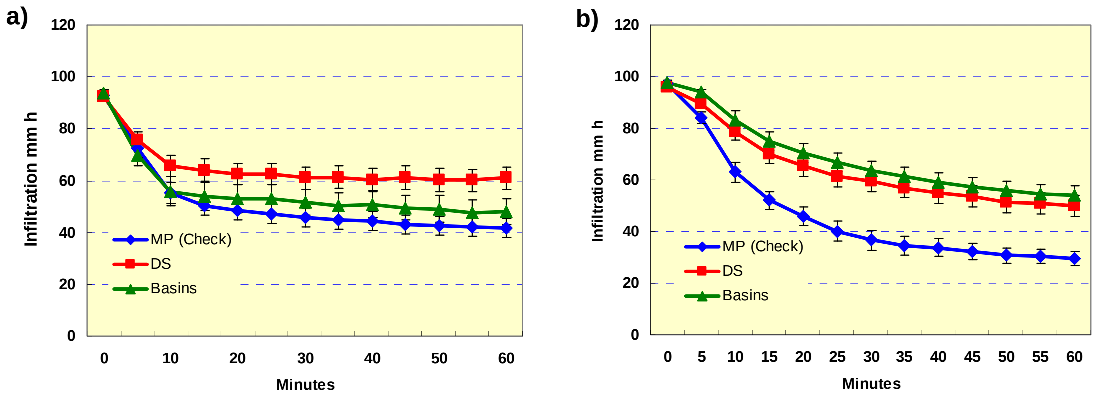
Table 1. Total water infiltration during a simulated rainfall of 95mm in one hour at two sites (Henderson Research Station, Zimbabwe, and the Monze Farmer Training Center in Zambia) in the 2005/2006 and 2006/2007 seasons.

	Total infiltration (mm) in 1 hour.			
	Henderson Research Station		Monze Farming Training Center	
Treatment	Jan-06	Jan-07	Jan-06	Jan-07
Check (MP)	38.2	58.1 b #	45.9 b	36.1 b
Direct seeding (DS)	50.2	75.7 a	60.1 a	56.4 a
Basin planting (CF)	37.2	68.2 ab	63.4 a	65.1 a
LSD		11.3	13.2	18.3
Probability level (PF)	NS	1%	10%	1%

means followed by the same letter in the same column are not significantly different at the specified probability level.

Mean infiltration curves over the period of the simulated rainfall are shown in Figure 1. In the Figure it is clear that the infiltration rate in the tilled treatment generally fell below the CA treatments shortly after the start of the infiltration test. This suggests that soil surface conditions are important factors in determining water infiltration at these sites, and adds weight to the hypothesis that the low infiltration rate of the basin treatment in 2006 at HRS may have been due to soil surface movement and damage to surface porosity by hand-hoe weeding.

Figure 1. Mean infiltration rate with simulated rainfall of 95 mm in one hour at a) Henderson Research Station, Zimbabwe, and b) Monze Farmer Training Center, Zambia. Curves are means of two measurements – one in January 2006 and one in January 2007. Error bars show the Standard Error of the mean at each time.



<u>Soil moisture measurements</u>

The soil moisture in the 0-60 cm horizon at both MFTC and HRS in both seasons is shown in Figure 2. At HRS the two CA treatments (DS and CF) had more moisture in the profile than the tilled check throughout almost the whole cropping period in both seasons. At MFTC the differences were less marked, but the basin treatment tended to have more moisture in the profile throughout most of both seasons. Soil moisture content at Permanent Wilting Percentage (PWP) in the whole of the 0-60 cm horizon would be approximately 80mm and it is evident from Figure 2 that the soil did not reach PWP, and nor were there many stress periods in either season. At HRS in the 2005-06 season the soil started the season at close to Field Capacity (FC), and the soil moisture in the 0-60cm was above FC for most of the season. This is because the land is on a slight slope and water from further up the slope kept the area almost completely waterlogged for much of the season. In the more normal 2006-07 season the plots were seldom above FC but also did not reach PWP. However, especially after flowering the crop had less than 50% of the potential available water in the profile and therefore probably suffered at least mild stress.

Soil moisture content tended to be far more variable in the basin treatment than in either the conventially tilled or the direct seeded treatment. The standard error of the mean moisture content of the basin treatment was approximartely double that of the other treatments at the Monze site in both years and at HRS in the 2005/06 season. At HRS in the 2006/07 season, the standard error of the mean soil moisture content (0-60cm) was approximately the same for all treatments.

Figure 2. Soil moisture (mm) in the 0-60cm horizon during the maize crop season at Monze Farmer Training Center in a) 2005-06 and b) 2006-07 and at Henderson Research Station in c) 2005-06 and d) 2006-07. Error bars show the Standard Error of the Mean of two treatments at each site on each sampling date: the check and the basin treatment at MFTC and the check and the direct seeded treatment at HRS.

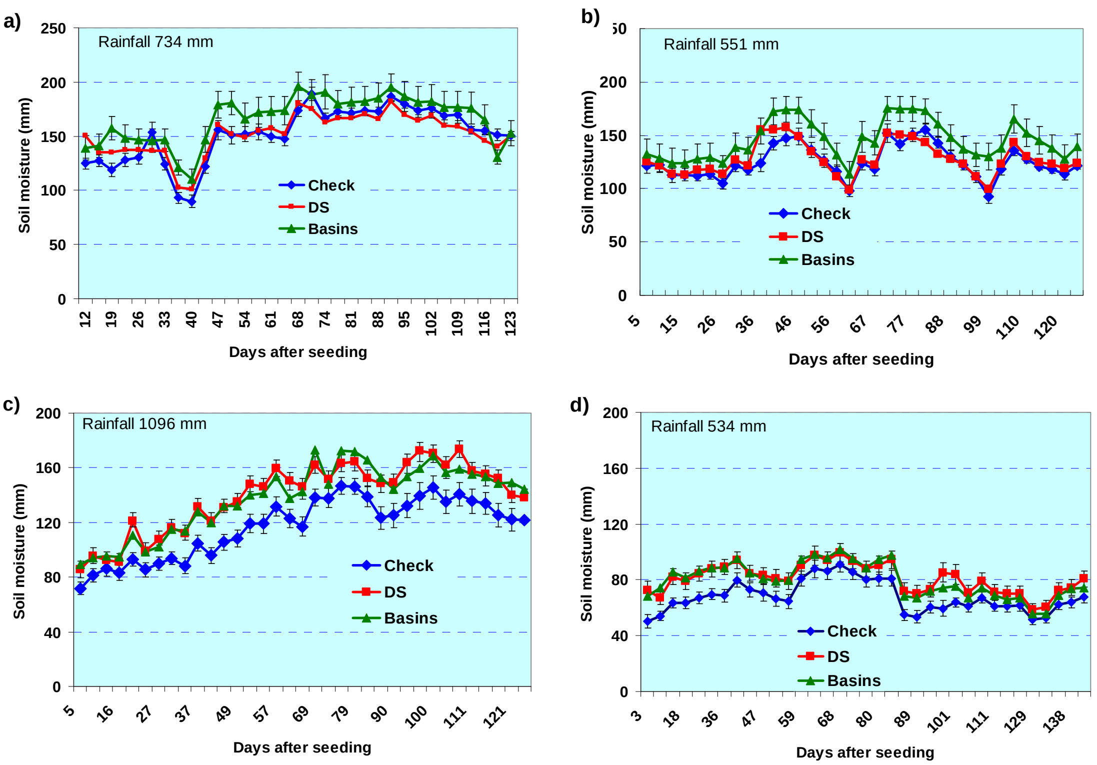


Table 2. Mean soil moisture content in the 0-60cm profile during the maize crop season at HRS and MFTC in two seasons. Differences between treatments within the same site and season are not significantly different (P=0.05).

	Average soil moisture in the 0-60cm profile (mm)			
	Henderson Research Station		Monze Farmer Training Center	
	2005-06	2006-07	2005-06	2006-07
Check (Tilled)	117	68	152	125
Direct seeded (DS)	139	81	152	128
Basins (CF)	138	80	156	146

The average of the bi-weekly measurements of soil moisture in the top 60cm of soil at both sites in the two seasons is shown in Table 2. In general there was more moisture in the profile over the season in the CA treatments at HRS, but little effect of treatment on mean soil moisture at MFTC. There are no statistical differences between treatments. However, this appears to be due to variability brought about by variations in soil texture over the trial sites. We believe that variation in texture over the trial site leads to the high variability and we are in the process of analysing soil texture alongside each access tube to allow for the correction of the available soil water.

Yield results

Given that there was little moisture stress in either season at either site and that fertilizer levels were the same on all treatments, differences in yield between treatments at both sites and in both seasons were small (Table 3). At HRS there were no significant differences between the three treatments in either year and only in the first year of the trial – the wetter season – were there any significant differences at the MFTC when the basin treatment did yield significantly more ($P<0.05$) than the tilled treatment, while the DS treatment yield was intermediate and not significantly different to the other treatments.

Table 3. Maize grain yields (12.5% moisture) in one conventionally tilled treatment and two conservation agriculture treatments at Henderson Research Station, Zimbabwe, and Monze Farmer Training Center, Zambia, in the 2005/06 and 2006/07 seasons.

	Maize Grain Yield t ha^{-1}			
	Henderson Research Station		Monze Farmer Training Center	
	2005/06	2006/07	2005/06	2006/07
Check	3.25	4.36	3.62b	4.88
Direct seeding (DS)	2.46	5.23	4.89ab	5.14
Basins (CF)	2.66	5.27	5.50a	5.24
PF	NS	NS	5%	NS
CV%	19.7	16.9	18.3	16.5

On-farm CA demonstration sites

Yield results from the on-farm demonstration plots for the first three seasons at the seven sites where plots were initiated in the 2004-05 season in the Zimuto Communal Area are shown in Table 4. The 2004/05 season was exceptionally dry and no yield was obtained from four of the sites. There are no significant differences (at PF = 5%) between treatment yields in any of the three seasons, because the variability associated with having the different replications at different sites is high, while the yield trend over time evident in Table 4 is simply a function of annual rainfall. However, it is worth noting that when the project started, the concept of CA was completely new to the Zimuto farmers, and so they were very reluctant to give "prime" land for the demonstration plots, and all seven demonstration plots were established on fields that had been abandoned to agriculture due to their low productivity. Even though the results are not statistically significant, they are very significant to many of the local farmers who are now beginning to experiment with CA.

Whereas at the Zimuto site the plots have been under continuous maize to date due to farmer reluctance to include a rotation crop, at the sites near Shamva a maize-soybean crop rotation is used in the demonstration plots with the plots on any one farm being sown to maize in one season and soybeans in the following season. Although this makes it difficult to compare trends over time, the results of the 2006/07 season are shown in Table 5.

Table 4. Maize grain yields with conventional tillage and two conservation agriculture treatments on seven farmer fields in the Zimuto Communal Area, Zimbabwe, in three seasons.

	Maize Grain Yield (kg ha^{-1})		
Tillage	**2004-05**	**2005-06**	**2006-07**
Check (Conventional)	141	962	1330
Rip-line seeded	191	1009	1859
Direct seeded	151	1300	2011
PF	NS	NS	13%
CV%	70	48	35

Table 5. The effect of conventional tillage and two conservation agriculture treatments on maize and soyabean yields each on three farmer fields in the Shamva District of Zimbabwe. 2006-07 crop season.

	Grain Yield (kg ha^{-1})	
Tillage	**Maize**	**Soybean**
Check (Conventional)	4011	1110
Rip-line seeded	4471	1050
Direct seeded	5994	1474
PF	NS	15%
CV%	30	18

Groundnut and maize on-farm trials in Mozambique (CPWF PN1)

The effects of mulch and microdosing of N fertilizer on the yields of maize and groundnuts in Gaza Province in the 2005/06 season are shown in Table 6. Whereas the groundnut results all come from the Macia District, three of the maize "Baby" Trials were in Chokwe. The results in Table 6 show two sets of maize results: one for all sites including Macia and Chokwe Districts, and the other with only the Macia results.

Mulch had a positive effect on maize yield both with and without a small dose of N fertilizer, but almost doubled yield when both mulch and a micro-dose of N were applied (although this interaction was not statistically significant). In the case of groundnuts, the positive effect of mulch on grain yield was highly significant, while there was no significant effect of the N fertilizer microdose on yield. The interaction of mulch and N fertilizer was also significant as there was a small reduction in yield with N fertilizer in the absence of mulch, but a larger positive effect of fertilizer when mulch was present.

In the 2006/2007 season the only comparison that could be made from the few trials harvested (4 Baby trials) was the effect of mulch. Mulch gave a 27% yield increase (1.37 vs. 1.05 t ha^{-1}), but because of the lack of sufficient replication, this effect was not significant.

Table 6. Grain yields of maize and groundnuts in on-farm trials in the Macia and Chokwe Districts of Gaza Province Mozambique. 2005/06 crop season.

		Grain Yields kg ha^{-1}		
Mulch	**N Topdress**	**Maize - All sites**	**Maize - Macia**	**Groundnuts**
		n=8	**n=5**	**n=7**
0	0	685	440	680
0	20 kg ha^{-1}	792	491	593
3 t ha^{-1}	0	857	669	740
3 t ha^{-1}	20 kg ha^{-1}	1232	811	904
Means				
0		739	466	637
3 t ha^{-1}		1045	740	822
	0	771	555	710
	20 kg ha^{-1}	1012	651	749
PF Mulch		<5%	<5%	<1%
PF Fert		7%	NS	NS
PF Mulch x Fert		NS	NS	5%
CV%		39	43	22

Discussion

The results presented show marked positive effects of CA technologies on soil water infiltration, soil water, and, especially in the on-farm results, on yield. These benefits are apparent after only a short period (1-3 years) of the application of the technologies, suggesting that a) the mulch cover provides benefits in water infiltration even from the first season, especially under dry or moisture-limited conditions, and possibly also that b) there are changes in soil physical structure in the short term associated with stopping tillage.

However, one feature that runs through these results is the relatively high variability which results in few statistically significant differences, at least at the commonly accepted level of 95% probability of making the correct inference. This is a common feature of on-farm work, and also of measurements on small areas of a heterogeneous substrate, such as soil. While increased replication can help increase the probability of statistical significance – but not decrease the variability – this is costly and has important implications for on-farm work under restricted budgets. Are we being too strict? Is a 20% level of probability of significance not more realistic and cost-effective? The answer to this question, which has been argued widely, is likely associated with the risk of negative consequences if an error is made, and is unlikely to be of major importance when risk is low. For instance, with CA technologies, where one of the major benefits seen by farmers is not a yield benefit, but rather the savings in energy – either in fuel or in the amount and drudgery of manual labour – the risk in making an error in attributing yield increases is not appreciable, although the risk in not attributing significance to yield decreases may be high.

The other avenue to increase statistical significance is improved management, either of field plots or of evaluation techniques. While the latter is definitely beneficial and as much precision as possible should be the objective of measurements and evaluations, improvement of plot management especially in applied on-farm research should only be to the level attainable by the target group (recommendation domain) of farmers. Excessive management to try to obtain statistical significance only serves to reduce the applicability of the results.

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Precision conservation agriculture for vulnerable farmers in low-potential zones

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Abstract

ICRISAT, FAO, and Non-Governmental Organizations (NGOs) in southern Africa have been testing modifications of conservation farming techniques that create what can be called precision conservation agriculture (PCA). These strategies for farmers in low potential zones, where a majority of the most resource-poor and vulnerable farm households exist, encompass four major principles: (i) minimum tillage – for instance, using planting basins, made with a hand hoe, which concentrate limited water and nutrient resources to the plant with limited labor input, (ii) the precision application of small doses of nitrogen-based fertilizer to achieve higher nutrient efficiency (from organic and/or inorganic sources), (iii) combining improved fertility with improved seed for higher productivity, and (iv) use of available residues to create a mulch cover that reduces evaporation losses and weed growth. These basic principles are taught to farmers who choose crop mixes adapted to their local conditions and household resource constraints. PCA spreads labor for land preparation over the dry seasons and encourages more timely planting, resulting in a reduction of peak labor loads at planting, higher productivity and incomes. Over four years these simple technologies have consistently increased cereal yields by 50 to 300% in more than 50,000 farm households (with the yield increase varying by rainfall regime, soil type and fertility, and market access). Although the area under PCA is not large enough yet to create a marketable surplus, food security has increased substantially. As expected, these farmers are adopting these techniques slowly. The area to which they have applied PCA has more than doubled from 0.1 ha to 0.3 ha per farm and this small area is accounting for 35% of household cereal requirements on average. PCA also enables diversification in cropping patterns and more reliable legume production. Returns to labor have been about two times higher than conventional practices on average and making planting basins every year leads to build up of soil fertility and organic matter over time resulting in a more sustainable system.

Key words

planting basins, zai, fertilizer, farm labor, organic matter

Background

In the drier areas of southern Africa, farmers experience drought once every two to three years. Relief agencies have traditionally responded to the ensuing famines by providing farmers with enough seed and fertilizer to enable them to re-establish their cropping enterprises (UNEP 2002; MEA 2005; Cooper et al. 2008). However, because of the lack of appropriate land and crop management interventions, vulnerable farmers are not necessarily able to translate the relief into sustained gains in productivity and incomes (Rockstrom et al. 2009; Twomlow et al. 2008a).

To improve crop production in the marginal rainfall regions of southern Africa, farmers have to adopt cultural practices that conserve fragile soils and extend the period of water availability to the crop, be it grain or forage. National and international research and development organisations have mostly focused on developing improved genotypes, tillage/soil management systems, and integrated pest/disease management packages. Unfortunately, many of these outputs, although technically sound, have failed to perform well in farmers' fields. They were largely developed and tested in researcher-managed trials, with limited consideration to the problems and priorities of smallholder farmers for whom they were intended (Anderson 1992; Ryan and Spencer 2001; Shiferaw and Bantilan 2004; Twomlow et al. 2006). Unfortunately, efforts to develop African agrarian economies and achieve the MDGs must contend with the increasing challenge of climate change (see for example, Love et al. 2006; Stern 2006; UNDP 2006; Cooper et al. 2008). Most scientists now agree that global warming is inevitable, (IPCC 2007), and that it will have major impacts on the climate worldwide and agricultural productivity, particularly in sub-Saharan Africa (Tadcross et al. 2007; Cooper et al. 2008).

Conservation agriculture (CA) is being promoted as a potential solution to the production problems faced by smallholder farming families in sub-Saharan Africa (Haggblade and Tembo 2003; Hobbs 2007; Rockstrom et al. 2009). Conservation agriculture is a suite of land, water and crop management practices that aim to improve productivity, profitability and sustainability (IIR and ACT 2005). The primary principles promoted for hand-based and draft animal powered cropping systems are:

- disturb the soil as little as possible,
- implement operations, particularly planting and weeding, in a timely manner,
- keep the soil covered with organic materials (crop residues or cover crops) as much as possible, and
- mix and rotate crops (IIR and ACT 2005).

Evolution of CA in southern Africa

Conservation Agriculture is generally defined as any tillage sequence with the objective of minimising or reducing the loss of soil and water; operationally a tillage or tillage and planting combination which leaves at least 30% or more mulch or crop residue cover on the surface (SSSA 1986; IIR and ACT, 2005). In the drylands of southern Africa, CA has been loosely applied to any tillage system whose objective is to conserve or reduce soil, water and nutrient loss, or which reduces draft power (human, animal, and mechanical) input requirements for crop production. With the cropping period in most semi-arid regions being relatively short, the timing of field operations is critical.

The following CA techniques have been evaluated and actively promoted in Zimbabwe since the 1980s: no-till tied ridging; mulch ripping; no-till strip cropping; clean ripping; hand-hoeing or zero till; tied furrows (for semi-arid regions) and open plow furrow planting followed by mid-season tied ridging. These have frequently been promoted in combination with mechanical structures such as: graded contour ridges; dead level contour ridges with cross-ties (mainly for semi-arid regions); infiltration pits dug at intervals along contour ridge channels; *fanya juus* (for water retention in semi-arid regions); vetiver strips and broad-based contour ridges (mainly used on commercial farms) (Mupangwa et al. 2006; Twomlow et al. 2006).

Unfortunately, despite nearly two decades of development and promotion by the national extension program and numerous other projects, adoption of CA has been extremely low in the smallholder sector of sub-Saharan Africa, compared to other continents such as South America, North America and Europe due to various constraints (Erenstein 2003; Goddard et al. 2008; Gowing and Palmer 2008). These include: a low degree of mechanization within the smallholder system; a lack of appropriate implements; a lack of appropriate soil fertility management options; problems of weed control under no-till systems; poor access to credit; a lack of appropriate technical information for change agents and farmers; blanket recommendations that ignore the resource status of rural households; competition for crop residues in mixed crop-livestock systems, and the availability of labor (Hobbs et al. 2007; Gowing and Palmer 2008).

Despite these constraints, a number of different initiatives have recently begun to re-examine the potential for CA to improve crop production within the smallholder sector of Zimbabwe. For the purposes of this paper we have adopted the terminology of the Zimbabwe Conservation Agriculture Task Force (ZCATF), as it has been noted that many organisations use the terms CA and conservation farming (CF) interchangeably in their reports and proposals as if they were the same, yet the two are different.

- *Conservation Agriculture (CA)* is a broader term that encompasses activities such as minimum tillage and zero tillage, tractor powered, animal powered and manual methods, integrated pest management, integrated soil and water management, and includes CF. It is generally defined as any tillage sequence the objective of which is to minimize or reduce the loss of soil and water; operationally a tillage or tillage and planting combination which leaves 30% or more mulch or crop cover on the surface (SSSA 1986; IIR and ACT 2005), equivalent to more than 3 t ha^{-1} of crop residues.

- *Conservation Farming (CF)* is the particular technology developed by Brian Oldrieve using planting basins and soil cover. This is a modification of the traditional pit systems once common in southern Africa and is a variation on the *Zai* Pit system from West Africa, which may also be considered a CF technology. Both are a sub-set of the broader CA term.

- *Precision Conservation Agriculture (PCA)* is a modification of the CF- planting basin approach that includes the precision application of small doses of nitrogen-based fertilizer to achieve higher nutrient efficiency from available basal fertility amendments (from organic and/or inorganic sources) concentrated in the planting basin.

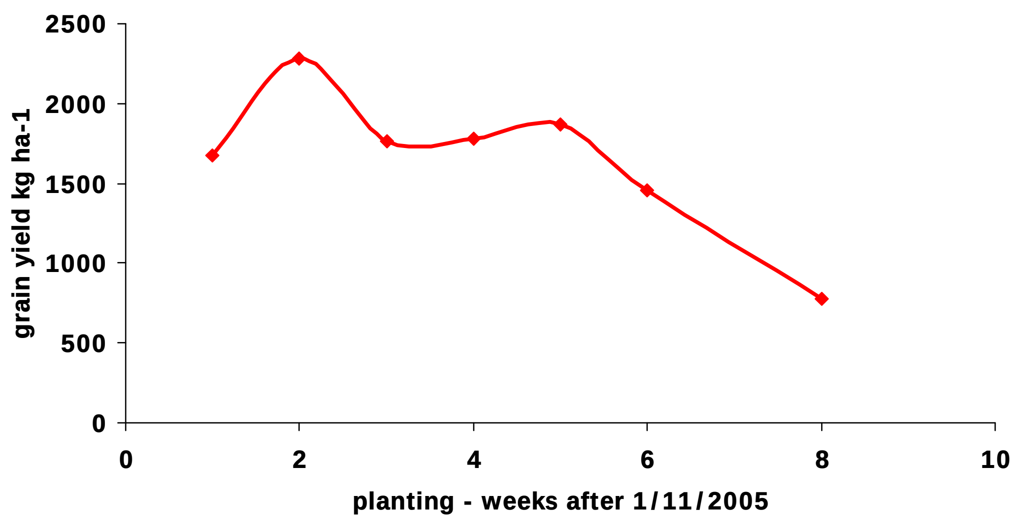
In order to ensure that a consistent message on CA was delivered by the many non-governmental organizations (NGOs) working in Zimbabwe, the United Kingdom's Department for International Development's Protracted Relief Program for Zimbabwe, on behalf of other humanitarian relief agencies, tasked the United Nations Food and Agriculture Organization Emergency Office for Zimbabwe to establish a broad-based partnership that would coordinate CA activities. The CA Task Force for Zimbabwe (ZCATF) was initiated in March 2004 and its successes to date have been summarized in Twomlow et al. (2008b).

The interventions currently being promoted/tested in Zimbabwe include:

- *Planting Basins* and *Shallow Planting Furrows* using a hand hoe,
- *Ripper* tines, attached to the beam of the animal drawn moldboard plow, to prepare planting lines in un-plowed soil for households with limited access to draft animal power; and
- *Specialised No-Till/ Direct Planting Seeders* aimed at the emerging commercial farmers with unlimited access to draft animal power.

All of these interventions are being compared with the traditionally applied practice of overall spring plowing with an animal-drawn moldboard plow and planting, sometimes referred to as 'Third Furrow Planting'. Seed is dropped into every third or fourth furrow opened by the plow (October through to December depending on the start of the wet season) when the soils have been softened by the rains. The next pass of the plow covers the seed, which is then left to germinate in a weed-free seedbed. Unfortunately, all too frequently many households with limited or no access to draft animals have to wait until better-resourced households have completed their own planting before they may borrow or hire a team of draft animals (Twomlow et al. 2006). This often means that the poorer resourced, most vulnerable households, typically plant 4 to 6 weeks later than other households. Some plantings occur as late as January, with resulting losses in yield potential. Figure 1, derived from field data collected by ICRISAT during the 2005 seasons, clearly shows the decline in yield as plantings get later and later in the season. Some may ask why land preparation does not take place in the dry season – a good question as a standing extension recommendation is to carry out winter tillage. Unfortunately, by the time all crops have been harvested and the land is ready for tillage the condition of the communal herd, which includes the draft animal resource, has declined due to a reduction in available forage.

Figure 1. Observed variation in smallholder cereal grain yield response to planting dates in southern Zimbabwe, 2005 (ICRISAT unpublished data)



The planting basins

The central component of the 'basin tillage package' is the planting basin. Seeds are sown, not along the usual furrow, but in small basins – simple pits that can be dug with hand hoes without having to plow the whole field. The technology is particularly appropriate to southern Africa, given that the majority of smallholder farmers struggle to plant their fields on time because they lack draft animals (Twomlow et al. 1999; 2006). The basin tillage concept was first developed by Oldrieve in Zimbabwe (1993), and subsequently modified and promoted in Zambia by the Zambian Farmers Union Conservation Farming Unit (Haggblade and Tembo 2003). This practice spreads labor for land preparation over the dry seasons and encourages more timely planting, resulting in reduction of peak labor loads at planting. The basic components of the CF practice agreed by the ZCATF are listed in Box 1.

Planting occurs in Nov/Dec after the basins have captured rainwater (and then drained naturally) at least once. Smallholder farmers without draft power can plant soon after an effective rainfall event,[1] rather than waiting for draft animals to become available several weeks into the season. In addition, farmers are encouraged to spread whatever crop residues might be available as a surface mulch to prevent soil losses early in the season, conserve moisture later in the season, and enrich the soil with nutrients and organic matter as the residues decompose.

When the basins are combined with the precision application of available basal soil fertility amendments and micro-doses of inorganic nitrogen fertilizer as top dressing (Twomlow et al. 2008c) it is termed 'Precision Conservation Agriculture' (PCA) irrespective of the quantity of surface residues retained as mulch.

This paper presents results from three related studies on the PCA package (basin planting plus targeted application of fertility amendments) for vulnerable households in southern Zimbabwe promoted through the relief and recovery programs operating in the country since 2004. The first study was the wide-scale testing of the PCA concept across multiple locations in southern Zimbabwe through relief and recovery programs (Hove and Twomlow 2008; Mazvimavi et al. 2007; Twomlow et al. 2007 2008d). The second study was a series of researcher-managed trials both on and off station to begin the disaggregation of the various components of the PCA package (Mashingaidze et al., 2007; Mupangwa et al., 2007). The third study focused on an initial quantification of the longer term impacts of various crop establishment practices, weeding regimes, fertilizer rates and mulching on crop yields, and water-use efficiency using systems simulation modeling.

[1]. An effective rainfall event is 30 mm for sandy soils and 50+ mm for heavier soils (Twomlow and Bruneau, 2000).

Box 1. Components of CF Planting Basins Package promoted in Zimbabwe

1. *Winter weeding*

The first step in preparing a field using CF methods is to remove all weeds. This should be done soon after harvesting in May/June. Weeding is done using implements such as hand hoes and machetes that disturb the soil as little as possible. The importance of weeding before land preparation is to ensure that the plot is weed-free at basin preparation and also to prevent the dispersal of weed seeds.

2. *Digging planting basins*

Planting basins are holes dug in a weed-free field into which a crop is planted. The basins are prepared in the dry season from July to October. The recommended dimensions of the basin are 15×15×15 cm, spaced at either 75×60 cm for Natural Region II and either 75x75 cm or 90×60 cm for Natural Regions III, IV and V. The basins enable the farmer to plant the crop after the first effective rains when the basins have captured rainwater and drained naturally. Seeds are placed in each basin at the appropriate seeding rate and covered with clod-free soil. The advantage of using basins is that they enhance the capture of water from the first rains of the wet season and enable precision application of both organic and inorganic fertilizer as it is applied directly into the pit and not broadcast.

3. *Application of crop residues*

Crop residues are applied on the soil surface in the dry season, soon after harvesting. The residues must provide at least 30% soil cover. The mulch buffers the soil against extreme temperatures (thereby reducing soil evaporation), cushions the soil against traffic, and suppresses weeds through shading and improves soil fertility.

4. *Application of manure*

Fertility amendments are applied soon after land preparation in the dry season. In CF, the application of both organic and inorganic fertilizers is recommended as they complement each other. Organic fertilizers such as manure and/or composts are applied at a rate of at least a handful per planting basin. More can be used in wetter areas.

5. *Application of basal fertilizer*

Inorganic basal fertilizer is also applied soon after land preparation before the onset of the rains. One level beer bottle cap is applied per planting basin and covered lightly with clod-free soil. This is equivalent to 80 kg of compound fertilizer per hectare. Application rates can be increased in wetter areas and may depend on crop types.

6. *Application of topdressing*

Nitrogen fertilizer is applied to crops at the 5 to 6 leaf stage soon after the first weeding at a rate of one level beer bottle cap per basin. This is equivalent to 80 kg of ammonium nitrate fertilizer per hectare. Application is done on moist soils. Precision application ensures that the nutrients are available where they are needed. Application rates can be increased in wetter areas and may depend on crop types.

7. *Timely weeding*

In conventional tillage systems, farmers plow/cultivate repeatedly in order to suppress weeds. With reduced tillage, weeds can be a problem requiring more effort initially. One strategy is to weed in a timely manner (ie, when the weeds are still small) preventing the weeds from setting seed. Timely weeding in combination with mulch should eventually lead to effective weed control.

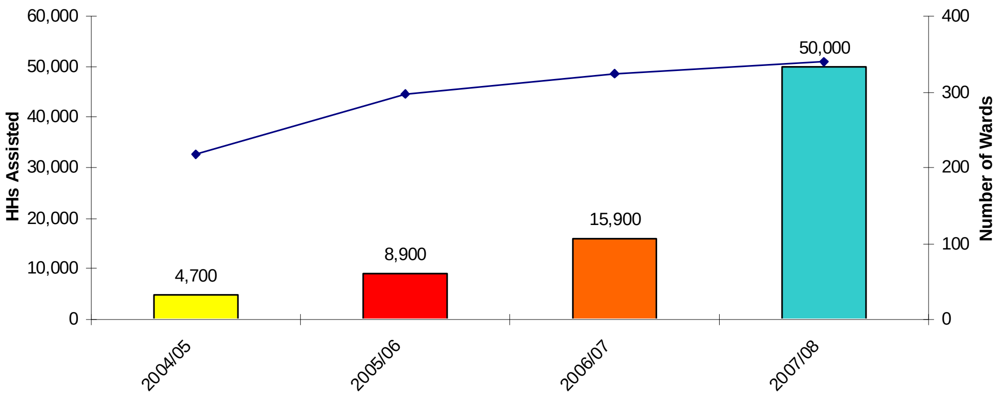
8. *Crop rotation*

Rotating crops is one of the key principles of CF. Cereal/legume rotations are desirable because the cereal benefits from nitrogen produced by the Rhizobium associated with the legume, and the legume benefits from the residues produced by the cereal. The advantages of crop rotation include improvement of soil fertility, controlling weeds, pests and diseases, and producing different types of outputs, which reduce the risk of total crop failure in cases of drought and disease outbreaks.

Study 1: Gains to vulnerable households from PCA through 4 years of field testing

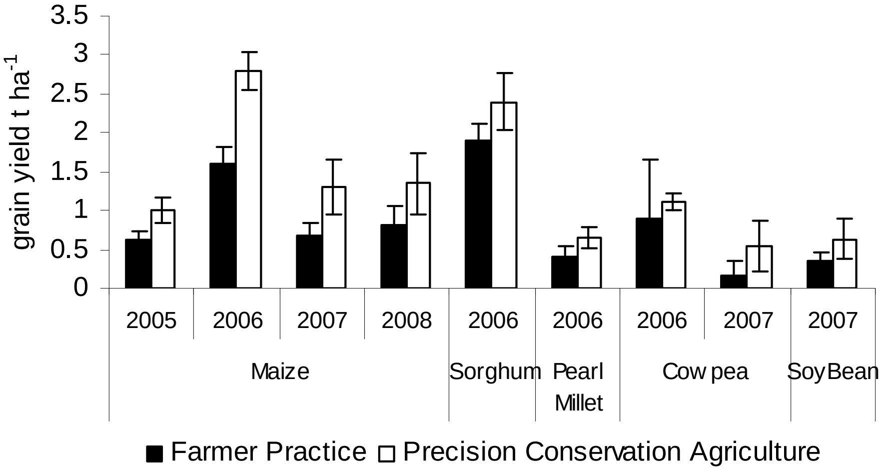
The PCA concept was introduced by NGOs and donors with technical assistance from ICRISAT in 2004/05 to a very small group of farmers. Since then the number of farmers practicing PCA has increased significantly over the intervening seasons (Figure 2). Over the fours seasons for which data are available from a nationwide system of 0.2 ha paired plots (0.1 ha under basins and 0.1 ha under traditional farmer practice), the basin package has consistently increased average cereal yields by 50 to 300% (Figure 3) in more than 50,000 farm households, with the observed yield increase varying by rainfall regime, soil types, fertility and farmers resource status.

Figure 2. Promotion of PCA in Zimbabwe between 2004 and 2008 showing the number of households receiving seed, fertilizer and technical support each season through the relief programs and the number of wards the NGOs are active in (adapted from Twomlow et al., 2008



DATA Source: FAO Database, NGOs
Map Production: FAO
Shape Files: CSO & SG

Figure 3. Cereal and legume grain yield responses to conventional farmer practice and PCA (planting basins) over three seasons averaged across 13 districts in semi-arid in Zimbabwe. Error bars represent the standard error of differences between the means of the treatments for each crop in each season of observation. (Source: ICRISAT, Bulawayo unpublished data)



Use of volunteer farmer clusters, rather than lead farmers or farmer field schools to demonstrate these principles, is leading to higher spontaneous uptake (Mazvimavi et al. 2007). For instance, in two wards in southern Zimbabwe, where paired plot demonstrations were established on less than 10% of farms, more than 1000 farm households have since invested their own capital and other resources, representing spontaneous uptake by nearly 90% of the population. Although the area under PCA is not large enough yet to create a marketable surplus, food security has increased substantially. As expected, farmers are adopting these techniques incrementally (Mazvimavi and Twomlow 2009). The area under PCA has doubled from around 0.1 ha per farm in 2004 to more than 0.3 ha per farm in 2008 (ICRISAT unpublished survey data), and this small area is accounting for 35% of household cereal requirements on average.

Precision conservation agriculture also enables diversification in cropping patterns and more reliable legume production. Returns to labor have been about two times higher than conventional practices on average (Table 1). Although making the basins requires time and effort, once prepared, the same planting position can be used repeatedly. With each successive season preparing the basins and weeding should become easier. Maintaining all other production costs constant, CF remains more profitable than conventional farmer practice, even when significant yield gains can be achieved from farmer practice in higher rainfall conditions with fertilizer use (Mazvimavi and Twomlow 2009).

Table 1. An enterprice analysis for PCA versus Traditional Farmer Practices under high-, normal-, and low-rainfall situations in Zimbabwe (microdosing with 28 kg N ha^{-1}) (adapted from Mazvimavi and Twomlow, 2009 based on survey data collected in April 2007).

		PCA		Traditional farmer practice	
		First year	**Second + year**	**No fertilizer**	**With fertilizer**
High rainfall					
Maize grain	kg ha^{-1}	2000	2650	678	1120
Gross margin	US$ ha^{-1}	654	867	197	357
Cost per kg	US$ kg^{-1}	0.07	0.07	0.15	0.12
Returns to labour	US$ day^{-1}	6.3	7.0	3.3	4.9
Normal rainfall					
Maize grain	kg ha^{-1}	1750	2200	560	728
Gross margin	US$ ha^{-1}	529	697	153	19
Cost per kg	US$ kg^{-1}	0.10	0.08	0.17	0.18
Returns to labour	US$ day^{-1}	5.5	6.3	3.0	3.3
Low rainfall					
Maize grain	kg ha^{-1}	1520	1780	368	400
Gross margin	US$ ha^{-1}	473	535	71	48
Cost per kg	US$ kg^{-1}	0.09	0.10	0.25	0.32
Returns to labour	US$ day^{-1}	5.2	5.3	1.9	1.5

These swift yield gains from planting basins are achieved because the technology enables farmers to plant and carry out all field operations in a timely manner.[2] The concentration of water and available soil fertility amendments within the planting basin is reducing the risk of crop failure, even under drought conditions.

It is estimated that throughout most of Zimbabwe, irrespective of rainfall regimes, if a household were to devote at least 0.6 ha to CA it would meet their basic cereal requirements in all but the worst rainfall season, with many seasons producing a surplus (Mazvimavi et al. 2007). This would then allow farmers to diversify the crops they are growing on the rest of their land holdings, making crop rotations feasible and giving many option of cash crop production and sustainable livelihood improvement and commercialisation. Additionally, yield increase and stabilisation will produce more biomass for mulching and/or stockfeed.

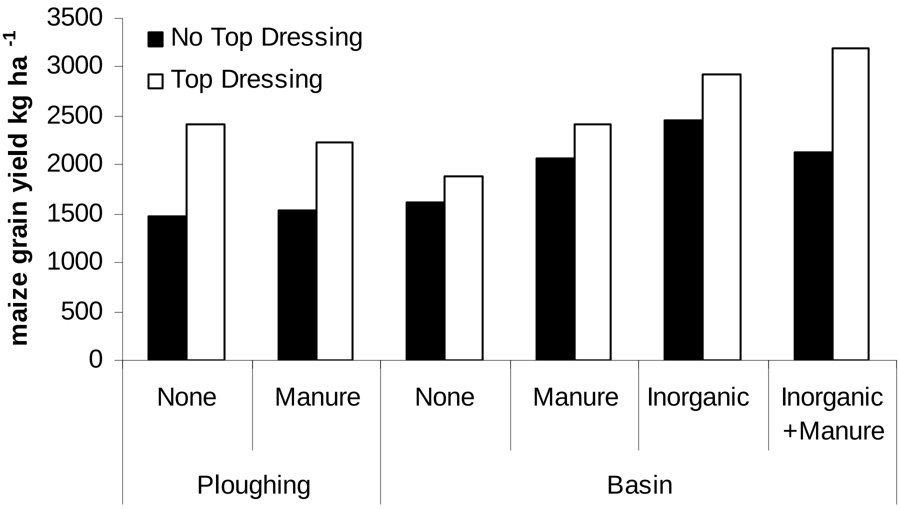
[2] Generally farmers depend on third party tillage (plowing) of their land. In CF farmers can prepare their plots by hand in the off-season. Delayed planting after the optimum planting date reduced the yield potential by around 30% per month.

Study 2: Disaggregation of the basin planting package

Impact of fertilizer amendments on maize yield responses

The impact of basal and top dressing fertility management regimes on maize grain yield responses to basin tillage and conventional spring plowing are summarized in Figure 4.

Figure 4. The impact of basal fertilizer only (filled bars) and combined with top dressing fertilizer open bars) regimes on maize grain yield responses to basin tillage compared with traditional spring plowing for 11 districts in southern Zimbabwe in the 2005/06 season.



There is a strong interaction between basal fertilizer application, top dressing and tillage system. Without any form of basal fertility amendments the basin tillage systems performed only slightly better than the farmers' traditional spring plowing – 1621 kg ha^{-1} compared to 1476 kg ha^{-1}. However, from Figure 4 it is clear that when farmers have access to a combination of manure and inorganic fertilizers, particularly inorganic fertilizer for top dressing, then significant grain yields can be achieved. Top dressing with inorganic nitrogen fertilizer increased yields by more than 30%. Thus, for smallholder farmers to derive long-term yield benefits from the basin tillage technique beyond the current relief and recovery programs, additional investment will be required to ensure that smallholder farmers have access to inorganic fertilizers locally, particularly inorganic nitrogen-based fertilizers for top dressing.

Effects of crop residue mulch on weed density and crop yields

High weed infestation is one of the major constraints facing farmers converting from conventional tillage to CA. Under conventional tillage, weeding labour accounts for more than 60% of all costs for producing a maize crop (Ellis-Jones et al. 1998). Smallholder farmers would welcome a reduction in weed pressure as out migration of males in search of off farm income and the HIV/AIDS pandemic in sub-Saharan Africa has exacerbated household labor shortages in the smallholder sector (Gowing and Palmer 2008). Unfortunately, very little research has been undertaken to assess the impacts of mulching on weed ecology. Data presented by Nyagumbo (1999) showed no reduction in weed pressure with mulching when maize was grown using the ripper tillage. However, recent studies by ICRISAT have shown that as the amount of maize residues is increased, mulching significantly reduced (P=0.01) weed pressure when maize was grown using planting basins at Matopos Research Station (Table 2). Similarly, the average soil water content in the top 15 cm of the profile was observed to significantly increase (P=0.01) with increasing mulch rate.

Table 2. Effects of applying graded levels of mulch on soil moisture, weed density and maize yields on a sandy soil at Lucydale, Zimbabwe, during the 2004/05 season (Adapted from Mupangwa et al., 2007).

Mulch rate (t/ha)	Average soil moisture content(%) 0–15cm depth for the 2004/05 season	Weed count (Weed m^{-2})	Maize yields (kg/ha)	
			Grain	Stover
0	4.14	14.7	478	1296
0.5	3.68	16.0	438	1235
1	3.45	17.3	521	1327
2	4.75	13.7	615	1466
4	4.52	12.0	633	1497
8	6.66	7.3	653	1491
10	6.73	5.0	599	1451
s.e.d	1.072	3.54	233.2	431.6

However, for this sandy soil, the significant reduction in weed density and increase in soil water content, observed with increasing mulch rate, were not translated to significant increases in stover and grain yields (Table 2). Similar lack of impacts of increasing mulch rates on crop yields have been observed for subsequent seasons (Mupangwa pers. comm.).

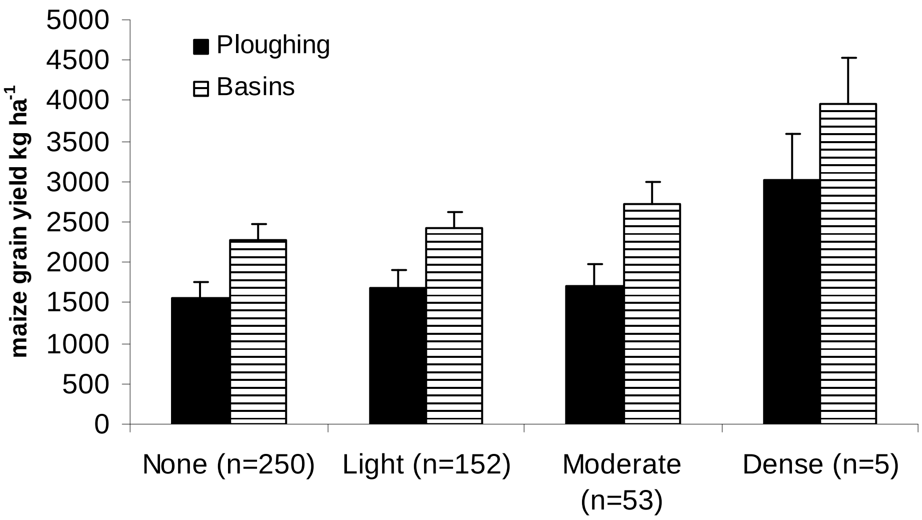
Two experiments were also conducted at West Acre (clay) and Lucydale (sand) in Matopos Research Station to determine the effect of different levels of residue retention on crop and weed growth over two seasons (Mashingaidze et al. undated). On both soil types, retaining the entire residue produced neither increased crop yield (Table 3) nor suppressed weeds (data not shown), which is to be expected given the small quantity of residues available in these environments.

Table 3. Maize yield (t ha^{-1}) responses to maize residue retention across two seasons for two sites with different soil types at Matopos Research Station

Site	West acre (Clay loam)				Lucydale (Sandy loam)			
Residue retention (%)	2004/05		2005/06		2004/05		2005/06	
	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover
0	2.02	2.34	4.94	3.88	1.51	1.60	0.87	1.00
25	1.69	2.14	3.72	2.71	2.25	1.72	1.03	1.07
50	1.87	2.68	4.12	3.62	0.93	0.99	0.94	0.60
75	1.74	2.34	3.95	3.56	1.96	1.83	1.41	1.25
100	2.04	2.18	3.02	3.51	1.89	1.40	1.14	0.93
s.e.d	0.415	0.401	0.709	0.957	0.695	0.608	0.310	0.353

Additional data from 508 farmers implementing the basin technology across 11 districts of southern Zimbabwe showed no significant benefits of mulching with up to 3 t ha^{-1} stover during the first two seasons of implementation (see Figure 5 for the 2005/2006 average rainfall season.). Increased yields were only observed when farmers mulched their own fields with 6 t ha^{-1} or more of crop and plant residues. Smallholder farmers rarely achieve this level of stover production. Also, it is still questionable how much mulch farmers will retain on their fields, given that a major source of household income in these mixed crop-livestock systems is from the sale of goats and sheep (ICRISAT unpublished data).

Figure 5. The impact of mulch cover of various levels on maize yield in response to basin tillage compared with conventional spring plowing for 11 districts in southern Zimbabwe in the 2005/06 season. Light – less than 1 t ha^{-1}, moderate – 3 t ha^{-1} (the target), and dense – more than 3 t ha^{-1}. Error bars represent the standard error of differences between the means of the tillage practice for each mulch rate.



Unfortunately, some organizations that are currently promoting CA, are encouraging their collaborating farmers to harvest what ever sources of plant residues that might be available from the communal resource base, in an effort to achieve the 3 plus t ha^{-1} of mulch advocated by the Global CA constituency. This is done without any due consideration of the potential social conflicts that might occur between households that have a strong bias to livestock production and those that are adopting CA.

Study 3: Evaluation of effects of CA technologies on land and water productivity using the APSIM model

This exercise was carried out with the objective to disaggregate conservation agriculture (CA) technologies and understand their effects on crop grain and stover yield and also on the soil water balance (runoff, drainage and evaporation). The simulation tool used was the Agricultural Production Systems Simulator (APSIM) model (Keating et al 2003). Analyses have been done for both a clay loam and sandy loam soil types, typical of southern Zimbabwe using a 38 year (1962–1999) weather record collected by the national Weather Bureau for Matopos Research Station The model is useful in capturing the interactions between climatic conditions, soil types and nutrient dynamics (Delve and Probert 2004; Ncube et al., 2008), and weed management (Robertson et al. 2005; Shamudzarira and Robertson 2002), and has been successfully used in the cereal based farming systems of southern Africa (Whitbread et al. 2004; Ncube et al., 2008). A short-duration maize variety (SC403) was used to simulate maize growth and development to various crop production scenarios. The four main crop production scenarios simulated are as follows:

1. *Farmer practice* – crop planted using overall spring plowing from mid December through to late January, followed by a single weeding 35 days after sowing (typical scenario for farmers with limited or no access to draft animals) (FP1weed)
2. As for farmer practice, but with two weedings at 25 and 50 days after planting (FP2weed)
3. Basin planting without residues with a planting window set 20 November – 31 December and two weedings at 25 and 50 days after planting (Basins) – equivalent to PCA.
4. As for basins but with crop residues applied at a rate of 3 t ha^{-1} which represents 30% soil cover applied on 19 November each year.

Superimposed on the four crop production practices were four fertilization routines

1. No soil fertility amendments (zero nitrogen)
2. Basal fertilizers applied at planting, equivalent to 7 kg N ha^{-1}
3. Top dressing with ammonium nitrate fertilizer equivalent to a rate of 28 N kg ha^{-1} (micro-dosing) applied 35 days after planting (Top Dress)
4. Basal and Top Dressing applied (35 kg N ha^{-1}).

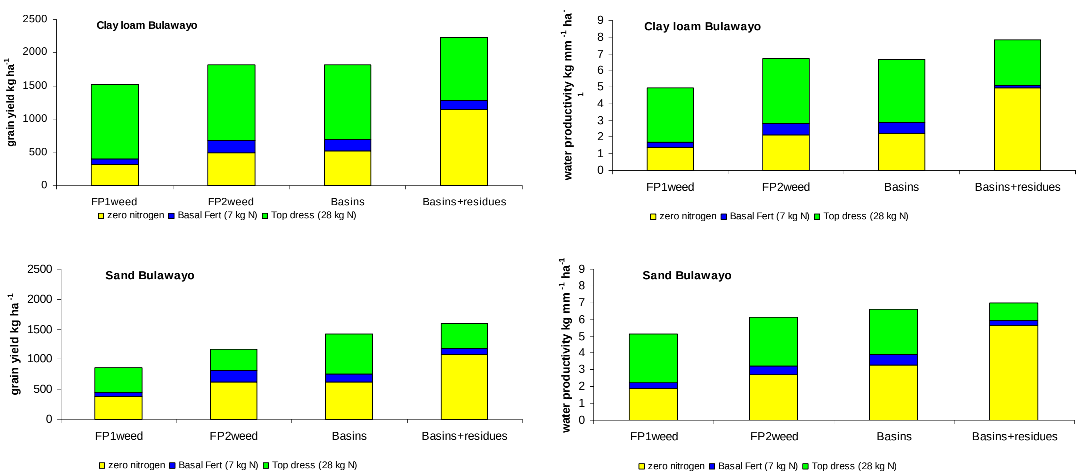
Full details of the models parameterization for these soil types are available on request.

A total of 16 treatment combinations were simulated for each site for the 38 year period.

Average simulated incremental yield responses for the four fertilization regimes superimposed on the four crop production practices and associated water productivities with respect to evapotranspiration (WP) are summarized in Figure 6. As might be expected from the literature, the highest yields and WPs for both soil types are observed for the Basins+residues, with the lowest yields and WP observed on the FP1weed. This is in contrast to the field observations made to date, which suggest that residue retention below 3 tons ha^{-1} in the short term does not have a positive effect on crop yields (Tables 2 and 3; Figure 5). However, the question remains – "Is the incremental grain yield increase observed between Basins and Basins+Residues of 400 kg ha^{-1} for the clay loam, and 180 kg ha^{-1} for the sandy soil, enough to compensate the farmer for loss of animal feedstuffs?". The largest incremental yield gain across the four crop production practices was achieved through the targeted (point application near the plants) application of 28 kg N ha^{-1} 35 days after planting.

Basin tillage with or without residues offers an opportunity for poor vulnerable households with no access to draft power to produce as much if not more grain per unit area than households with full draft power in the drier areas of Zimbabwe. Furthermore, if the access to nitrogen fertilizer can be improved there is a great chance that households will move from a food insecure state to one of surplus.

Figure 6. Mean simulated incremental yield responses and associated water productivities for four crop production scenarios (FP1weed, FP2weed, Basins, Basins+residues) with four different superimposed fertilization regimes (Zero N, 7kg N, 28kg N, 35kgN). Means of 38 years of simulation runs.



Conclusions

PCA spreads labor for land preparation over the dry seasons and encourages more timely planting, resulting in a reduction of peak labor loads at planting, higher productivity and incomes. Over four years these simple technologies have consistently increased cereal yields by 50 to 300% in more than 50,000 farm households (with the yield increase varying by rainfall regime, resource status of the household, soil types and fertility, and market access). Although the area under PCA is not large enough yet to create a marketable surplus, food security has increased substantially. As expected, these farmers are adopting these techniques slowly. The area to which they have applied PCA has more than doubled from 0.1ha to 0.3 ha per farm and this small area is accounting for 35% of household cereal requirements on average. PCA also enables diversification in cropping patterns and more reliable legume production. Returns to labor have been about two times higher than conventional practices on average and making planting basins every year leads to build up of soil fertility and organic matter over time resulting in a more sustainable system.

While PCA promises to have potential to increase productivity of the crop-livestock systems in the smallholder sector of southern Africa, the promotion of the four principles should be sequenced in a manner that reflects the social, economic and biophysical constraints that these smallholder farmers face. Currently, crop residues are extensively used as feed and using them as mulch is bound to be unacceptable to farming communities as a whole in the short term. It is proposed that when promoting PCA in these systems, the initial focus should be on raising the productivity of the systems through the optimization of other management variables: planting on time, efficient use of organic and inorganic fertility amendments and effective weeding. When adequate crop residues for feed and mulch are produced, mulching can be encouraged in a sustainable manner.

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Tillage, residue management and fertilizer application effects on crop water productivity in western Kenya

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Abstract

A long-term conservation tillage experiment was established in Nyabeda, western Kenya in March 2003 to investigate the effects of tillage and residue management on crop water productivity (CWP, kg grain m^{-3} rain) in continuous maize and maize-legume cropping systems. Seasonal CWP of maize over the first eight cropping seasons ranged from 0.1 to 0.8 kg m^{-3} of in-season rainfall. For continuous maize, there was a consistent trend for lower CWP with reduced tillage (RT) compared to conventional tillage (CT) for the first few years, for respective residue retained/removed treatments, but with few significant differences. After 5 seasons, CWP was similar with RT and CT, with and without crop residues (CR). There was also a consistent trend for higher CWP of RT with CR than without CR for the first 5 seasons, but with no significant differences. Similar trends in maize CWP occurred in the maize-legume rotation, except in the first year where CR led to reduced yields, presumably due to N immobilization as no N fertilizer was applied. CWP of soybean was not affected by tillage treatment or residue management. With low rainfall, crop residue (CR) application increased yield by up to 30% under RT. The yield advantage of CR (over no CR) decreased with increasing rainfall (R^2 = 0.9 for continuous maize and R^2 = 0.7 for soybean-maize rotation). CR disappearance was fast (daily % loss of 106 $e^{-0.019x}$). Phosphorus (P) and nitrogen (N) application had large effects on CWP. In the maize-soybean rotation, P application increased CWP of maize by 120%, while application of N with P increased CWP by a further 35%. Thus fertilizer application is important for increased CWP. The results suggest that RT with mulching gives similar maize CWP in continuous maize and maize-legume rotations. Rotation with soybeans brings further benefits including reduced N fertilizer requirement, while soybean CWP is also maintained in the RT.

Key words

reduced tillage, crop residue, rotation, rainfed, maize, soybean

Introduction

Producing more food with less water has been proposed to address the growing human populations' food demands, to avert a world crisis that could be ignited by fights for water, to enhance ecosystem sustainability, to keep up with changing lifestyles and eating habits, and to enhance competitiveness among competing uses (FAO-AGL 2002). Current changes in lifestyle aggravate water demands, and future projections show a world of increasing food scarcity (Ringler and Msangi 2007). The large gaps between current and potential crop water productivity (CWP) with respect to ET clearly indicate opportunities for improvement for many crops (Zwart and Bastiaanssen 2004). This may be achieved through both more efficient water capture and improved management of other yield increasing factors. Low agricultural productivity is the main cause of poverty and food insecurity in Africa, and improving water productivity through integrated water, crop and nutrient management is one of the approaches to help reverse this situation.

Conservation agriculture (CA), which involves reduced tillage (RT), soil cover and crop rotation, is receiving increasing attention in Africa as it can increase yield and CWP through its effects on soil-plant interactions. Studies have shown soil structure improvements (Madari et al. 2005), reduced runoff, decompaction, better root growth and penetration (Busscher et al. 1995), and increased crop yields (Belay et al. 1998) resulting from CA approaches. Surface mulching with crop residues (CR) can impede water runoff and soil loss and increase infiltration, resulting in better water utilization. Rockstrom et al. (2003) observed that 70 to 85% of rainfall in sub-Saharan Africa is lost as non productive green and blue water flows. In the humid-tropics, farmers are faced with twin residue problems: the limited availability of crop residue (CR) to apply as mulch and its fast disappearance (breakdown), both of which constrain the degree of soil protection which may be achieved through the use of residues. It is thus necessary to investigate the potential for limited amounts of CR to increase CWP.

Research conducted by the Tropical Soil Biology and Fertility institute of CIAT over the last 15 years has demonstrated that use of inorganic fertilizers and their combination with organic resources result in significant yield increases. Such approaches result in better crop establishment and increase the efficiency of crop water utilization (Bouman 2007). Large rotational benefits to cereals in legume-cereal rotation systems cannot be attributed only to the effects of nitrogen (N) fixation by the legume crop (Carsky et al. 1997). Additional effects such as soil water conservation during the legume phase of the rotation benefit the succeeding cereal. These benefits could result in greater CWP in such rotations compared to the common farmers' practice of continuous maize.

In this study, we investigated the effects of tillage, CR and fertilizer on CWP on a Ferralsol in the sub-humid environment of western Kenya. The research question that we sought to answer is "how do tillage system, CR application and fertilizer application affect rain water productivity under continuous maize and soybean-maize rotation systems in western Kenya"? The study sought to determine those effects through the following objectives:

1. Assess how tillage practices and residue management affect crop water productivity over several seasons in western Kenya
2. Determine the effects of N and phosphorus (P) fertilizers on crop water productivity

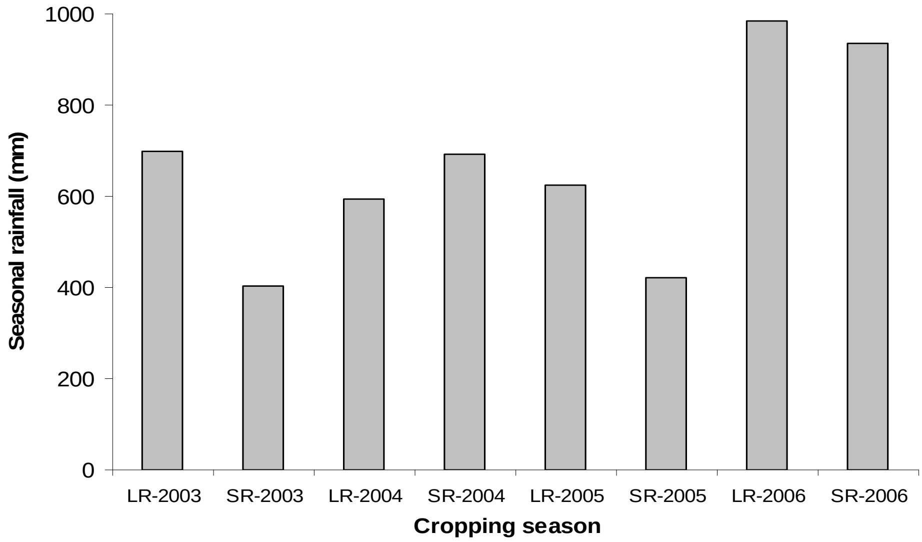
These were achieved through an on-farm researcher-managed experiment which started in March 2003 in western Kenya. The experiment involved two tillage systems (RT and CT), two residue management systems (plus and minus CR) and two cropping systems (continuous maize and soybean-maize).

Methodology

Study location

The study was conducted in Nyabeda in western Kenya. The site is at an altitude of 1420 m a.s.l., a latitude of 0° 07' N and a longitude of 34° 24' E. Annual rainfall ranges from 1200 to 1600 mm and is normally distributed in two rainy seasons; the long rainy (LR) season from March to August and the short rainy (SR) season from September to January. Long-term mean, minimum and maximum daily temperatures are 23, 14 and 31°C, respectively. Daily rainfall was measured using a manual rain gauge installed on the experimental farm. Figure 1 shows seasonal rainfall during the first eight seasons.

Figure 1. Seasonal rainfall (mm) at Nyabeda, western Kenya in eight consecutive cropping seasons (March 2003 to January 2007), LR= long rainy season (Mar-Aug), SR=short rainy season (Sep-Jan)



Soil type

The soil is a Ferralsol (Sombroek et al. 1980) with 64% clay, 21% silt and 15% sand at the 0-15 cm. At the start of the trial the soil had 1.3% organic carbon, 0.15% total N content and pH in water (1:2.5) of 5.1. Prior to establishment of the experiment, the farm had been grazing land under mixed native vegetation of grasses and shrubs.

Experimental design and treatments

The study was conducted within a long-term conservation agriculture experiment run by AfNet/TSBF-CIAT and involving a factorial combination of tillage system in main plots (RT and CT), crop residue management in split plots (plus and minus CR), cropping system in split-split plots (continuous maize and maize-legume rotation) and N or P in split-split-split plots (Table 1). Crop residue was surface applied in RT, while it was partially incorporated in CT during tillage; the practice of CT followed the common practices among small-scale farmers in the area and therefore a treatment of surface CR under CT was not implemented. In the continuous maize system, four levels of N fertilizer (0, 30, 60 and 90 kg N ha^{-1}) were applied to assess N fertilizer response. For the maize-legume rotation, three fertilizer combinations were used; control (without N and P), minus N plus P, and plus N plus P.

Application of N only was not included as the response to N without P, in soils that are P-fixing (i.e., where P is immobilized) was not expected. The design was a split-split-split plot with 4 replicates. The main plots (tillage treatment) were 14 m x 60 m while sub-sub-sub-plots measured 7 m x 4.5 m.

Table 1. Treatments combining tillage practice, crop residue management, cropping system and fertilizer application in Nyabeda, western Kenya

Treat no.	Tillage Method	Crop residue management	Cropping System	Fertilization[1]
1	RT	-Crop residue	Continuous maize	+4N
2	RT	+Crop residue	Continuous maize	+4N
3	CT	-Crop residue	Continuous maize	+4N
4	CT	+Crop residue	Continuous maize	+4N
5	RT	-Crop residue	Legume-cereal rotation	P&N
6	RT	+Crop residue	Legume-cereal rotation	P&N
7	CT	-Crop residue	Legume-cereal rotation	P&N
8	CT	+Crop residue	Legume-cereal rotation	P&N

RT=reduced tillage, CT=conventional tillage,

[1] Plots labeled +4N were split to accommodate four levels of N fertilizer (0, 30, 60 and 90 kg N/ha). Rotation plots (labeled P&N) were split to accommodate P and N combinations (-N-P; -N+P; and +N+P)

Crop management

Initial land preparation was by hand plowing to 15 cm depth for all plots. Subsequent seasonal land preparation in CT was done in the same way as the initial land preparation, while the preparation in RT was by surface scratching to about 3 cm depth using a hand-hoe and only in the places with weeds. Weeding was done using hand hoes by shoveling to about 10 cm depth in CT, and in RT it involved surface scratching. Each season, there were three (3) such weeding operations in each tillage practice. Crop residue (maize stover of the harvested crop comprising stalks and leaves) was chopped into pieces (about 25 cm in length) and applied seasonally at 2 t ha^{-1} at about one week before planting; the residue was surface applied in RT and incorporated in the case of CT during tilling operations. At the beginning of LR2007 cropping season, the crop residue was characterized as having 40% C, 0.35% N, 0.04% P, 0.98% K, 4.0% lignin and 0.51% polyphenol. Phosphorus and potassium (K) fertilizers were applied at 60 kg P ha^{-1} and 60 kg K ha^{-1} each season as triple supper phosphate (TSP) and muriate of potash. The fertilizers were hill-placed below the soil surface (at about 3-5 cm depth) with the seed at the time of sowing. Fertilizer N (urea), was split-applied with $^1/_3$ at planting and $^2/_3$ at knee height (5 weeks after planting). The fertilizer (urea) application at knee height was placed on the soil around the base of the stems, when the soil was moist. Maize (*Zea mays* L.) Hybrid 513 was sown in season 1, Hybrid 502 (from Western Seed Company) in seasons 2, 3, 6 and 8, IR (Imidazolinone-Resistant) during seasons 4 and 7 and Hybrid 403 (Western Seed Company) during season 5. For the legumes, common bean (*Phaseolus vulgaris* L.) was used in season one and soybean (*Glycine max* (L.) Merr) (TGX 1448-2E, locally known as SB20) was used in subsequent seasons. Legume above-ground residues, minus pods removed at harvest, were left on the respective plots where they had been grown. The maize was planted at 0.75 m (row spacing) by 0.25 m (hill spacing) by placing 2 seeds per planting hill. The crop was thinned to one seed per hill 2 weeks after germination, giving

53,000 plants ha^{-1}. The soybean was planted at 0.75 m x 0.05 m (i.e., seed rate of 266,667 seeds ha^{-1}).

Grain and stover yield

The crops were harvested from the net plots at maturity leaving 2 border plants (0.25 m spacing) on either end and one row (0.75 m spacing) from the sides to eliminate edge effects. The maize cobs were separated from the stover and the fresh weight of each determined. Moisture content of grains and stover was determined on sub-samples by air drying the cobs, after which the grains were separated from the cobs, oven dried at 60°C for 48 hours and dry weights determined. A similar procedure was followed for the legume crop parts. Dry grain and stover/straw yield were calculated from fresh weight and moisture content.

Assessment of the rate of residue disappearance

The disappearance of CR at the soil surface was determined in both RT and CT systems in the maize-legume system, in the minus N plus P treatments. The selected plots had received CR seasonally at 2 t ha^{-1} since beginning of the experiment in 2003. Four litterbags of 5 mm mesh size, containing 50 g (dry weight) of maize stover were placed on the soil surface in each plot at the beginning of the March-August 2007 cropping season. The litterbags allowed soil macro- and meso-fauna, mainly termites, to access CR. One of the litterbags was retrieved from each plot at 4, 7, 11 and 15 weeks after planting. Crop residues recovered from the litterbags were carefully washed with water to remove soil, oven dried at 105°C for 48 hours and resulting dry weight determined. The loss of CR from the litterbags is here termed 'disappearance'.

Available soil phosphorus

At the end of the eighth season, soil samples were taken from 0-15 cm depth, at 5 points in each tillage x CR x cropping system plot in each replicate, mixed well, and a subsample was taken for analysis. The samples were air dried to constant weight before analysis for available P. The analysis, done at ICRAF laboratories in Nairobi, was based on a modified Olsen extractant (0.5 $\underline{M}$ $NaHCO_3$ + 0.01 $\underline{M}$ EDTA, pH 8.5) according to ICRAF laboratory protocol (ICRAF 1995).

Crop water productivity

Experimental data for the first eight (8) seasons were used to calculate CWP using dry grain yield as the numerator, and (1) in-season rainfall and (2) pre-sowing (30 days before planting) plus in-season rainfall received as the denominator (Rockstrom et al. 2003). In both analyses, rainfall received during the last two weeks before harvest was not included as this was taken as not contributing to crop water use since the crop had already senesced. Pre-sowing rainfall can be preserved within the soil profile and contribute to CWP, as demonstrated using pre-sowing irrigation by Li et al. (2001). The statistical analysis was done using mixed model procedure of SAS version 9.1 statistical software for Windows to derive least square means. Regressions of yield and seasonal rainfall did not include season 6 which had drought.

Results

Crop water productivity for maize varied from 0.1 kg/m^3 in the driest season (season 6) to 0.8 kg m^{-3} in season three, a moderate rainfall season (Table 2). There was no significant effect of tillage on CWP in any season. However, there was a consistent trend for higher CWP for maize with CT than RT within respective CR treatments in both cropping systems except in the drought year. There was also a consistent trend for lower CWP in RT-CR than RT+CR in the continuous maize, but the differences were never significant. There was no such trend in the maize-legume rotation. There were no differences in the productivity between RT plus CR and CT±CR in the continuous maize cropping system; however RT minus CR had lower productivity ($P<0.05$) than CT±CR during seasons 2 (the season of lowest rainfall) and 5 (which had intra-season drought between 84 and 120 days after planting when only 40 millimeters rainfall was received).

For the maize-legume rotation, maize CWP was lower ($P<0.05$) in at least one of the RT treatments than in CT during the initial 4 seasons, but with no further significant differences thereafter. Also, maize rainwater productivity for maize grown in rotation with soybean was in the same range as that grown in continuous maize system, despite the fact that fertilizer N was added only in the latter cropping system. The significantly lower CWP in CR treatments during the first season is interesting; since no N had been applied, and there was no biological N fixation benefit from a previous crop during this season; CR application likely immobilized available plant soil nutrients and thus reduced crop growth. Taking pre-season rainfall into account decreased CWP for maize.

Soybean grain CWP averaged over the first 8 seasons of experimentation ranged from 0.18 to 0.20 kg m^{-3} across the 4 tillage x CR treatments (Figure 2). There were no significant differences in the productivity among the tillage or CR treatments for the 8-season average, or in any of the 8 seasons.

Table 2. Effect of tillage and crop residue management on maize grain rain water productivity (CWP) in continuous maize and soybean-maize rotation systems in different seasons (March 2003 to January 2007) in Nyabeda, western Kenya

Tillage	Season 1	Season 2	Season 3	Season 4	Season 5	Season 6	Season 7	Season 8
	CWP[1] (kg m^{-3}) in-season rainfall							
	Continuous maize grain							
RT-CR	0.40 a	0.54 b	0.78 a	0.60 a	0.64 b	0.06 a	0.40 a	0.42 a
RT+CR	0.51 a	0.69ab	0.84 a	0.60 a	0.78ab	0.13 a	0.37 a	0.42 a
CT-CR	0.49 a	0.71ab	0.93 a	0.74 a	0.98 a	0.10 a	0.44 a	0.43 a
CT+CR	0.51 a	0.82 a	0.91 a	0.75 a	0.89ab	0.06 a	0.44 a	0.49 a
SE	*0.041*	*0.074*	*0.120*	*0.067*	*0.085*	*0.042*	*0.042*	*0.055*
	Rotation maize grain							
RT-CR	0.42a	0.45 b	0.75ab	0.56 b	0.76 a	0.04 a	0.30 a	0.45 a
RT+CR	0.33b	0.60ab	0.64 b	0.53 b	0.73 a	0.05 a	0.30 a	0.45 a
CT-CR	0.45a	0.73 a	0.87 a	0.87 a	0.96 a	0.09 a	0.33 a	0.49 a
CT+CR	0.34b	0.69 a	0.78ab	0.77ab	0.92 a	0.06 a	0.36 a	0.52 a
SE	*0.031*	*0.067*	*0.060*	*0.094*	*0.083*	*0.023*	*0.028*	*0.029*
	CWP[2] (kg m^{-3}) in-season plus pre-season rainfall							
	Continuous maize grain							
RT-CR	0.40 a	0.39 b	0.72 a	0.53 a	0.50 b	0.05 a	0.32 a	0.40 a
RT+CR	0.51 a	0.49ab	0.77 a	0.53 a	0.61ab	0.10 a	0.29 a	0.40 a
CT-CR	0.49 a	0.50ab	0.86 a	0.65 a	0.77 a	0.08 a	0.34 a	0.41 a
CT+CR	0.51 a	0.58 a	0.84 a	0.66 a	0.70ab	0.05 a	0.34 a	0.47 a
SE	*0.041*	*0.053*	*0.111*	*0.059*	*0.066*	*0.033*	*0.033*	*0.052*
	Rotation maize grain CWP[2]							
RT-CR	0.42a	0.32 b	0.69ab	0.50 b	0.59 a	0.03 a	0.23 a	0.42 a
RT+CR	0.33b	0.43ab	0.59 b	0.47 b	0.57 a	0.04 a	0.23 a	0.42 a
CT-CR	0.45a	0.52 a	0.80 a	0.77 a	0.75 a	0.07 a	0.26 a	0.46 a
CT+CR	0.34b	0.49 a	0.72ab	0.69ab	0.72 a	0.04 a	0.28 a	0.49 a
SE	*0.031*	*0.047*	*0.055*	*0.083*	*0.065*	*0.018*	*0.022*	*0.027*

[1] calculated using in-season rainfall from planting to maturity

[2] calculated using seasonal and pre-season (one month) rainfall; there was an extended dry season prior to sowing in the first season, so no differences in the two CWP determinations

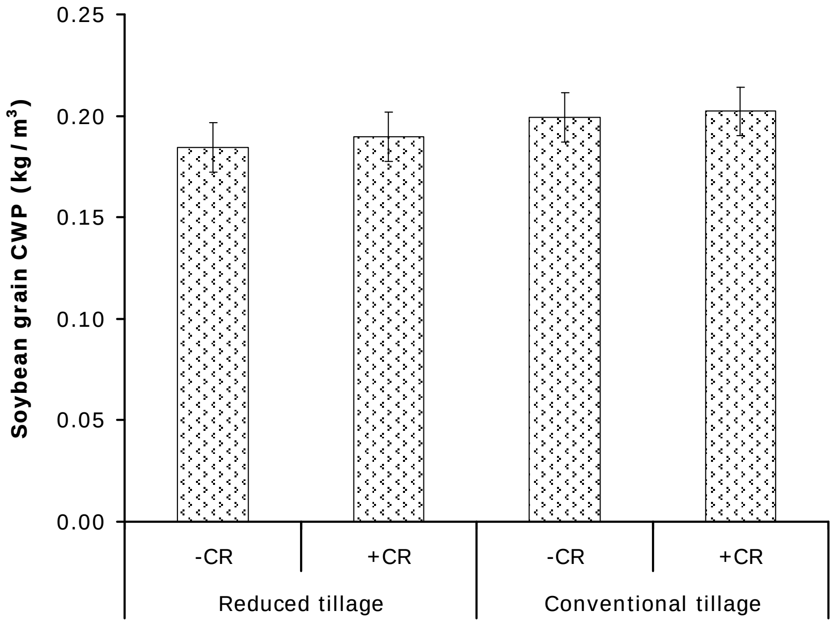
Data in the same column followed by the same letter are not significantly different

RT=reduced tillage, CT=conventional tillage

SE=standard error of means,

60 kg N ha^{-1} was applied to each crop in continuous maize cropping system treatments, but no N was applied in the maize-legume system.

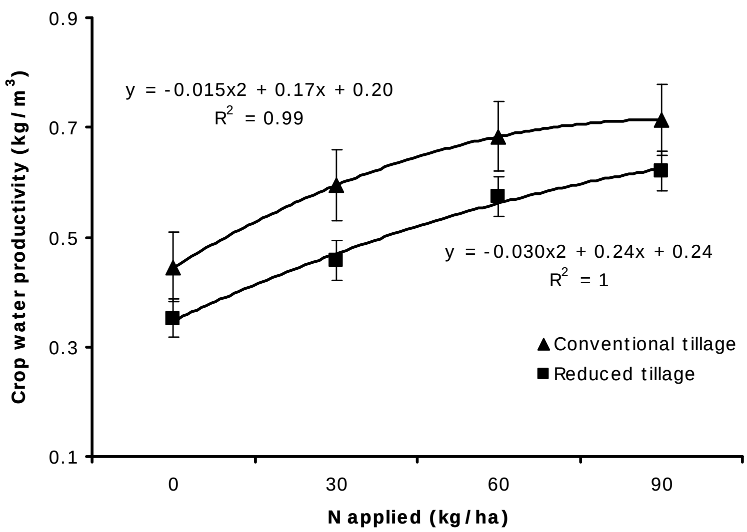
Figure 2. Effect of tillage and crop residue management on soybean grain rain water productivity (CWP) in soybean-maize rotation systems over 8 seasons (March 2003 to January 2007) in Nyabeda, western Kenya, bars are lsd (p=0.05)



Fertilizer nitrogen and phosphorus

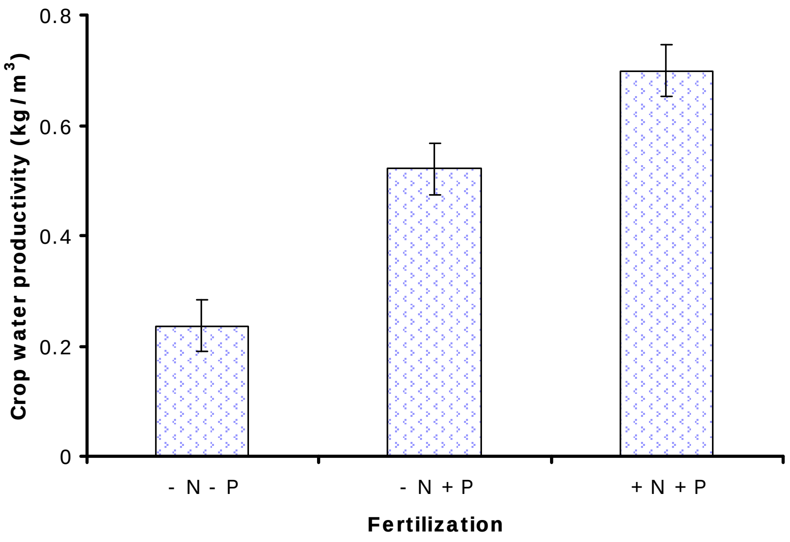
Averaged over the eight seasons, maize CWP in continuous maize increased with fertilizer N application (Figure 3). The increase was significant at N rates up to 60 kg N ha^{-1} for RT and up to 30 kg N ha^{-1} for CT. As reported earlier, CWP for maize was always increased in CT compared to RT regardless of the fertilizer application rate.

Figure 3. Effect of N fertilizer on maize grain rain water productivity from continuous maize cropping system under two tillage practices averaged over 8 seasons in Nyabeda, western Kenya, bars are lsd (p=0.05)



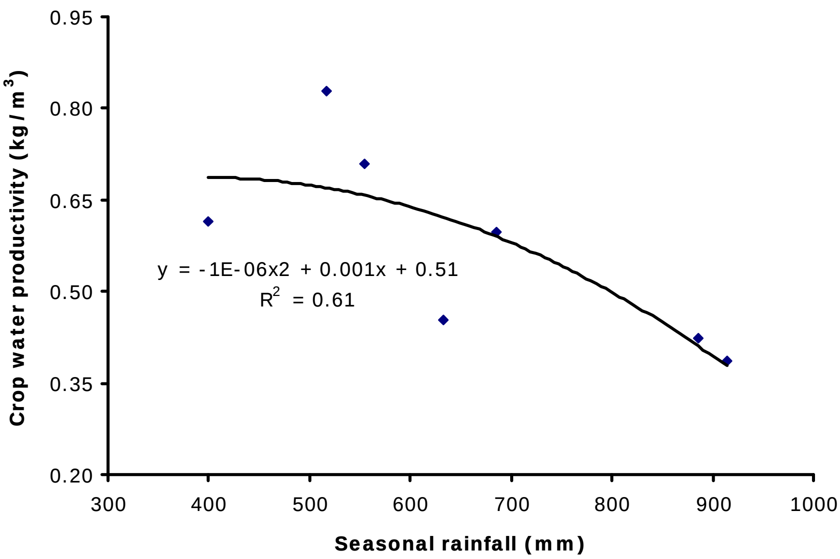
In the maize-legume system, application of P more than doubled CWP (increase of 120%) over the no input control (-N-P), while addition of N with P increased productivity by another 34% (Figure 4). The same case was observed under continuous maize where P increased CWP by 129% and addition of N with P increased CWP by a further 20% (data not presented).

Figure 4. Effect of N and P fertilizers on average maize rain water productivity in a maize-legume rotation in Nyabeda, western Kenya, bars are lsd (reduced tillage only is shown; data are average for 8 seasons)



Seasonal rainfall had a significant effect on maize CWP in both cropping systems ($p<0.01$; data not shown), and CWP decreased with increasing rainfall (Figure 5). The decrease in CWP with rainfall is probably due to greater non-consumptive rainwater losses during higher rainfall seasons.

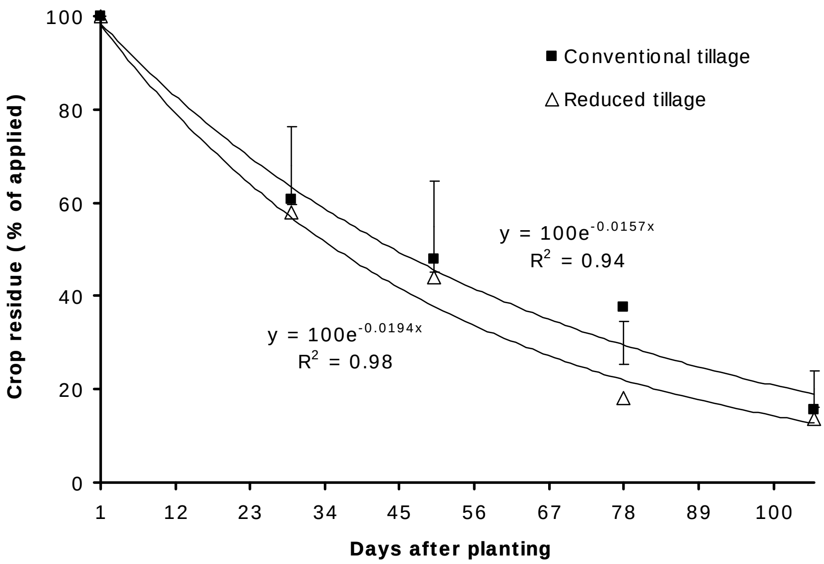
Figure 5. Maize crop water productivity as affected by rainfall in Nyabeda, western Kenya in continuous maize under reduced tillage for the period March 2003 to January 2007



Crop residue

Crop residue disappearance was fast, with almost half gone after 4 weeks, and 85% disappearance in 3.5 months (Figure 6). The residue disappearance rate was similar for both CT and RT except at 11 weeks after planting when there was significantly less residue remaining in RT. The increased rate of residue loss in RT relative to CT may be an indication of increased activity of soil macro- and meso-fauna following changed micro-environment in RT. The generally fast residue disappearance rates in the study site are attributed to a high activity of macro- and meso-fauna, specifically termites.

Figure 6. Disappearance of surface-placed crop residue in tillage treatments as measured during long rainy season 2007 in Nyabeda, western Kenya. Vertical bars are LSD for comparing residue disappearance in the two tillage systems.



Surface CR application with RT increased yield over RT without CR in all seasons except the wettest season which received 986 mm (Figure 7). There was a strong linear inverse relationship between the yield increase due to CR and rainfall. In contrast, there was no effect of residue incorporation on productivity of maize in CT plots in any of the two cropping systems (Table 3).

Figure 7. Maize (grain) yield advantage of crop residue application over no crop residue treatments in reduced tillage in continuous maize at different rainfall amounts at Nyabeda, western Kenya, March 2003 to January 2007.

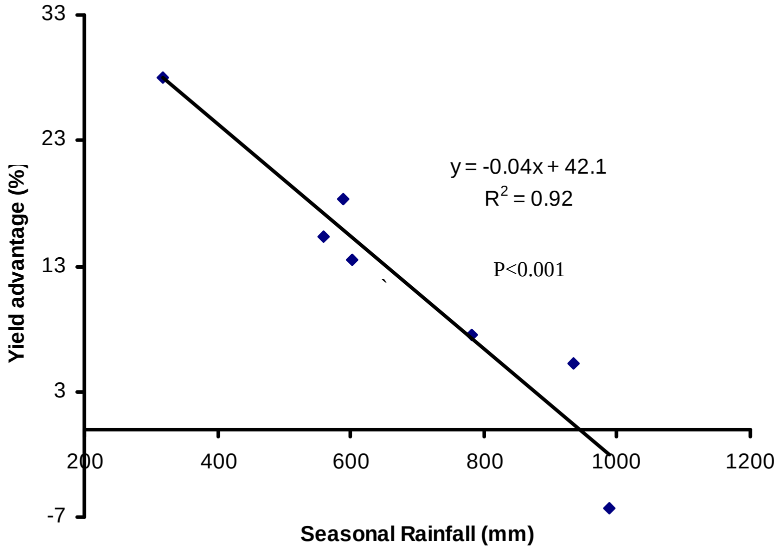
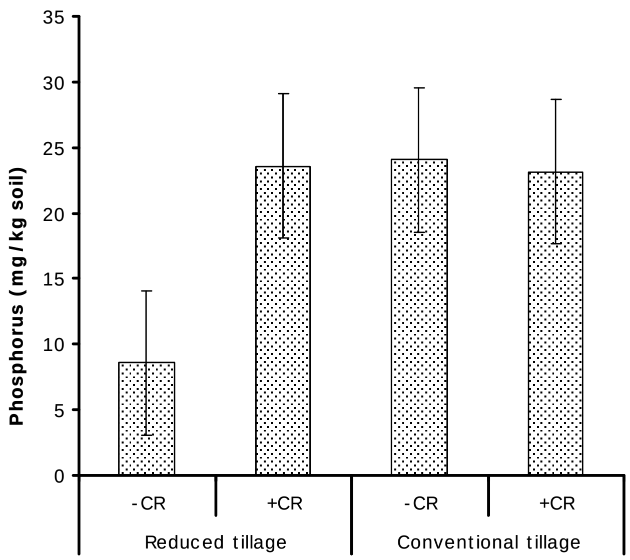


Table 3. Regression coefficients of maize yield advantage of crop residue application over no crop residue treatments versus seasonal rainfall at Nyabeda, western Kenya, March 2003 to January 2007

Tillage	Cropping system	Correlation coefficient (R^2)	Linear regression	P
Reduced tillage	Continuous	-0.92	y = -0.045x + 42.12	<0.001
	Rotation	-0.68	y = -0. 090x + 73.39	<0.05
Conventional tillage	Continuous	0.02	y = 0.004x - 4.07	NS (P=0.87)
	Rotation	0.07	y = 0.038x - 1.28	NS (P=0.75)

Available P concentration was only 8.6 mg P kg^{-1} soil in RT minus CR, significantly lower than the 23 to 24 mg P kg^{-1} soil observed in RT plus CR and in CT treatments (P<0.05; Figure 8). With CR application, P in RT was similar to that in the CT treatments.

Figure 8. Effect of tillage practice and crop residue on available P at 0-15 cm soil depth in Nyabeda, western Kenya as observed in March 2007; -CR= no crop residue, +CR= plus crop residue, bars are lsd



Discussions

Tillage

Crop water productivity was used as a measure of efficiency of utilization of applied (rain) water. Crop water productivity tended to be higher in CT than RT, more so during the first 5 seasons, but with few statistically significant differences. This may have been due to greater water percolation in the soil matrix following loosening of surface by tillage. Such loosening could also increase water storage in the root zone (Bouman 2007). Perhaps the large macropores that act as water conduits in RT (Olaoye 2002) were not yet sufficiently developed for water infiltration, and surface crusting was visually observed in the RT system. Even though greater soil-water evaporation is expected from the loosened CT plots than in RT, such evaporation may be small relative to the greater amount of rainwater that infiltrated in CT than in RT. The similar CWP of the tillage systems after the fifth season in both cropping systems could indicate progressive improvement in RT with time (e.g., in soil structure and microbial activity). Such progression could ultimately result in greater productivity in RT than CT (Ozpinar and Cay 2005; Six et al. 2002) but after more than the 4 years of our experimentation. An alternative explanation can be that, except for the crop failure season 6, water was not limiting (e.g for the last two seasons where rainfall was over 900 mm and well distributed) in any of the tillage practices during those last seasons. Thus, to confirm these findings, further assessments are necessary so that the CWP in the two tillage systems can be compared for a range of rainfall seasons.

Crop residue

Surface CR protects soil from erosion and surface evaporation (Lal 1974), promotes infiltration of water into the root zone and adds nutrients to the soil when mineralized (Wang *et al.* 2006). In the RT system, for example, the surface residue is known to benefit crop plants by reducing runoff and thus loss of nutrients (Erenstein 2003; Russell 1991), and several studies have reported positive effects on yield following such residue application (Doran et al. 1983; Erenstein 2003; Lal 1974). In our site there was a consistent trend for higher yield following surface mulching with CR in RT in continuous maize, especially at low rainfall, although the differences were never significant. This shows that even with application of only moderate amount of CR, CWP is increased and this could cushion farmers against low yields during seasons of low rainfall. The positive effects due to CR in the RT practice is partly attributable to reduced nutrient losses in runoff, the most likely reason for higher available P in RT with CR compared with RT without CR, as also reported elsewhere (Andraski *et al.* 2003). In other words, loss of P in runoff could be partly responsible for the lower CWP in RT minus CR than in the other treatments. But the short residue residence time due to fast comminution by soil macro- and meso-fauna could decrease CWP, especially within RT where also surface crusting commonly occurred, resulting in increased surface runoff. The residue disappearance rate was fast compared to 50% disappearance over 4 months during summer in Zimbabwe (Nhamo 2007) and 60% disappearance of millet straw over 6 months in Burkina Faso (Mando and Brussard 1999), but slower than the 85% over 2.5 months reported for irrigated millet straw in Niger (Fatondji 2002). A combination of warm and sub-humid conditions in our case could lead to the fast residue disappearance due to effects on population and activity of soil macro- and meso-fauna involved in breaking down the residues into debris, and which differ from site to site. Increasing the amount of surface residue to more than the 2 t ha^{-1} used in our study could increase its residence time and reduce non-productive outflows such as through runoff and thus increase CWP in RT. The other approach to increase rainwater infiltration into the root zone for RT is subsoiling and ripping (Bouman 2007).

We suspect that the somewhat low response under CT to residue retention was due to some nutrient immobilization (Blaise and Ravindran 2003; Jensen 1997) as the residue was low quality maize stover, and due to increased soil evaporation as a result of tillage. Indeed, the results showed that application of CR without also applying mineral fertilizer N is not appropriate as this resulted in lower CWP as observed for the maize-legume system during season 1. For both tillage practices, leaving whole (un-chopped) CR as a surface mulch and ensuring limited incorporation during tillage operations could be a good practice.

Crop rotation

Legume-cereal rotation usually results in substantial rotational benefits to the cereal crop. The similar maize CWP of maize grown without N fertilizer in rotation with soybean and maize grown under continuous maize system indicate that maize benefited from the having a legume in the rotation. One of the main benefits would have been biological fixation of N in the soybean phase. There may also have been differences in residual soil water content at harvest of the maize or soybean, affecting water availability at time of planting the subsequent maize crop. In our case, soybean achieved earlier and greater soil cover than maize, and could thus suppress soil evaporation relative to maize, which may help explain why CWP of soybean was similar in RT with and without mulching. Given the similar soybean CWP in RT and CT and the large additional benefits (e.g. reduced labor, environmental) of reduced tillage (Landers 2008), soybean is better grown under RT than CT in this environment.

Fertilizer nitrogen and phosphorus

Nitrogen and P have been identified as the main nutrients limiting crop production in several parts of Africa (Schlecht et al. 2007), and their application led to much greater crop productivity in our experiment. There are many reports of higher yield due to fertilizer application (Fapohunda and Hossain 1990; Fatondji 2002). Thus in order to increase CWP, addressing crop nutrient limitations through appropriate fertilizer application is major prerequisite. As the quality of water outflows from agricultural fields is also of concern (FAO-AGL 2002), fertilizer application should be optimal and, at the present state of maize production in western Kenya, our data suggest that N application should not exceed 60 kg N ha^{-1}.

Seasonal rainfall

Crop water productivity was generally low and reflects the low crop productivity in many parts of sub-Saharan Africa. Greatest CWP was observed for seasonal rainfall between 400 and 700 millimeters, with a large decline in CWP when rainfall was around 900 mm. Thus to increase productive rain water utilization by crops during seasons when rainfall is not the limiting factor, more effort is needed focusing on strategies such as genetic improvement of the crop itself (Bouman 2007) or addressing other limitations such as soil fertility. Crop water productivity during seasons of highest rainfall was similar to that of 0.40 and 0.55 kg m^{-3} irrigation water productivity observed for irrigated maize in Tanzania (Igbadun et al. 2006). The lower CWP during season 6 than during season 2 (both had similar total seasonal rainfall) indicates the importance of seasonal distribution of the rainfall and points to the need for targeted supplemental irrigation during intra-season or end of season drought spells. Also, with reliable weather forecasting, short-duration drought tolerant varieties could be used during such a dry season.

Conclusions and recommendations

In the continuous maize cropping systems, CWP tended to be lower with reduced tillage (RT) than conventional tillage (CT) for the first few seasons, and reached similar CWP after about 5 seasons. Reduced tillage plus mulching with maize residues (CR) also lead to higher CWP of maize than without CR. CWP of soybean was similar regardless of tillage treatment and residue management. Crop water productivity of maize increased significantly with N application up to 60 kg ha^{-1}, with RT and 30 kg ha^{-1} with CT, in the continuous maize system. Crop water productivity decreases with increased seasonal rainfall beyond about 700 mm, and this shows the need for identifying and overcoming constraints to higher productivity. Maximum CWP was achieved by using N and P fertilizers in combination. The results suggest that continuous maize and maize-legume cropping systems have similar maize CWP in the short to medium term. They also suggest that fertilizer N for maize can be greatly reduced if grown in rotation with soybeans, but that some N should be applied at maize sowing if mulching with CR.

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Rainfed conservation agricultural systems in the Yellow River Basin, China

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Abstract

The agricultural sector of the Yellow River Basin (YRB) plays an important role in national food security. It contains 15.3 million hectares of cultivated land, representing about 12.4% of the total cultivated land in China. Some 63% of the cultivated land of the YRB lies in central portion of the Basin and most of it can be characterized as dry, rainfed, farming systems. In the YRB, the main dryland food grain crops are wheat, maize and millet, and the main cash crops are cotton, oil seeds (peanut, sesame and rape), tubers, fruit (notably apple) and sugar beet. Typically, one crop is grown per year in the upper and central regions, whereas in the downstream areas in Henan and Shandong Provinces two crops per year are common, with the main rotations being wheat-maize, wheat-soybean and wheat-potato. Soil erosion, poverty and water shortages are three major problems that constrain the development of agriculture in the YRB. Severe soil erosion is leading to loss of the most fertile topsoil and decreasing soil productivity, particularly evident in dry and sloping lands associated with rainfed agriculture where rural poverty is also widespread. Water use efficiency is generally quite low in rainfed agriculture in the Basin due to high evaporation rates and runoff. Conservation agriculture (CA) is the most promising option for sustainable agriculture in the YRB. Not only does CA generate immediate benefits in terms of increased farm productivity, it also offers social benefits of great relevance to YRB. Results from Shouyang County in 2007 and 2008 show that no tillage and reduced tillage can increase soil water availability and soil organic carbon (SOC stocks). Straw retention in tilled and no till systems significantly increased grain yield in both years, however yields with tillage were significantly higher than no-till, both with and without residue retention, and the reasons for this require further investigation.

Key words

rainfed farming system; agricultural research; No-till; stubble mulch; water productivity; soil and water conservation

Introduction

The Yellow River Basin (YRB) is the birthplace of Chinese civilization. The Basin is situated in Central China, between latitudes 32°- 42°N and longitudes 96°- 119°E. It has a catchment area of 795,125 km^2 stretching from the Bayankala Mountain in the west to the Bohai Sea in the east, and from the Yinshan Mountain in the north to the Qinling Mountain in the south. The Yellow River originates in the west on the border of Qinghai and Sichuan Provinces and flows through Gansu, Ningxia and Inner Mongolia, along the boundaries of Shanxi and Shaanxi, and finally through Henan and Shandong Provinces before it empties into the Bohai Sea.

The Basin has a fairly rugged topography. About 80% has an elevation less than 2500m; approximately 75% of the basin is covered with mountains and hills, while plain areas account for only 17%. Most of the YRB is arid and semiarid: the annual average precipitation is 466mm, and most falls in the 7 monsoon months from April to October (and the 4 months from June to September account for more than 60% of annual precipitation). Precipitation varies greatly within and between years. Severe flood and drought occur frequently in the Basin. Soil erosion, poverty and water shortage are three major problems that affect the development of agriculture in the YRB. Severe soil erosion removes the most fertile topsoil and leads to decreasing soil productivity and sedimentation in the river bed which exacerbates flooding in the lower reaches. Erosion is particularly prevalent in the sloping drylands, the principal location of rainfed agriculture. The incidence of poverty (defined as income of less than 1,067 Yuan per capita per annum) was over 20% in the YRB in 2007 (Wong Shiyou and Wang Biqiang 2008), which amounts to approximately 70 million people. Agriculture is generally the main source of income for households in this region; therefore, increasing agricultural system productivity and water use efficiency is urgently needed to improve farmers' livelihoods.

Following the classification of the Ministry of Land and Resources, arable land can be divided into irrigated paddy, rainfed paddy, irrigable fields, rainfed fields and vegetable fields (see Table 1). Irrigable and rainfed fields account for 34% and 62% respectively of the total arable land in the YRB. The irrigated paddy is for wetland crops such as rice or lotus, and can be irrigated when needed. The rainfed paddy is still for wetland crops, but lacks irrigation facilities and so crop production depends on rainfall. In the irrigable fields water supply channels are well established, and irrigated or rainfed crops, including maize and wheat, can be cultivated. Rainfed fields lack irrigation infrastructure and are used for rainfed crops only, including maize and wheat. Vegetables, including melon, cabbage and carrot, are planted in the vegetable fields.

In the YRB farming systems the main crops are wheat, maize, millet, potato, oil plants and cotton. The cropping intensity depends on the climate, varying from one crop per year, to three crops per two years and two crops per year. Pasture/cropping ecotone regions predominate in the upper region of the YRB, such as between Xining and Lanzhou, Ningxia and Inner Mongolia, where only one crop per year is possible. In the middle region, such as the northern part of the Wei River Basin and the valley area of Wei-Fen River Basin, three crops can be cultivated in two years due to greater water availability and solar radiation. In the irrigated regions of the lower YRB, such as the southeastern plain of Shandong and Henan, two crops per year are common (Liu Xunhao 2005). Thus, the cropping index in the southern plain of Shandong, Henan and part of Shaanxi, which has fertile soil and abundant water resources, can be as high as 140~170%, in contrast to the cold dry north of Inner Mongolia and parts of Shaanxi and Shanxi Provinces where the cropping index tends to be below 80%.

Table1. Provinces and arable land in the YRB

Provinces in YRB	Total counties	Counties in YRB	Irrigated paddy (1,000ha)	Rainfed paddy (1,000ha)	Irrigable field (1,000ha)	Rainfed field (1,000ha)	Vegetable field (1,000ha)
Shanxi	119	82	11	0.1	868	3183	20.1
Inner Mongolia	118	30	81	0.4	1714	5257	47.8
Shandong	139	30	130	0.8	4341	2872	174.9
Henan	158	46	646	50.7	3093	4055	81.2
Shaanxi	107	74	173	22.9	870	3006	17.8
Gansu	86	54	11	2.4	1004	3642	8.0
Qinghai	43	33	0	0.0	177	357	8.4
Ningxia	23	19	45	0.0	353	699	3.2
Total	793	368	1,096	77	12,419	23,072	361

Note: 2005 data from Ministry of Land and Resource, P. R. China. Six counties in Sichuan are not included in the table, because of very little arable land in these counties. The three categories of fields are sown to non-rice crops.

Conservation agriculture in the YRB

One of the most promising options for sustainable agriculture, if not the only option in the long term, is Conservation Agriculture (CA), which offers an approach of integrated farming systems improvement. It is characterized by the following basic principles:

- reduction in tillage, with the ultimate goal of no-till seeding systems that normally disturb only a small fraction of the soil surface, reducing carbon loss and physical deterioration of soils;
- crop residue retention on the soil surface, with the ultimate goal of protecting the soil from water and wind erosion, reducing run-off and evaporation and enhancing soil fertility, in the long term of improving soil health;
- effective crop rotations with the ultimate goal of creating viable, diversified crop rotations to foster weed, disease and pest control and improved soil health; and
- annual economic benefits, with the ultimate goal of reliable farm household food security and livelihoods, reduced production costs, increased economic productivity and reduced production risk.

In recent years, the Chinese government implemented a series of policy and economic measures to promote the adaptation and extension of CA in the YRB. Since 2002, the Ministry of Agriculture (MOA) has established 59 CA demonstration counties to extend CA, including five counties in which the CPWF project also operates (Table 2). With significant subsidies for CA machinery and support for CA training, it is estimated that components of CA have been adopted at a rate of about 3,300 hectares of arable land per CA demonstration county per year up until 2007 (authors' estimates). In general, CA was adopted faster in irrigated land, especially under summer maize-winter wheat rotations. Because of different climate, soil, landform, farming system, and level of rural economic development, the experience with the development and impact of CA varies widely across the YRB (Yan Changrong 2006).

Table 2. CA pilot counties in YRB, 2002-2007

Province	County name	Number of counties
Shanxi	Zuoyun, Pianguan, ***Shouyang****, Changzi, Xiaoyi, Tunliu, Xiyang, Xiangfen	8
Inner Mongolia	Liangcheng, Wuchuan, Yijinhuoluoqi, Dongsheng, Guyang, Chayouzhongqi ***Qingshuihe****	7
Shaanxi	Shenmu, Dingbian, Tongchuan, Pucheng, Heyang, Binxian, Fuping, Henshan, Longxian, Jingbian, Huangling, Hancheng, QIanxian, Qianyang, Chengcheng	15
Gansu	Xifeng, Gangu , Yuzhong, Jingchuan, Ningxian, Lingtai	6
Ningxia	Pingluo, Lingwu, Yanchi, Zhongwei ***Pengyang****	5
Qinghai	Huangzhong, Xinghai, Huzhu, Datong, Pingan, Huangyuan	6
Henan	Yanshi, Puyang, Huaxian, Boai, Junxian, Wushe, ***Luolong****, Xiuwu	8
Shandong	Huiming, ***Zhangqiu****, Gaoqing, Yanggu	4
Total		59

Note: * CPWF project also operates in this county

The characteristics of traditional and improved farming systems vary across the YRB. In the northern part of the loess plateau in Gansu, Ningxia, Inner Mongolia and Qinghai, Shanxi and Shaanxi Provinces, single cropping of winter wheat or summer maize is common. For improved water and soil conservation CA options of reduced or no-tillage with stubble and straw mulching are being tested. More than 10 cm of standing wheat stubble is left in the field after combine harvesting: the wheat stubble, straw and loose residues amount to 8-10 t/ha and provide soil cover during the fallow period. Sometimes, the stubble and straw are flattened with a stone roller. Before the

Figure 1 Reduced tillage with stubble mulch, Shaanxi, Province

sowing of the subsequent crop, the loose residues are raked into heaps in the tramlines (Figure 1) and 3-4 t/ha of organic fertilizer are broadcast. About 150 kg N and 80 kg P_2O_5 per hectare of inorganic fertilizer are utilized – the P_2O_5 and half the N fertilizer are banded below the seed at sowing, and the remaining N fertilizer is broadcast at flowering. After sowing, the wheat residues in the tramlines are spread across the sown area. After about 3~4 years of this practice the field is subsoiled, the straw is buried and the land is left fallow for one crop season (Wang Zhaohua, 2001).

In the upper region of the YRB, especially the ecotone of agriculture and pastoralism in Inner Mongolia, northwest Gansu and southern Ningxia, only one crop is cultivated per year, commonly wheat, maize, potato or oats. For large scale CA, the key technology is a reduced tillage and strip intercropping system (3.6~8.4 m wide strips) (Figure 2), largely to reduce wind and water erosion. This strip intercropping system involves no-till and stubble retention for oats. In spring, oats are direct seeded (no-till) in the former potato strip, while the former oat strip, with about 20 cm of oat stubble which remains after some oat straw has been collected for feeding, is tilled for sowing potato.

Figure 2. Strip intercropping system after harvesting, Inner Mongolia Province

A novel stone mulching CA technique is used in Ningxia and Gansu Provinces, using stones of about 3~5cm diameter to a depth of about 10 cm. This mulch lasts for about 10 years, allowing farmers to plant cash crops such as melon and vegetables in such stone mulched fields.

The Huanghuahai Plain in Henan and Shandong Provinces is the food bowl of the lower reaches of the YRB, where two crops are cultivated per year, commonly winter wheat and summer maize. Whereas maize residues are removed after harvest before wheat, a subsidy from government has successfully encouraged the use of no-till and direct seeding CA machinery for maize after harvesting wheat. In this system, the harvester leaves about 15 cm of wheat stubble standing in the field and the balance is chopped and spread by a straw chopper at the back of the combine harvester.

Figure3 .Maize harvesting and straw chopping, Shanxi Province

In eastern Shanxi Province and western Henan, one crop per year is the main dryland cropping system; crops include spring maize, oats, millet and potato and common rotations are maize-maize, millet-maize, and less often maize- potato. Maize residue is chopped for mulch during harvesting, allowing no-till seeding (with simultaneous fertilizer application) the following spring. This process is used on about one third of the maize area now in Shanxi Province (Figure 3).

As noted in Table 2, the CPWF project has established CA trials and demonstrations in 5 counties (Zhangqiu County, Shandong Province; Mengjin County, Henan Province; Pengyang County, Ningxia Province; Qingshuihe County, Inner Mongolia; Shouyang County, Shanxi Province) whose locations are shown in Figure 4. These counties were selected to cover a range of rainfall, geographical features and dryland faming systems (Yan Changrong, 2009). In this paper we present results from the site in Shouyang County.

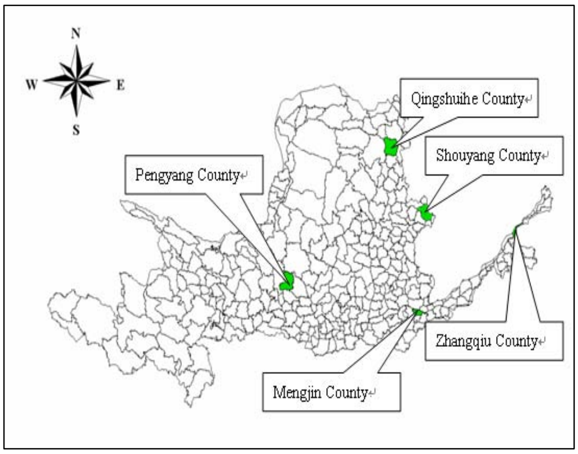


Figure 4. Location of the CA pilot counties, YRB

Performance of CA in Shouyang County pilot site

Site description and trial design

The experimental site is located in Zongai village located at 37º58´N，113º54´E and elevation 1135m, in Shouyang County, Shanxi Province. The climate is warm temperate, and relevant climate data from Shouyang County weather station, 10 km from Zongai village, are summarized in Table 3. Annual precipitation is generally low (350-550 mm) with uneven spatial and temporal distribution, and heavy rainstorms are common. Droughts are very common, in 60 to 80% of years; and the probability of combined spring and summer droughts is 53 to 77%. Precipitation is much lower than potential evapotranspiration. The main crops are maize, millet, buckwheat and soybean, and a typically there is a fallow year between crops. Maize-fallow-maize is a common rotation (Du Jiantao 2008).

Table 3. Key characteristics of climate, Shouyang County weather station

Characteristic	Mean (1961-2005)
Elevation above mean sea level	1200 m
Annual ≥10°C accumulated temperature	2994 °C
Annual average temperature	7.6°C
Lowest temperature ever recorded	-26.6°C
Highest temperature ever recorded	35.5°C
Annual precipitation	491.3mm
Potential evapotranspiration (PET)	850mm
Average frost-free period	151 days
Average total annual sunlight	2518 hours
Average total radiation	128 k cal/cm^2

Brown soil and meadow soil are the dominant soil types in Shouyang County and at the experimental site: the main characteristics of the soil at the experimental site in Zongai Village are shown in Table 4.

Table 4. Key characteristics of soil at the experimental site, Zongai Village, Shouyang County

Bulk density ($g\ cm^{-3}$)	Water holding (%)	SOM (mg/kg)	Total N (mg/kg)	Dissolved P (mg/kg)	Available K (mg/kg)
1.26	27	10.9	0.69	9.6	91.7

Source: Zhou Huaiping (1999)

The trial has been conducted since 2005, with four tillage/residue retention treatments and three replicates on plots of 200 m^2 (Table 5). A fifth treatment (no till, without straw – NTWS) was added in 2008 . Spring maize (Jindan34 bred by Shanxi Academy of Agricultural Sciences) was planted at the end of April each year, at 0.6 m row spacing. After emergence was completed the crop was thinned to 49500 plants/ha in all treatments. The tillage x residue management treatments are described in Table 5. All treatments were sown and fertilized used a human drawn chisel plough. Ammonium polyphosphate (600 kg ha^{-1} – 206 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1}) was banded at a depth of about 10 cm, 5 cm from the seed row, in all treatments. This paper presents detailed results from the 2007 and 2008 maize seasons.

Table 5. Experimental treatments, Zongai Village, Shouyang County

Treatments	Notes
Conventional tillage (CT)	Most residues of the previous maize crop were removed for fodder, leaving 10-15 cm standing stubble on the field after harvest (in October), after which the field was plowed by a tractor drawn plough to 20-25 cm depth, turning the soil over. During spring (in April), the field was harrowed (to 5~8 cm depth) by tractor drawn harrows, just before sowing. A human-drawn chisel planter was used for sowing. At the same time, fertilizer was applied by hand.
Whole stalk return till (ASRT)	All residues (6-7 t/ha) of the previous maize crop were plowed into top 20-25cm soil layer by a tractor drawn plough, shortly after harvest. In spring, the field was harrowed (to 5~8cm depth) by tractor drawn harrows. Sowing and fertilization as for CT.
No tillage with mulching (NTSM)	All residues (6-7 t/ha) of the previous maize crop were flattened and mulched in the field. There was no tillage. Sowing and fertilization as for CT.
One-third residue with rotary till (RRT)	All maize residues were removed after harvest, and about one-third of maize residues (~ 2 t/ha) were chopped and incorporated into the top 15 cm soil layer in autumn using a rotary plow. Sowing and fertilization were performed in spring using a tractor drawn no till planter (a locally produced semi precision planter)
No tillage without straw (NTWS) (new 2008)	All residues of the previous maize crop were removed for fodder, leaving 10-15 cm standing stubble in the field. There was no tillage. Sowing and fertilization as for CT.

Note: Fertilizer application for all treatments was 206 kg N and 90 kg P_2O_5-90 per hectare.

Methods

Weather data

An automatic weather station was established in the trial field in 2005, and rainfall and other weather parameters were measured daily from 2006.

Soil moisture and soil temperature

Gravimetric soil water content was determined every ten days, from planting to harvesting, in 2008. Soil water content was measured in 20 cm layers throughout the profile to a depth of 200 cm. The soil was sampled in each plot with a soil drill on each occasion. Soil temperature was measured at 10, 20 and 40 cm soil depth in all treatments from March 25 to May 10, every 2 days, in 2008.

Soil organic matter (SOM)

Soil organic matter was determined by wet oxidation (Black 1965) and the percentage of organic carbon was calculated by applying the Van Bemmelen factor of 1.73. Soil samples were collected from the 0-10cm soil layer in March 2008 (3 replicates of each treatment, bulked by soil layer).

Crop emergence, yield and water productivity

The number of emerged plants was counted every 2-3 days from the commencement to the end of the emergence. Counts were performed on two 2 m rows in each replicate.

Crop yield was measured on the total plot area in early October each year. Water productivity (WP) was calculated as:

$$WP=\frac{Y}{CWC}$$

where WP represents water productivity (kg/mm/ha), Y is grain yield of maize (kg/ha), and CWC is crop water consumption (mm) during the crop growth period. CWC was calculated from the water balance equation:

$$CWC=P+I-\Delta W-D-R,$$

where P is precipitation during the crop growth period, I is irrigation water application, ΔW is soil water difference between seeding and harvesting; D is percolation loss of water from soil; and R is surface water runoff. There was no irrigation, and the values of D and R can be assumed to be zero in this trial, so the equation reduces to:

$$CWC=P-\Delta W.$$

Statistical analysis

Statistical analysis was performed using SPSS 11.0 for Windows. One-way ANOVA was applied to analyze means and determine the least significant difference.

Results and discussion

The effect of tillage and residue retention on soil water content and temperature

Soil water content was strongly influenced by rainfall (Figure 5) and crop water use. The trends in soil water content for all treatments were similar, however soil water content was generally higher under ASRT. Soil water content was relatively constant from seeding to seedling emergence (Figure 6). At this stage the crop water requirement is limited and the differences in soil moisture mainly stem from treatment effects. Soil drying in NTS and CK was greater than in the other treatments. During the period from July to August there was net soil drying because of high crop water requirement due to both rapid leaf area expansion and high evaporative demand. From early July to mid-August, soil water content dropped to its lowest level. From mid-August, temperature and crop water requirement gradually decreased.

Figure 5. Monthly precipitation (mm), 2007-2008

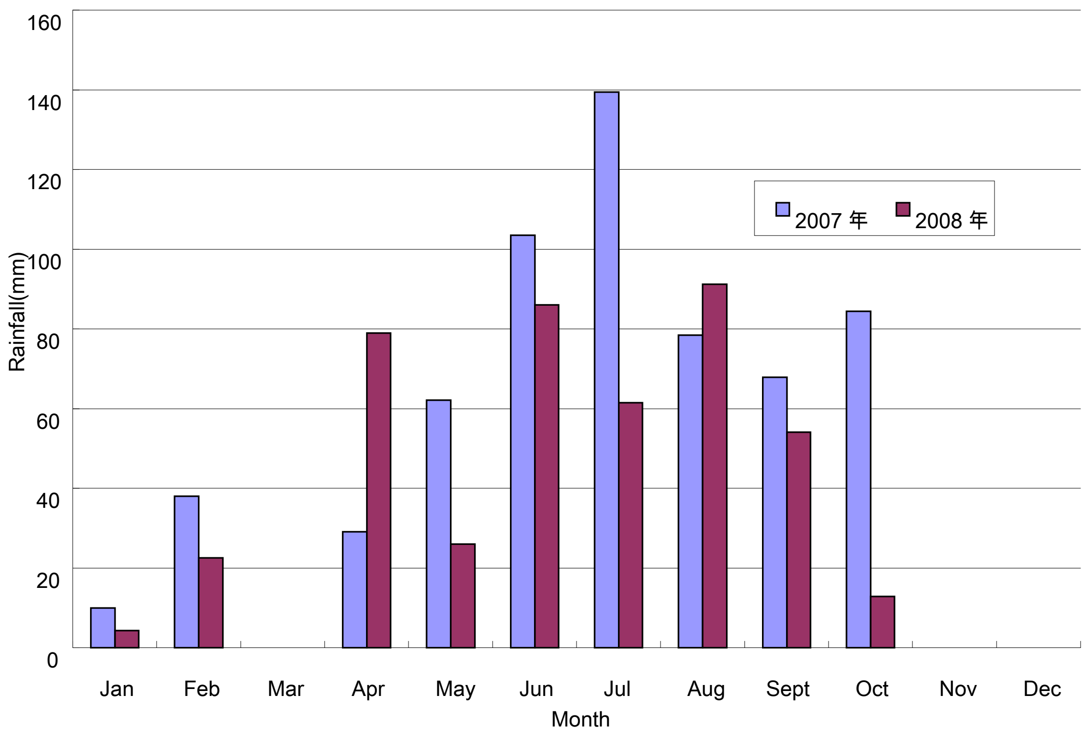
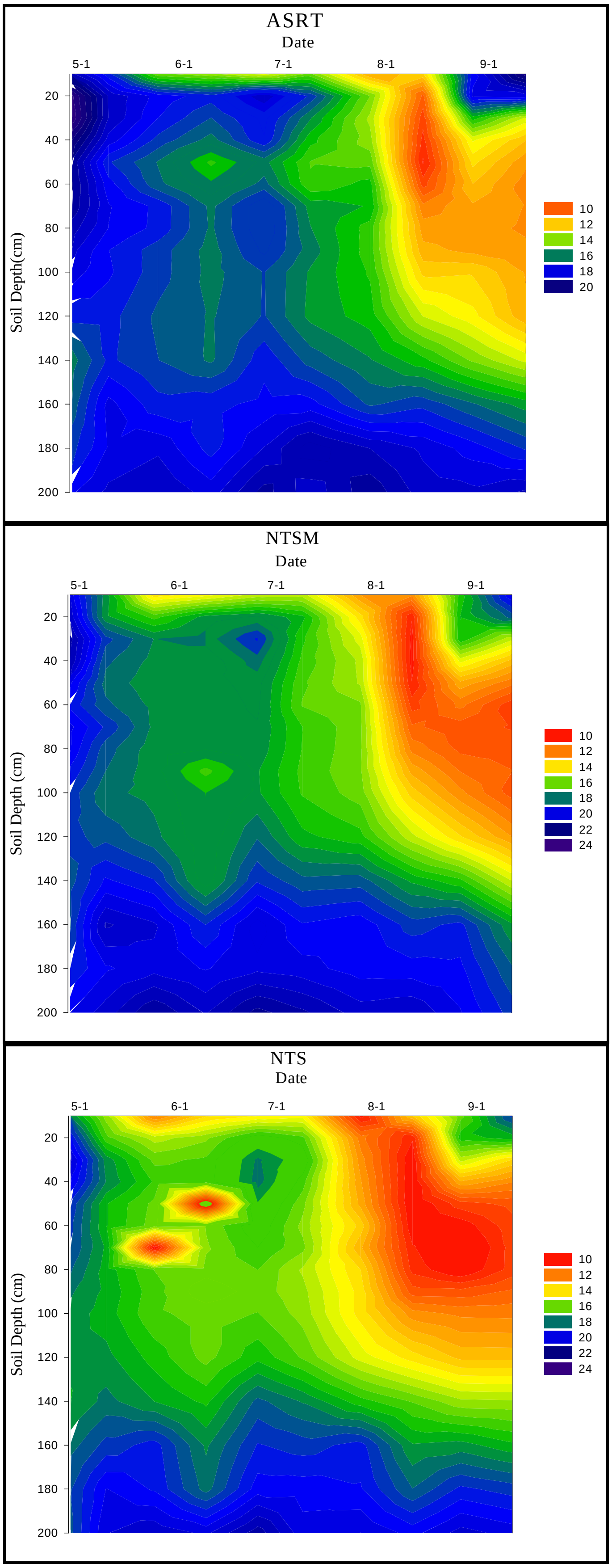


Figure 6 also shows the soil water content at different soil depths. In general, below 160 cm, soil water content maintained a steady state of about 20%. However, soil water content in CT and NTS tended to be lower than in the other treatments. The data suggest that no tillage and mulching can increase soil water content.

Soil temperature is a critical determinant of maize germination, with a threshold value of 10-12^{o}C. Our results show that soil temperature at 10 cm increased over time from April 25, and exceeded the threshold for germination in all treatments on the same date (April 29) (Table 6). However there was a consistent trend for lower soil temperature in NTSM and NTWS at 10 cm than in the other treatments up to May 7, with a larger temperature depression in the mulched treatment (NTSM). There was also a consistent trend for lower soil temperature at 20 cm in NTSM. The results are consistent with many studies showing that mulching decreases soil temperature e.g. Sidhu et al. (2007).

Figure 6. The spatial distribution of soil water content (%) under different tillage and residue treatments in 2008



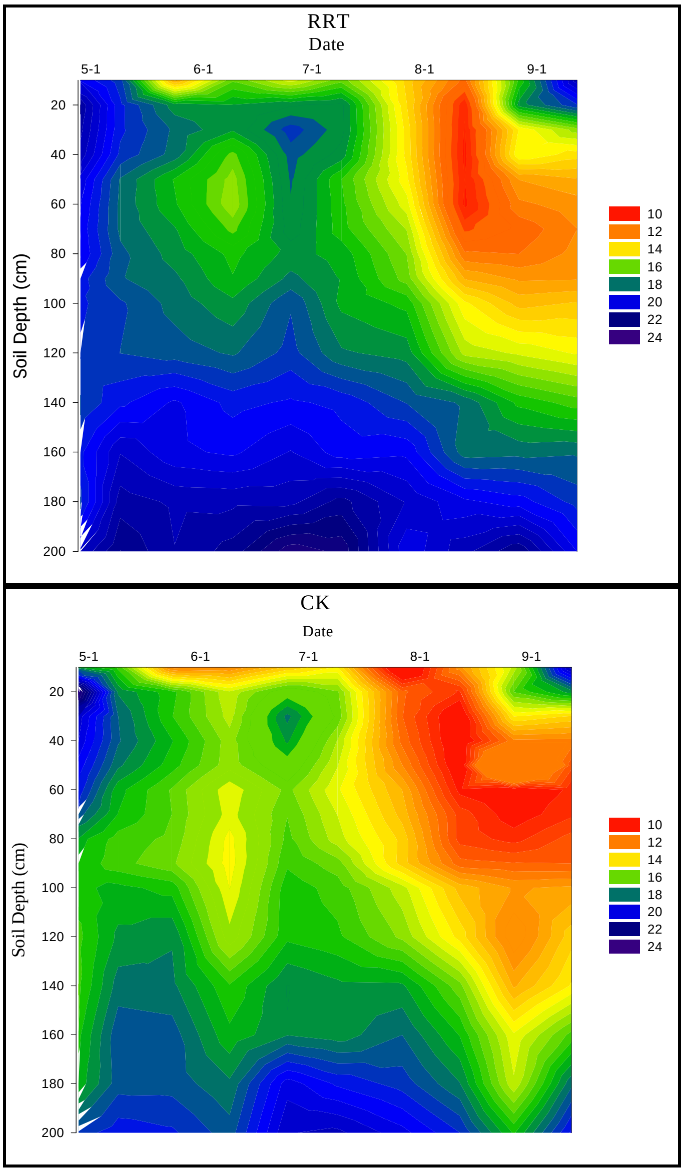
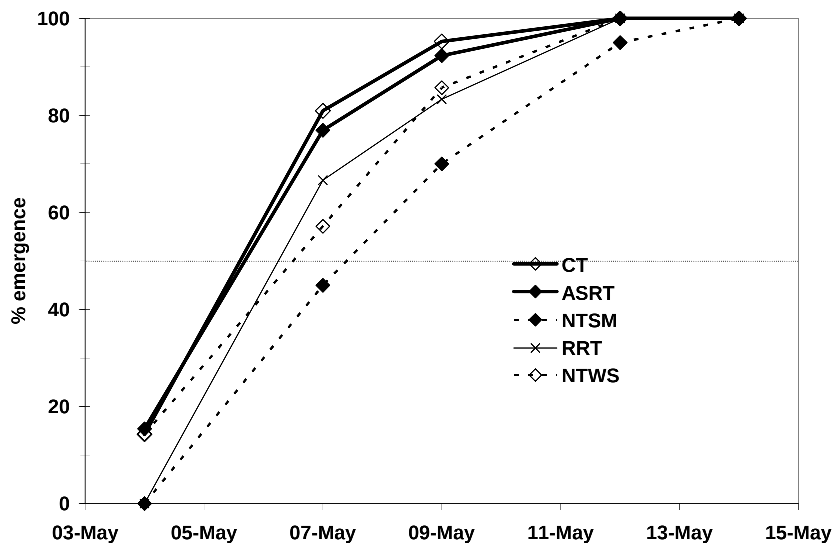


Figure 7 shows that crop establishment was delayed slightly in the no till treatments compared with the tilled treatments. Fifty per cent emergence was delayed by about 1 day in no till in the absence of straw residue (NTWS) compared with conventional tillage (CT) in the absence of straw, and addition of mulch (NTSM) further delayed 50% emergence by one day. There was little effect of residue retention on the rate emergence with straw incorporation (ASRT) compared with CT. These results are consistent with the lower soil temperature in the no till and mulched no till treatments.

Table 6 Soil temperature at different soil depths during the early stage of growth period in 2008

Treatment	Depth (cm)	April 25	April 27	April 29	May 1	May 3	May 5	May 7	May 9
CT	10	9.1	11.9	16.0	17.1	14.1	16.1	17.2	12.3
	20	7.5	9.5	12.7	14.2	13.7	13.0	16.2	12.4
	40	6.8	8.0	10.4	12.0	13.0	11.4	14.6	12.7
ASRT	10	9.3	11.1	15.7	16.2	14.2	15.8	17.1	13.4
	20	7.3	8.6	12.6	13.7	13.6	13.1	16.1	12.9
	40	6.8	8.0	10.3	12.1	13.1	11.6	14.5	13.2
RRT	10	8.4	9.9	13.5	14.3	13.4	13.6	15.8	12.4
	20	6.8	8.1	11.1	12.3	12.8	11.4	14.7	12.0
	40	6.4	7.2	9.2	10.8	11.8	10.5	13.0	11.9
NTSM	10	7.3	9.5	12.8	14.2	13.4	13.2	16.0	12.5
	20	6.2	8.0	10.9	12.5	12.9	11.3	15.1	12.3
	40	5.5	6.8	9.0	10.8	11.9	10.5	13.3	12.1
NTWS	10	8.4	10.3	13.9	15.2	13.1	13.9	16.0	12.5
	20	7.9	9.3	12.6	14.0	14.0	12.9	16.4	13.2
	40	7.7	8.6	10.9	12.6	13.5	12.0	15.0	13.4

Figure 7. The effect of tillage/straw treatments on the rate of crop emergence in 2008



The effect of tillage and residue retention on soil organic carbon

Soil organic carbon (SOC) declined with depth, from at least 10 g/kg in the 0-5 cm layer to around 1 g/kg at 90-100 cm in all treatments (Table 7). However, in the upper layers, SOC differed significantly (P<0.05) among the tillage/residue management treatments four years after the treatments were initiated. In the 0–5cm layer, organic matter content increased with decreasing tillage intensity and residue retention. No tillage with surface mulching had significantly higher SOC in the top 10 cm than all other treatments, including the two tillage treatments with full and partial straw retention (ASRT and RRT, respectively). At 10-20 cm, SOM was lower under NTSM than ASRT or CT. The ASRT and RRT treatments incorporate residues into a larger volume of soil and therefore increase the rate of organic matter decomposition and C mineralization (Salinas-Garcı´a et al., 2002) by increasing the contact between soil microorganisms and crop residues (Henriksen and Breland 2002). Long-term ASRT did not increase the SOC in the 0–20 cm layer in comparison with CT after 4 years (Table 8). The effects were extended to the 20–40 cm depth, where ASRT had higher SOC than all other treatments except RRT and NTSM at 20-30 cm (Table 7). Below 50 cm, the treatments with full straw retention, ASRT and NTSM, had higher SOC than RRT and CT.

Table 7. The effect of tillage/residue management treatment on SOC (g/kg) in the soil profile in 2008 (4 years after the treatments were initiated)

Treatment	CT	ASRT	RRT	NTSM
0-5	10.0 c	11.1 b	12.1 b	15.7 a
5-10	10.6 b	10.4 b	10.2 b	11.9 a
10-20	10.9 a	10.7 a	9.9 c	10.3 b
20-30	6.7 b	9.5 a	9.2 a	9.3 a
30-40	5.7 b	7.5 a	4.6 c	4.9 bc
40-50	4.3 a	4.1 a	4.2 a	3.3 b
50-60	1.6 b	3.1 a	1.5 b	2.5 a
60-70	1.4 b	2.3 a	1.5 b	2.0 a
70-80	1.2 b	1.7 a	1.6 a	1.8 a
80-90	1.1 b	1.7 a	1.3 b	1.8 a
90-100	0.8 b	1.5 a	1.0 b	1.4 a

[1] Values marked with different letter in the same column are significantly different at p=0.05 according to ANOVA

Table 8. Analysis of SOM (g/kg) at 0-20cm and 20-40cm

Soil depth(cm)	Treatment	Average value of SOM	Significantly different at *p*=0.05	Significantly different at *p*=0.01%
0-20	CT	10.5	b	A
	ASRT	10.7	b	A
	RRT	10.7	b	A
	NTSM	12.6	a	A
20-40	CT	6.20	b	A
	ASRT	8.50	a	A
	RRT	6.90	b	A
	NTSM	7.10	ab	A

[1] Values marked with different letter are significantly different

SOC stock has been identified as a good indicator of carbon dynamics under different management systems (Farage et al. 2007). Comparison of horizon and cumulative carbon stocks showed significant ($P<0.05$) effects of the tillage and residue retention treatments. At 0–20 cm, NTSM had significantly ($P<0.05$) higher stocks than all other treatments. At 20-40 cm ASRT had higher SOC stock than other treatments. After 4 years, CT (55.4 Mg C/ha) and RRT (56.4 Mg C/ha) had about 19.5% lower ($P<0.05$) total carbon stocks in the 0–100 cm soil profile than ASRT (65.9 Mg C/ha) and NTSM (67.8 Mg C/ha). These increases in carbon stocks indicate attainable carbon sequestration by converting from conventional tillage to straw return tillage and no tillage systems (Table 9).

Table 9. The spatial distribution and cumulative soil organic carbon stocks after 4 years (Mg C/ha)

Treatment	CT	ASRT	RRT	NTSM
0-10cm	10.7 b	10.2 c	11.0 b	17.4 a
10-20cm	14.0 a	12.7 b	12.4 b	13.4 a
20-30cm	9.0 c	13.2 a	12.2 b	12.7 b
30-40cm	7.6 b	10.4 a	6.2 c	6.7 b
40-50cm	5.9 a	5.6 a	5.5 a	4.5 b
50-60cm	2.2 c	4.1 a	2.0 c	3.4 b
60-70cm	1.8 b	3.1 a	1.9 b	2.7 a
70-80cm	1.6 b	2.3 a	2.2 a	2.5 a
80-90cm	1.5 c	2.3 a	1.7 b	2.5 a
90-100cm	1.2 b	2.0 a	1.3 b	1.9 a
Cumulative stock	55.4 b	65.9 a	56.4 b	67.8 a

Values marked with different letter in the same column are significantly different at p=0.05 according to ANOVA

Grain yield and water productivity (WP)

Grain yield in 2008 was much higher in 2007 than in 2008 in respective treatments. Total precipitation in both years was fairly similar (535 and 509 mm), however precipitation during the growth period of 2007 was higher than that of 2008, while the reverse was true in the fallow period. The higher yields probably reflect higher solar radiation in the drier 2008 growing season, plus the importance of precipitation in the fallow period. Storage of precipitation during the fallow period can provide enough available water for establishment and can diminish the effect of spring drought (Moret et al. 2006).

The tillage and residue management treatments had significant impacts on grain yield and WP, and treatment trends in grain yield were similar each year (Table 10). Yields with no tillage were significantly lower than yields with tillage, in respective treatments with and without straw retention, in both seasons. Residue retention had a significantly positive effect on grain yield for both mulching with no till and plowing into the soil. This is consistent with the findings of Wang and Cai (2000) who reported that straw incorporation out-yielded straw mulching in terms of improvement of water use efficiency and grain yield for spring maize in Shouyang county. ASRT had the highest yield and WP in both seasons.

In maize-wheat systems in Mexico, Govaerts et al. (2007) showed the importance of residue retention on the soil surface in no till systems, where yields declined in the absence of residue retention after the first few years. In other studies, higher yield and water use efficiency (WUE) were also always observed in treatments with no till and stubble mulching in dry years or in normal rainfall years (Eckert 1984; Hussain et al.1999; Su et al. 2007; Patil et al.2006). However, during wet years, yields tended to be lower (10%-15%) with no-till than with conventional tillage in Shouyang County (Wang et al. 2007) due to lower soil temperature and delayed germination and early growth. The frequency of in-season drought in this region is 50%, but there was no drought experienced during the 2007 and 2008 seasons, as rainfall was adequate and well-distributed, and therefore there was no benefit of the mulch in reducing soil water deficit stress. In our study, no till with mulching lowered soil temperature by up to 3^{o}C during the sowing/establishment period, which only slightly delayed crop emergence. Cai et al. (2002) also found that the topsoil temperature under mulch during the seeding period was 2-6^{o}C lower than with stubble removed or incorporated. The effect of delayed emergence on crop performance and yield in this region is not known. Yields were higher in the no till mulched treatments than in the bare no till treatments, while emergence in the mulched treatment was delayed by only about 1 day. Elsewhere, Griffith et al. (1986) found that the lower soil temperature early in the growing season due to mulching delayed germination and growth, and resulted in reduced grain yield. Well drained soils with light to medium texture and low humus content are more suitable for conservation tillage than fine textured and poorly drained soils (Butorac, 1994).

Table 10 . Maize yield (kg/ha) and water productivity (kg/ha/mm)

Year	Treatment	Grain yield (kg/ha)	WP (kg/ha/mm)	Rainfall in fallow period (mm) (1Oct-25Apr.)	Rainfall in growth period (mm) (25Apr-31.Sep)
2007	CT	6830b	13.06	54.4	480.5
	ASRT	7591a	14.97		
	NTSM	6171c	11.56		
	RRT	7042b	13.56		
2008	CT	7740b	15.43	111.2	397.9
	ASRT	8356a	16.40		
	NTSM	7017c	14.19		
	RRT	7675b	15.60		
	NTWS	6081d	12.36		

[1] Values marked with the same letter are not significantly different at p=0.05 within each year

Conclusions

The trial results and analysis confirm that CA is a promising sustainable agriculture option for YRB. No tillage and reduced tillage CA treatments can greatly improve soil moisture and increase SOC stocks which combat land degradation and CO_2 emissions. However, crop yield decreased with no tillage or reduced tillage compared with CT; and the reasons for this are not known and further investigations are needed. Within tillage treatments, crop yield increased with straw retention (incorporation or mulching). In the study area, the higher soil moisture achieved by adoption of appropriate tillage and residue management is critical for the grain yield due to spring drought which occurs frequently, but not in the two years of our study when rainfall was adequate in terms of both distribution and amount. This points to the need for longer term studies and the use of simulation models (Nangia et al. 2009) to evaluate the tillage/residue retention treatments over the full range of likely seasonal conditions. No-till with residue mulch could have positive effects on crop growth in dry years due to improved soil moisture.

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Quesungual slash and mulch agroforestry system improves rain water productivity in hillside agroecosystems of the sub-humid tropics

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Abstract

The Quesungual Slash and Mulch Agroforestry System (QSMAS) is a smallholder production system with a group of technologies for the sustainable management of water, soil and nutrient resources in drought-prone areas of hillside agroecosystems of the sub-humid tropics. QSMAS integrates local and technical knowledge and provides resource-poor farmers with an alternative to the environmentally unfriendly slash and burn (SB) traditional production system. The main objective of this study was to determine the key principles behind the biophysical resilience of QSMAS and its capacity to sustain crop production and alleviate water deficits on steeper slopes with risk of soil erosion. Activities included the evaluation of QSMAS performance compared to the traditional SB system in terms of water dynamics (including crop water productivity), nutrient dynamics, and greenhouse gas fluxes (including global warming potential). Results indicate that the application of the four principles behind QSMAS productivity and sustainability (no slash-and-burn, permanent soil cover, minimal disturbance of soil, and improved fertilizer practice), has positive effects on the soil-plant-atmosphere relationships, soil quality, and on landscapes and the environment. Validation in Nicaragua and Colombia underpin the potential of QSMAS to enhance support for livelihoods in vulnerable rural areas in sub-humid tropics.

Key words

Quesungual, crop water productivity, slash and burn, shifting agriculture

Introduction

The Quesungual Slash and Mulch Agroforestry System (QSMAS) is a smallholder production system consisting of a group of technologies for the sustainable management of vegetation, water, soil, and nutrient resources in drought-prone areas of hillside agroecosystems of the sub-humid tropics. QSMAS is an indigenous production system that was identified by agricultural officers and extension agents of the Food and Agriculture Organization of the United Nations (FAO) and then improved in collaboration with local farmers, resulting in a suitable option to replace the slash and burn (SB) traditional system. QSMAS is being practiced by smallholders in southwest Honduras to produce major staples (maize, bean, sorghum), where the system has been successfully adopted by over 6,000 resource-poor farmers on 7,000 ha.

Widespread adoption of QSMAS has been driven by its biophysical and socioeconomic benefits at multiple scales ranging from farm (increased crop-water productivity, food security) to landscape (better amount and quality of available water, resilience to extreme water deficits and to excess water) (FAO 2005; Ayarza and Wélchez 2004). Adoption of QSMAS has contributed to improved livelihoods of the rural poor through increased water resources and food security in sub-humid hillside areas, while maintaining the soil and plant genetic resources for future generations. The main objective of the work described in this paper was to define the key principles behind the biophysical resilience of QSMAS by determining the role of the management components of the system and QSMAS' capacity to sustain crop production and alleviate water deficits on steeper slopes with high risk of soil erosion.

Methods

The performance of QSMAS was studied in southwest Honduras, within the Lempa River upper watershed department (district) of Lempira, from 2005 to 2007. Mean annual (bimodal) precipitation is approximately 1400 mm, falling from early May to late October, with a long dry season of up to 6 months. Field plots were established in April 2005 to compare five main treatments (replicated on three different farms): QSMAS of three different ages (<2, 5-7 and >10 years old), the traditional SB system, and secondary forest (SF) as reference. The four production system treatments (QSMAS of different ages and SB) were split in order to apply a fertilizer treatment (addition vs. no addition).

Consistent with the traditional practices, SB and QSMAS plots were established (in 2005) or prepared (2006 and 2007) in April, before the start of the rainy season. The establishment of SB system had different management compared with subsequent management over the years. In 2005 the system was established through complete slashing of trees and shrubs, removal of firewood and uniform burning of the remaining dried material throughout the plot. Since the SB plots have a significant reduction in biomass production, in 2006 and 2007 the biomass was slashed and then piled and burnt in isolated sites within the plots. The QSMAS plots were managed in the same way in all three years, with the partial, selective and progressive slashing and pruning of trees and shrubs; manual and/or chemical control of weeds; fertilization of maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) crops; and the homogeneous distribution of litter, and biomass of trees, shrubs and of crop residues shortly before and at the middle of the cropping season.

Every year maize and common bean were established in the early (late May) and later (late August) part of the rainy season, respectively, and managed following the standard timing, spatial arrangement and management practices used in the region for the production systems under comparison. In the fertilized treatments, the maize received 49 kg N ha^{-1} and 55 kg P ha^{-1} at 8-10 days after planting (DAP) and 52 kg N ha^{-1} around 30 DAP; the common bean received 46 kg N ha^{-1} and 51 kg P ha^{-1} around 8-10 DAP.

Measurements and observations included: monitoring and analysis of soil water dynamics, crop yield and water productivity, nutrient (nitrogen and phosphorus) dynamics, greenhouse gas (GHG) fluxes, global warming potential (GWP), emergy[1] sustainability index and ecological footprint index. Water dynamics were monitored through the assessment of infiltration, runoff and soil water availability during the rainy and dry seasons of 2007. Water infiltration and runoff were measured through rainfall simulation for 30 minutes using two intensities (80 and 115 mm h^{-1}). Soil water content was determined through soil sampling at three depths (0-10, 10-20 and 20-40 cm). Susceptibility of the soil to erosion was assessed in erosion plots (5 m length *x* 1.5 m width) over 3 years. Soil losses were determined through the comparison of the indices of soil erodibility K-USLE [(t ha^{-1} h^{-1} MJ^{-1} mm^{-1}] and Ki-WEPP (kg^{-1} s^{-1} m^{-4}), corresponding to the Universal Soil Loss Equation (Wischmeier and Smith 1978) and to the Water Erosion Prediction Project (Nearing et al. 1989), respectively. Nutrient losses through erosion were quantified by determining total contents of N, P, K, Ca and Mg from samples of eroded soils. Water quality was assessed through the determination of NO_3^-, NH_4^+, total P, PO_4^{-3} and soluble solids in samples collected 45 DAP. Both eroded soil and water samples were collected in the erosion plots in 2007. Crop water productivity (CWP), expressed as kg of grain produced per m^3 of water used as evapotranspiration, was calculated using the crop yield and soil water data obtained in 2007 and by estimating the evapotranspiration according to the method of Penman and Monteith (FAO 1998).

Measurements for the study on nutrient dynamics were carried out during three years, from 2005 to 2007, and included: (1) nitrogen (N) aerobic mineralization (NH_4^+ and NO_3^- + NO_2^-), determined by mineralization of the whole soil (Anderson and Ingram 1993); and (2) partitioning of soil total phosphorus (P) following a shortened sequential P fractionation (Tiessen and Moir 1993, after Hedley et al. 1982).

GHG fluxes including N_2O, CH_4 and CO_2 were determined using a closed chamber technique, with 16 sampling dates from July 2005 to July 2006. Global warming potential was determined using CH_4 and N_2O fluxes, and C stocks in soil (soil organic carbon) and in tree biomass. GWP values were extrapolated to the region where QSMAS is practiced and were projected in time considering land use change. An emergy evaluation was conducted as in Diemont et al (2006) to quantify resource use and system sustainability, using data from plots and relationships (energy input per unit of energy output) reported in other studies.

Results and discussion

Evaluation of water dynamics at the middle of the rainy and dry seasons of 2007 showed a lower infiltration and higher runoff in SB system. During the rainy season, SB had the lowest infiltration[2] (29.8 mm) and highest runoff (12.0 mm); in contrast, QSMAS >10 years had the highest infiltration (38.5 mm) and lowest runoff (4.8 mm). During the dry season differences between treatments in infiltration and runoff were small. Infiltration ranged from around 44

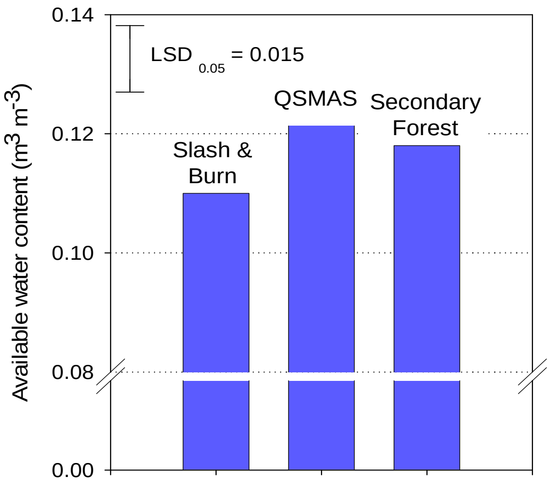
[1] Emergy is defined by H.T. Odum (1996) as the total solar equivalent of available energy that is needed directly and indirectly in making a product, good or service.

[2] Infiltration and runoff expressed as mm 30 min^{-1}.

mm in both QSMAS treatments to 41.9 mm in SB. Runoff ranged from 0.91 mm in QSMAS to 2.4 mm in SB.

In 2007, precipitation and evapotranspiration (after FAO 1998) were 1005 and 491 mm in the early part of rainy season, and 419 and 272 mm in the later part, respectively. In the early part of the rainy season available soil water (0-40 cm soil depth) varied between 0.09 and 0.104 m^{-3} m^{-3}, with QSMAS <2 and QSMAS 5-7 and was 10 and 16% higher, respectively, than in SF. In the later part of the rainy season the amount of available soil water varied between 0.11 and 0.127 m^{-3} m^{-3} in SB and QSMAS <2, respectively. The mean value of available soil water content (0-40 cm) in QSMAS systems (average of the three different ages) was significantly greater than that of the SB system (Figure 1), suggesting increased availability of water for crop growth. These improvements in QSMAS were related to changes in soil porosity due to increases in mesoporosity (30%) and macroporosity (19%), and decreased the soil bulk density. This increased the plant available soil water storage capacity and availability of water for crops in the dry season, and increased the capture of rainfall at the beginning of the rainy season.

Figure 1. Average available soil water content in the dry season of 2007. QSMAS value is the average of the three different ages.

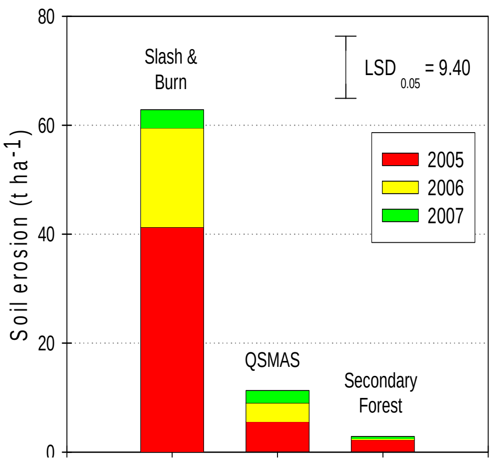


The highest soil loss occurred in 2005, and was markedly higher in SB followed by QSMAS and SF (Figure 2). The same trend was observed in 2006 and 2007, although differences were more remarkable in 2005 due to higher rainfall intensity and to the recent conversion of SB plots from SF that resulted in bare soil and therefore higher susceptibility to erosion. Total soil losses over the 3 years from SB were 5.6 times greater than from the three QSMAS treatments, and 22 times greater than from SF. As a result, the SB system had the highest nutrient losses (kg ha^{-1}) of N (9.9), P (1.3), K (6.9), Ca (22.8) and Mg (24.2), while SF had the lowest losses of N (1.7), P (0.2), K (1.2), Ca (2.6) and Mg (2.7).

Water quality was poorest in the SB system, with highest concentration (mg L^{-1}) of total P and PO_4^{3-} (2.30 and 0.29, respectively), and was best in QSMAS >10 (0.18 and 0.25, respectively). SB also had the highest concentration of (mg L^{-1}) of NO_3^- and NH_4^+ (7.97 and 0.70, respectively), while QSMAS 5-7 had the lowest concentration of NO_3^- (6.13) and QSMAS >10 of NH_4^+ (0.24). Highest soluble solids (mg L^{-1}) was observed with QSMAS 5-7 (183), and lowest with QSMAS <2 (83.3). SF had values (mg L^{-1}) of 0.65 for P, 0.43 for PO_4^{3-}, 4.73 for NO_3^-, 0.92 for NH_4^+, and 25.0 for total soluble solids.

There was no interaction between land use system (LUS) and fertilizer treatment on crop water productivity (CWP). CWP for maize was greatest in fertilized systems of QSMAS <2 (0.48 kg grain m^{-3}) and least with QSMAS >10 (0.18 kg grain m^{-3}) (Figure 3). In plots with no fertilizer application, the highest CWP was observed with QSMAS <2 (0.26 kg grain m^{-3}) and the lowest with SB (0.10 kg grain m^{-3}). In both fertilized and non-fertilized systems, CWP for common bean was greatest in QSMAS <2 (0.32 and 0.27 kg grain m^{-3}, respectively) and least with SB (0.10 and 0.07 kg grain m^{-2} , respectively). Fertilization increased CWP of maize (by 92%) and common bean (by 23%). These results may reflect adequate available soil water during the maize crop (from sowing to grain physiological maturity) in the early part of the rainy season, as precipitation was higher than evapotranspiration (ET). In the case of common bean, commonly growth in the later (drier) part of the rainy season, available water content in the soil decreased from flowering to physiological maturity, with lower precipitation than ET and therefore with a negative water balance. Under these conditions, QSMAS showed greater available water content in soil that resulted in greater grain yield and CWP.

Figure 2. Accumulated soil loss in three land use systems in 2005. QSMAS value is the average of the three different ages.



Total soil N content across the years showed a trend to decrease with time in the SB system while it increased significantly in QSMAS >10, with and without fertilization. The comparison of total N in SB system vs. QSMAS <2 (with a similar period under production) and SF (the natural condition which is disturbed for the establishment of either QSMAS or SB), suggest that the use of SB can rapidly reduce this nutrient in the landscape while QSMAS maintains and even increases the pool of N. Over the 3 years, potential N mineralization (N-min) was also higher in QSMAS >10, although it was only significantly higher than in SF. The study on P dynamics showed no differences among LUS in total P content across the years, although different trends were observed in SB and QSMAS, with SB showing an increase in the organic (P_o) pool and QSMAS increasing its inorganic (P_i) pool. In terms of P availability, over the years the average size of the different P pools relative to total P were: available P (AP) 12% of total P, moderately available P (MAP) 29%, and residual (not available) P (RP) 59%. The non-available RP pool tended to increase and the MAP and AP pools tended to decrease over time in the SB system relative to SF, while QSMAS (average of <2 and >10 years old plots) exhibited the opposite tendency (Figure 4).

Figure 3. Crop water productivity in two land use systems with (+F) and without (-F) fertilization

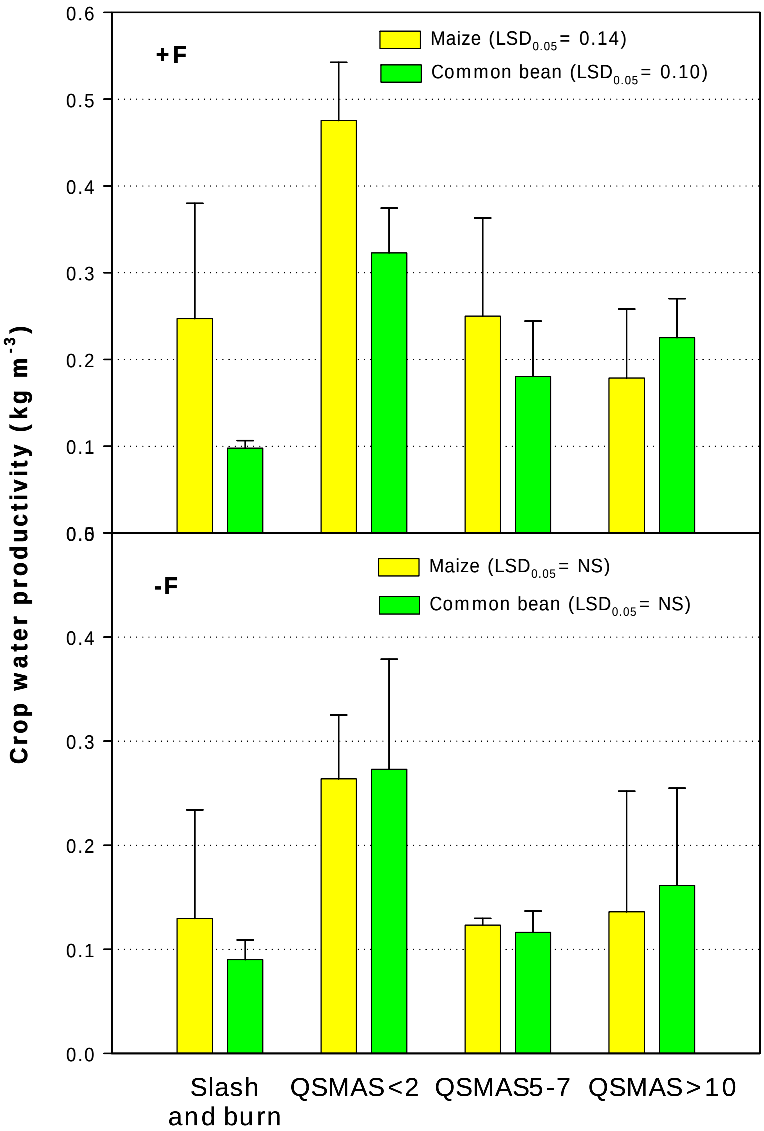
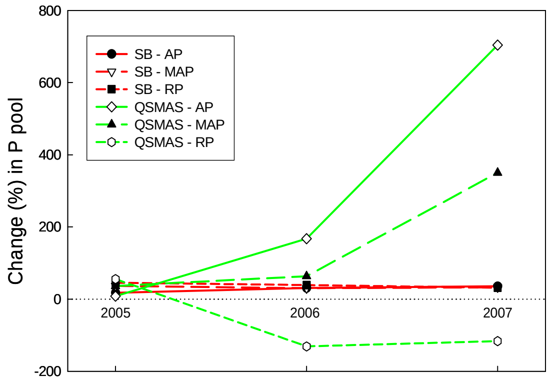


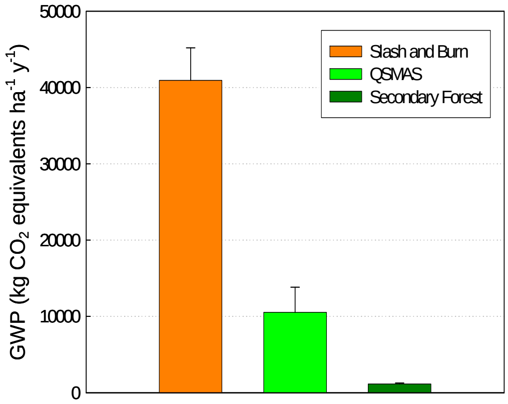
Figure 4. Changes on P pools in soil from SB without fertilization and QSMAS (average of fertilized QSMAS lots of <2 and >10 years old) in relation to SF.



The similar behavior in N-min and available P pools among production systems is a positive finding, because it implies the following: (i) QSMAS is as good as SB as a source of N and P, even though in QSMAS their content is more a result of biologically mediated process than of an accelerated process that drives immediate availability of nutrients as a result of burning; and (ii) QSMAS performs consistently over time, suggesting that this form of management may provide a sustainable source of N and P. Additionally, at similar rates of N-mineralization, the N balance in the SB system is expected to be less positive than in QSMAS, considering that yearly SB has lower additions of N (no fertilization and fewer sources of biomass) and higher losses of N through burning (volatilization losses of ammonia and wind-related losses of ash) than QSMAS.

Results from the study on GHG emissions showed that QSMAS and SF were CH_4 net sinks, with values (mg CH_4 $m^{-1}year^{-1}$) of -102 and -36, respectively. The only CH_4 net source was SB, with 150 mg CH_4 $m^{-1}year^{-1}$. All LUS were found to be N_2O and CO_2 sources, resulting from natural processes (soil organic matter decomposition) and from management (fertilization). QSMAS presented a much lower GWP (10.5 Mg Equiv. CO_2) than SB system (40.9 Mg Equiv. CO_2) (Figure 5). SF had a very low GWP (1.14 Mg Equiv. CO_2). According to land use change trends, when projecting GWP to the region where QSMAS is practiced and using a 20-year time horizon, we estimate a decrease of 0.10 Tg Equiv. CO_2. Higher C stocks in soil and tree biomass indicate a gradual accumulation of C in SF and QSMAS >10. According to the emergy evaluation SF and QSMAS had less environmental impact than SB as noted in the Environmental Loading Ratio (with values of 0.63, 0.14, and 0.02, respectively), the Ecological Footprint Index (1.02, 1.14 and 1.63, respectively) and the Energy Sustainability Index (4124, 136 and 35, respectively), indicating higher sustainability in QSMAS and SF.

Figure 5. Global Warming Potential (GWP) in a 20-year scenario of three land use systems in Lempira, southwest Honduras. QSMAS value is the average of three different ages.



Conclusions and recommendations

The improved knowledge and understanding of the QSMAS system and the results from field studies lead to the following general conclusions:

- The set of technologies responsible for the success of QSMAS can be synthesized in four basic principles of conservation agriculture that contribute synergistically to its superior performance: (1) no SB, through the management of natural vegetation; (2) permanent soil cover, through the continual deposition of biomass from trees, shrubs, and weeds, and through crop residues; (3) minimal disturbance of soil, through the use of no tillage, direct seeding, and reduced soil disturbance during agronomic practices; and (4) efficient use of fertilizer, through the appropriate application of fertilizers.
- Management practices based on the key principles result in increased C synthesis and accumulation, accelerated nutrient cycling, and improved crop water productivity in a resilient production system, thereby enhancing support for livelihoods through water-efficient and soil-conserving technologies in vulnerable rural areas in the hillside agroecosystems of sub-humid tropics.
- Experience in on-farm participatory validation suggests that QSMAS will be readily accepted and adopted by smallholders in similar agro-ecosystems, and it also could receive strong support from local authorities and policy makers.

Acknowledgments

This paper presents findings from PN15, 'Quesungual Slash and Mulch Agroforestry System (QSMAS): Improving Crop Water Productivity, Food Security and Resource Quality in the Sub-humid Tropics', a project of the CGIAR Challenge Program on Water and Food. It is co-executed by the Tropical Soil Biology and Fertility (TSBF) Institute of CIAT at Latin America, Integrated Management of Soil (MIS, in Spanish) Consortium in Central America, Inter-

institutional Consortium for Sustainable Agriculture in Hillsides (CIPASLA, in Spanish), and National University of Colombia–Palmira.

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Maize productivity under supplementary irrigation in the Olifants River Basin, South Africa

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Abstract

A daily field water balance experiment was conducted for three consecutive cropping seasons to study the effects of supplementary irrigation on grain yield and water productivity of maize (*Zea mays L.*) in the semi-arid Olifants River Basin, South Africa. Maize yield was affected by seasonal total rainfall and its distribution. Average maize yields under rainfed and supplementary irrigated conditions were 0.7 t ha^{-1} (standard deviation of 0.44 t ha^{-1}) and 1.7 t ha^{-1} (standard deviation of 0.28 t ha^{-1}) respectively. Supplementary irrigation during dry spells increased average yields by 196%. The benefits of supplementary irrigation were greatest during a season with low rainfall which was poorly distributed. Average evapotranspiration under rainfed and supplementary irrigation for the three seasons was 344 mm and 431 mm, respectively. However, crop water productivity with respect to evapotranspiration was significantly greater for supplementary irrigation (4.0 kg mm^{-1} ha^{-1}) than for rainfed (2 kg grain mm^{-1} ha^{-1}). The mean incremental water productivity from supplemental irrigation of 12.8 kg mm^{-1} ha^{-1} implied that timely application of 1 m^3 of irrigation water can produce ZAR 2.56 (US$ 0.26) worth of maize, 5 times the cost of the water used. The values demonstrate the monetary gains from timely and adequate supplementary irrigation to bridge dry spells. The results show significant yield increases irrespective of the season under supplementary irrigation, demonstrating the potential of supplementary irrigation to improve and stabilise smallholder farmer maize yields, thereby enhancing livelihoods.

Key words

dry spells, moisture stress, rainfed agriculture, water productivity

Introduction

Increasing the productivity of rainfed agriculture which caters for 60 % (OECD 1998; FAO 2008) of the world's food, would help make strides towards global food security. However, the potential to improve yields for the growing populations in semi-arid regions, home to 2 billion people of which half are poor (DFID 2003) depends on appropriate adaptation to rainfall patterns. Even though total seasonal rainfall might be adequate for maize cultivation, poor distribution during the growing season often results in total crop failure, disrupting livelihoods. Research from semi-arid tropical regions shows that the occurrence of 2 to 4-week dry spells during the growing season is more frequent than yearly droughts (Botha et al. 2003). Magombeyi and Taigbenu (2008) reported the occurrence of 14-day intra-seasonal dry spells in the Olifants River Basin of South Africa with a probability of 0.52 and the associated shortfall in the average family food requirement of 500 kg ha^{-1} $year^{-1}$ occurring once every two years. Similar results from Kenya and Tanzania were obtained by Barron et al. (1999) of a 20%-30% chance of dry spells exceeding 10 days during the crop growing period. Supplementary irrigation can help increase water productivity (produce more crop per unit of water) and stabilise rainfed agricultural production in resource constrained regions of the semi-arid tropics (Rockström 2002; Rockström et al. 2002; DFID 2003; Mupangwa et al. 2006).

Over the years, yields of maize (a staple food) have plummeted in Ga-Sekororo, Olifants River Basin. The farmers are vulnerable to recurrent droughts and dry spells which significantly reduce yield and consequently their income, thereby making them fall back on social grants from the central government (Magombeyi and Taigbenu 2008). Furthermore, the high cost of irrigation infrastructure is beyond the reach of resource-constrained subsistence farmers. Further, major developments of irrigation water sources in the study area are unlikely, unless through irrigation water savings, as Olifants River Basin is a closed basin with 70 % of the catchment water consumed by agriculture (DWAF 2004). This paper quantifies the effects of supplementary irrigation on rainfed maize to assist farmers to avoid crop yield failure due to climate and weather variability.

Study area

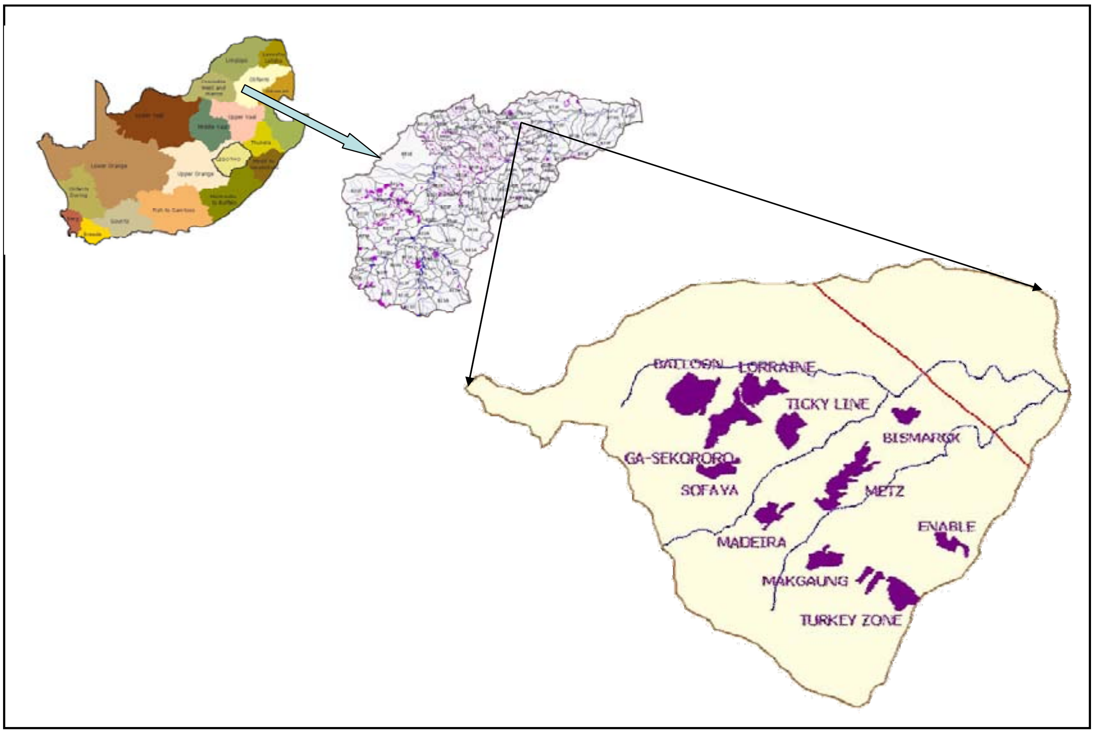
The study area is located in Ga-Sekororo (part of the B72A quaternary catchment) in the Olifants River Basin of South Africa (Fig. 1). The Olifants is a sub-basin of the Limpopo River Basin shared by South Africa, Zimbabwe, Mozambique and Botswana. The total rural population is estimated at around 56,000 (South Africa Census 2001).

The area is characterized by high temperatures, erratic rainfall and recurrent droughts. Rainfall average is 630 mm; with potential evapotranspiration rates above 1500 mm (actual evapotranspiration is around 840 mm). The permanent wilting point, field capacity and saturated volumetric water content for the sandy loam soil in the study site is 9.5 %, 20.7 % and 45.3% respectively (Rawls et al. 1982; Mzirai et al. 2001).

Compared to rating guidelines by Marx et al. (1999) the 2005/2006 season soil macronutrients (nitrogen, phosphorus, potassium) and cation exchange ratio in the study sites are low. Soil parameter analysis in 2005/2006 gave the following results: nitrate (0.56 ppm), phosphate (2.4 ppm), potassium (100 ppm), calcium (1 927 ppm), magnesium (284 ppm) and organic carbon (0.013 %) (Rasiuba 2007).

Maize is grown by more than 70 % (Magombeyi and Taigbenu 2008) of the farmers as a stable food for the community even in zones where success is not guaranteed, yet it is still the preferred choice for cultivation. The above formed the basis for choosing the maize crop for analysis.

Figure 1. Location of the study area in northern South Africa, and in the Olifants River Basin.



Materials and methods

Field experiment

Controlled plot experiments were conducted in collaboration with three smallholder farmers with two replicates per farm to determine various parameters for the water balance model. The field layout for the experiment consisted of one hectare plots, with two equal smaller runoff plots of dimensions 4 m × 2 m. The farmers were initially taught about daily field data capturing. The experiments were conducted in 2005/2006, 2006/2007 and 2007/2008. In the irrigated plots, water was supplied by a gravity-fed furrow irrigation system from a weir built across a seasonal stream. Irrigation scheduling was left at discretion of the farmers but measured by a 90^0 V-notch weir. The farmers scheduled irrigation by a combination of two methods i.e. by intuition (when the maize crop showed signs of moisture stress) and calendar days since the last rainfall or irrigation (Shock et al. 2007). All plots were planted on the same day and farmers agreed on the same farm management strategies. The planting density was 3 plants m^{-2} (30 000 plants ha^{-1}). N fertilizer was applied at 14 kg N ha^{-1} per season in all plots. This rate was based on affordability and potential maize yields above average (0.5 t ha^{-1}) as recommended by ICRISAT (Kgonyane and Dimes 2007) from studies in the area, and was applied in all plots after the first weeding except for the 2006/2007 rainfed plot because of little rainfall. The first weeding was done 28 days after sowing. Soil moisture levels at 200 mm depth were measured on a daily basis during the growing season at 12 positions diagonally across the field using a hydrosense neutron probe (Campbell Scientific, Inc. 2001). Daily rainfall and runoff were also recorded from each field. The soil micronutrients were analysed from samples collected shortly before harvest in the 2007/2008 season. The plots were harvested by hand and the grain yield recorded.

Water balance model

Using data on precipitation, supplementary irrigation, soil moisture, and runoff a seasonal root zone soil water balance over a daily temporal scale for three cropping seasons (2005/2006, 2006/2007 and 2007/2008) was constructed from Equation (1) (Walker and Ogindo 2003; Zhang et al. 2006).

$$D = (P + I) - (R + E_c + \Delta S) \tag{1}$$

where all parameters have the units mm season^{-1}, and D is the deep drainage beyond the 1 m (Ali et al. 2007) root zone, P is the daily precipitation, I is the irrigation amount, R is the runoff from the field, E_c is the evapotranspiration and ΔS is the change in soil-water content (soil moisture at harvest minus soil moisture at sowing) in the root zone. D was determined as a residual in Equation 1.

The maize crop actual evapotranspiration was estimated by Equation (2) (Chow et al. 1988; Allen et al. 1998; Moroizumi et al. 2009):

$$E_c = K_s K_c E_0 \tag{2}$$

where E_c is the actual evapotranspiration (mm d^{-1}), K_s is the water stress condition, K_c is the maize crop coefficient, and E_0 is the reference evapotranspiration (mm d^{-1}). E_0 was calculated by the FAO Penman-Monteith equation (as a function of net radiation, air temperature, wind speed and vapour pressure). K_c values from SAPWAT for maize were used according to the maize growth stages.

SAPWAT is a computer program based on FAO, Penman-Monteith method (FAO 2002) developed to estimate crop water requirements (not a crop growth model) only for areas within South Africa (van Heerden and Crosby 2002). It uses local climate, irrigation systems and planting dates which represent the general production patterns found in the area. The K_s value was calculated using Equation (3) (Chow et al. 1988; Moroizumi et al. 2009):

$K_s = 1$ for $\theta \geq \theta_t$

$$= \frac{\theta - \theta_{wp}}{\theta_t - \theta_{wp}} \text{ for } \theta_{wp} \leq \theta < \theta_t \tag{3}$$

Where θ is the soil water content at any day and θ_{wp} is the soil water content at the wilting point (9.5% in this study). The value of θ_t was calculated from Equation (4) (Moroizumi et al. 2009):

$$\theta_t = \theta_{fc} - p(\theta_{fc} - \theta_{wp}) \tag{4}$$

Where θ_{fc} is the field capacity water content (20.7% in this study). A value of p = 0.43 for maize was adopted based on Allen et al. (1998) (θ_t = 15.9% in this study).

Crop water productivity (W_p) was calculated from the ratio of yield (kg ha^{-1}) to seasonal water evapotranspired (mm) (van Der Zel et al. 1993; Rockström et al. 1998; DFID 2003; Grove 2006; Zhang et al. 2006). Marginal supplementary irrigation water productivity (M_{SIWP}) was calculated from the ratio of change in yield to change in irrigation water applied (assuming no irrigation water loss to deep drainage), with other inputs held constant (Ali et al. 2007).

Results and discussion

Soil analysis

Soil parameter analysis in 2007/2008 gave the following results: nitrate (12.3 ppm), phosphate (11.2 ppm), potassium (207 ppm), calcium (2 090 ppm), magnesium (311 ppm) and organic carbon (1.33 %). Compared to rating guidelines by Marx et al. (1999) of low nutrient levels (nitrate: < 10 ppm, phosphate: < 20 ppm, potassium: < 150 ppm, calcium: < 1000 ppm and magnesium: < 60 ppm), phosphate levels in the study site are lower than recommended levels for maize. Hence, phosphate is the most limiting nutrient in the soil. The 2007/2008 soil nutrient status showed an improvement from the 2005/2006 season.

Evapotranspiration and yield

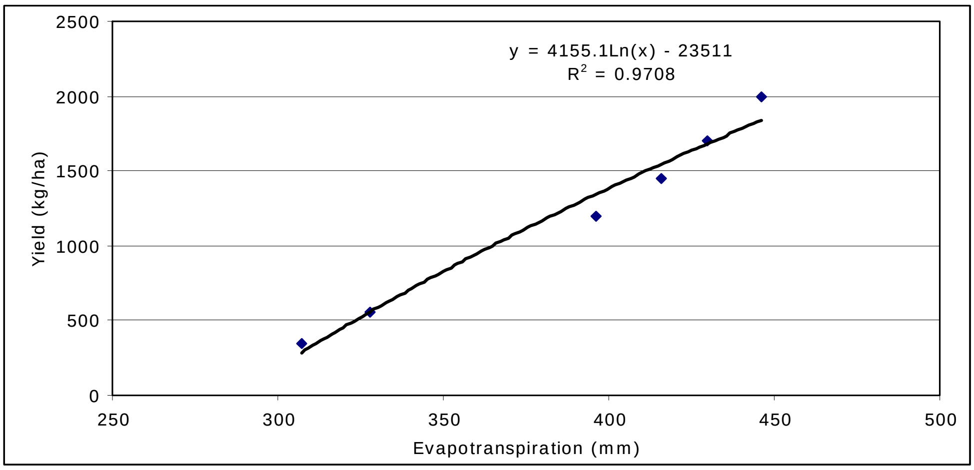
The seasonal rainfall during the three seasons for maize varied from 388 to 1422 mm (Table 1). The 2006/2007 season was very dry, well below the long-term average (630 mm), while 2005/2006 season received more than double the average rainfall. The average evapotranspiration (E_c) under rainfed and supplementary irrigation for the three seasons was 344 mm and 431 mm respectively. The observed E_c values are less than the general maximum (500-800 mm) required by a medium maturity maize crop for maximum yields (FAO 2002). Water balance components, maize grain yield and water use efficiencies (kg dry matter grain per mm rainfall) for the areas studied are shown in Table 1.

Table 1. Water balance components, water productivity, marginal irrigation water productivity and yield reduction from the study area.

Season	P (mm)	I (mm)	ΔS (mm)	R (mm)	D (mm)	E_c (mm)	**Grain yield** (kg ha^{-1})	W_p (kg mm^{-1} ha^{-1})	M_{SIWP} (kg mm^{-1} ha^{-1})
Rainfed with supplementary irrigation									
2005/ 2006	1422	48	120	540	364	446	2000	4.5	16.7
2006/ 2007	388	112	-54	82	56	416	1450	3.5	9.8
2007/ 2008	611	96	-87	293	71	430	1700	4.0	11.9
Control exclusive rainfed									
2005/ 2006	1422	0	120	557	349	396	1200	3.0	0
2006/ 2007	388	0	-66	105	42	307	350	1.1	0
2007/ 2008	611	0	-30	257	56	328	556	1.7	0

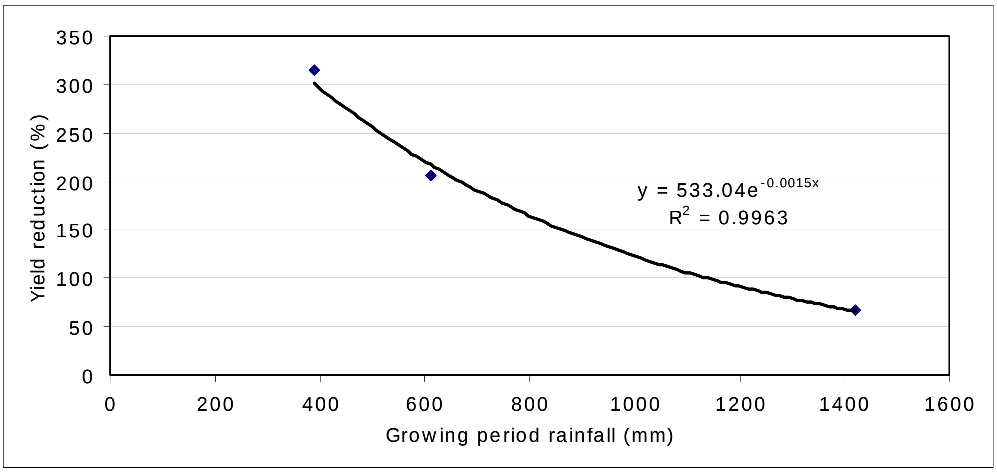
The variation of grain yield with evapotranspiration (Fig. 2) for rainfed and rainfed plus supplementary irrigation showed a strong correlation. This implies that the yield potential of maize increases as the E_c and seasonal rainfall increases.

Figure 2. Correlation of yield variation with evapotranspiration in the study plots.



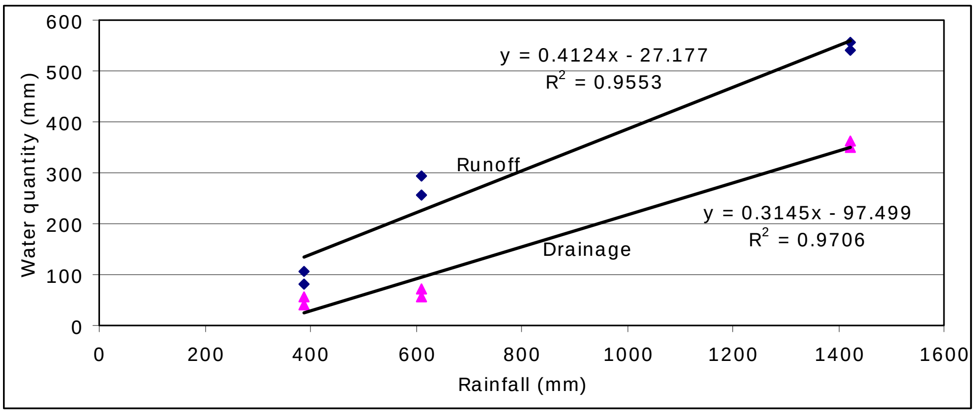
Maximum grain yields in fields with supplementary irrigation ranged from 1.45 to 2 t ha^{-1}, while yields in exclusive rainfed fields ranged from 0.35 to 1.2 t ha^{-1} (Table 1). Similar results were reported by earlier researchers working on maize in South, East and West Africa (Rockström et al. 1998; Oweis and Hachum 2003). Maize yield was affected by seasonal rainfall (Fig. 3) and its erratic distribution throughout the growing season, as reflected in the soil moisture changes in the rainfed plots (Figs 5a-c). The strong correlation between yield reduction of rainfed relative to supplementary irrigated maize and rainfall during the crop growing period (Fig. 3) suggested that lack of soil water during critical crop growing stages reduced maize grain yield.

Figure 3. Correlation between yield reduction under rainfed compared to supplementary irrigation and rainfall during the 3 growing seasons from 2005 to 2008.



Supplementary irrigation during dry spells increased yields on average by 196% (Fig. 3 and Table 1). Fox and Rockström (2000) reported a similar result of 180% yield increase in semi-arid Burkina Faso. During the dry seasons 2006/7 and 2007/8 the grain yield reduction without supplementary irrigation ranged from 206 % to 314 %, while for the wettest year (2005/2006) the yield reduction was 67% indicating greater yield improvement with supplementary irrigation in drier years. There was high potential maize yield due to the more favourable high and evenly distributed rainfall in 2005/2006 season. Hence, the yield gap between rainfed and supplementary irrigation was smaller compared to drier seasons (2006/2007 and 2007/2008).

Figure 4. Correlation of surface runoff and deep drainage beyond the 1 m root zone with rainfall during the crop growing period.



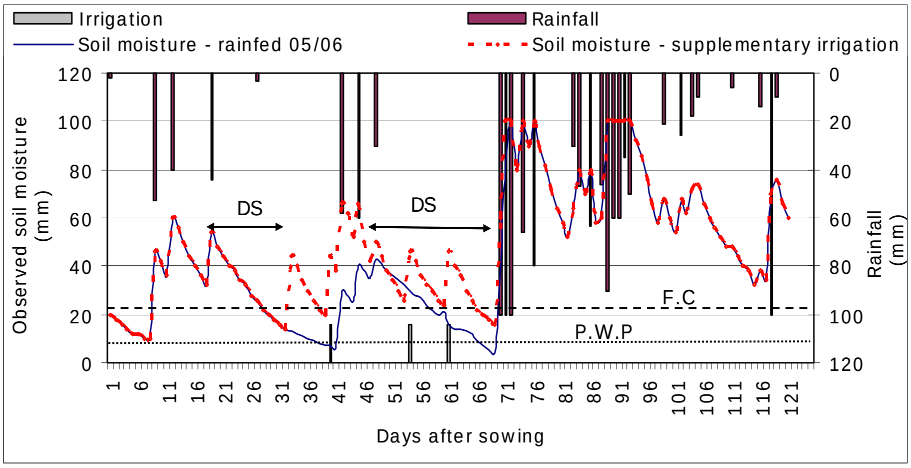
Surface runoff and drainage (Fig. 4) from the field showed a strong linear relationship with seasonal rainfall. These results indicate the great potential for surface runoff water harvesting and groundwater recharge at the site as the quantity of rainfall increases. Runoff was high as the rainfall events occurred in pockets of 2-4 consecutive days which allowed little time for infiltration. The field results indicate there is a significant scope for improving water productivity in rainfed farming through supplemental irrigation from local runoff harvesting, especially when combined with soil fertility management as reported in other parts of Africa (Rockström 1999; Fox and Rockström 2000).

Soil moisture variation and grain yield effects

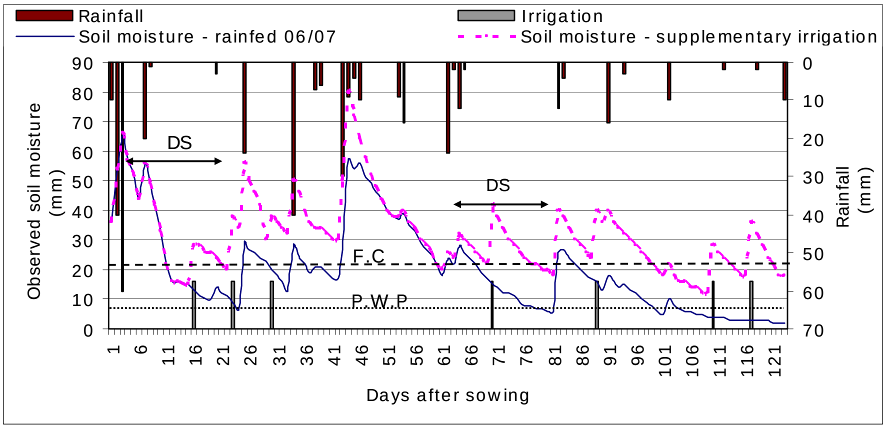
Figs –5a-c show the variation of soil moisture in the experimental sites for the three seasons from sowing to harvest. On some days the volumetric soil moisture content of the rainfed treatment fell below the permanent wilting point (9.5% volumetric water content) (Mzirai et al. 2001), causing severe crop water stress. In addition, the sub-soil acidity (pH < 5) in the study area could have further restricted water uptake by the crop roots (Robertson et al. 2003). Despite high annual rainfall of 1422 mm in 2005/2006, the rainfed crop suffered from periods of water shortage during the vegetative stage (Fig. 4a) (18-32 days after sowing) and flowering (50-70 days after sowing). In the 2006/2007 season (Fig. 4b) crop water stress at soil moisture content less than 15.9% (Moroizumi et al. 2009) occurred in the vegetative and grain filling stages, while in 2007/2008 (Fig. 4c) crop water stress was experienced in the rainfed crop from flowering through to grain filling (80-100 days after sowing) (Rockström et al., 1998; FAO 2002).

Figure 5. Rainfall, irrigation and soil moisture changes in rainfed and supplementary irrigated maize during the. DS = intra-seasonal long dry spells during the crop growing period. Dashed horizontal lines indicate average soil field capacity (F.C = 20.7%) and the permanent wilting point (P.W.P = 9.5%)

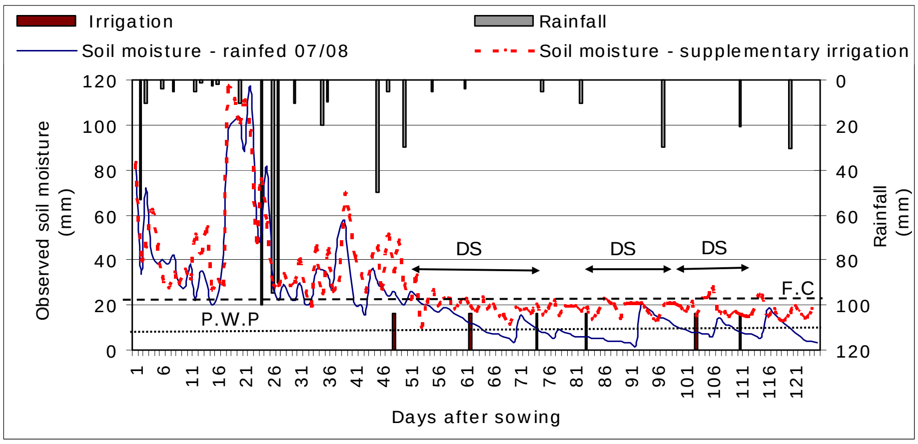
a. 2005-2006



b. 2006=2007



c. 2007-2008



Dry spells that were greater than 10 days resulted in volumetric soil moisture levels falling below 5 %. Soil moisture deficits adversely affected plant growth and yield attributes under rainfed plots due to increased total resistance in the soil-plant system resulting in reduced photosynthesis and growth (FAO 2002). In 2006/2007 the rainfed maize grain yield was reduced to 350 kg ha^{-1} because of the soil moisture stress experienced in the early growth stages (12-25 days after sowing) which could have reduced the crop leaf area index and radiation use efficiency and thus dry matter accumulation in plants (Rockström et al. 2002; Ali et al., 2007), and during grain filling. Soil moisture levels could be used to determine the onset of crop water stress for the efficient utilisation of irrigation and precipitation (Abraha and Savage 2008). With improved timely and adequate supplementary irrigation coupled with good soil management, farmers could ensure minimum crop water stress to crops thereby enhancing families' food and income.

Marginal irrigation water productivity (M_{SIWP})

The M_{SIWP} is a good indicator for assessing the performance of supplementary irrigation management methods, to ascertain whether higher crop yields offset the cost of supplying additional water (Rockström et al. 2002). The M_{SIWP} ranged from 9.8 to 16.7 kg mm^{-1} ha^{-1} (average of 12.8 kg mm^{-1} ha^{-1}) for 2005/2006, 2006/2007 and 2007/2008 seasons respectively (Table 1). The results are higher than 2.5-7.6 kg mm^{-1} ha^{-1} reported in Burkina Faso (Rockström et al. 2002) but on the lower side on comparison with 15-62 kg mm^{-1} ha^{-1} of supplemental irrigation elsewhere (Li et al. 2003; Tingem et al. 2008). With the current (2008) price of maize grain at South Africa Rand (ZAR) 2.0 per kilogram, on average a timely application of 1 m^3 of irrigation water can produce ZAR 2.56 equivalent to US$ 0.26 (using 2009 exchange rate of 10 ZAR = 1 US$) worth of maize. The monetary return per m^3 of supplementary irrigation is five-fold higher than the cost of 1 m^3 water under full irrigation of ZAR 0.5 m^{-3}. The values demonstrate the large gains possible with timely and adequate supplementary irrigation to bridge dry spells.

Crop water productivity (W_p)

Shifting from exclusive rainfed to supplementary irrigation maize production in the study area increased average crop water productivity with respect to evapotranspiration (W_p) from 1.1 to 4.5 kg mm^{-1} ha^{-1} (a 309 % increase) (Table 1). The corresponding average yield increase was from 800 kg ha^{-1} to 1144 kg ha^{-1}. The results are comparable to average grain water productivity increases from 1.5 kg mm^{-1} ha^{-1} for rainfed to 3.5-10 kg mm^{-1} ha^{-1} with supplementary irrigation (Rockström et al. 2002). The yield improvement can be attributed to timely water application to crops to avoid severe water stress and the availability of more soil water for the plant. Similar results from Burkina Faso reported tripling yields from 460 kg ha^{-1} to 1400 kg ha^{-1} by combining supplemental irrigation and fertiliser application (Rockström et al. 2002). On the other hand, for seasons with severe dry spells, e.g., 2006/2007 in Ga-Sekororo, the result was a complete crop failure in the absence of supplementary irrigation.

The results indicate that water harvesting for supplementary irrigation for dry spell mitigation can play a critical role in avoiding crop failure during cropping seasons with severe dry spells. There is need to investigate the levels of nutrients at which supplemental irrigation perform best, including nitrogen and phosphorus, which were below optimum at the study site.

Conclusions and recommendations

The daily soil moisture from water balance can be used to investigate the impact of dry spells on soil water availability during the crop growing season, and its impact on yield, and to determine when to schedule supplementary irrigations. Supplementary irrigation to bridge the intra-seasonal dry spells greatly increased maize yield. The benefits were greatest when rainfall was below average and unevenly distributed throughout the season. Ex-field rainwater harvesting from a river weir offers one way of realizing supplementary irrigation.

More appropriate rainwater harvesting techniques should be employed to harness the large amounts of surface runoff generated in the study area. With the water productivity for rainfed agriculture lower than with supplementary irrigation, the results demonstrate the great opportunities that exist for upgrading rainfed agriculture and ensuring food security in rural communities through timely and adequate supplementary irrigation to bridge dry spells.

Acknowledgments

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SECTION 2

Application of crop models to evaluate options for increasing water productivity in rainfed cropping systems

Quantifying water productivity in rainfed cropping systems in Limpopo province, South Africa

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Abstract

The Challenge Program for Water and Food (CPWF) project, "Integrated Water Resource Management for Improved Rural Livelihoods in the Water Scarce Limpopo Basin" (PN17), aims to improve the livelihoods of resource poor smallholder farmers in the Limpopo Basin through improved soil and water resources management. The project is developing an integrated water and soil resource management framework to help identify optimum resource management. Crop-soil simulation modelling is an essential tool in developing the necessary analytical framework to help quantify the changes in water balance components as improved crop management interventions are developed and adopted to varying degrees. However, there is a need to evaluate model performance and establish local credibility of simulation outputs as a first step in the application of any such tool.

This paper describes field experimentation conducted in the 2007/08 cropping season in which crop and stover yield and water use of maize, cowpea, and groundnut were measured. The observed results were used to evaluate the performance of the crop-soi model APSIM in simulating the water balance, yield and water productivity of maize and legume crops in the Limpopo Province, RSA. APSIM was able to simulate very closely the observed range of crop yields in terms of both total biomass (3750 to 7000 kg ha^{-1}) and grain yield (1250 to 2900 kg ha^{-1}). It also simulated the observed differences in soil water content over time under the 3 crops, reflecting differences in crop water use due to planting date and crop duration and soil water distribution patterns. Using in-crop rainfall, the water productivity (WP) of the 128 day maize (fertilized) and groundnut crops was the same (6 kg mm^{-1} ha^{-1}) whereas it was 3.8 kg mm^{-1} ha^{-1} for the 94 day cowpea. Using model outputs to fill measurement gaps at the start and end of the crop cycle, WP with respect to total water input (rainfall plus soil water depletion), was reduced to 5.5 and 3 kg mm^{-1} ha^{-1} for maize/groundnut and cowpea, respectively. Including the total seasonal rainfall, which was above average, in the total water input reduced WP to about 4 kg mm^{-1} ha^{-1} for maize and groundnut and to only 1.8 kg mm^{-1} ha^{-1} for the short duration cowpea crop.

Key words

fertility, field-crops, modelling, risk, water-productivity, APSIM

Introduction

The Challenge Program for Water and Food (CPWF) project, "Integrated Water Resource Management for Improved Rural Livelihoods in the Water Scarce Limpopo Basin" (PN17), aims to improve the livelihoods of resource poor smallholder farmers in the Limpopo Basin through the development of an integrated water and soil resource management framework. The project recognises that while increasing water productivity (WP) is largely an issue of management of farming systems, the resulting upstream-downstream impacts and need for water re-allocation at the basin scale can only be resolved institutionally. Accordingly the project has a focus on institutional development and reform in addition to participatory technology development.

At the core of any institutional or technological innovations that emanate from this project will be the need for reliable information on the water balance at the various scales of land management – plot, farm, catchment and basin level. In adopting a multi-scale, integrated platform, there is an onus upon the project to develop and use an analytical framework that adequately quantifies surface runoff and deep drainage, since these site-specific flows interact with and contribute directly to the water balance of the catchment and basin systems.

However, this is a difficult task. Firstly, runoff and deep drainage are difficult to measure experimentally, and measurement is rarely done. Hence scarcity of data and the need to extrapolate are major challenges for the project. Secondly, rainfed farming systems in the Limpopo Basin are afflicted with highly variable and un-predictable seasonal rainfall patterns. Any experimental data derived in the relatively short time-frame of a 3 to 5 year project should therefore be considered with an appropriate degree of caution. Further, the vast array of cropping systems and management options for which the runoff and drainage terms would need to be quantified experimentally would quickly exhaust available resources. Lastly, site-specific runoff and drainage flows have impacts at the watershed and basin system levels as amalgamations of these flows from adjoining units of similar (and dissimilar) land management in the landscape. Quantifying these flows across land units and ensuring conservation of mass in the overall water balance is perhaps the most daunting analytical challenge that the project faces.

Crop-soil simulation models are useful research tools when they adequately describe the key bio-physical and management interactions of the farming system of interest. In rainfed semi-arid farming systems, simulation models, in conjunction with long-term climate data, offer a cost effective tool for capturing the effects one of the most important factors influencing crop response functions, namely rainfall variability both in season and between seasons. The capability to simulate a continuous water balance for the plant-soil-atmosphere system also makes modelling a valuable tool for quantifying water productivity for a range of crop species, environmental factors and management conditions. Where surface runoff and deep-drainage are included as outputs from the crop-soil simulation model, the modelling tool has the necessary attributes and capabilities to form part of the analytical framework to help overcome the challenges outlined above for PN17, and which can be assumed to apply more broadly across CPWF projects.

The cropping systems model APSIM (Keating et al. 2003), has been described and promoted previously for use in the Limpopo Basin CPWF (Dimes and Malherbe 2004). However, for the uptake and application of APSIM as a key analytical tool in the current project, there is a need to evaluate APSIM performance and establish local credibility of its simulation output. To pursue this initial objective, field experimentation was conducted in the 2007/08 cropping season in which crop yield and water use of maize, cowpea, and groundnut were measured at one site in Limpopo Province, RSA. This paper describes the field experimentation and the results of the evaluation of APSIM against observed grain and total biomass yields and soil water data. It also examines the simulated estimates of components of the water balance and WP of maize and legume crops using APSIM.

Materials and Methods

Field Experimentation

Field experiments were conducted at Tafelkop, a smallholder-farming village located on the Nebo Tableland in Sekukhune District of Limpopo Province, RSA. The soils are shallow (up to 1.0m rooting depth) loamy sands to sandy loams. The rainfall season is uni-modal (October/November to March/April) with an average total of 500 mm (2002-2008 rainfall). The smallholder cropping system is dominated by maize production, but farmers experience high seasonal variability of maize yields due to the unreliability of the seasonal rainfall and its distribution.

The Grain Crops Institute and the smallholder farmer association at Tafelkop established varietal trials of groundnut and bambara nut in the 2007/08 cropping season. Separate trials were established for each legume species, with 6 cultivars and 3 replicates laid out in a RCBD design. Plot sizes were 3m x 5m in groundnut and 4.5m x 3m in Bambara. Each plot contained 4 rows of plants. Demonstration plots of maize (PAN6479) and cowpea (Betch White) were established with the farmer association in plots (10 m x 30 m) adjoining the legume varietal trials. The groundnut and maize crops were sown on November 14, whilst the bambara and cowpea crops were sown on December 5th. The maize received 120 kg of starter fertiliser (3:2:1(25) containing 15 kg N ha^{-1},10 kg P_2O_5 ha^{-1} and 5 kg K ha^{-1}) at planting and top-dressed N fertiliser (14 kg N ha^{-1} as lime ammonium nitrate) on January 14, 2008. Both fertilisers were banded along the plant row. On the same date, the groundnut also received N top-dressing (11.2 kg N ha^{-1}) to compensate for yellowing of the plants following high rainfall. The maize was harvested on April 29, groundnut on March 26 and cowpea on March 18, 2008. For the purposes of model evaluation, replicated treatment plots of Nyanda groundnut and SB7-1 Bambara were sampled (9.1 m^2) at crop maturity for stover and grain yield. Bulk samples were also taken from the maize (stover 72 m^2, grain 109 m^2) and cowpea (36 m^2) demonstration plots to determine stover and grain yield.

ICRISAT monitored the trial plots for changes in soil water content during crop growth using gravimetric methods. Initial soil samples were collected on December 12, 2007 in the groundnut and bambara trials. Subsequent samplings took place on February 22 (all 4 crop areas), March 29 (groundnut, maize and cowpea) and May 5 (bambara), 2008. Sampling depth intervals were 0-0.1m, 0.1-0.3m, 0.3-0.6m and 0.6-0.9m. Each replicate of the groundnut (Nyanda and SB7-1) cultivars was sampled on each occasion. For maize and cowpea, 3 in-plot areas of the final harvest area were sampled on each occasion. Gravimetric soil water content was converted to volumetric using a bulk density of 1.5g cm^{-3} in all soil layers. Soils collected on Dec 12th were analysed for soil pH and %OC. The farm owner of the trial field recorded daily rainfall at the site.

Model analysis

Plant biomass, grain yield and soil water balance of the maize, groundnut and cowpea crops were simulated using the APSIM cropping systems model (Keating et al. 2002, Version 6.0), and the model outputs were compared to observed data. Model input parameters for the maize (Pan6479) and groundnut (Nyanda) cultivars have been previously estimated (Dimes and Carberry 2008, Ncube et al. 2008). Growth and yield of Betch White cowpea was found to be adequately simulated using the short duration 'Banjo' cultivar description in APSIM. (As yet, there is no bambara module in APSIM). Dates of crop sowing and N fertiliser applications in the model were specified according to experimentation (see above). Nutrients other than N were assumed non-limiting for plant growth. Plant populations were specified in the model as follows; maize – 2.3 plants m^{-2}, groundnut – 11.7 plants m^{-2}, cowpea - 8.8 plants m^{-2}.

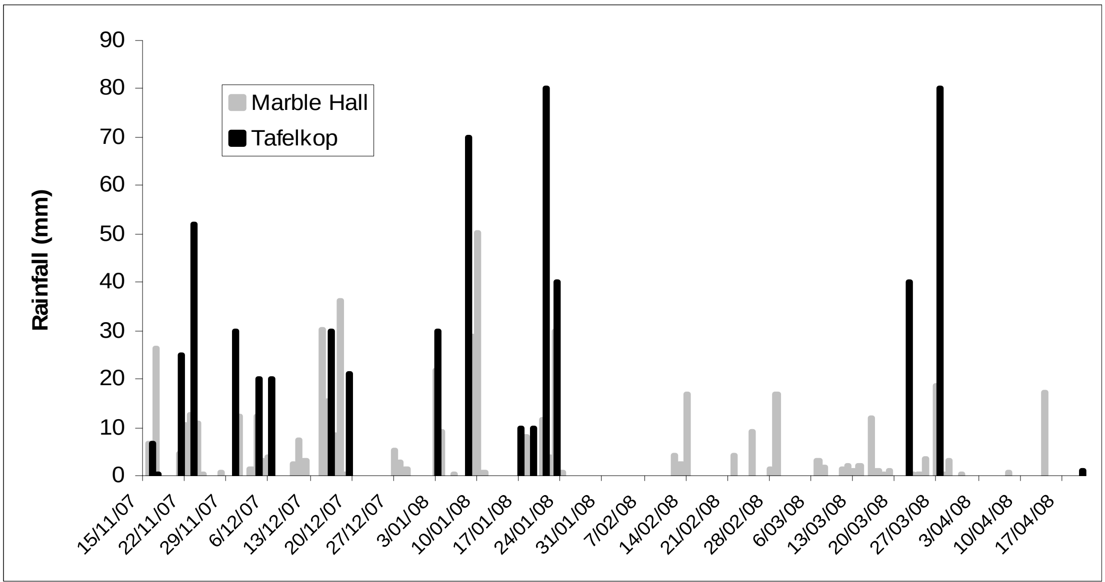
Table 1. APSIM input parameters used in simulation of Tafelkop experiments.

Layer Number	1	2	3	4
SoilWat parameters				
Layer thickness (mm)	100	200	300	300
Bulk density (g cm^{-3})	1.50	1.50	1.40	1.40
SAT	0.250	0.270	0.300	0.320
DUL	0.140	0.155	0.176	0.185
LL15	0.052	0.064	0.070	0.081
Airdry	0.045	0.052	0.070	0.081
Swcon	0.5	0.5	0.4	0.4
CN2_bare	85			
U	3			
Cona	4			
SoilN parameters				
Organic C (%)	0.51	0.46	0.32	0.22
Finert	0.40	0.50	0.80	0.90
Fbiom	0.04	0.020	0.01	0.01
Nitrate-N (mg kg^{-1})	3.79	1.52	0.76	0.38
Ammonium-N (mg kg^{-1})	0.98	0.49	0.25	0.25
Soil C:N	12			
Crop parameters				
LL (maize, groundnut and cowpea)	0.052	0.064	0.070	0.081
Kl	0.08	0.08	0.08	0.08
Xf	1.0	1.0	1.0	1.0

Soil description parameters for simulation of the soil water and N balances in the nominated rooting depth of the soil (0.9m) were specified as shown in Table 1. The crop lower limit of plant extractable water (LL) and the soil drained upper limit (DUL) were derived using the measured soil water contents as a guide. The plant available water capacity (PAWC) of the soil layers to the nominated rooting depth is 90mm. The Runoff Curve Number and soil evaporation coefficients were chosen based on previous simulation studies in these environments (e.g. Ncube et al. 2008)

Soil water and N conditions at sowing of crops were not measured. The start date of simulations was therefore chosen as October 1st with the initial soil water content of layers specified at LL and starting mineral N in the profile set to 15g NO^{-}_{3}-N ha^{-1} and 5 kg NH^{+}_{4}-N ha^{-1}. The model output was used to provide estimates of the soil water conditions at sowing of the crops on Nov 14th and Dec 5th.

Figure 1. Daily rainfall (November 15, 2007 to April 20, 2008) at Tafelkop (farmer record) and Marble Hall (climate station), Limpopo Province, RSA.

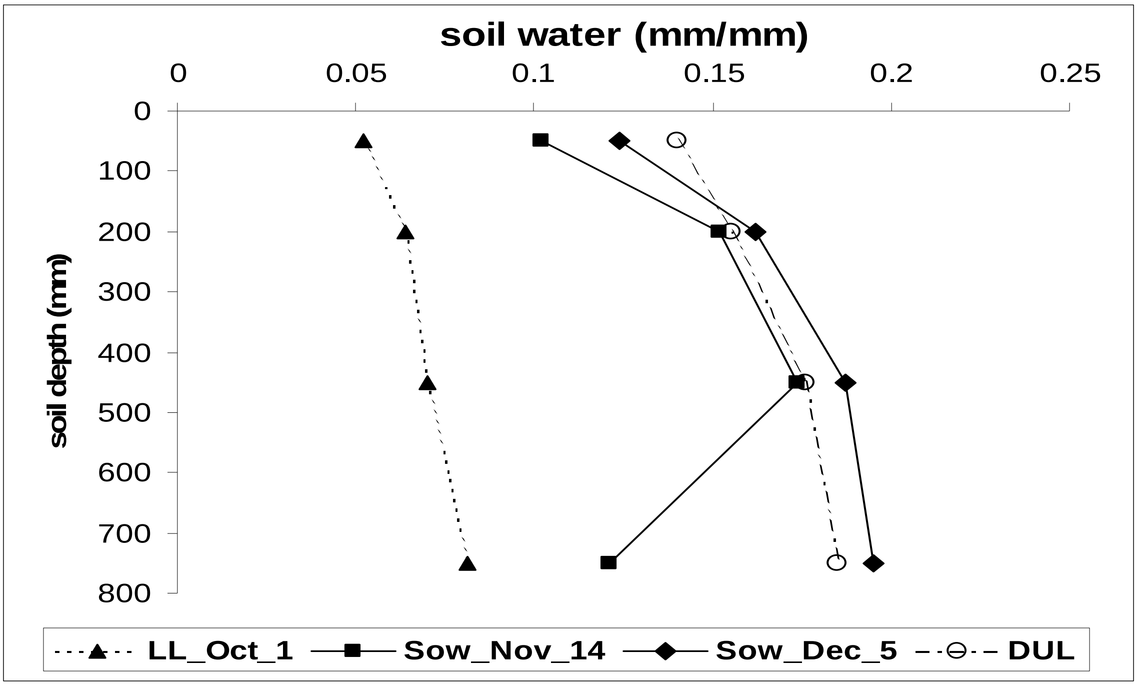


The climate data inputs for ASPIM include daily maximum and minimum temperature, solar radiation and rainfall. Only daily rainfall data was collected at the site. The temperature and radiation data from a nearby (20 km) climate station (Marble Hall, 29º 37' E, 25º 03' S, altitude 878 m) in conjunction with the measured rainfall was initially used in simulations. However, two issues arose in regard to the climate data. Firstly, the Tafelkop site has an altitude above 1200m and it was found that the simulated duration of all 3 crops was under-predicted using the lower altitude Marble Hall temperature data (crops maturing in late February (cowpea) or early March). Consequently, daily temperature data from another site in Limpopo Province with similar altitude to Tafelkop (Polokwane, altitude 1153amsl) were used in the simulations. Secondly, the rainfall record collected by the farmer appeared to comprise cumulative period totals at times, rather than daily amounts (Figure 1). In particular, the 40 mm on March 23 and 80 mm on March 27 had a large influence on over-prediction of simulated soil water content on March 29 (all above DUL) in comparison with observed data. These two rainfall amounts were adjusted based on the rainfall distribution recorded at Marble Hall (Figure 1) and elsewhere - the 40 mm was re-allocated as 20 mm on Feb 29 and 20mm on March 16, while the 80 mm was reduced to 30 mm, in line with the rainfall recorded at another Met Bureau rainfall station (Groblersdal, within 20 km of site). This dramatically improved the prediction of soil water content on March 29th, with only small changes in simulated plant yields (+30 to 150 kg ha^{-1} for grain, +35 to 240 kg ha^{-1} for biomass).

Results and Discussion

The simulated changes in soil water content from Oct 1, 2007 to sowing of the experimental crops are shown in Figure 2. At sowing of maize and groundnut on Nov 14, the soil profile contained 85 mm of PAW to 0.9 m. Notably, the predicted profile distribution indicates that none of the 180 mm of rainfall to this date had yet drained below the sampled rooting zone. At sowing of the cowpea on Dec 5th, after a further 134 mm of rainfall, simulated soil water content shows free draining water in the profile (i.e. above DUL). The model output shows that 10 mm of drainage below 0.9 m had occurred by this date. Predicted runoff of the pre-sowing rainfall was 31 mm up to Nov 14th and a further 48 mm of runoff up to Dec 5th. The corresponding amounts of simulated soil evaporation in these periods were 84 mm and 45 mm.

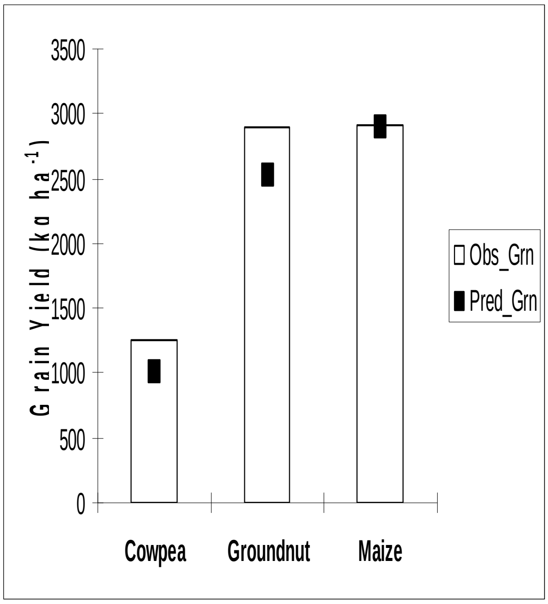
Figure 2. Predicted water content of soil layers at Tafelkop for crop sowings on November 14 and December 5, 2007, following model initialisation of soil layers on October 1 at crop LL, and using Marble Hall daily rainfall from Oct 1st to Nov 16th, and Tafelkop rainfall thereafter.

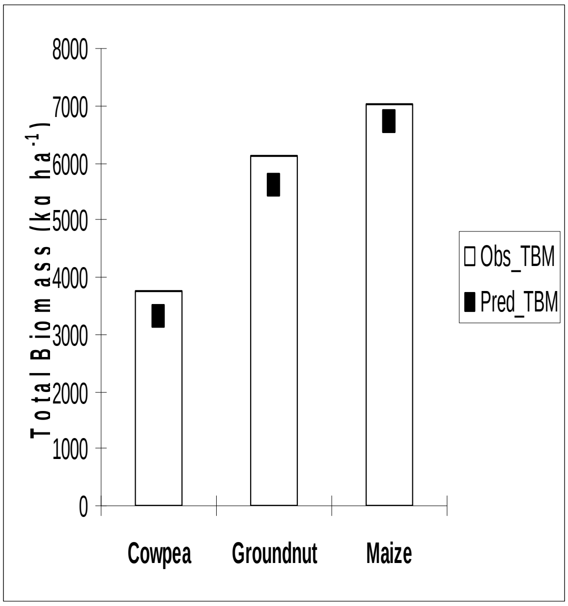


There was very close agreement between observed and predicted total biomass and grain yield ($RMSD_{grain}$ = 257 kg ha^{-1}, $RMSD_{tbm}$ = 436 kg ha^{-1}) of the 3 experimental crops grown at Tafelkop (Figure 3). There was closer agreement for predicted and observed maize yields compared to the two legume crops, for which both grain and biomass yields were slightly under-predicted. However, in general, the observed differences in plant growth and yield due to species and crop duration and the interaction of these effects and planting dates with rainfall distributions (e.g. wet Dec and Jan, much drier February, Fig. 1) were very well captured by the APSIM modelling platform used in this analysis.

The observed and predicted soil water content at sampling dates in maize, groundnut and cowpea plots are shown in Figure 4. There is close agreement between the predicted and observed soil water content ($RMSD_{tsw}$ = 7mm) and its distribution in the sampled rooting layers, for all 3 crops, on December 12. This is partially to be expected since the observed data for Dec 12 were used to help determine the DUL boundary condition of soil layers, at least below 0.3 m. Similarly, fairly close agreement for observed and predicted soil water on February 22 can be expected as the observed values on this date were used to determine the crop LL of the soil layers. However, for groundnut, simulated soil water use by the crop below 0.3 m was noticeably over-predicted on Feb 22.

Figure 3. Observed and predicted grain yield (kg ha^{-1}) and total biomass of cowpea, groundnut and maize crops grown at Tafelkop in 2007/08 cropping season.





The real test on the water balance simulations was therefore how well the model predicted the water content and distribution of the soil layers as measured on March 29, following the late rainfall in March. In this regard it is unfortunate that the observed rainfall at the site for this period appeared to have cumulative period totals rather than daily amounts, and had to be adjusted. However, having done the adjustments in line with ancillary rainfall data from nearby sites, the observed re-filled profile distributions of March 29 were very well predicted by the model in all 3 crops. Overall, the performance of APSIM in predicting changes in profile soil water content under the maize crop was the most reliable ($RMSD_{tsw}$ = 7mm), followed by cowpea ($RMSD_{tsw}$ = 10 mm) and groundnut ($RMSD_{tsw}$ = 14mm). For groundnut, over-prediction of simulated soil water use by the crop below 0.3m on Feb 22nd contributed to the poorer overall performance of the model for groundnut.

The simulated in-crop water balance (sowing to crop maturity) of the maize and cowpea grown at Tafelkop in the 2007/08 season shows both runoff and soil evaporation higher than crop transpiration (Table 2). For groundnut, simulated crop transpiration was the largest component of the water balance, but there is some uncertainty with this estimate given the over-prediction of crop water uptake implicit in the predicted soil water contents at Feb 22 seen in Figure 4. Using in-crop rainfall in Table 2 as the benchmark water input for crop productivity and the measured grain yields in Figure 3, the calculated water productivity (WP, kg grain per mm of rainfall ha^{-1}) of the 3 crops is maize = 6.0 kg mm^{-1} ha^{-1}, groundnut = 6.0 kg mm^{-1} ha^{-1} and cowpea = 3.8 kg mm^{-1} ha^{-1}. Including crop water use of pre-sowing water storage, (i.e. delta_sw and rainfall), the WP estimates are reduced to: maize = 5.6, groundnut = 5.4 and cowpea = 3.0 kg mm^{-1} ha^{-1}.

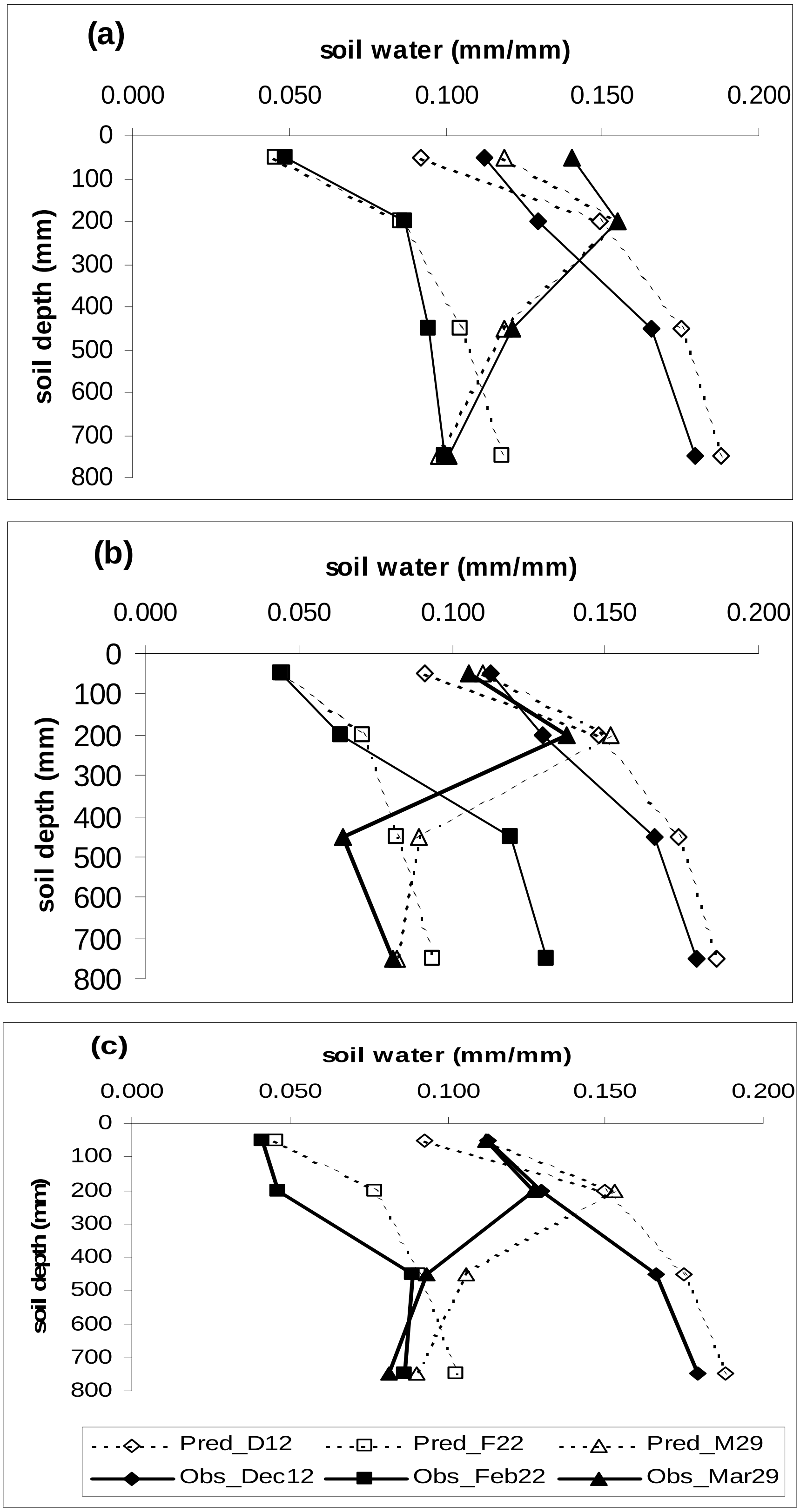
Table 2. Simulated components of the soil water balance of maize, groundnut (Gnut) and cowpea crops grown at Tafelkop in 2007/08 in relation to the crop growth period and the seasonal rainfall period.

Crop	In_Crop rainfall (mm)	Ep (mm)	Runoff (mm)	Drain (mm)	Es (mm)	Delta_sw (mm)	Water use(mm)	% of Water Use as: Ep.	Runoff	Drain	Es
Maize	485	115	170	78	158	-35	520	22	33	15	30
Gnut	485	209	119	65	145	-53	538	39	22	12	27
Cowpea	311	101	123	86	112	-86	417	24	29	21	27
	Season rainfall										
Maize	717	115	201	78	296	+28	689	17	29	11	43
Gnut	717	209	150	65	277	+15	702	30	21	9	40
Cowpea	717	101	202	95	298	+22	695	15	29	14	43

In-crop rainfall – sowing to crop maturity
Season rainfall - Oct 1, 2007 to May 28, 2008
Ep – crop transpiration; Es – soil evaporation; Drain – drainage below 0.9m
Delta_sw = soil water content at crop maturity (May 28)- soil water content at sowing (Oct 1)
Water use = rainfall - delta_sw.

However, given the uni-modal rainfall distribution and the long dry season of semi-arid environments, the overall productivity of crops in such an environment is perhaps best compared using the seasonal water balance as shown at the bottom of Table 2. In this case, crop WP is reduced even further, to: maize = 4.2, groundnut = 4.1 and cowpea = 1.8, kg mm^{-1} ha^{-1}. What is notable about using the seasonal water balance is the much higher proportion of the water balance attributable to soil evaporation (>40%), which largely accounts for the lower WP estimates using this approach. Another notable aspect of this analysis is the very low WP of the short duration cowpea relative to the longer duration maize and groundnut. However, all these results can be considered to be highly seasonal-dependent, and it is likely that in lower rainfall seasons, the short duration cowpea could provide the higher WP outcomes.

Figure 4. Observed and predicted water content of soil layers on December 12, 2007, February 22, and March 29, 2008 under (a) maize and (b) groundnut crops planted on November 14, 2007 and (c) cowpea planted on December 5, 2007.



General discussion

There were shortcomings in this model evaluation study due to issues related to the climate data and the lack of independent data to determine the soil water parameters for model input. Despite these detractions, there are reasons to be encouraged by APSIM's good performance in simulating the observed crop growth and yield of the three crops and the associated observed changes in soil water contents in the rooting zones.

Firstly, reliable prediction of total biomass is a prerequisite to simulation of the soil water balance. This is because simulated crop water uptake and canopy cover estimates by the crop have important feedback mechanisms on the simulation of soil water balance processes such as partitioning of rainfall into runoff and infiltration, and soil evaporation. Secondly, reliable partitioning of biomass to grain yield across the species is essential in determining estimates of WP that can be used with confidence in comparing the different cropping options, from a biological yield perspective or, more particularly, on an economic basis (e.g. to take account of the high value of legume grain relative to cereal grain). Thirdly, while the only component of the soil water balance measured in the experiments were changes in soil water storage, the good agreements achieved in predicting the different soil water distribution profiles observed over the course of the crops provide indirect evidence for having confidence in the simulated output for the other components of the water balance, namely crop water use, runoff, drainage and soil evaporation.

As a consequence, the model was able to provide estimates to fill measurement gaps in water balance components of the field experiments, thereby allowing more detailed and appropriate calculations for comparing the WP of the different crops. Such measurement gaps can be expected to be a common feature of field evaluation studies commissioned by the CPWF. Further, the analysis presented 3 alternative approaches to calculating the WP. Which approach will be adopted and used by the CPWF for consistent analysis within and between basins is perhaps an important issue yet to be resolved. What is clear from this study is that crop-soil simulation modelling can, and should play an important role in these analyses, firstly by adding value to any field experimentation (as done here) and secondly, as a cost effective means of extrapolating the experimental results to alternative management, environment and seasonal conditions. But ultimately, for research projects such as PN17 with a focus on improved water management within a basin across multiple users, it becomes an essential tool to provide estimates of the changes in water balances components (deep drainage and runoff) of proposed crop improvement interventions that have clear consequences for water users and ecological needs beyond the field scale.

Acknowledgement

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Water use and yield of millet under the zai system: understanding the processes using simulation

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Abstract

In the drylands of Africa about 90% of the population are rural and depend on subsistence agriculture for their livelihoods. There is increasing pressure on natural resources due to high population growth, and farmers are forced to cultivate marginal lands due to limited availability of good cropping land, thereby compounding the land degradation problem. Low and erratic rainfall, its poor distribution within the growing season, prolonged dry spells, lack of adequate water infiltration due to soil physical degradation (crusting) and nutrient shortage adversely affect crop growth and yields. To address these problems, indigenous, easy to implement innovations such as the zai system may help increase productivity.

The effect of three planting techniques (flat, zai pits of 25cm or 50cm diameter) and three fertility management options (none - control, crop residue, cattle manure) were tested at Damari, Niger in 1999. Soil water content was monitored weekly throughout the growing period.

Data from that experiment were used to determine the ability of the CERES-Millet model of the Decision Support System for Agrotechnology Transfer (DSSAT) to predict yield response to the zai water harvesting system. The model simulated the observed yield response of the control and the manure amended plots with high r-squared (0.99), low residual mean square error (340 kg ha^{-1} for total biomass and 94 kg ha^{-1} for grain yield) and high d-statistic (0.99), but this was not the case for the crop residue treatment where yield was over-predicted. Soil water content and extractable soil water were also well simulated for the control and manure treatments. This evaluation of DSSAT provides a starting point for research to evaluate the performance of these technologies over wider areas in West Africa. The application of models for such studies must be interpreted in the context of limitations of the model to address constraints related to soil and climate. Nevertheless, the highly variable crop response to technologies in this region due to the interacting effects of rainfall, management and adverse soil conditions make this an extremely important approach in planning for outscaling technology adoption and in interpreting results from experimental field research.

Key words

crop model, rainfed, dryland, Africa, CERES, DSSAT

Introduction

In the dry lands of Africa, about 90% of the population are rural and depend on subsistence agriculture for their livelihoods (Bationo et al. 2003). Low and erratic rainfall, its poor distribution within the crop growing period, prolonged dry spells, lack of adequate water supply due to soil physical degradation (soil crusting, low water retention) and nutrient shortage often adversely affect crop growth and yields in this zone (Zougmoré 2003). According to Sundquist (2004) desertification along the Sahara desert proceeds at an estimated 1000 km^2 every year, which further increases the pressure on arable land. One reason for this is mounting population pressure (3% yearly growth on average) and limited availability of fertile land. Many researchers have studied a wide range of management practices for increasing productivity, including use of better adapted varieties, inorganic and organic fertilizer (Buerkert et al. 2002; Schlecht et al. 2004; Bationo et al. 1995; Yamoah et al. 2002; Tabo et al. 2007), crop rotation and residue management (Bado et al. 2007; Fatondji et al. 2006; Adamou et al. 2007), and rain water harvesting (Agyare et al. 2008; Roose et al. 1993).

One of the techniques studied is the zai system, an indigenous technology that combines rain water collection (Roose et al. 1993; Fatondji 2002), and nutrient management. Research has shown that the zai technology increases crop yield and straw (residue) production on highly degraded soils and helps to alleviate the adverse effects of dry spells, which are frequent during the cropping period in the Sahel (Roose et al. 1993; Hassan 1996; Fatondji et al. 2006). The improved crop performance results from soil fertility improvement derived from the applied amendment, and wind-driven materials that collect in the pits, and from improved soil water status following the breakage of the surface crust and consequently higher water infiltration (Fatondji 2002). Applying the zai technology on crusted soils results in rapid progress of the soil wetting front, which may drain to deeper layers to recharge ground water and also leach nutrients (e.g., nitrates, Fatondji et al. 2007). Depending upon the soil and crop growth conditions, the proportion of drained water is variable. Using the zai system or other soil and water conservation techniques for crop production may improve productivity and help eliminate hunger in the dry land of West Africa. However soil type, climate and other conditions vary over time and space and influence the ways those technologies interact.

Because many studies do not collect enough data to understand the interactive effects of soil, weather and management conditions that impact on crop yield, it is difficult to extrapolate results from specific experiments to other soil and weather conditions. Crop simulation models deal with these interactions and have been used to predict the effect of management technologies across sites and seasons, and may also help identify better management techniques for a wide range of conditions. However it is not clear whether the models are suitable for predicting crop performance in the degraded soils and extreme climatic conditions of West Africa. Although models have been used in many studies in Africa, they usually take into account only 1 or 2 limiting factors, such as variable rainfall and fertilizer input. Degraded soils have a number of factors that interact to limit crop growth and yield in complex ways. In order to use crop models for those conditions, they first need to be calibrated and tested in experiments in which measurements are made to provide all of the needed soil parameters, weather conditions, initial soil conditions, management inputs and soil and crop growth responses. If the models perform well, they can be used to predict performance of the technologies for a range of site and seasonal conditions, and reduce the need for expensive and time-consuming field experimentation across regions. They can also be used to predict parameters which are very difficult or expensive to measure, such as evapotranspiration (ET) and crop water productivity with respect to ET.

Crop models in the Decision Support System for Agrotechnology Transfer (DSSAT) (Tsuji et al. 1994; Jones et al. 2003) have been used widely worldwide. This modeling system was designed for users to create computer experiments, simulate the outcomes of the agricultural practices, soil, and weather conditions, and suggest appropriate solutions for specific sites (Jones et al. 1998). The millet model (CERES-Millet; Singh et al. 1991), like other models in DSSAT, is designed to be independent of location, season and management since it simulates the effects of weather, soil water, cultivar, and nitrogen dynamics in the soil on crop growth and yield. This model has not been evaluated for simulating production using zai technologies.

An experiment was conducted on a farmer's field at Damari in Niger (West Africa) to evaluate management systems that would increase yield and water productivity of millet (Fatondji et al. 2006). The overall objective of that work was to study the productivity and resource use efficiency of millet under rainfed conditions in the zai system as compared to flat planting on a highly degraded soil. In this study, we used data from that experiment to determine the ability of the CERES-Millet model to predict yield response to the zai water harvesting system. This experiment was selected because of the potential importance of the zai system in the Sahel, which has highly degraded soils, and because an intensive set of data was collected on soil physical and chemical properties, daily weather, weekly volumetric soil water at different depths, and crop yields. The soil and climate conditions of this site challenge the capability of crop models because of the extreme values of some of the soil physical and chemical properties and intensive rainstorms. The low soil water holding ability, soil crusting, low organic carbon, variable quality of organic amendments, low fertility, low pH and intensive rainfall events, when combined, may stretch the limits of crop models beyond their capabilities. In this study we hypothesized that millet crop performance and soil water status in the zai technology could be predicted with the CERES-Millet crop model using carefully measured weather and soil data at the experimental site. The specific objective was to evaluate the ability of this model to simulate the performance of millet in the zai system.

Material and methods

Experimental site

The experiment was conducted in 1999 in a farmer's field at Damari in Niger. Damari (13°12' N and 2°14' E) is located 45 km from Niamey, the capital city of Niger. The long-term average annual rainfall at Damari is 550 mm, which falls between June and September. The long term monthly average minimum and maximum temperatures vary, respectively, between 16°C in January and 28°C in April and May and between 32°C in January and 42°C in April and May (Figure 1). Monthly potential evapotranspiration (PET) is very high; monthly rainfall exceeds PET only in August (Sivakumar et al. 1993). During the experiment in 1999, weather conditions followed this trend; total rainfall for the season was 499 mm (Figure 2).

The soil at the experimental site at Damari is a Kanhaplic Haplustult (Soil Survey Staff 1998). Table 1 shows measured soil properties (0-600 mm) at the experiment site. The soil is highly acidic (pH-H_2O = 3.6 - 4.5), with 84% sand content, low effective cation exchange capacity (ECEC) (2.8 cmol kg-1), and very low soil water holding capacity (PAWC = 25mm to 600 mm soil depth). Because of the soil properties and intense rainfall events in the region the soils are prone to surface crusting (Casenave and Valentin 1989) and high runoff. The soil organic carbon ranged from 0.04 – 0.14% (Fatondji et al. 2006), even lower than the typical levels in Niger (about 0.22%, Bationo et al. 2003). The nutrient levels of soils in the region are very low (Bationo et al. 2003) and severely limit yield compared to the genetic potential of the rainfall environment. Available P was far below the level of 2.1 mg/kg reported by Sinaj et al. (2001) typical of the soils of the Sahel, indicating the advanced degradation status of the soil. Total nitrogen level was also very low compared to the average levels for Sub-Saharan Africa reported in Bationo et al. (1996). For other details on the experimental site, refer to Fatondji et al. (2006).

Figure 1. Long term weather data at Damari, Niger; 1983 - 1999

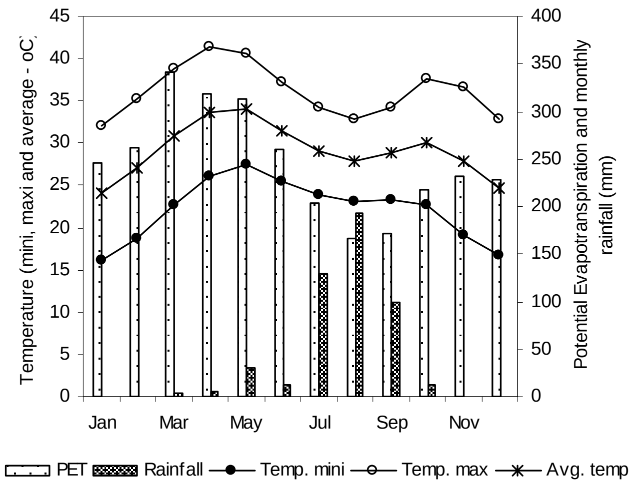
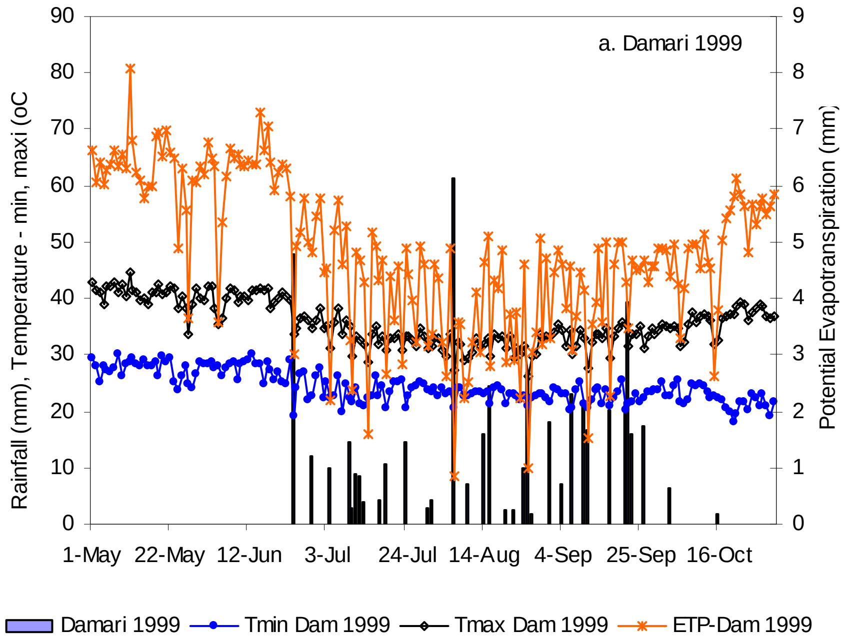


Figure 2: Daily rainfall, minimum and maximum temperature, and potential evapotranspiration at the experiment site, Damari in 1999



Despite these extreme conditions, farmers are forced to use soils such as this for producing crops because of limited land availability. Water harvesting technologies are therefore used to assure better soil water conditions for the crop. Due to the high price of mineral fertilizer, and also the risk of leaching of nutrients, farmers mostly use organic manure in the zai technology. These amendments are often of variable quality and with variable decomposition properties.

Table 1. Soil profile characteristics of the experiment field at Damari, Niger, measured in 1999*

Land management	Depth	pH	Total N	P-Bray 1	C org	Sand	Clay	Bulk density
	(cm)	(H_2O)	(mg kg^{-1})	(mg kg^{-1})	(%)	(%)	(%)	(g.cm^{-3})
Flat	15	3.9	0.13	1.73	0.14	84	13	1.6
	30	3.9	0.11	1.03	0.09	83	13	1.5
	45	3.7	0.12	0.74	0.07	84	13	1.5
	60	3.6	0.12	0.46	0.06	85	12	1.5
Zai 25 cm	15	4.6	0.11	1.03	0.09	84	13	1.5
	30	3.9	0.12	0.74	0.07	83	13	1.5
	45	3.7	0.12	0.46	0.06	84	13	1.5
	60	3.6	0.12	0.46	0.06	85	12	1.5
Zai 50 cm	15	4.2	0.11	1.03	0.09	84	13	1.5
	30	3.9	0.12	0.74	0.07	83	13	1.5
	45	3.7	0.12	0.46	0.06	84	13	1.5
	60	3.6	0.12	0.46	0.06	85	12	1.5

*Adapted from Fatondji, et al (2006)

Field experiment

The effect of planting technique (planting on the flat vs. planting in zai pits of 25 cm or 50 cm diameter – 15 to 20 cm deep) and amendment type (none - control, millet straw, and cattle manure) on millet growth and development were studied. The zai pits were dug during the dry season in the third week of May 1999. When digging the pits, the excavated soil was placed perpendicular to the slope on the lower side of the pit so that water flow would be oriented into the pit. The organic amendments were applied 36 days before sowing at 300 g dry weight per pit or pocket (location of the plants on flat plots) (i.e. 3 t/ha for both manure and straw). When applied in the flat planting treatments, the amendment was incorporated to 5 cm depth to protect it from wind that could displace it. When applied in the zai pit, it was not initially covered, but it was covered later due to accumulation of sand and plant material blown and washed into the pit. Where needed, the field was kept free of weeds throughout the growing season by hand hoeing. In fact weeds did not grow between the crop lines in most of the plots.

The millet straw used as amendment in the study had been collected from experimental fields at Sadoré and cut into small pieces of 10 cm length, and the cattle manure was collected from a barn on the same station. Urine was mixed with the faeces, which increased N and K content and improved the quality. Table 2 presents the chemical composition of these amendments. The 2.53% N concentration of the manure was higher than the 1.2% N for cattle manure typically collected in farmers' corralled fields (Esse et al. 2001).

The experimental design was a randomized complete block design (RCBD) with 3 amendment treatments and 3 planting techniques (9 treatment combinations) replicated 4 times. Millet variety Sadore (the locally grown landrace) was sown on 28 June at a planting density of 10000 pockets per ha and harvested at maturity. Plants were thinned to 3 plants per pocket, approximately 3 weeks after planting.

Table 2. Nutrient composition (%) of the organic material used in the experiment and nutrient applied (kg ha^{-1})*

Organic	Nutrients content and C/N ratio				Nutrients applied per ha (kg)		
amendment	N (%)	P (%)	K (%)	C/N	N	P	K
Millet straw	1.18	0.10	1.57	50	32.7	2.8	43.5
Manure**	2.53	0.94	1.72	21	62.9	23.3	42.8

* Adapted from Fatondji et al. 2006

** Manure mixed with urine

Measurements

At maturity, grain and straw dry weight were collected from whole plots after excluding one border row on each side of the plots. The data were used to calculate grain and total biomass yields on a per hectare basis.

Volumetric soil moisture content was measured weekly at 15 cm intervals (0-15, 15-30 cm etc) down to 210 cm depth using a neutron probe (Didcot Instrument Company Limited; Wallingford, UK). The probe had been calibrated in-situ for the soil of the experimental site using the gravimetric method suggested by the manufacturer (Fatondji et al. 2006). The raw neutron probe data were converted to volumetric soil water content (cm^3 cm^{-3}). Two 48 mm inner diameter aluminum access tube were installed in each experimental plot. One tube was installed between the planting pockets while the second was about 5 cm from the plants on flat as well as in the pits (in zai-treated plots). Data of the tubes installed close to the plant (on the pocket or in the zai pit) are reported in this paper. The first measurements were made before the first rainfall on 7 June in 1999 and were continued throughout the growing period until harvest. To study the progress of profile wetting, several dates were selected to match soil water measurements with the dates of other observations. These were the date of first measurement before planting, the day of planting, and the days of plant sampling. Extractable soil water was calculated as the difference between the stock of water at field capacity (or soil water drained upper limit, DUL) in the soil profile to the maximum rooting depth of 60 cm and the stock of water in the same soil profile at permanent wilting point (or lower limit). Rainwater productivity was calculated as the ratio of total biomass or grain yield to the amount rain between planting and grain harvest dates and was expressed in kg per ha per mm of rain water (kg ha^{-1} mm^{-1})

CERES-Millet model simulation

The CERES-Millet model in DSSAT (Tsuji et al. 1994) was used to simulate the effects of the planting methods and amendments on straw and grain yields, soil water content, and extractable soil water. The CERES-based organic matter and nitrogen dynamics module (Godwin and Singh 1998) was used. Measured soil properties and weather parameters were used to provide the needed inputs to the model. These inputs are: (1) the initial chemical and physical status of the soil, which was determined through soil characterization measurements made on samples collected on 12 May 1999, prior to the installation of the experiment; soil samples were collected up to 200 cm depth to measure nutrient content (including nitrate) and particle size distribution; (2) nutrient contents of the amendments; (3) initial soil water content, determined using the first neutron probe measurement on 7 June before rain started; (4) weather data, collected with an automatic Campbell scientific weather station at the site (daily rainfall, solar radiation, and minimum and maximum air temperature); (5) crop phenology, monitored throughout the cropping season. For comparison with the simulated variables, grain and straw yield and weekly soil water content and plant extractable soil water were determined. The root mean square error (RMSE), mean absolute error (MAE) and d-statistic (Willmott 1981) were used to assess the agreement between simulated and observed values.

For the determination of all soil parameters at different depths in the zai treatments, the first measurement started from the bottom of the pit as the rooting zone of the crop sown in the pit started from this level. This was taken into account in the initial conditions and in the soil characteristic input parameters for the model. Therefore 9 sets of initial conditions and soil analysis were used, one for each treatment combination tested.

Estimating model inputs not directly measured

Some model parameters are difficult to measure directly and must be estimated from other measurements. In this study, three soil parameters were estimated using weekly soil water content at different depths in selected treatments: the lower limit of plant available water (LL), the drained up limit (DUL), and the surface water runoff curve number (ROCN). Although there are pedotransfer functions for estimating LL and DUL, from measured soil texture, these functions are not reliable for specific field sites (Gijsman et. al 2003).

To estimate LL, we took the average of the soil water contents of the first two soil layers (0-15 and 15-30 cm) measured on 7 June before the first rain of the season. Due to the long dry season from October in the previous year, these first two layers were dry. The average volumetric water content of the two layers was 0.024 cm^3 cm^{-3}. To estimate DUL, the water contents of the flat-planted control and 50 cm zai control treatments after significant rain were used to estimate DUL for each layer for flat and zai treatments, respectively. The soil water content at saturation (SAT) was estimated from SAT= F_s*(1-BD/PBD) where F_s is the fraction of the porosity that is wet when water is applied which ranges from 0.93 to 0.97 (we used 0.95), BD is bulk density, and PBD is particle bulk density. The results are reported in Table 3

Due to soil crusting, runoff was high in the flat-planted treatments. Therefore a high coefficient ROCN was set for this treatment by comparing the time series of measured and simulated soil water contents in the control and manure flat-planted treatments. Iteratively, ROCN values were changed until simulated soil water vs. depth and time of season in these two treatments were in good agreement with observed soil water contents. Following this procedure, a runoff coefficient of 98.4 was obtained for the flat treatment. To estimate the runoff coefficient for the two zai pit sizes, we calculated the proportion of area occupied by a zai pit relative to the total area per pocket (1 m^2). Although water falling between the pits has a chance to be captured in the pits, for simplicity we assumed that any water falling between the pits would runoff at a rate determined by the ROCN of the flat treatment and that all rain falling on the area of the pit would be retained. Based on this assumption we calculated a weighted average ROCN using the runoff coefficient of the flat planting and relative area of the zai hole to the area not in the hole. Therefore we obtained a ROCN of 93.5 for the zai of 25 cm diameter and 79.1 for the zai of 50 cm diameter. One ROCN was used for each planting technique regardless of amendment.

Genetic coefficients

Genetic coefficients were estimated using measured biomass and grain yield and physiological maturity date for the zai manure treatments. Ideally, genetic coefficients should be estimated using data collected in experiments without water and nutrient stresses, but this is not possible in many cases such as in this experiment. We used the zai manure treatments as water and nutrient stress would be least in these treatments. Following Boote et al. (2003); Mavromatis et al. (2001), the coefficients for a variety in the DSSAT millet cultivar file were initially used, and phenology coefficients (P1, P2R, and P2OP5) were adjusted so that the simulated maturity date closely approximated the mean observed date for the

Table 3. Initial (measured) soil water content and nitrate concentration, and hydraulic properties estimated from measured data at Damari in 1999

Land management	Depth	Initial soil water content	Soil water lower limits (LL)	Soil drained upper limit (DUL)	Saturation point (SAT)	Nitrate content
	(cm)	($cm^3.cm^{-3}$)	($cm^3\ cm^{-3}$)	($cm^3.cm^{-3}$)	($cm^3.cm^{-3}$)	($g[N].Mg^{-1}$ soil)
Flat	15	0.022	0.024	0.065	0.361	0.007
	30	0.028	0.024	0.075	0.354	0.004
	45	0.038	0.024	0.08	0.354	0.003
	60	0.042	0.024	0.08	0.358	0.002
zai 25cm	15	0.026	0.024	0.08	0.361	0.004
	30	0.037	0.024	0.08	0.354	0.003
	45	0.044	0.024	0.09	0.354	0.002
	60	0.046	0.024	0.09	0.358	0.002
zai 50 cm	15	0.027	0.024	0.08	0.361	0.004
	30	0.038	0.024	0.08	0.354	0.003
	45	0.041	0.024	0.09	0.354	0.002
	60	0.046	0.024	0.09	0.358	0.002

manure treatments (Table 4). Afterwards, coefficients that determine biomass production and its partitioning into grain yield were considered. However, this was done simultaneously with adjustments to the soil fertility factor (SLPF), which must be used to account for limited nutrients in the soil that are not included in the model. Other researchers (e.g., Singh et al. 1994; Naab et al. 2004) found that values ranging between 0.63 and 1.00 were necessary for some soils in India and Ghana. In this case, it was noted that soil P levels were very low, which justified our modification of this factor. Thus, G5, the parameter that partitions assimilates into grain, and SLPF were modified together using both grain and biomass yield as criteria.

Maximum rooting depth is determined by a root growth factor (SRGF) in each soil layer. Layers down to the maximum root depth have values computed from the DSSAT software, and values below that were set to 0.0. In this study, it was assumed that due to Al toxicity and low pH below 30 cm depth, roots would not grow below 30 cm. This was consistent with the neutron probe data that showed no soil water extraction below that depth. Therefore SRGF was set to zero for all layers below that depth.

Although all these estimates were obtained by indirect methods, they were based on measurements that provided consistent predictions taking into account the many interacting factors.

Table 4. Genetic coefficients for the millet local variety (Sadore local) used in the study

Parameter	Initial values from DSSAT file (Variety CIVT)	Estimated values (Sadore local)
Thermal time from seedling emergence to the end of the juvenile phase (P1)	180	170
Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate (P20)	12	12
Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above (P2R)	150	150
Thermal time (degree days above a base temperature of 10°C) from beginning of grain filling (3-4 days after flowering) to physiological maturity(P2OP5)	500	450
Scalar for relative leaf size (G1)	2	1
Scalar for partitioning of assimilates to the panicle (G5)	0.50	0.77
Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances. (PHINT)	43	43

Results and discussion

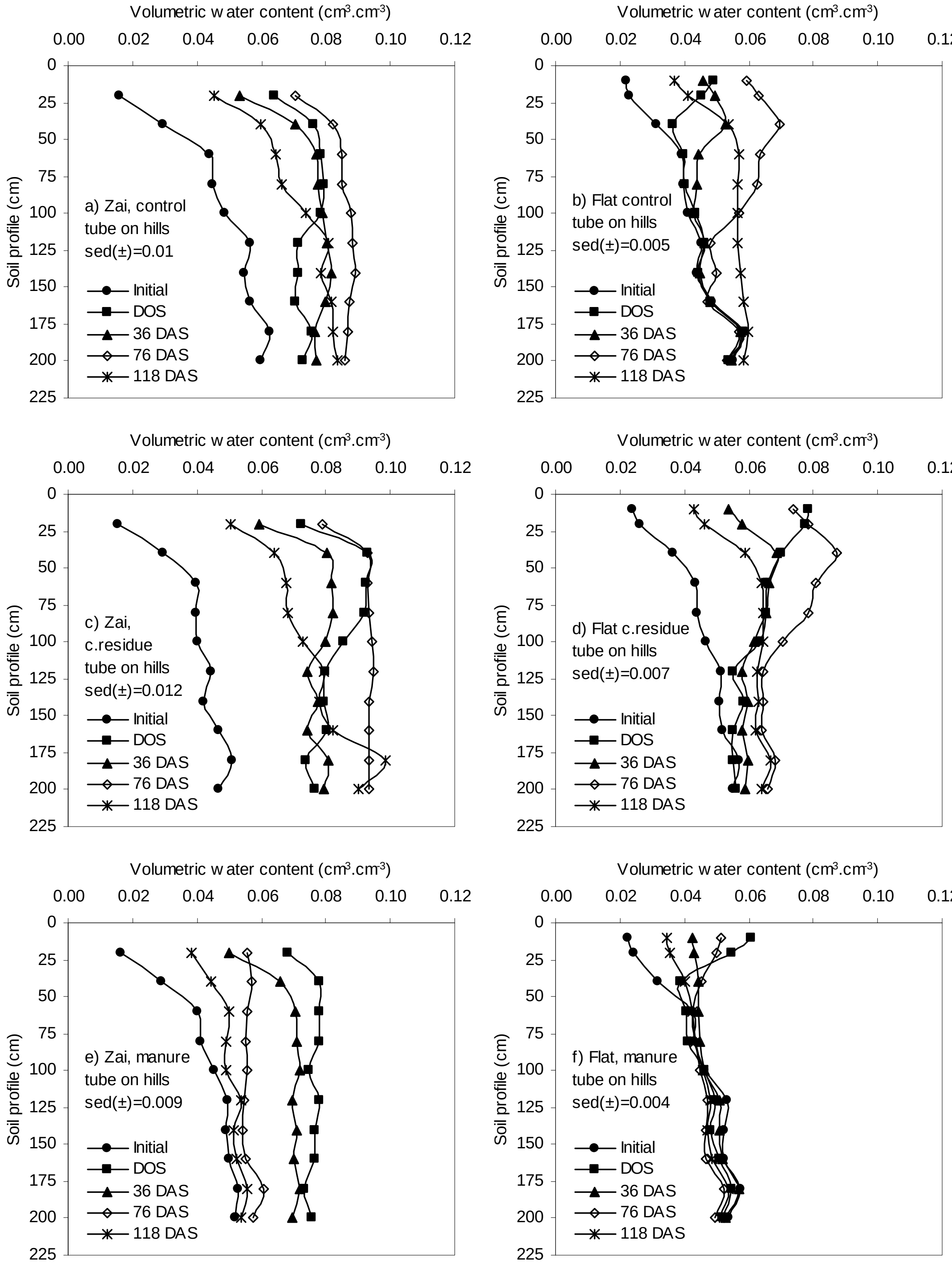
Experiments

Soil water content: Figure 3 shows soil water content vs. depth for different measurement dates for the 25 cm zai and flat planted treatments. The soil had wetted up to below 200 cm depth in comparison with initial soil water content in the zai, (Figure 3 a, c, e), whereas in the flat treatments the depth of wetting ranged from about 25 to 115 cm (Figure 3 b, d, f). The same trend was observed for both pit sizes, but soil water content in the zai of 50 cm diameter was much higher to the measurement depth (200 cm) throughout the profile. The results indicate that even though the structure of the soil is sandy, breaking the surface crust and digging the pits was highly favorable for water infiltration compared to the flat treatment.

Volumetric soil water content (VWC) was also higher at deeper layers in the zai than in the flat control and residue treatments, respectively, even towards the end of the season. However soil water content in the zai and flat manure treatments was similar in the latter part of the season.

In general, the soil water profile was drier in the manure treatments than the other treatments regardless of planting technique, especially towards the end of the cropping season, reflecting high water consumption of the crop due to increased biomass production with manure (Table 5). In the flat treatment amended with cattle manure, the wetting front remained at 60 cm during the whole growing period, which is an indication of lower water infiltration and/or increased crop water uptake due to increased biomass production.

Figure 3. Effect of planting technique (25 cm zai, flat) and amendment (none-control, crop residue, manure) on soil water content at Damari; sed = standard error of difference between means; DOS = day of sowing; DAS= days after sowing



In the flat-planted treatments, extractable soil water (to 60 cm) was lower than in the zai-treatments regardless of the amendment type (Figure 4). This was more pronounced in the manure treatments, probably due to higher plant consumption as reported in Fatondji et al. (2006). Biomass and grain yield in these treatments were much higher than in the control. The same thing may have happened in the 25 cm diameter zai amended with manure where extractable soil water dropped substantially from day 240 until the end of the cropping season, which was not the case of the zai of 50 cm diameter. This suggests that more water was collected in pits of 50 cm diameter as grain and straw yields in 25 and 50 cm zai were similar (and therefore crop water use would have been similar) in respective amendment treatments (Table 5).

Straw and grain yields: In the control non-amended treatments, the zai treatment increased straw yield by a factor 3 for both pit sizes, while grain yield increased by a factor 19 for pit size 25 cm diameter and 9 for pit size 50 cm (Table 5). Nevertheless the yields were extremely low compared to the average millet grain yield in Niger, which is 300 kg ha-1 (Bationo et al. 1989). No farmer would crop a field that would produce 1 kg ha^{-1} of grain. This is an indication that crop production would not be possible without external nutrient inputs in the soil where the experiment was conducted. It also shows that water is not the major constraint.

In general zai increased straw yield by factor 2 regardless of the pit size, and the increase was statistically significant ($p = 0.008$). Manure application significantly ($p < 0.001$) increased straw yield by factors of 4 and 18 compared to crop residue and the control (none), respectively. There were statistically significant interactions between soil management and amendment type ($p < 0.001$) only in terms of straw yield. Zai significantly increased straw yield (3461 kg ha^{-1} and 3796 kg ha^{-1} for the 25 cm and 50 cm zai, respectively) compared to 1863 kg ha^{-1} for flat planting, when cattle manure was applied. Straw yields were similar among soil management treatments when crop residue was applied.

Manure application significantly ($p < 0.001$) increased grain yield by factors of 7 and 110 compared to crop residue and control (none) respectively. No significant interactions were observed between the factors in terms of grain yield. However a 39% grain yield increase was observed (1156 kg ha^{-1} and 1100 ka ha^{-1} for 25 cm zai and 50 cm zai, respectively) compared to 705 kg ha^{-1} for flat planting in manure amended plots (Table 5). This shows that by breaking the crust by digging the zai pits and application of manure, better conditions were created for crop growth. This may have also helped the crops to escape from the effect of dry spells. In the Sahel, and particularly during this experiment, dry spells resulting in two weeks without rain were frequent (Fatondji et al. 2006). No statistically significant differences were observed between the zai pit sizes in terms of straw and grain yield. This could be due to high variability in the data because of the harsh conditions of the experiment, particularly in the control and the crop residue amended treatments. The residual mean square error was even higher than the treatment mean for crop residue amended treatments. Nevertheless, we speculate that soil nutrient content was so low that water availability alone without application of nutrients made only small differences in crop productivity between the soil management techniques.

These data show that for better results with the technology there is a need of additional input of good quality. Nevertheless due to the excess of water that would collect in the zai it may be preferable to use organic amendment as the basis of this input to minimize leaching losses.

Table 6 shows the effect of organic amendment type on observed rain water productivity and simulated results for the same parameter for comparison. Manure application in the zai resulted in total biomass yield of 12 kg ha^{-1} mm^{-1} of rain on average versus 0.6 kg ha^{-1} mm^{-1} of rain for the control. Grain yield per mm of rain water also increased by factors of 64 and 128 for zai 25 cm and zai 50 cm, respectively, compared to the control non-amended plots. On flat-planted treatments manure application increased rain water productivity by a factor 31. All the differences observed were statistically significant. These results indicate that the crop made better use of rain water in the zai when manure was applied. Similar results were reported by Fatondji et al. (2006) on another experimental site where the same technologies were tested.

Figure 4. Effect of planting technique and amendment type on extractable soil water (0-600 mm). Vertical bars are sed

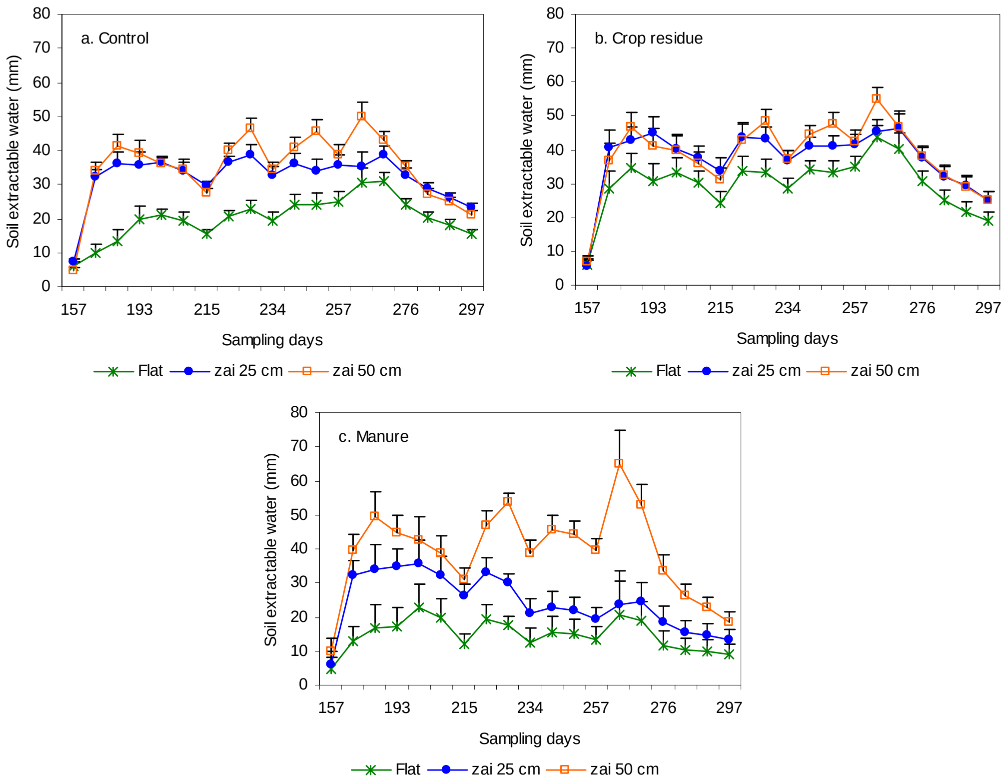


Table 5: Millet straw and grain yield as affected by planting technique under various fertility management conditions. Damari. 1999*

Soil management (M)	Soil amendment (A)			
	Control (none)	Crop residue	Manure	Mean
Straw yield (kg ha^{-1})				
Flat	86	919	1863	956
Zai 25 cm	245	878	3461	1528
Zai 50 cm	171	614	3796	1527
Mean	167	803	3040	
Sed(M) = ± 191.8; Fprobability = 0.008				
Sed(A) = ± 191.8; Fprobability = < 0.001				
Sed(MxA) = ± 332.3; Fprobability = < 0.001				
Grain yield (kg ha^{-1})				
Flat	1	127	705	278
Zai 25 cm	17	168	1157	447
Zai 50 cm	8	157	1100	422
Mean	9	151	987	
Sed(M) = ± 85.8; Fprobability = ns				
Sed(A) = ± 85.8; Fprobability = < 0.001				
Sed(MxA) = ± 148.7; Fprobability = ns				

* Adapted from Fatondji et al., (2006)
Sed = Standard error of difference between means

Table 6: Rainfall water productivity as affected by amendment type under various soil management practices; Damari, 1999

	Rain water productivity ($kg.mm^{-1} ha^{-1}$)			
	Total biomass		Grain	
	Observed	Simulated	Observed	Simulated
Zai 25 cm				
Control	0.67	0	0.04	0
C.residue	2.65	6.6	0.37	1.82
Manure	11.38	13.4	2.56	3.11
Sed(±)	1.476		0.249	
Fprob	< 0.001		< 0.001	
Zai 50 cm				
Control	0.62	0	0.02	0.00
C.residue	2.05	6	0.35	1.62
Manure	12.66	12.9	2.44	2.82
Sed(±)	0.902		0.18	
Fprob	< 0.001		< 0.001	
Flat				
Control	0.21	0	0	0
C.residue	2.57	5.7	0.28	1.42
Manure	6.58	6.2	1.56	1.52
Sed(±)	1.324		0.477	
Fprob	0.008		0.036	

C.residue = Crop residue
Sed = Standard error of difference between means

Model evaluation

Soil water content: Figure 5 shows the simulated soil water contents for the control flat planted treatment for soil layers 5-15 and 15-30 cm compared to the observed data. In general there is a good prediction of the movement of the wetting front on the layer 5-15cm all along the sampling period except for slight under prediction of soil water content on the 4th and the 14th samplings which occurred shortly after rainfall (the 4th sampling was taken one day after 3 days of rain – total of 26mm, and the second one day after rain of 21 mm). Water content on the 7th and 10th sampling dates, which were taken after 11 and 7 days of dry spell respectively, were over-predicted.

In the 15-30cm layer the model under-predicted soil water content at the second sampling, which was 4 days after rain of 48mm, and in the third sampling which was 2 days after rain of 10mm. Subsequently the model tended to slightly over predicted water content, except for samplings 11, 13 and 14, which were taken 4 days after cumulative rains of 39, 38 and 20 mm which were well predicted. In both soil layers the dry spells were over-predicted. In the layers to 45cm and 60cm soil water content was under-predicted from the 3rd to 7th and over-predicted later. However the RMSE was low (0.01) and the d-statistic was high (0.8).

Figure 6 shows the simulation results of the control 25 cm zai for the same soil layers. The general trend was well simulated but the model simulated more peaks which were not observed from the field measurements. Similar trends to layer 30 cm were observed in layers 45cm and 60cm with a RMSE of 0.02 and d-statistic of 0.6. However the r-squared was very low at 0.3. But in layer 45cm except for three, most of the samplings were highly over-predicted

Figure 5. Soil water content in the flat control treatment, soil layers 5-15 (a) and 15 – 30 cm (b). Simulated (Sim) and Observed (Obs) data

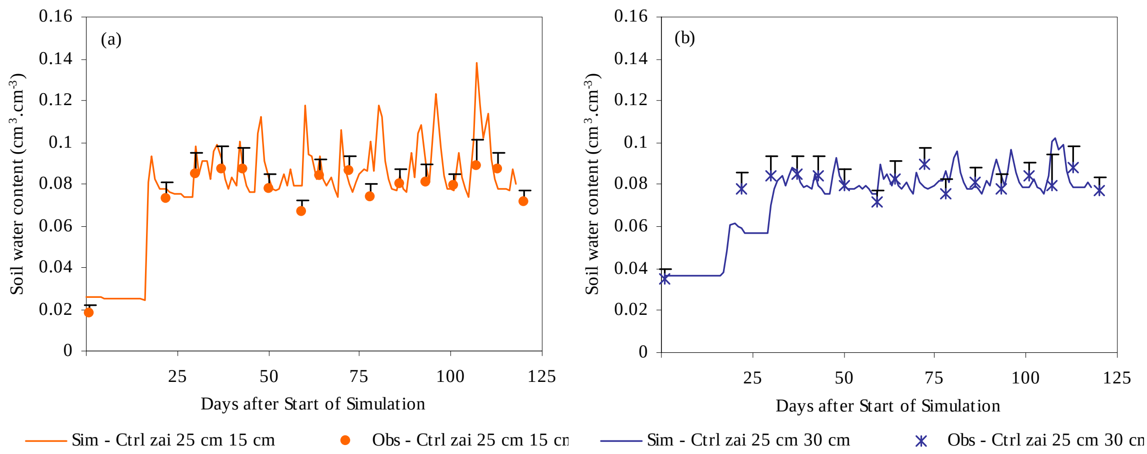


Figure 6. Soil water content in the zai control treatment, soil layers 5-15 (a) and 15 – 30 cm (b). Simulated (Sim) and Observed (Obs) data

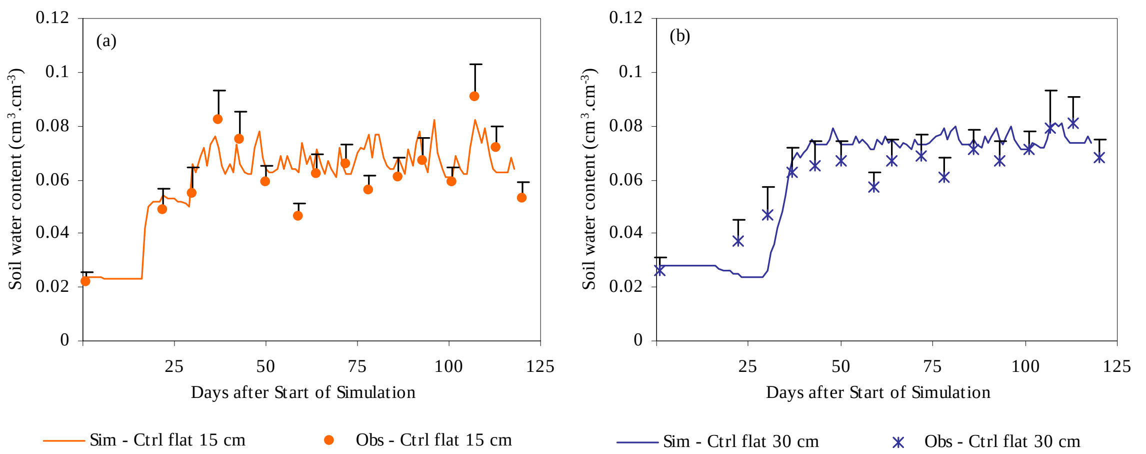


Figure 7 shows the simulated soil water content in the manure amended 50 cm zai. In general the measured trend was captured; nevertheless the 11th sampling that was after 4 days of cumulative rainfall of 39 mm was not simulated accurately by the model. Similar trends were observed in layers 45cm and 60cm with a RMSE of 0.01, d-statistic of 0.8 and r-square of 0.8. There was no consistent relationship between soil water content and the number of days before or after rainfall events. Nevertheless we have to admit that the time resolution of this model would not allow this level of detail. There will be some errors in prediction due to the fact that the model has a daily time step and uses an assumed distribution over time for rainfall, whereas the rainfall generally occurs at much smaller time steps, and the soil measurements were taken at an instant in time. Overall, the ability of the model to simulate over most of the season was pretty good as supported by the low residual mean square error (RMSE = 0.01), high d-statistic of 0.9 and r-square of 0.7 in most cases. Nevertheless further studies may be needed to address these details which may help us understand why the model over-predicted water content in some cases while in other less water content was predicted compared to the observed value.

Figure 7. Soil water content in thr zai 50 cm manure treatment, soil layers 5-15 and 15-30 cm. Simulated (Sim) and Observed (Obs) data

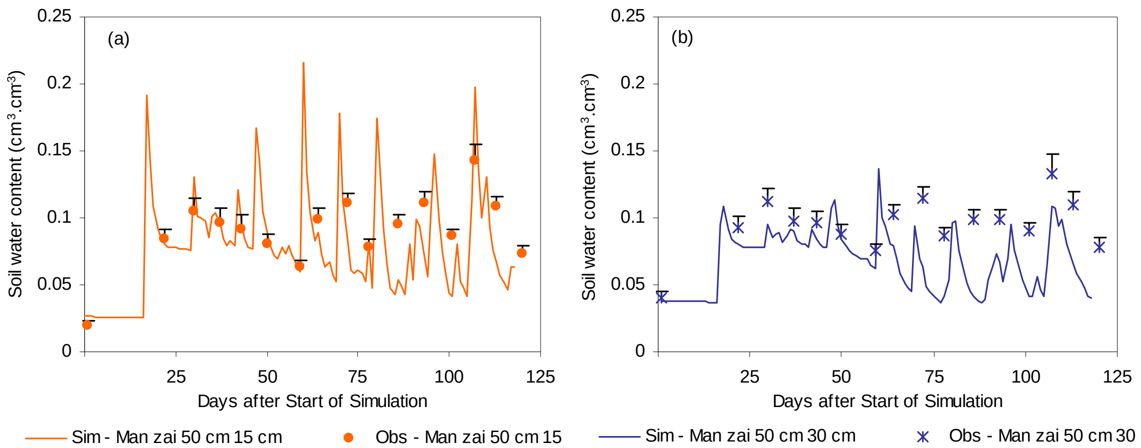
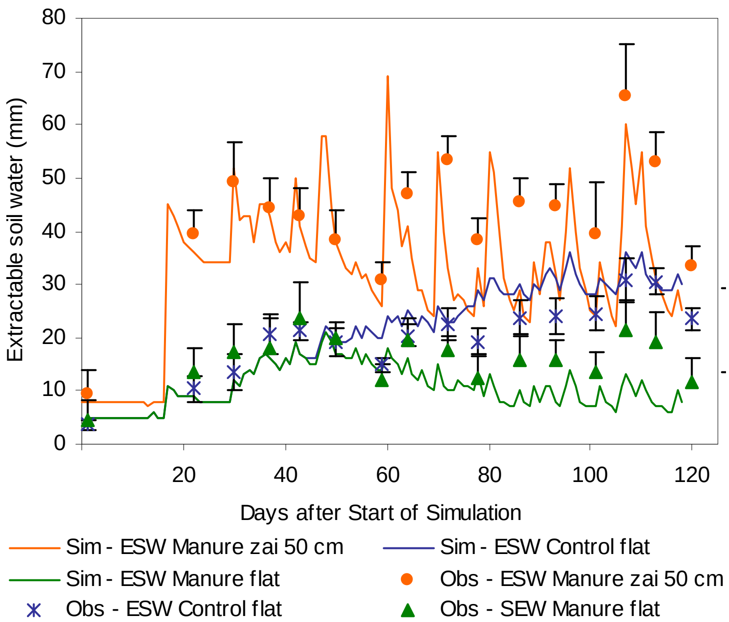


Figure 8 shows the extractable soil water in the top 60 cm of soil. The observed trend was captured by the model in the control flat and manure zai 50 cm with high d-statistics (0.91 and 0.82). Extractable soil water content was overestimated for the samplings 11 and 12, as discussed above. The manure flat treatment had a lower d-statistic (0.62) and very low r-squared of 0.37; but a fairly low RMSE (6.0).

Figure 8. Extractable soil water (ESW, 0-60 cm) in the control and manure flat + manure zai 50 cm treatments. Simulated (Sim) and Observed (Obs) data



One of the major effects of the zai technology is the breakage of the soil crust while digging the pits. Depending up on the size of the pit, the amount of water collected may differ. The results presented here were obtained by using a different runoff curve number for each land management treatment (flat, zai 25 cm and zai 50 cm) to try and reflect this. The general trend was that almost no water extraction occurred below the top 45 cm of soil, which according to Fatondji (2002) was the depth above which 98% of the plant roots (dry weight basis) were concentrated. High Al content (29%) of the experiment soil (Fatondji et al 2006) hampered root growth beyond the zone of application of the organic amendment, which could explain why water extraction did not occur at those depths. Nevertheless some water would move upward from the 30-60 cm layer as the upper layer dries out, and thus plants will extract some of the water from the 30-60 depth due to diffusion even if roots are not in that layer.

Straw and grain yield

Table 7 shows statistics comparing simulated vs. observed total biomass and grain yields for flat-planted and 25 and 50 cm zai treatments with manure and with no amendments (6 treatment combinations). Although the manure treatments were used to estimate the genetic coefficients, these results demonstrate good ability of the millet model to simulate differences among these six treatments, with high r-squared and d-statistics and low root mean square errors between simulated and observed data. Due to the marginal conditions of the experiment in terms of soil physical and chemical characteristics, the crops were so stressed in some treatments that they could hardly grow and simulated growth was very low relative to the crop's genetic potential (control non-amended plots). Although these conditions are extreme to be simulated by conventional models, these results show that by setting the parameters for conditions in this experiment the model was able to simulate the observed responses to these six treatments.

However, the simulation results for the crop residue treatments substantially over-predict the observed yields (Figure 9 – circled symbols). The model may have under-predicted immobilization of N following addition of the high C:N residues in this treatment. One other possibility is that the low response observed with crop residues relative to simulated yield may have been due to the very low phosphorus content in the crop residue. Phosphorus concentration in the crop residue was 0.10%, whereas it was 0.94% for cattle manure. The version of the millet model in DSSAT v4.5 used in this study did not account for phosphorus limitations to growth, although this option is available for other crops (Dzotsi, 2007). This means that simulated yields for this experiment were based only on water and nitrogen availability in addition to weather and genetic coefficients. When soils have very low phosphorus levels, and very little or no phosphorus is applied as an amendment or fertilizer, the model may over-predict biomass growth and grain yield, which is what happened in the crop residue treatments. It is also possible that the nutrient content of the crop residue was highly variable and inputs for this amendment were not accurate. In manure treatments, as manure decomposed it released about 9 times more phosphorus than the decomposing crop residue (Fatondji et al. 2009), which apparently favored crop growth and yield. This trend is not captured by the model as the phosphorus module is not yet available in DSSAT for millet.

The model performed very well in terms of rain water productivity for manure and control treatments, but the effect of crop residue was not well captured in the model outputs (Table 8). This implies that water productivity estimated by the model can be used to estimate rain water productivity for comparing the zai with manure amendment vs. control flat planted management systems in other years or locations if the required soil, weather, amendment, and planting technique model inputs are known.

Table 7. Simulated vs observed total biomass and grain yield - statistical comparisons..

Variable Name	Mean (kg ha^{-1})		r-square	Mean (kg ha^{-1})		RMSE (kg ha^{-1})	d-stat
	Observed	Simulated		Difference	Abs. diff.		
Control, crop residue and manure							
Total biomass	1974	2441	0.847	467	711	943	0.948
Grain yield	382	591	0.728	209	225	328	0.885
Control and manure only							
Total biomass	2415	2339	0.988	-76	290	340	0.995
Grain yield	498	536	0.991	39	63	93	0.993

d-stat = Willmott (1981) d-statistic
Abs.Diff. = Absolute difference

Figure 9. Observed versus simulated total biomass and grain yield. Circulated points are for the crop residue treatments

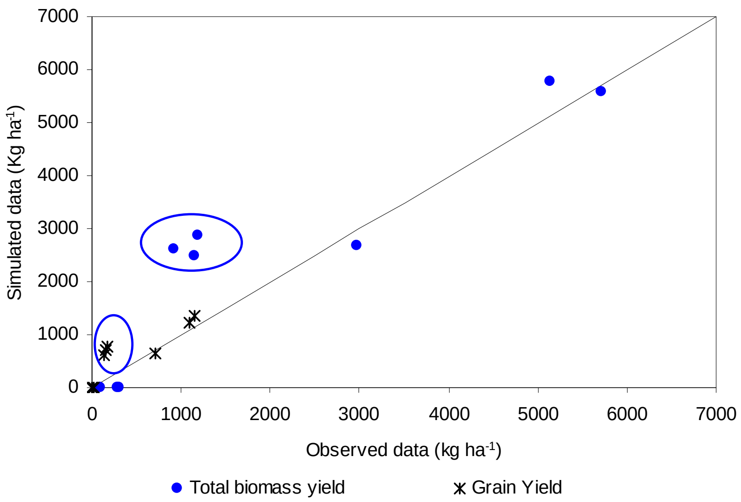


Table 8. Rainfall water productivity as affected by amendment type under various soil management practices (Damari 1999)

	Rain water productivity (kg.mm-1.ha-1)			
	Total biomass yield		Grain	
	Observed	Simulated	Observed	Simulated
Zai 25 cm				
Control	0.67	0	0.04	0
C.residue	2.65	6.6	0.37	1.82
Manure	11.38	13.4	2.56	3.11
Sed(±)	1.476		0.249	
Fprob	< 0.001		< 0.001	
Zai 50 cm				
Control	0.62	0	0.02	0.00
C.residue	2.05	6	0.35	1.62
Manure	12.66	12.9	2.44	2.82
Sed(±)	0.902		0.18	
Fprob	< 0.001		< 0.001	
Flat				
Control	0.21	0	0	0
C.residue	2.57	5.7	0.28	1.42
Manure	6.58	6.2	1.56	1.52
Sed(±)	1.324		0.477	
Fprob	0.008		0.036	

C.residue = Crop residue
Sed = Standard error of difference between means

Discussion and conclusions

This study addressed the challenge of simulating the low productivity of millet due to the combination of crusting soils (with adverse effects on infiltration), extremely low PAWC soils, nitrogen and phosphorus constraints on crop growth and low and erratic rainfall. We explored the possibility of simulating millet production in one of the extreme conditions that farmers have to deal with using an experiment in which detailed data were collected on soil physical and chemical properties, organic amendment properties, weather, yield components, and weekly soil water content vs. depth measurements for nine treatment combinations of planting technique and organic amendment. These carefully-collected data provided a good test of how well the millet model would predict the range of responses that were observed. But even with the extensive data set, we found that several input parameters needed by the model had to be estimated using indirect methods. Although this need may exist in other conditions, the model was highly sensitive to these uncertain inputs for the conditions at this site. The most sensitive inputs that had to be estimated indirectly were the genetic coefficients for the variety used in the experiment, the runoff curve number for different zai vs. flat planted treatments, and the soil fertility factor. Nevertheless, simulated yield results were very good for the control and manure treatments on flat planted and zai treatments, predicting straw yields with manure that ranged between about 2022 and 4434 kg ha-1 and grain yield ranging between about 700 and 1200 kg ha-1. For the control treatments, simulated and observed straw and grain yields were all very low, and represented crop failure.

The output of the model in terms of rain water productivity as a ratio of straw/total biomass or grain production to the amount of rain from planting to harvest was captured when compared to the observed data, particularly for manure and control treatments. This indicates that the measured data were adequately used to estimate the model parameters. The model calculates the amount of rain received during the cropping period based on weather data. Therefore this result could be expected as those two treatments were well simulated in terms of total biomass and grain yield.

Water harvesting techniques are one of the means to help combat desertification in the sub-Saharan Africa. They are mostly used on the prevailing degraded bare land of the region. The results of the field study demonstrated that the zai is a powerful technology, which under extreme physical and chemical conditions, substantially increased crop yield and provides conditions for crops to escape from the adverse effects of dry spells. Even though zai technologies are indigenous ones in some countries, there is a need to extend them for broader use by others. A study for evaluating their effectiveness across environments is therefore needed because, among the water harvesting technologies, the zai is the simplest and easy to implement by farmers as it requires locally available material.

We contend that simulation analysis of these options can be used to provide insight on the effectiveness of alternative management systems. However, realistic inputs are needed for environments to be studied, and results must be interpreted relative to uncertainties in the inputs as well as limitations in the models. For example, the comparison of manure amendments in zai vs. flat planting, based on these results, could be simulated for a range of similar soils and climates with a reasonably high confidence. However, simulating the use of lower quality amendments, particularly in similar highly degraded soils, would need to be interpreted in the context of limitations of the model. Although this is always true for model applications, the harsh conditions in this region make this an extremely important issue when conducting and interpreting results from such studies.

Acknowledgement

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Modeling the effects of conservation agriculture on land and water productivity of rainfed maize in the Yellow River Basin, China

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Abstract

In the dryland regions of North China, water is the limiting factor for rainfed crop production. Conservation agriculture (featuring reduced or zero tillage, mulching, crop rotations and cover crops) has been proposed to improve soil and water conservation and enhance yields in these areas. Conservation agriculture systems typically result in increased crop water availability and agro-ecosystem productivity, and reduced soil erosion. To evaluate the potential of conservation agriculture to improve soil water balance and agricultural productivity, the DSSAT crop model was calibrated using the data of a field experiment in Shouyang County in the semi-arid northeastern part of the Yellow River Basin. The average annual precipitation at the site is 472 mm, 75% of which falls during the growing season. The site had a maize-fallow-maize rotation. We used data from two crop seasons (2005 and 2006) and four treatments for calibration and analysis. The treatments were: conventional tillage (CT), no-till with straw mulching (NTSM), all-straw incorporated (ASRT) and one-third residue left on the surface with no-till (RRT). The calibration results gave satisfactory agreement between field observed and model predicted values for crop yield for all treatments except RRT, and for soil water content of different layers in the 150cm soil profile for all treatments. The difference between observed and predicted values was in the range of 3-25% for maize yield and RMSE was in the range of 0.03-0.06cm^3/cm^3 for soil water content measured periodically each cropping season. While these results are encouraging, more rigorous calibration and independent model evaluation are warranted prior to making recommendations based on model simulations. Medium-term simulations (1995-2004) were conducted for three of the treatments using the calibrated model. The NTSM and ASRT treatments had similar or higher yields (by up

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to 36%), higher crop water productivity by up to 28% and reduced runoff of up to 93% or 43 mm compared to CT.

Key words

tillage, mulch, incorporation, residues, CERES, DSSAT

Introduction

In China, the easily eroded soil of the Loess Plateau dryland region is intensively cropped with dryland maize (*Zea mays* L.). Rainfed croplands comprise about 80% of the total cultivated land (Shan 1993). Rainfall distribution is uneven, with more than 60% concentrated in the July-September period. Water is the most limiting factor for crop production. In this region, maize is planted in late April and harvested in mid-September. Because planting occurs right at the beginning of the rainy season, crop yields strongly depend on the amount of rain stored as soil moisture and this often mitigates the annual variation in precipitation. Traditionally, farmers leave their fields fallow during summer and practice conventional tillage (CT) to maximize soil water levels. But conventional farming with extensive cultivation and little use of crop residues exacerbates soil, water and nutrient losses, causing decreases in water availability, soil fertility and crop productivity. This has led to low crop yields and low land and water productivities. Conventional tillage in the dry farming areas of northern China involves moldboard plowing (animal drawn or motorized) to a depth of 16-18cm, followed by a sequence of harrowing, smoothing, rolling and hoeing. These operations are done with all crop residues removed, being used as fodder for animals or as fuel (Gao et al. 1991). Burning of crop residues has increased during the last few decades (Wang et al. 1999). Intensive plowing has contributed to increased risk of soil erosion by wind and water, soil compaction and the formation of a hard pan in the subsoil layer (Cai and Wang 2002). It has also resulted in the depletion of soil organic matter, and reduction in soil structural stability, soil fertility and soil water retention (Cai et al. 1995).

Conservation agriculture (featuring reduced or zero tillage, mulching, crop rotations and cover crops) offers a possible solution. Conservation agriculture systems typically result in increased crop water availability and agro-ecosystem productivity, reduced soil erosion, increased soil organic matter and nutrient availability, reduced labor and fuel use, and increased biological control of pests. But the effectiveness of conservation agriculture on land and water productivity depends on soil type, crop water use requirements, rainfall distribution and amount, and soil-water storage capacity (Hemmat and Eskandari 2004). Some researchers found that switching from conventional tillage to conservation tillage improved soil-water storage capacity and crop yields (Oleary and Connor 1997; Pikul and Aase 1999; Tolk et al. 1999; Li and Gong 2002; Li et al. 2005; Gicheru et al. 2004; Fabrizzi et al. 2005; Govaerts et al. 2005; Sayre et al. 2005), but Merril et al. (1996), Tan et al. (2002) and Mark and Mahdi (2005) observed no difference among tillage systems in volumetric water content. Furthermore, Guzha (2004) found that zero-till grain yields were lower than with CT, and Lampurianes et al. (2002) found no difference among tillage systems in volumetric water content and water productivity. Baumhardts and Jones (2002) compared conservation and conventional tillage and observed diverse results. Thus, before conservation tillage practices are widely adopted in any particular region, the suitability of this system should be assessed locally.

Several advances with conservation agriculture have been made in recent years in the northern provinces of China. Most of these studies have been in irrigated areas and have resulted in positive results (Wang et al. 2003; Li et al. 2005; Su et al. 2007). The conservation practices generally involved a reduction in the number and intensity of tillage operations compared to conventional tillage, with direct sowing ("zero" or "no" till) as the largest reduction. Crop yields and water productivity have increased (by up to 35%) following the implementation of reduced tillage practices (Wang et al. 2007). Under no-till, crop yields are equivalent to or higher than those from conventional tillage methods, especially in dry years. However, during wet years yields have tended to be lower (by 10-15%) with no-till.

Crop growth simulation models can be useful in evaluating the impacts of different tillage systems on the changes in crop productivity and soil-water balance components. Compared to field experimentation, the use of crop models to evaluate crop responses to a wide range of management and environmental scenarios can give more timely answers to many management questions at a fraction of the cost of conducting extensive field trials. As a result, a wide range of crop models such as APSIM (Agricultural Production Systems sIMulator; McCown et al. 1996), CropSyst (Cropping System Simulation Model; Stockle and Nelson 1994), DSSAT (Decision Support System for Agro-technology Transfer; Jones et al. 2003), EPIC (Erosion Productivity Impact Calculator; Williams 1990), NTRM (Nitrogen-Tillage-Residue Management; Shaffer and Larson 1987) and PERFECT (Productivity Erosion and Runoff Functions to Evaluate Conservation Techniques; Littleboy et al. 1989) have been developed and are being used to evaluate the impact of agricultural management practices. Simulation models offer a potentially valuable set of tools for examining questions related to the performance of conservation agriculture. This can be both to improve our understanding or conceptualization of processes and to improve quantitative predictions for use by agronomists, growers, policy makers or others. The DSSAT development team has recently enhanced the model's capability by incorporating algorithms which can simulate the influence of conservation agriculture practices such as crop residue cover and tillage on soil surface properties and plant development. The modeling study reported in this paper is one of the first studies applying the enhanced DSSAT model for investigating the effects of conservation agriculture practices.

The objectives of this research are: (i) to calibrate the DSSAT crop simulation model for an experimental site in a dryland region of the Yellow River Basin, and (ii) to simulate, quantify and explain changes in yield and soil-water balance components with medium-term simulation of different conservation agriculture treatments.

Materials and Methods

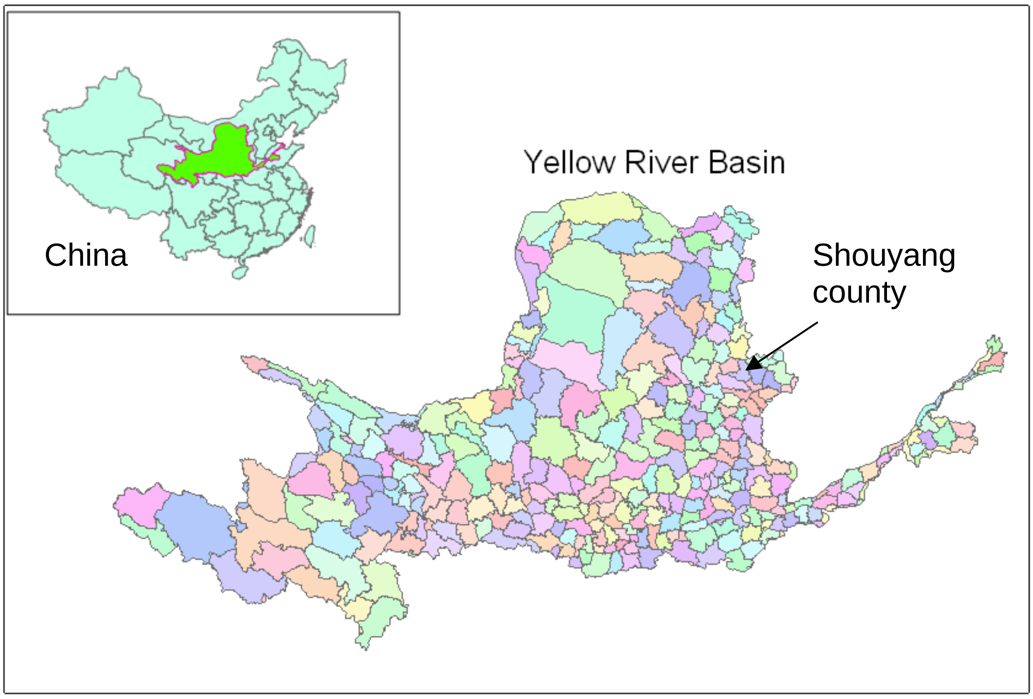
DSSAT Model

DSSAT is a package which incorporates the CROPGRO and CERES crop growth models. The CERES-maize model is used to simulate maize cultivation. A detailed description of the CERES models can be found in Ritchie et al. (1998). The CERES models can predict growth duration, average growth rates and the amount of assimilate partitioned to grain and straw. The soil water balance in DSSAT is based on Ritchie's model, where the concept of upper and lower drained limits of soil water is used as a basis for the available water in the soil (Ritchie 1981a, b). In simulations, the modified Priestly-Taylor method is used to estimate evapotranspiration. We used DSSAT version 4.5 which includes the new tillage model based on the improved CERES-Till (Dadoun 1993) - a model used to predict the influence of crop residue cover and tillage on soil surface properties and plant development. CERES-Till has been tested for maize and has demonstrated the ability to simulate differences in soil properties and maize yield under several tillage systems. Andales et al. (2000) improved the CERES-Till model which now accounts for residue incorporation and its effects on the soil nutrient balance as well as the water balance and soil temperature. The model has provisions for the input of tillage date, type of tillage implement, and tillage depth, and it accounts for changes in soil physical properties (bulk density, hydraulic conductivity, porosity, surface residues and soil temperature) caused by tillage. A detailed description of the improved CERES-Till model can be found in Andales et al. (2000).

Site Description

The experimental site is located in Zong Ai village, Shouyang County (37º 32´-38º 6´North latitude, 112º 46´-113º 54´East longitude) (Fig. 1) which belongs to the warm-temperate zone and semi-arid grassland region in the sub region of Shaanxi-Gansu-Ningxia gully region of loess plateau. Table 1 describes some of the climate characteristics for the experiment site.

Figure 1. Location of the experimental site in the Yellow River Basin



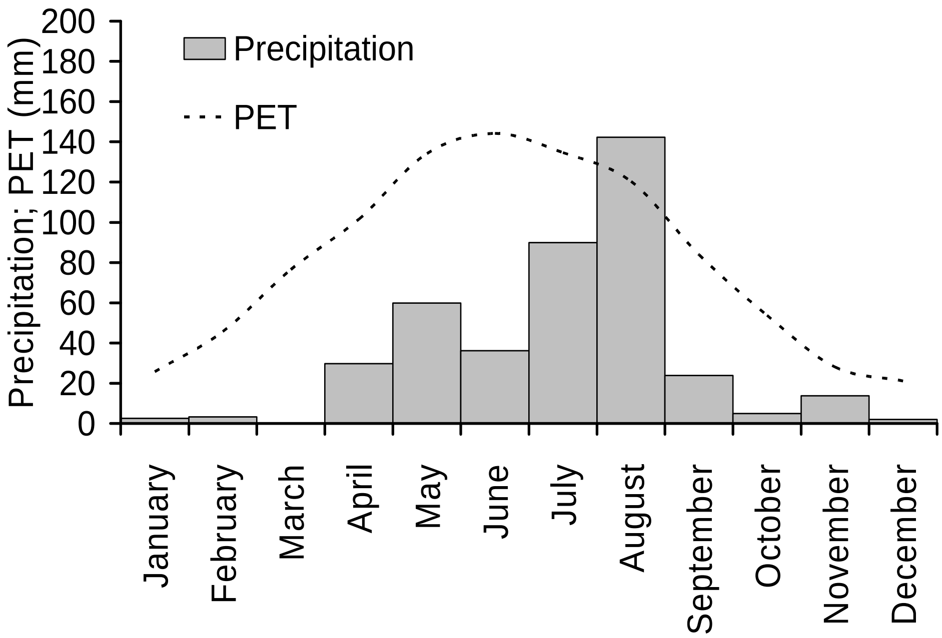
The annual precipitation in Shouyang is generally low and is distributed non-uniformly in space and time, and often as large rainstorms (Fig. 2). Droughts are very common with frequency in the range of 60 to 80%. Drought frequency during the spring to summer period ranges from 53 to 77%.The longest drought period was 140 days in 1973.

Since precipitation is low and much less than PET, there is not enough soil moisture to grow more than one crop per year. Monoculture is a common practice in the region. A maize-fallow-maize annual cropping experiment comparing conventional tillage and conservation agriculture practices has been conducted at Zong Ai since 2005 (Yan et al. 2009), and the data from 2005 and 2006 were used to calibrate and evaluate the DSSAT model.

Table 1. Site climate characteristics at Zong Ai village

Characteristic	Value
Elevation above mean sea level	1135 m
Annual ≥10°C accumulated temperature	2500-3100°C
Annual average temperature	7.6°C
Lowest temperature ever recorded	-26.6°C
Highest temperature ever recorded	35.5°C
Annual precipitation	350-550mm (average: 491.3 mm)
Potential Evapotranspiration (PET)	852mm
Average frost-free period	135-168 d
Average total annual sunlight	2518 h
Average total radiation	128 k cal/cm²

Figure 2. Average (50-year) precipitation and potential evapotranspiration (PET) at the experiment site.



Experimental Design and Monitoring

Maize (cv Jindan34) was grown from April-September each year. There were three conservation agriculture treatments and one conventional tillage treatment on four adjacent fields (Yan et al. 2009). Each treatment was replicated 3 times. Crops were planted on April 29 of each year at 60030 plants/ha, 10-15cm depth, and row spacing of 0.6m. Ammonium polyphosphate was applied at planting alongside the seed at a rate of 600 kg/ha (N-P2O5-K: 20-60-0) on April 29 of each year. Each plot was 667 m² in size. There was a 7-month fallow period between harvest of the maize in autumn (October) and planting in spring (May) in the following year.

Table 2 describes the four treatments carried out at the experiment site. For the conventional tillage (CT) treatment, most residues of the previous maize crop were removed for fodder, leaving 10-15cm stubble on the field after harvest (in October), after which the field was plowed by a tractor drawn plough to 20-25 cm depth, turning the soil over. During spring (in April), the field was harrowed (to 5-8cm depth) by tractor drawn harrows, just before sowing. A human-drawn chisel planter was used for sowing. At the same time, fertilization was done by hand. For the ASRT treatment, all residues of the previous maize crop (3 t/ha) were plowed into top 20-25cm soil layer by tractor. In spring, the field was harrowed (to 5-8cm depth) by tractor drawn harrows. Planting and fertilizer application were as for CT. In the NTSM treatment all residues of the previous maize crop were flattened and mulched in the field. Direct seeding and fertilization were performed by hand in the spring. For RRT treatment all maize residues were removed after harvest, and about one-third of maize residues were chopped and incorporated into the top 15cm soil layer in autumn using a rotary plow. Direct seeding and fertilization were performed in spring using the no till planter.

Table 2. Description of conservation agriculture treatments at the experiment site (Yan et al. 2009).

Treatment	Planting date	Fertilizer application	Tillage operations and residue management
		kg ha^{-1}	
Conventional Tillage (CT)	April 29	600	All maize straw was removed after harvesting; during spring, plowing and harrowing operation were carried out prior to sowing and fertilizing using a human drawn chisel planter
No-Till with Straw Mulching (NTSM)	April 29	600	All maize straw (3 t/ha) was chopped and mulched in the field; in spring, direct seeding and fertilizer application were simultaneously applied using the no-till drill
All Straw with Return Till (ASRT)	April 29	600	All the previous maize straw was returned to field and plowed into top 20cm soil layer. The following year, sowing and fertilizer application were carried out simultaneously using a human-drawn chisel planter
One-third residue left with rolling till (RRT)	April 29	600	Maize residues were removed after harvest; in spring, one third of the residues was chopped and spread across the field, and seed and fertilizer sown in a single pass

Gravimetric soil water content was measured on samples collected (using soil drill) from different depths up to 200 cm, at three locations within each plot. Measurements were made at 10-14 day intervals from May 2005 to October 2006. Soil moisture was determined by calculating the difference between the weight of soil samples before and after drying in an oven at 105°C for 24 hrs. Soil samples were collected from the 0-10cm soil layer (3 replicates for each treatment, bulked by soil layer) for determination of soil organic matter by wet oxidation (Black, 1965), and the percentage of organic carbon was calculated by applying the Van Bemmelen factor of 1.73. Soil bulk density was measured at 0-15, 15-30, 30-60, 60-80 and 80-100 cm depths at three locations within each treatment. The soil bulk density was measured in April 2005 a few days before planting. For the 100-150 depth, soil bulk density was derived using the SBuild pedotransfer function in-built into DSSAT (Uryasev et al. 2003).

The particle size distribution (clay, silt and sand content) and hydraulic conductivity were acquired from the Shouyang County Soil Survey handbook. Table 3 presents the measured and calculated soil properties used in the model.

Table 3. Soil physical properties and initial conditions used for the DSSAT simulations.

Soil depth	Saturated hydraulic conducti-vity#	Organic carbon	Bulk density	Sand#	Silt#	Clay#	Drained upper limit*	Drained lower limit*
cm	cm h^{-1}	mg kg^{-1}	g cm^{-3}		%		mm mm^{-1}	
0-15	0.68	8.7	1.37	20.7	55.1	24.2	0.28	0.14
15-30	0.68	6.9	1.32	16.7	57.1	26.2	0.30	0.15
30-60	0.68	4.4	1.30	12.6	67.1	20.3	0.29	0.12
60-80	0.68	5.7	1.30	16.7	57.1	26.2	0.30	0.14
80-90	0.68	3.3	1.30	17.0	58.9	24.1	0.27	0.13
90-150	1.32	4.3	1.29*	28.9	49.0	22.1	0.21	0.11

from the Shouyang County Soil Survey handbook
* Derived using SBuild pedotransfer function (Uryasev et al. 2003)

Maize grain yield was determined by harvesting an area of 4 m^2 in each plot at maturity. The maize grains were dried in an oven at 80°C for 24 hours. Maize maturity date was based on the advice of the research staff in-charge of the experiment site. he date was chosen when the bract of the ears completely became pale, a black layer formed on the grain and the kernel moisture content reached about 33%.

Weather data (including maximum and minimum ambient air temperature, precipitation and solar radiation) for the county weather station were downloaded from the Chinese national weather service website. The weather station is located approx. 20 m from the experimental plots. The 2006 precipitation was measured using an automated weather station installed at the experimental site using a tipping-bucket automatic rain gauge. Table 4 presents monthly total precipitation for the simulation period. Precipitation varied greatly between the two years, especially during April, June and August; 2005 was a relatively dry year and 2006 was a normal precipitation year. During the growing season, the 2005 precipitation was 39% lower and 2006 precipitation was 6% lower than the long-term average of 413 mm. The 2005 and 2006 fallow period rainfall was 35% and 39% less than the long-term average fallow rainfall (58.7mm), respectively.

Model Parameterization and Calibration

The DSSAT model was run in its “sequence analysis” mode for this study. In “sequence analysis”, the soil parameters at the end of a simulation year are carried over to the first day of the following simulation year. This way there is a continuation of simulation unlike the “experiment mode” in which the model is reinitialized on the first day of the following simulation year. The model was calibrated by adopting the procedure laid out by Hu et al. (2006) using site-specific soil hydraulic properties and plant growth parameters for the site and the crop being simulated. Field measured values of weather parameters, crop management and soil properties were used for setting up the DSSAT model. Missing data such as soil drained upper limit, the lower limit and saturation soil water content were estimated using the soil data tool-SBuild pedotransfer function (Uryasev et al. 2003) in DSSAT. The initial C:N ratio was set to 11 (default DSSAT value) and soil mineral nitrogen to 0.022%. We used the iterative approach of Godwin et al. (1989) to reach reasonable estimates of the genetic coefficients of the DSSAT crop models through trial-and-error adjustments to match the observed phenology and yield with simulated values. A literature review was carried out and values for an irrigated maize cultivar grown in north China (Yu et al. 2006) were used as the baseline values. We modified the coefficients one at a time to check sensitivity of output to their change. We searched for optimum values of coefficients in increments of 5% between specific lower and upper bounds, based on literature and default values available.

Table 4. Monthly total precipitation received at the experiment site from January 2005 to December 2006, and the long term average, at the experimental site.

	Month	2005	2006	Average
			mm	
	January	0.2	3.5	2.8
	February	5.2	7.9	3.8
	March	2.5	0.0	16.4
Maize cropping season	April	6.6	25.6	18.2
	May	37.1	38.7	47.0
	June	30.8	84.8	68.9
	July	42.9	39.1	105.0
	August	77.6	155.5	120.0
	September	68.4	45.5	54.0
	October	3.0	8.8	23.0
	November	0.0	13.4	11.6
	December	0.4	2.0	1.1
	Total Cropping Season	263.4	389.2	413.1
	Total Yearly	274.7	424.8	471.8

We calibrated the model for maturity date, grain yield at harvest and soil moisture content of different layers for all treatments during the growing season. The accuracy of the model predictions was determined by computing the percentage error in crop yield prediction and the root mean square error (RMSE) in predicting daily soil moisture. The RMSE is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(p_i - o_i)^2}$$

where n is the number of values, p_i and o_i are the predicted and observed values, respectively.

Model simulations

Using the calibrated model, we simulated the medium-term (1995-2004) effects of the conservation agriculture and conventional tillage treatments on land and water productivity and components of the water balance. The field-scale soil water balance can be written as:

$$\Delta S = P - E - T - D - R$$

where ΔS is the change in soil-water storage, P is precipitation, E is soil evaporation, T is crop transpiration, D is deep percolation and R is surface runoff. In this study, deep percolation was set to zero following advice of fellow regional researchers. Crop water productivity (WP) was defined as:

$$WP = \frac{Y}{ET}$$

where WP represents water productivity for crop (kg/m^3), Y is grain yield of maize (kg ha^{-1}) and ET (mm) is the evapotranspiration during the year.

Results and Discussion

Model calibration

Calibrated genetic coefficients for plant growth are listed in Table 5.

Table 5. Calibrated genetic plant growth coefficients in DSSAT for simulation of maize (cv. Jindan34) at the Shouyang experiment site.

Parameter	Value
Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod	250.0
Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours)	0.7
Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C)	950.0
Maximum possible number of kernels per plant	510.0
Kernel filling rate during the linear grain filling stage and under optimum conditions (mg day^{-1})	11.0
Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances	75.0

In addition to the genetic plant growth coefficients, we modified some soil-water parameters to match the field observed soil moisture data with the model predicted data. We changed the runoff curve number from model default value of 81 to 73, soil albedo from the model default value of 0.13 to 0.10, soil fertility factor from the model default 1.0 to 0.8, soil slope from 0 to 2%, and soil drainage rate from 0.4 to 0.5. By changing these parameters, we found a better match for soil moisture and grain yield; and predicted PET (900mm yr^{-1}) was also very close to the 852mm yr^{-1} reported for Shanxi Province in Wang et al (2007). The combination of cultivar and soil-water parameters that gave the minimum error for yield, daily soil moisture and maturity date was selected.

Model evaluation

Crop Yield

Grain yield at harvest for all four treatments during the two cropping seasons of the experimental period, 2005-2006, was used for model calibration. Table 6 lists the values and their respective prediction differences. There was generally good agreement between predicted and observed yield, except for RRT in 2006. There was a high error (25.2%) in predicting yield for RRT during 2006 season which we cannot explain.

Less rainfall in 2005 compared to 2006 resulted in lower grain yield of CT in 2005, which was also predicted by the model. During the dry year (2005), the model predicted the highest yield with NTSM, but during the normal year (2006) the predicted yield of NTSM was much lower than yield of all other treatments, consistent with the observations by Cai and Wang (2002). They reported that, spring maize seedling emergence with conservation tillage (subsoiling between rows or no-till with whole maize stalk mulching after fall harvest, and direct seeding the following spring) was 2-3 days earlier and 17-23% higher in a dry spring in Shouyang County, but that the benefit of conservation tillage was much less in a relatively wet year. In their study surface temperature under mulch during crop establishment decreased by 2-6°C compared with stubble removed or incorporated, thus affecting establishment and crop yield. While the differences between observed and predicted yields of the conventional and conservation agriculture treatments are generally small, the results show that the model is sensitive to the differences between treatments.

Table 6. Comparison of observed (standard deviation of observed yield) and model predicted crop yield results during the calibration period.

Year Treatment	Observed (SD)	Simulated	Error*
	kg ha^{-1} x 10^{3}		%
2005	Grain Yield		
CT	4.73^{b} (0.12)	5.29	12.0
NTSM	5.18^{a} (0.27)	5.74	10.2
ASRT	5.30^{a} (0.33)	5.13	-3.1
RRT	4.65^{b} (0.07)	5.05	8.7
2006	Grain Yield		
CT	6.14^{a} (0.27)	6.34	3.3
NTSM	4.62^{c} (0.28)	4.48	-2.3
ASRT	5.58^{b} (0.31)	5.74	2.8
RRT	4.91^{c} (0.23)	6.14	25.2

Note: CT: conventional tillage treatment, NTSM: no-till with straw mulching, ASRT: all straw with return till treatment, RRT: One-third residue left with rolling till;

% Values marked with the same letter are not significantly different at p=0.05 within each year

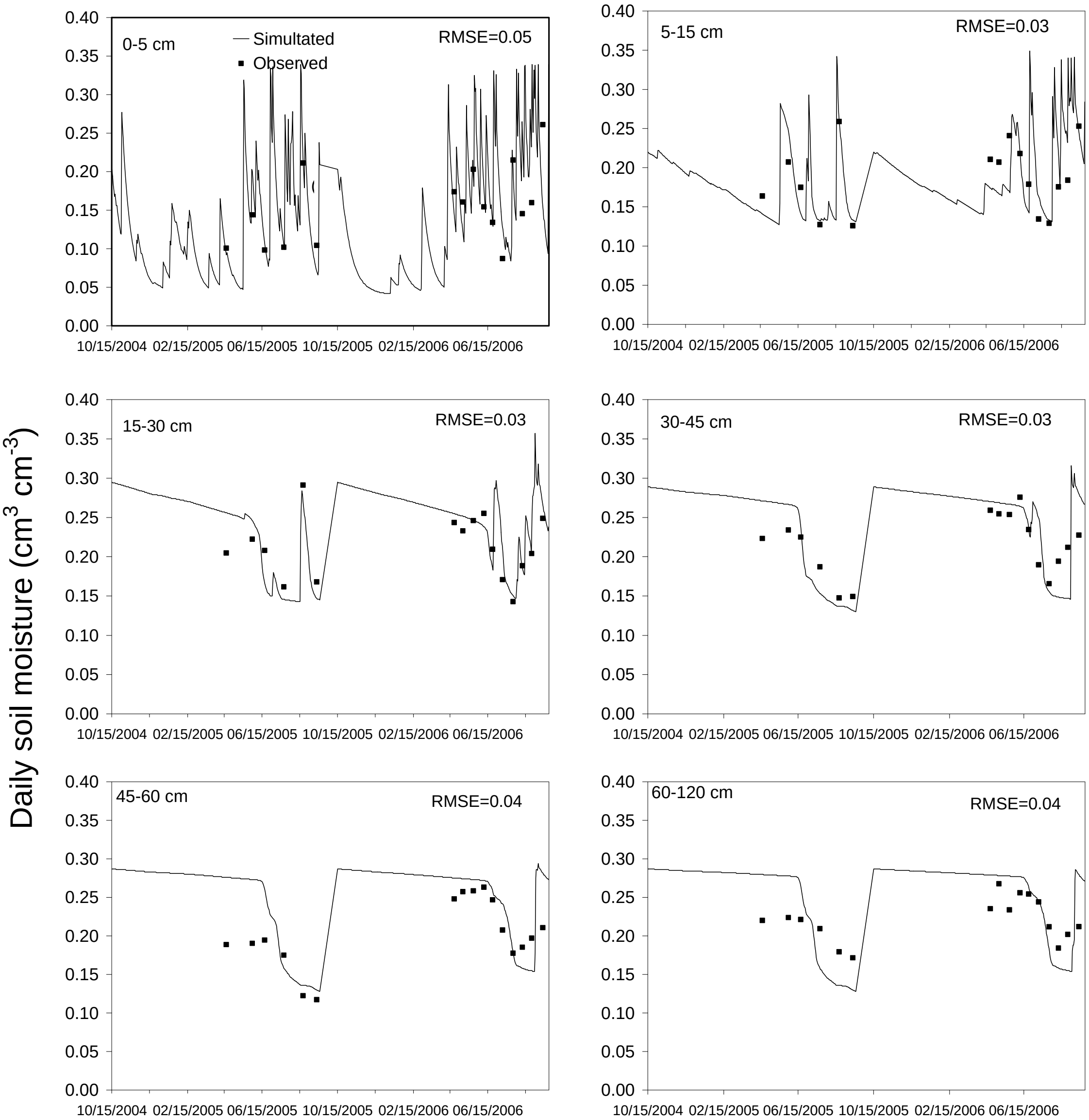
*Negative sign represents under-prediction

Soil water content

Soil layers of thickness 5-15, 15-30 and 30-45 cm are important for simulating correct plant water uptake and thus the soil-water balance. Soil moisture dynamics in the surface soil layers (0-5cm) are more complex than deeper layers due to high spatial and temporal variations in organic matter content, macroporosity, and other properties. Fig. 3 shows very good agreement in soil water content of simulated and observed values throughout the profile to 45 cm in the conventional tillage treatment. There was similar agreement between the model predicted and field observed values of the daily soil moisture for all treatments (data not presented) with the RMSE ranging from 0.03 to 0.06cm3 cm^{-3}. Furthermore, simulated as well as observed soil water content was higher at depth under all three conservation agriculture treatments than under conventional practice (Yan et al. 2009), resulting in up to 15% more deep percolation for ASRT treatment in 2006 (normal rainfall year). Soil moisture for all treatments was relatively constant from seeding to seedling emergence. At this stage the crop water requirement is limited and the differences in soil moisture mainly stem from treatment effects. In general, the soil moisture strongly depends on the rainfall.

Once there was satisfactory agreement between observed and model predicted values for crop yield and daily soil moisture content, we applied the model for predicting medium-term changes in land and water productivity with the adoption of conservation agriculture practices at the site.

Figure 3. Comparison between predicted and observed soil moisture (n=16 at each depth) at various depths for the conventional tillage (CT) treatment at the Shouyang experiment site. Units of root mean squared errors (RMSE) of soil moisture predictions are cm³ cm⁻³.



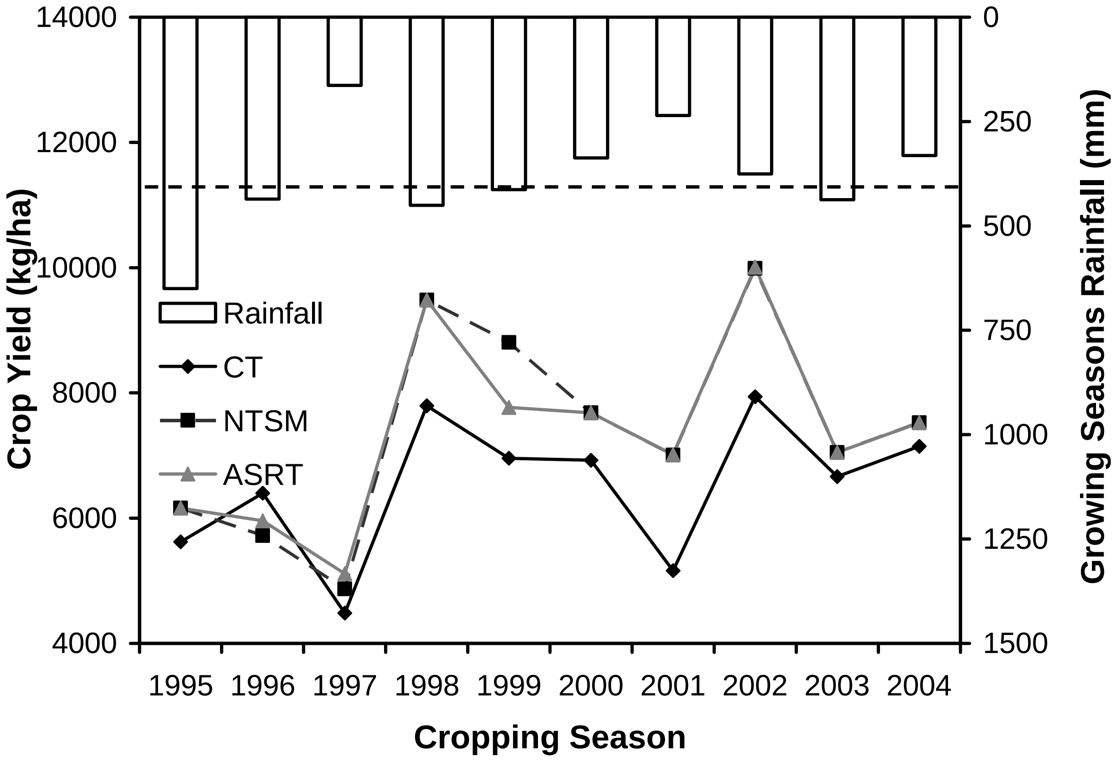
Medium-term simulations

Simulations were conducted for 1995-2004 to predict the medium-term field-scale changes in yield, soil-water balance components and water productivity for NTSM and ASRT in comparison with CT. As there was a very high prediction error during calibration of the model for RRT (Table 6), we did not include that treatment in the medium-term analyses.

Crop yield

Predicted yields varied with seasonal conditions; for example, yield of CT varied from about 4500 kg ha^{-1} in 1997 to about 7500 kg ha^{-1} in 2002 (Fig. 4). The NTSM and ASRT conservation agriculture treatments always had similar or higher crop yields compared to CT. During the first three years of simulation (1995-1997), the differences in crop yields between treatments were small but were much larger after that. In maize-wheat systems in Mexico, Sayre et al. 2005 also found that the benefits of conservation agriculture treatments only became apparent after several years. The reasons for the relatively small differences between yields of CT and NTSM and ASRT during later years (2003 and 2004) are not known. Growing period rainfall of 2001 (235.5 mm) was very low compared to long-term average rainfall of 413 mm. In that year NTSM and ASRT generated about 36% higher crop yields than CT. The yield trends were affected by pre-season (fallow) rainfall which was better conserved in NTSM and ASRT than CT. During normal rainfall cropping periods also the crop yields for NTSM and ASRT treatments were higher by 5-27%. In maize-wheat systems in Mexico, Govaerts et al. (2007) also showed the importance of residue retention on the soil surface in no till systems, where yields declined in the absence of residue retention after the first few years (Govaerts et al. 2007).

Figure 4. Comparison of predicted crop yields for conventional tillage (CT), no till straw mulching (NTSM) and all straw return till (ASRT) during the 1995-2004 simulation period. The broken line shows the long-term average growing season rainfall (413mm).



Soil water balance

The soil-water balance comprises gains and losses in the soil-water storage (ΔS). In dry areas such as Shouyang County transpiration is a beneficial loss, while run-off and deep drainage are losses to the cropping system (but may have downstream and ecosystem benefits). Soil evaporation in such places is a non-beneficial loss. The predicted soil-water balance was compared for CT, NTSM and ASRT over the crop and fallow periods. The fallow period is generally used for recharging the soil moisture (Huang et al. 2003). But at this site the rainfall magnitude and distribution is such that except for the 1995 cropping period, and the 1997 and 1999 fallow periods, there was a net loss of soil water in all crop and fallow periods (Table 7). This is consistent with the fact that there is a 60 to 80% probability of drought in the Shanxi Province to which this site belongs. These results are also in line with Wang et al. (2007) who report a water deficit of 414-493mm/yr for Shanxi Province.

Fig. 5 shows the relative change in crop yield, soil water and water productivity with respect to ET for the three treatments. The two conservation agriculture treatments performed better than CT in terms of grain yield and water productivity. During 9 out of 10 years, grain yield of NTSM and ASRT was higher than of CT. During 6 out of 10 cropping periods and all 9 fallow periods the evaporation losses of NTSM and ASRT were lower than of CT, however the differences were very small, the greatest values being about 10 mm (Table 7). This probably reflects the generally dry conditions in this region, and thus the limited scope for mulch to reduce evaporation. The largest benefits of the conservation agriculture treatments were reduced runoff, by up to 43 mm during the cropping season. Soil erosion caused by surface runoff is a major problem in the Yellow River Basin. This is degrading water quality in the Yellow River. The conservation agriculture treatments reduced runoff and thus may help reduce erosion (Table 7).

Conclusions

To evaluate the potential to improve land and water productivity with adoption of conservation agriculture practices, the DSSAT crop model was calibrated and applied to the Shouyang County experiment site in the Shanxi Province of the Yellow River basin of China. The calibration results gave satisfactory agreement between field observed and model predicted values for crop yield with differences between observed and predicted values normally in the range of 2.8-12%. There was good agreement between observed and predicted daily soil moisture contents for all treatments with RMSE in the range of 0.03-0.06cm3/cm3. While these results are encouraging, more rigorous calibration and independent model evaluation are warranted prior to making recommendations based on model simulations.

The calibrated model was used for analyzing the medium-term changes in crop yield, soil-water balance and crop water productivity for CT, NTSM and ASRT. The conservation agriculture practices increased grain yield by up to 36%, soil-water storage by up to 81%, and water productivity by up to 28%, while runoff was reduced by up to 93% or 43 mm. The reductions in soil evaporation with the conservation agriculture treatments were always very small during both the fallow period and cropping season.

Figure 5. Predicted changes in (a) crop yield, (b) stored soil-water, and (c) water productivity (with respect to ET) for the three conservation agriculture treatments relative to the CT treatment during the 1995-2004 simulation period.

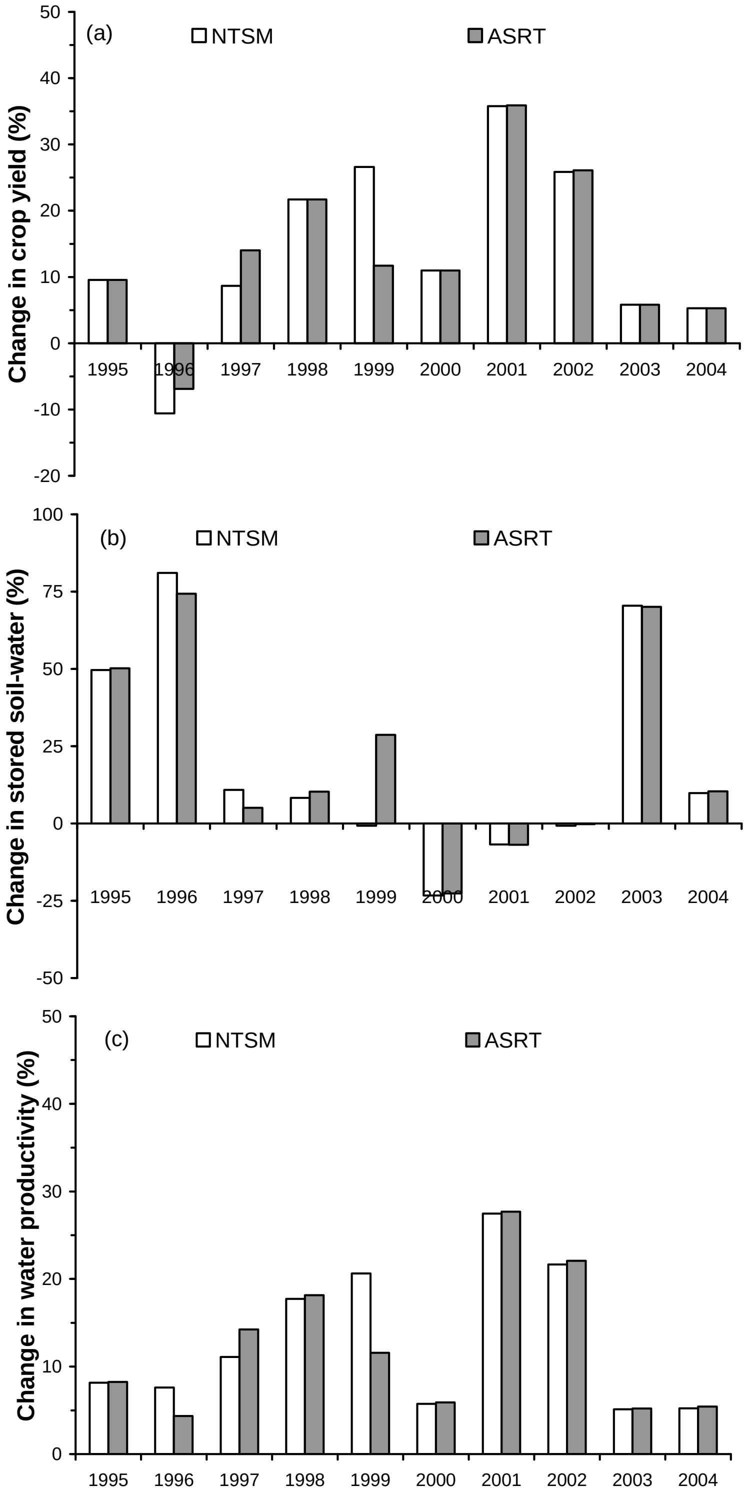


Table 7. Components of the water balance for the four treatments.

	Fallow Period					Cropping Period						Yield	WP
	P	E	R	D	ΔS	P	T	E	R	D	ΔS		
						mm						kg ha^{-1} x10^{3}	kg m^{-3}
1995						29 April, 1995-6 November, 1995							
CT						650	235	196	144	0	75	5.62	1.30
NTSM						650	246	190	101	0	112	6.16	1.41
ASRT						650	246	190	101	0	113	6.16	1.41
1996	7 November, 1995-28 April 1996					29 April, 1996-4 November, 1996							
CT	64	73	0	0	-9	436	235	184	56	0	-39	6.40	1.30
NTSM	64	72	0	0	-9	436	216	187	34	0	-1	5.72	1.20
ASRT	64	72	0	0	-7	436	219	187	34	0	-4	5.96	1.25
1997	5 November, 1996-28 April 1997					29 April 1997-18 October, 1997							
CT	109	95	5	0	10	164	211	107	7	0	-161	4.43	1.08
NTSM	109	94	2	0	12	164	199	110	2	0	-148	4.87	1.21
ASRT	109	94	2	0	13	164	208	110	2	0	-157	5.11	1.24
1998	19 October, 1997-28 April 1998					29 April 1998-27 October, 1998							
CT	33	76	0	0	-43	451	277	169	65	0	-61	7.79	1.49
NTSM	33	76	0	0	-43	451	294	170	39	0	-52	9.49	1.76
ASRT	33	75	0	0	-42	451	294	169	39	0	-51	9.49	1.76

1999		28 October, 1998-28 April 1999						29 April, 1999-28 October, 1999					
CT	54	53	0	0	1	413	259	158	72	0	-75	6.96	1.47
NTSM	54	53	0	0	1	413	292	148	49	0	-76	8.81	1.78
ASRT	54	52	0	0	2	413	268	151	50	0	-55	7.77	1.65
2000		29 October, 1999-28 April, 2000						29 April 2000-30 September, 2000					
CT	31	71	0	0	-40	337	238	126	24	0	-51	6.92	1.59
NTSM	31	71	0	0	-40	337	268	117	24	0	-72	7.68	1.68
ASRT	31	70	0	0	-39	337	268	117	24	0	-72	7.68	1.68
2001		1 October, 2000-28 April, 2001						29 April, 2001-26 September, 2001					
CT	10	86	0	0	-76	236	221	104	27	0	-116	5.16	1.25
NTSM	10	86	0	0	-75	236	256	97	13	0	-130	7.01	1.59
ASRT	10	85	0	0	-75	236	256	97	14	0	-131	7.01	1.60
2002		27 September, 2001-28 April, 2002						29 April, 2002-19 October, 2002					
CT	11	86	0	0	-76	375	290	151	40	0	-105	7.94	1.55
NTSM	11	86	0	0	-75	375	310	148	23	0	-106	9.99	1.89
ASRT	11	85	0	0	-75	375	311	148	23	0	-106	10.01	1.89
2003		20 October, 2002-28 April, 2003						29 April, 2003-19 October, 2003					
CT	92	119	1	0	-28	437	244	151	36	0	6	6.66	1.29
NTSM	92	119	0	0	-27	437	252	147	18	0	20	7.05	1.36
ASRT	92	119	0	0	-27	437	252	147	18	0	21	7.05	1.36

2004			20 October, 2003-28 April, 2004						29 April, 2004-15 October, 2004				
CT	51	87	1	0	-37	331	253	140	24	0	-86	7.15	1.49
NTSM	51	86	0	0	-35	331	253	141	13	0	-75	7.53	1.57
ASRT	51	86	0	0	-35	331	252	141	13	0	-75	7.53	1.57

* Negative sign represents net loss of soil-moisture at the end of the period

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Efficient agronomic practices to increase water productivity of barley in the highlands of Eritrea

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Abstract

To enhance food security and alleviate poverty in the highlands of Eritrea, participatory approaches were used to develop, in partnership with farmers, barley management practices that will increase crop water productivity, minimize risk and ensure sustainability of production.

Trials with fertilizer application, weed control and rainfall harvesting treatments, alone and in combination, were conducted in farmers' fields in three representative barley growing areas in the highlands of Eritrea: Tera Emni, Wekerti and Adi Guadad. The trials were designed to assess the individual and combined effects of these practices on the yield of barley. A Cobb-Douglas production function was developed from the results of the field trials. This function was used to estimate the effects of the agronomic practices on barley yield over a range of seasonal (rainfall) conditions using 10 years of rainfall data from 1995 to 2004. The generated yields were then used to calculate rain water productivity, and total and net returns of barley for thirteen years (1995-2007). The net returns were used to identify the most efficient agronomic practices using stochastic dominance analysis.

Compared with farmers' practice, all the treatments increased water productivity. However, only two treatments, fertilizer application and fertilizer plus weed control, were less risky than farmers' practice.

First degree stochastic dominance suggested that fertilizer application, farmers' practice, and the combination of fertilizer and weed control were the most economically efficient practices. Second degree stochastic dominance results excluded farmers' practice from the efficient set in Tera Emni.

Key words

stochastic dominance analysis, participatory research, production function.

Introduction

Eritrea's economy is largely based on subsistence agriculture, with over 80% of the population living in rural areas and dependent on farming and livestock production for their livelihoods. Rainfed crop production constitutes 95% of the national crop production. Cereals are the dominant dietary component, and barley accounts for 16% of total crop production. Barley is one of the staple crops in the Highlands of Eritrea where it is widely used in various preparations as human food and in beer making. The straw is an important source of animal feed. Barley is grown both as a single crop, and also in a mixture with wheat known as hanfets.

War, droughts and famines have resulted in major disruptions and population movement in Eritrea. In addition, there are many major technical constraints to crop production including highly variable and erratic rainfall, with recurrent droughts; genetic erosion of indigenous landraces; land degradation due to erosion and mining of soil nutrients by crops; minimal use of inputs; and lack of improved cultural practices and cultivars adapted to local conditions. All these factors led to food production dropping by about 60% over the last decade. In addition, little change has taken place in the technology base over the last 30 years.

A key challenge to increasing crop production in the highlands of Eritrea is to increase the productive use of rainfall, which is often more than adequate for high yield, but unreliable and poorly distributed in relation to crop need. In the case of rainfed agriculture, on which the poorest farmers depend, the only way to increase water productivity is through increasing crop yield with the given rainfall. This can be achieved through the use of improved varieties, increased use of inputs and improved management. This may involve actions such as the use of drought and disease resistant varieties, timely planting, use of fertilizers, and use of soil management technologies that increase capture and infiltration of rainfall (such as tied ridging) and that conserve water (such as mulching and removal of weeds).

The objective of the paper is to evaluate the effects of different agronomic practices on improving farmers' income and reducing the risk associated with production of rainfed crops in the Highlands of Eritrea. Participatory approaches were used to develop and evaluate, in partnership with farmers, barley management practices that will increase crop water productivity, minimize risk and ensure sustainability of production (CPWF/ICARDA 2007). This involved evaluation of a range of management practices in replicated experiments in farmers' fields, and use of the results to develop production functions that predicted yield in response to management practices and seasonal rainfall. Identification of the most productive and most economic management practices, taking into account seasonal rainfall variability and its effects on yield and net returns, was undertaken using production functions and stochastic dominance analysis.

Methods

The Cobb-Douglas production function

A production function approach was used to estimate barley yield as function of monthly rainfall during the growing season (July-October), fertilizer application, tied ridging and weed control, while holding all other input levels fixed. Since our primarily interest is in forecasting the level of barley output (yield) given a description of its inputs, estimates derived by Cobb-Douglas (CD) production function may be acceptable (Varian 1984). Moreover, the CD function can easily be extended to the case of n inputs, and takes the form:

$$Y = A\prod_{i=1}^{n=a_i} X_i \qquad \text{or} \qquad \ln Y = \ln A + \sum_{i=1}^{n} a_i \ln X_i$$

where Y is output level, X_i are input levels and A and a_i are parameters to be estimated. The equation in logarithms form is linear for the parameters A and a_i and thus estimation of these parameters by the use of the ordinary least squares method. The derived CD production function can be used to predict the effects of different agronomic practices on yield as affected by climatic (seasonal rainfall) conditions, and the outputs can be used to provide inputs for optimizing an objective function.

The predicted yields of barley were then used to calculate total and net returns to determine economically efficient sets of agronomic practices for risk averse producers in the highland of Eritrea, using stochastic dominance analysis.

Stochastic Dominance Analysis

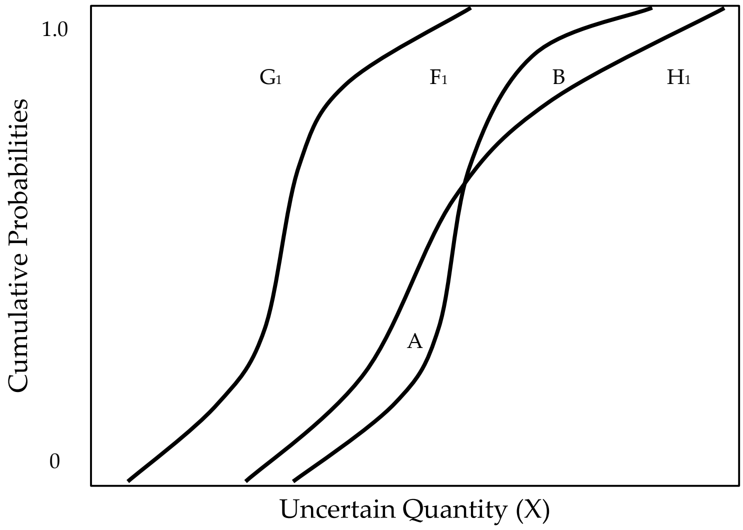
Stochastic Dominance (SD) analysis is theoretically superior to other available methods for selecting an efficient set from a given number of alternatives. Under SD analysis, pairwise comparisons of probability distributions from a finite set of choices are made to determine if one alternative is inefficient and therefore should be discarded from the efficient set. The efficient (dominant) set of alternatives is obtained by ranking cumulative density functions (CDF). Cumalative density functions indicate the likelihood of obtaining a given return or less of production activities. The given return should be based on the producer's preferences. As a decision criterion, SD generally states that a risky prospect dominates another stochastically if the consequences of the dominant distribution are at least as preferred as the dominated distribution for all possible values within a specified range and are preferred for at least one value (Anderson 1974).

There are three alternative stochastic dominance approaches depending upon the assumption regarding a producer's behavior, illustrated in Figure 1. The first degree (FSD) approach is based on the assumption that the producer prefers more net returns to less. The second degree stochastic dominance (SSD) approach is based upon the assumption that the producer not only has an increasing utility function of net returns but is also risk averse. This requires that the second derivative of the utility function to be negative, i.e. $U'(X) > 0$ and $U''(X) < 0$. Third degree stochastic dominance (TSD) is based on the assumption that $U'''(X) \geq 0$ in addition to the two assumptions for SSD. This last assumption implies that the decision maker becomes decreasingly averse to risk as he gets wealthier.

In Figure 1, the probability distribution f(X), labeled 'F_1', dominates the probability function g(X), labeled 'G_1', as the CDF curve of f(X) lies more to the right than the CDF curve of g(X), and this is an example of FSD. In Figure 1, $F_1(X)$ dominates $H_1(X)$ if the area A exceeds the area B between the CDF curves, and this is an example of for a SSD.

The efficiency criteria are transitive. In addition, two conditions are required for a distribution to dominate another in any degree. The lowest value of a dominant distribution cannot be smaller than the lowest value of the dominated one, and the mean of the dominant distribution cannot be smaller than that of the dominated distribution (Anderson et al. 1977)

Figure 1. Illustration of First and Second Degree Stochastic Dominance



Field data

To understand the limiting barley production factors, a trial evaluating fertilizer application, weed control and rainwater harvesting was conducted on farmers' fields. The trial was conducted in three representative barley growing areas: Tera Emni and Wekerti in Zoba Debub and Adi Guadad in Zoba Maekal over 3 years from 2005 to 2007. The trials were laid down as complete block design with four replications and 8 treatments (ICARDA 2007):

Control	regular farmer's practice;
F	fertilizer application using di-ammonium phosphate (16% N and 48% P) and urea (46% N) at 100 and 50 kg ha^{-1}, respectively;
M	moisture conservation (rainwater harvesting) using tied ridges;
W	weed control: two hand-weedings at 20 and 40 days after emergence;
F+M	combination of fertilizer and moisture conservation;
F+W	combination of fertilizer and weeding;
W+M	combination of weeding and moisture conservation;
F+M+W	combination of fertilizer, weeding, and moisture conservation.

Plot size was 5m x 2m (10 m^2); the barley cultivar used was Yeha, a landrace recommended for planting in the study area; planting was done in the first week of July each year at a seeding rate of 100kg ha^{-1}.

Data collection included barley grain yield, rainfall, the costs of seeds, fertilizer, ridging, weeding and other management practices, harvesting, threshing and transportation, and the price of barley.

The CD production function for barley in the Eritrean highlands

Barley yield and inputs of the different treatments and monthly rainfall for the growing season in the three locations over the three seasons (2005-2007) were used to estimate the production function using the ordinary least square (OLS) method. The Cobb-Douglas production function was suitable to reflect the nonlinear relationship between barley yield and the seven explanatory variables included in the analysis. Logarithmic transformation was used to transfer the Cobb-Douglas function into a linear function that allowed use of the OLS method of estimation.

In each location there were only 24 yield observations, a small sample for the estimation of a production function. Therefore, the data from the three locations were pooled resulting in 72 observations. To determine whether this pooling would affect our results or not, two production functions were estimated; one with two dummy variables for the three locations and one without the dummy variables. The Chow test was used to test the hypothesis that the two regression equations were the same (Gujarati 1978), and the test accepted this hypothesis. Thus, the regression equation without the dummy variable was used to estimate the effects of rainfall and different agronomic practices on barley yield.

The estimated production function was used to predict the barley yield of the different agronomic practices for the years 1995-2004 at Adi Guadad and Wokerti, and for the years 1999-2004 at Tera Emni, using the monthly rainfall data for the barley growing season (July-October) in each location. Availability of weather data was the reason for selecting these periods. The predicted yields were used to calculate:

- Rain water productivity for barley under the different agronomic practices, to see the effect of seasonal rainfall on the performance of these practices.
- Total and net returns of barley for each practice in all locations.

Water productivity was calculated by dividing barley yield by the total amount of rainfall during the growing season.

Theil's inequality coefficient (U) was used to evaluate the accuracy of the predicted data where this data can be compared to actual data. It is defined as:

$$U = \frac{\sqrt{\frac{1}{T}\sum_{t=1}^{T}(Y_t^s - Y_t^a)^2}}{\sqrt{\frac{1}{T}\sum_{t=1}^{T}(Y_t^s)^2} + \sqrt{\frac{1}{T}\sum_{t=1}^{T}(Y_t^a)^2}}$$

Where: Y_t^s = predicted value for Y_t

Y_t^a = actual value

T = number of periods in the prediction

The numerator of U is the root mean square (rms) forecast error; it provides a measure of the ability of the model to forecast well. The scaling of the denominator is that U will always fall between 0 and 1. If U = 0, Y_t^s = Y_t^a for all t and there is a perfect fit. If U = 1, on the other hand, the predictive performance of the model is as bad as it possibly could be (Pindyck and Rubinfeld 1981). The calculated value of U was 0.072, meaning that the predictive performance of the model (the CD function derived from our data) is good.

To evaluate the effects of these practices on farmers' income and the associated risk, the costs of each practice, total and net returns under different practices and different climatic conditions were considered.

Two methods of price specification can be used to calculate total returns. The first takes barley price as fixed at the 2006 level. The second uses the naive expectations model - the expected price is the same as the market price in the previous year. Fixed price was used in this study to eliminate economic variability so that the results would reflect the effect of the agronomic practices on yield variability. The costs of different barley agronomic practices were calculated. Input quantities such as seed rate, fertilizer, labor for moisture conservation and weeding were established for different agronomic practices. Only variable costs were considered in this study, and they were taken at their 2006 levels. Fixed costs of production were excluded because they were identical for all agronomic practices.

Using fixed output prices for this analysis, total returns were derived by multiplying the estimated yields by the price of barley. Net returns were derived by subtracting the corresponding costs from the total returns. For each of the agronomic practices, a set of 13 replications for Wokerti and Adi Guadad (9 for Tera Emni) were made using 1995-2007 rainfall data.

Results

The highest yields were achieved each year at each location from the application of fertilizer and from a combination of fertilizer, weeding and moisture conservation treatments (Table 1). The lowest yields were obtained from the control (farmers' practice). The differences between the yields of most of the treatments and the control were statistically significant in 2005 except for the yields of weeding plus moisture conservation treatments in Tera Emni and Wokerti. In 2006 and 2007, yields at all sites were significantly higher than the farmers' practice except for the yields of the weeding treatment in Adi Guadad. Yields were highest in Adi Guadad and least in Tera Emni for the same treatments.

An example of the variable costs, total returns and net returns for the experiment data for Tera Amni in 2006 is presented in Table (2).

Table 1. Effect of individual and combined agronomic practices on grain yield (kg ha^{-1}) for 2005-2007 in three locations in Eritrea.

Growing season	Trail Location	Control	Fertilizer (F)	Moisture (M)	Weed (W)	F + M	F+ W	M + W	F+M+ W
2005	Tera Emni	525	1306	1016	923	995	1309	593	1350
	Adi Guadad	967	2236	1321	1371	1609	1395	1356	1989
	Wokerti	979	1539	1119	1204	1446	1746	871	1674
2006	Tera Emni	844	1498	1162	1068	1233	1281	1270	1445
	Adi Guadad	1529	2233	1627	1589	2069	1970	1952	2156
	Wokerti	945	1973	1299	1480	1408	1862	1785	1932
2007	Tera Emni	665	1543	1134	1293	1365	1409	1163	1664
	Adi Guadad	852	1834	1199	1345	1454	1461	1462	1950
	Wokerti	651	1492	1031	1237	1315	1315	1220	1649
	Mean	884	1739	1212	1279	1433	1528	1297	1756

Table 2. Variable costs and returns of agronomic treatments in Tera Emni, 2006.

Variable Cost	Agronomic Practices							
	Control	Fertilizer	Moisture	Weed	FM	FW	MW	FMW
Seed	1000	1000	1000	1000	1000	1000	1000	1000
Fertilizer	0	525	525	525	525	525	525	525
Weed	0	0	0	1505	0	1750	1455	1790
Ridging	0	0	1500	0	1500	0	1500	1500
Harvesting	1200	1750	1350	1350	1600	1600	1400	1650
Threshing	750	1050	700	750	950	950	650	1100
Transport	400	752	569	535	630	667	643	738
Total costs	3350	5077	5644	5665	6205	6492	7173	8303
Yield kg ha^{-1}	813	1503	1138	1070	1260	1333	1285	1475
Total return	6098	11273	8535	8025	9450	9998	9638	11063
Net return	5236	9913	6129	5332	5483	6542	5489	6128

Exchange rate for 2006 (1 US$ = 11 negfa).

The estimated parameters (coefficients) for the Cobb-Douglas production function of barley are presented in Table 3. These coefficients are elasticities, measuring the percentage change in yield resulting from a percentage change in the explanatory variables. The results show that July and September rain are very significant in barley production and have positive effects, while August rain was insignificant and October rain had a highly significant negative effect. This reflects the negative effect of pre-harvesting rain. Decreasing rainfall and all the input variables by 10% will decrease yield by 73%, with 57% of the decrease caused by the decrease in July rainfall, and 12% caused by the decrease in September rainfall. However, a 10% decrease in October rainfall will result in 9.7% increase in yield. Fertilizer can cause a 6.8% increase in yield for a 10% increase in fertilizer use. A 10% increase in moisture conservation or weed control led to 3.3% and 1.7% increases in yield, respectively. The R^2 shows that about 70% of the change in yield is explained by the changes in the explanatory variables. An F test was used to test the significance of the explanatory variables included in the model. Comparing the computed F value (20.91) with the tabulated critical value (2.82, p=0.05) shows that the group of variables included in the model were statistically highly significant determinants of yield.

Table 3. Estimated co-efficients for the Cobb-Douglass barley production function.

Variable	Regression coefficient	Std. error coefficient	Computed T
Constant	3.7	0.011	7.376**
July rainfall (mm)	0.574	0.011	5.057**
August rainfall (mm)	0.006	0.008	0.079
September rainfall (mm)	0.124	0.023	6.426**
October rainfall (mm)	-0.097	0.019	-4.128**
Fertilizer (kg ha^{-1})	0.068	0.073	8.211**
Moisture conservation (working day)	0.033	0.114	2.935**
Weed control (working day)	0.017	0.502	1.523*
R^2	0.696		
F	20.906		
Df	64		

**, * Significant at 1% and 10% respectively

Average water productivity predicted from the CD function, and average net returns and their coefficient of variation (CV), are presented in Table 4, and the details of net returns each year are presented in Table 5. The fertilized treatment had the highest average NR in all three locations, but with a very high CV at Adi Guadad and Wokerti. For most of the practices there was very high variation in NR.

Table 4. Average water productivity WP (kg m^{-3}), average net return NR (negfa* ha^{-1}) and coefficient of variation CV for NR for different agronomic practices for 1999-2007. (n=number of seasons for which the data were estimated)

Agronomic practice	Average	Farmer practice	Fertilizer application	Moisture conservation	Weed control	F+M	F+W	M+W	F+M+W
Adi Guadad (n=13)	WP	0.25	0.39	0.28	0.29	0.37	0.38	0.32	0.43
	NR	3144	4991	1611	1979	3608	3564	1078	2727
	CV for NR	137	322	366	374	396	394	401	440
Wokerti (n=13)	WP	0.25	0.39	0.29	0.31	0.38	0.42	0.32	0.45
	NR	2981	4639	1509	2076	3478	4069	902	2957
	CV for NR	288	311	280	290	298	305	355	299
Tera Emni (n=9)	WP	0.29	0.47	0.35	0.34	0.46	0.49	0.37	0.53
	NR	3085	5226	2169	1813	3909	4395	1061	3464
	CV for NR	61	30	67	108	51	34	346	53

Table 5. Distribution of net return NR for agronomic practices in three locations of Highlands of Eritrea for 13 years (1995-2007)

Location	Agronomic practice	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean	S.D	CV
Adi Guadad	Control	4670	135	3275	5294	3795	3039	2845	2243	138	387	3901	8115	3036	3144	2223	137
	Fertilizer	6225	-165	4259	7105	4992	3926	3653	2805	-162	190	11696	11673	8681	4991	4017	322
	Moisture	2903	-1930	1416	3568	1971	1165	958	316	-1927	-1661	4260	6561	3349	1611	2554	366
	Weeding	3403	-1724	1827	4110	2415	1559	1340	659	-1721	-1439	4619	6255	4425	1979	2573	374
	F+M	5839	-971	3745	6778	4526	3390	3098	2195	-967	-592	5859	9310	4700	3608	3116	396
	F+W	6288	-938	4066	7283	4894	3689	3380	2421	-934	-536	3972	8280	4465	3564	2960	394
	M+W	2491	-2973	811	3244	1437	526	292	-433	-2970	-2669	2997	7463	3794	1078	3011	401

Location	Agronomic practice	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean	S.D	CV
	F+M+W	5316	-2384	2948	6377	3831	2547	-838	1195	-2380	-1956	6613	7863	6323	2727	3707	440
Wokerti	Control	2236	2613	343	2780	4247	4787	6634	3509	3211	-870	3989	3741	1532	2981	1931	288
	Fertilizer	2796	3327	127	3561	5629	6390	8993	4589	4169	-1582	6469	9724	6113	4639	3162	311
	Moisture	309	711	-1709	889	2452	3028	4996	1665	1348	-3001	2746	4098	2085	1509	2182	280
	Weeding	652	1078	-1489	1266	2925	3536	5625	2091	1754	-2861	3364	5438	3610	2076	2443	290
	F+M	2185	2751	-659	3001	5204	6016	8789	4096	3649	-2480	4642	4357	3659	3478	2817	298
	F+W	2410	3011	-607	3276	5614	6475	9418	4438	3964	-2540	6600	7472	3372	4069	3233	305
	M+W	-441	13	-2723	214	1982	2633	4858	1092	734	-4184	-640	6215	1980	902	2795	355
	F+M+W	1184	1825	-2032	2107	4598	5516	8652	3345	2840	-4091	4253	6184	4065	2957	3353	299
Tera Emni	Control	-	-	-	-	2738	5059	3186	4948	4167	2468	587	2981	1634	3085	1475	61
	Fertilizer	-	-	-	-	3502	6773	4134	6618	5516	3122	4715	6154	6494	5226	1402	30
	Moisture	-	-	-	-	844	3317	1322	3200	2367	556	1978	3074	2862	2169	1051	67
	Weeding	-	-	-	-	423	2744	871	2633	1852	153	1260	2346	4032	1813	1256	108
	F+M	-	-	-	-	2938	6424	3612	6258	5084	2533	1257	3042	4033	3909	1730	51
	F+W	-	-	-	-	3209	6908	3924	6732	5487	2780	3328	3118	4073	4395	1584	34
	M+W	-	-	-	-	163	2960	704	2827	1886	-162	-2727	2348	1552	1061	1806	346
	F+M+W	-	-	-	-	2036	5978	2797	5790	4463	1578	1826	2533	4174	3464	1689	53

The water productivity results also showed that all the treatments in the three locations increase water productivity compared to farmers' practice. However, the average water productivity at Tera Emni, is higher than in the more favorable areas under farmer practice as well as under the interventions, despite the lower yields in Tera Emni (Table 1). This is due to the lower rainfall at Tera Emni. While all agronomic practices increase water productivity compared to farmer practice, the case is not the same for net returns, which reflect changes in both yield and variable production costs. Average net returns for farmer practice is higher than that of many of the other agronomic practices, namely moisture conservation, weed control and moisture conservation plus weed. However, fertilizer application shows a very significant positive impact on net returns compared with farmer practice. The highest net returns at all three locations were with fertilizer alone. Fertilizer plus moisture conservation plus weeding control has higher total returns but similar or lower average net returns than farmer's practice in two locations due to the high costs associated with the three actions included in this practice. The increment in yield due to fertilizer application was high enough to make the additional return exceed the additional cost of fertilizer and generate higher net return. However, the marginal increments in yield for the other practices were not high enough to compensate for the additional costs associated with these practices, and thus generated lower net returns.

The coefficient of variation (CV) measures the variability in net returns, which reflects the risk associated with each practice; a higher CV reflects a more risky practice. All practices at Tera Emni have a lower CV, usually considerably lower, for net returns than the same practices in the other two locations. Net return for farmers' practice has the lowest CV at Tera Emni, and the second lowest at Wokerti (Table 2). That means all other agronomic practices are more risky to farmers than his/her practice. This reflects the clear tradeoff between yield level and its variability across different practices. This trade off demonstrates the need for formal analysis that takes into account both yield level and its variability to draw sound recommendations.

Although yield and total returns for all intervention practices are much higher than those of farmers' practice, the net returns of these practices are sometimes lower than or similar to those of farmers' practice due to the higher costs of the intervention practices.

The results of the stochastic dominance analysis are presented in Table 6. The results for Adi Guadad and Wokerti were similar, and showed that fertilizer application dominated all the other practices except for the farmers' practice. The riskiness of farmers' practice and fertilizer application or its combination with moisture conservation or weed control were similar ("undetermined"). However, farmers' practice was risk efficient with respect to four other practices; moisture conservation, weed control, combination of weed control and moisture conservation and combination of fertilizer, weeding, and moisture conservation.

In Tera Emni, fertilizer application dominated all the other practices including farmers' practice. Farmers' practice was also dominated by the combination of fertilizer and weed control, and the combination of fertilizer, moisture and weed control. Farmers' practice dominated the three other practices. At Tera Emni the riskiness of farmers' practice and the combination of fertilizer and moisture conservation were similar. The combination of fertilizer and weed control dominated all the other practices other than fertilizer application alone. The combination of fertilizer, moisture and weed control was risk efficient with respect to five other practices, while moisture and weed control practices were inefficient and dominated by all the other practices in all locations.

Table 6. Pairwise comparisons of probability distributions of eight agronomic practices for three locations.

Location	Agronomic Practice	Farmers' Practice	F	M	W	F+M	F+W	M+W	F+M+W
Adi Guadad	Farmer's Practice	-	?	1	1	?	?	1	1
	F	?	-	1	1	1	1	1	1
	M	0	0	-	0	0	0	1	?
	W	0	0	1	-	0	0	1	?
	F+M	?	0	1	1	-	?	1	1
	F+W	?	0	1	1	?	-	1	1
	M+W	0	0	0	0	0	0	-	0
	F+M+W	0	0	?	?	0	0	1	-
Wokerti	Farmer's Practice	-	?	1	1	?	?	1	1
	F	?	-	1	1	1	1	1	1
	M	0	0	-	0	0	0	1	?
	W	0	0	1	-	0	0	1	?
	F+M	?	0	1	1	-	?	1	1
	F+W	?	0	1	1	?	-	1	1
	M+W	0	0	0	0	0	0	-	0
	F+M+W	0	0	?	?	0	0	1	-
Tera Emni	Farmer's Practice	-	0	1	1	?	0	1	0
	F	1	-	1	1	1	1	1	1
	M	0	0	-	1	?	0	1	0
	W	0	0	0	-	?	0	1	0
	F+M	?	0	?	?	-	0	1	0
	F+W	1	0	1	1	1	-	1	1
	M+W	0	0	0	0	0	0	-	0
	F+M+W	1	0	1	1	1	0	1	-

1=dominates the other, 0=dominated by the other, ?=undetermined result.

The analysis shows that first and second degree stochastic dominance (FSD & SSD) criteria had similar discriminatory power, with SSD showing slightly higher discrimination (Table 7), consistent with the findings of Gebremedhin et al. (1998). In other words, the FSD and SSD criteria gave similar results. Risk efficiencies of fertilizer application and farmers' practice were the same based on FSD and SSD in Adi Guadad and Wokerti (Table 7). Both were risk efficient with respect to all other practices in the two locations. In Wokerti, the combination of fertilizer and weed control was also determined as stochastically efficient by both FSD and SSD. In Tera Emni, FSD suggested that fertilizer application and the combination of fertilizer and weed control were the risk efficient practices that dominated all the other practices, while SSD suggested that fertilizer application was the only efficient practice at Tera Emni (Table 7).

Table 7. Stochastic dominance results of the agronomic practices included in the study

Location	Agronomic Practice	First-Degree Stochastic Dominance (FSD)	First-Degree Stochastic Dominance (FSD)
Adi Guadad	Farmers' practice	Dominates	Dominates
	F	Dominates	Dominates
	M	Dominated	Dominated
	W	Dominated	Dominated
	F+M	Dominated	Dominated
	F+W	Dominated	Dominated
	M+W	Dominated	Dominated
	F+M+W	Dominated	Dominated
Wokerti	Farmers' practice	Dominates	Dominates
	F	Dominates	Dominates
	M	Dominated	Dominated
	W	Dominated	Dominated
	F+M	Dominated	Dominated
	F+W	Dominates	Dominates
	M+W	Dominated	Dominated
	F+M+W	Dominated	Dominated
Tera Emni	Farmers' practice	Dominated	Dominated
	F	Dominates	Dominates
	M	Dominated	Dominated
	W	Dominated	Dominated
	F+M	Dominated	Dominated
	F+W	Dominates	Dominated
	M+W	Dominated	Dominated
	F+M+W	Dominated	Dominated

Conclusion

All seven intervention practices (fertilizer, moisture conservation, weeding, and their combinations) increased water productivity compared with farmers' practice in all locations; however, the high costs associated with these practices off set the returns from productivity improvement. In addition, this improvement was accompanied with increased variability that reflects the increased risk associated with these practices.

The estimated parameters of the production function show that July and September rain are very significant in barley production and have positive effects that sum up to 69% increase in yield when the rainfall of these two months increases by 10%. However, increasing October rainfall has a highly significant negative effect on yield. A 10% increase in October rainfall will result in 9.7% reduction in yield as October rainfall coincides with crop harvesting resulting in crop damage. Fertilizer, moisture conservation and weed control have less effect on yield than rainfall, with a combined average effect of 11% yield increase for a 10% increase in all 3 interventions.

The seven agronomic treatments all had higher average water productivity than farmers' practice in all locations. However the benefits of weeding and moisture conservation were very small. Adding fertilizer gave water productivity increases of around 50%, and there was no or little additional water productivity increase from combining fertilizer with moisture conservation or weeding. Average water productivity in the low rainfall area, Tera Emni, was higher than that in the more favorable areas under farmers' practice as well as under all respective interventions. This has important implications in the sense that the introduced treatments were more effective in enhancing water productivity in low rainfall areas. This suggests that enhancing water productivity in more favorable rainfall areas requires a different set of treatments. One potential intervention is to introduce an improved variety that is highly responsive to more rainfall.

Pairwise comparisons of probability distributions of net returns from the set of alternative practices showed that fertilizer application in all locations was a risk efficient practice, with a similar risk (2 locations) or lower risk than farmers' practice. In Adi Guadad and Wokerti, farmers' practice was risk efficient with respect to four practices: moisture conservation, weed control, combination of weed control and moisture conservation, and combination of fertilizer, weeding, and moisture conservation. In Tera Emni, farmers' practice was risk inefficient with respect to three practices: fertilizer application, combination of fertilizer and weed control, and combination of fertilizer, weeding, and moisture conservation.

FSD suggested that, in Adi Guadad, fertilizer application and farmers' practice dominated all other practices, while in Wokerti, the combination of fertilizer and weed control was efficient in addition to these two practices. For Tera Emni, farmers' practice was not risk efficient and only fertilizer and the combination of fertilizer and weed control were efficient. SSD suggested the same results as FSD except for Tera Emni, where fertilizer application was the only efficient practice.

Farmers' practice was one of the efficient practices in Adi Guadad and Wekerti, this meaning that the increase in yield of the dominated practices was not high enough to cover the additional costs associated with these practices; i.e. the net returns of these practices are not high enough to trade off the high variability associated with them.

The sets of efficient practices do not necessarily result in maximum water productivity. If water productivity is used as the selection criterion between the dominant practices, fertilizer application is recommended over farmers practice as water productivity of fertilizer application was higher (range 0.39 to 0.47 kg m^{-3}) than that of farmers' practice (range 0.25 to 0.29 kg m^{-3}) in all locations. Meanwhile, the combination of fertilizer and weed control is recommended over fertilizer application in Wokerti and Tera Emni since its WP is higher (range 0.38 to 0.49 kg/m^3) than that of fertilizer alone (range 0.42 to 0.47 kg m^{-3}). Also the combination of fertilizer, weed control and moisture conservation (range 0.43 to 0.53 kg m^{-3}) is recommended over fertilizer application alone in the three locations since its WP is higher.

Fixed prices were used in this study to eliminate economic variability and study only the effect of the agronomic practices on yield variability. Using variable prices would reflect both economic and yield variability. Work will continue to study the effect of economic variability as well as yield variability and see their effect on decision criteria and the choice of efficient practices.

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Water productivity of temperate cereals in Eritrea: complementing the participatory breeding programme

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Abstract

The project CPWF PN2 "Improving Water Productivity of Cereals and Food Legumes in the Atbara River Basin of Eritrea" has as major component a participatory breeding programme that deals with several trials grown in different rainfed conditions. To understand the performance of lines under these different conditions it is necessary to know water availability at the time of key phenological stages driven yield as well as interacting crop management events. The present paper shows how the water balance will be calculated and how phenological development and crop management in the field will be followed.

Key words

water productivity, water balance, integrated management

Introduction

The Participatory Breeding Component of project CPWF PN2 "Improving Water Productivity of Cereals and Food Legumes in the Atbara River Basin of Eritrea" works in 18 different conditions if we consider the combination of rainfall and soil type and depth. The breeding crosses are based on visual evaluation done by farmers and researchers and on the grain and straw yield obtained in previous years. The last shows large variation among sites probably as a result of the interaction between different stresses as trial management is generally the same. In rainfed conditions drought is consider the major limitation, however, in Eritrea soil fertility and weed competition are also relevant. In fact, common yields of 1 t/ha are low for rainfalls of more than 400 mm and favorable photothermal quotients indicating that water is not always the main constraint (Sadras and Angus 2006; French and Shultz 1984).

Yield components are formed at different time. For example, in the case of wheat and barley, the final number of fertile florets is mostly determined between booting and anthesis whereas grain weight is obtained during grain filling. Therefore, a drought period at heading will decrease grain number but if it occurs after anthesis then grains will be smaller. Understanding the dynamics of water availability and matching the phenological development accordingly would increase water productivity and yield (Gómez-Macpherson et al. 2003). Furthermore, crop management should also match the prevailing system in order to assure maximum water productivity. For example, most rainfall in project sites occurs between July and August but often early rains occur as well and any option that advances sowing date will allow better fit of the crop to the rainfall period and lower evaporative demand (Gómez-Macpherson and Richards 1995; Fischer et al. 1998). Direct sowing is one of the options explored by the project that goes in this sense.

This paper presents the methodology that will be followed along the season to determine the water balance and to record phenological stages and crop management. The methodology requires least field work due to transport difficulties in the country and a large number of sites to follow.

Methods

The water balance will be calculated using measured rainfall and soil water content at sowing and at harvest and estimated evapotranspiration. Rainfall (R, mm) and maximum and minimum temperature (Tmax and Tmin, °C) will be measured daily with Decagon stations in 4 sites and with rain gauges and Hobo thermometers in the rest of sites.

Soil water content will be measured at sowing and harvest with hand auger in three points of the check variety plots. Soil will be sampled at least to 0.6 m deep, but preferably to 1.2 m, by layer: 0-15, 15-30, 30-60, 60-90 and 90-120. Samples will be dried at about 105°C and the gravimetric water content (%) calculated as ((weight wet soil sample–weight dry soil)/weight of dry soil)*100. Bulk density for each layer will be calculated from intact soil cores obtained with special auger (dry weight of soil core/volume of core; g/cm^3). The volumetric water content of layer will be calculated as gravimetric water content (%) x bulk density (g/cm^3) x depth of layer (cm) x 0.1 (multiplier to give mm water).

Soil water content at field capacity (θ_{fc}, cm^{3}cm^{-3}) will be estimated from soil samples taken 2 days after a heavy rain whereas soil water content at wilting point (θ_{wp}, cm^{3}cm^{-3}) will be estimated from samples taken before the start of the rainy season.

Crop evapotranspiration (ET_c) will be calculated using FAO method (Allen et al. 1998) by which reference evapotranspiration (ET_o) is multiplied by a dual coefficient that considers separately direct soil evaporation from plants transpiration.

ET_o (mm d^{-1}) will be calculated using the Hargreaves equation (Hargreaves and Samani 1985) as it requires only daily mean, maximum and minimum air temperature (T, Tmax, Tmin, °C) and extraterrestrial radiation (Droogers and Allen 2002):

$$ET_o = 0.0023 R_a (T + 17.8)\sqrt{T_{\max} - T_{\min}} \quad (1)$$

R_a (mm d^{-1}) is the water equivalent of the extraterrestrial radiation calculated according to Allen et al. (1998).

The dual crop coefficient includes the basal crop coefficient (K_{cb}), which represents primarily the transpiration component, and the evaporation component (K_e). The basal crop coefficient curve will be adjusted by the fraction of soil covered by vegetation (f_c), the crop height (h, m) and the recommended values for the initial stage and maximum development ($K_{cb,ini}$ and $K_{cb,mid}$ in Table 1, from Allen, et al. 1998) according to:

$$K_{cb} = K_{cb,ini} + \frac{K_{cb,ini} - K_{cb,\max}}{0.8} f_c^{1/(1+0.5h)} \qquad \text{if } f_c < 0.8 \qquad (2a)$$

$$K_{cb} = K_{cb,mid} \qquad \text{if } f_c > 0.8 \qquad (2b)$$

The average fraction of total available soil water that can be depleted from the root zone before moisture stress occurs (p) and ET_c is reduced, and maximum root depth (Zr, m) are taken from Allen, et al. (1998) as well (Table 1). Maximum root depth will be substituted by soil depth the last is smaller than the values proposed in Table 1.

Table 1. Initial, mid and final crop coefficients ($K_{cb,ini}$, $K_{cb,mid}$, $K_{cb,end}$), fraction of available soil water that can be depleted from the root zone before ET_c is reduced (p) and maximum root depth (Zr).

Crop	$K_{cb,ini}$	$K_{cb,mid}$	$K_{cb,end}$	p	Zr (m)
Barley, Wheat	0.15	1.10	0.30	0.55	1.2
Chikpea	0.15	0.95	0.25	0.50	0.7
Lentil	0.15	1.05	0.20	0.50	0.7
Faba bean	0.15	1.10	0.20	0.45	0.6

The data required from the crop includes sowing and harvest dates and fortnight information on fraction of soil covered by vegetation (f_c), crop height (h, m) and phenological stage (Zadoks et al. 1974). Field sheets will be used for each trial to record this information and any management event; they will include also target check points of seedlings m^{-2}, shoots m^{-2}, spikes m^2, kernels m^{-2} and kernel weight and possible constraints if current values disagree substantially with the targets (Gómez-Macpherson et al. 2003).

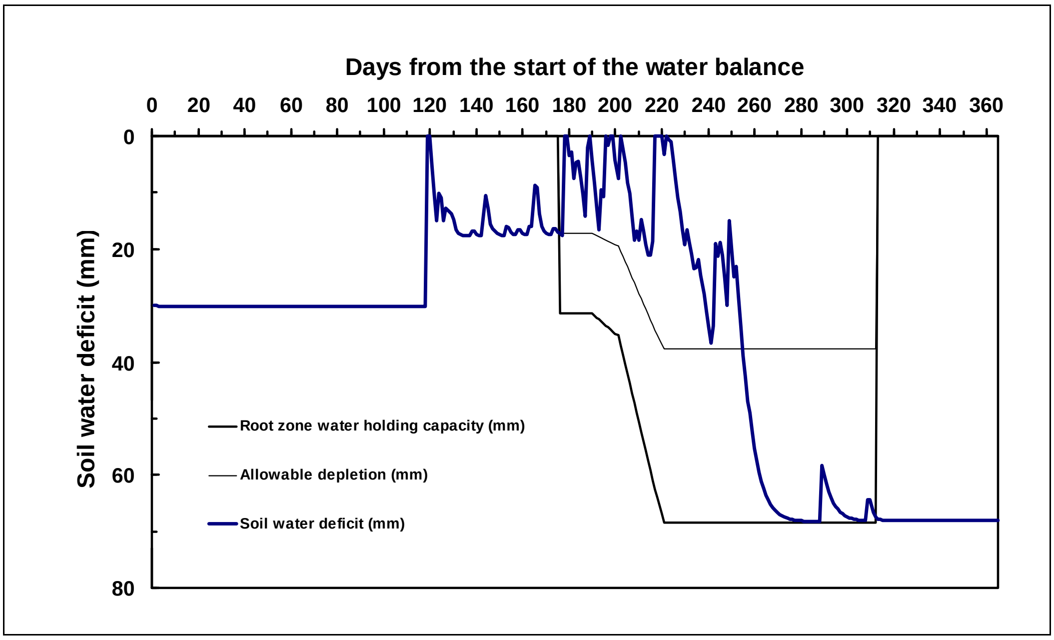
The fraction of soil covered by vegetation (f_c) can be estimated by looking at the crop 2 metres in front through a circle formed with the thumb and index finger and held about 10 cm from the eye (Gómez-Macpherson et al. 2003). The ground area covered by leaves and shadows should be guessed, repeating for different areas and looking in different directions. The best time of the day to estimate ground cover is midday.

Runoff can be calculated when first soil layer is saturated and there is a rainfall. Additionally, a visual soil assessment will be carried out following Shepherd et all (2008).

The water balance will be calculated using an excel sheet. The water deficit in time can be visualized as is the example provided in Figure 1. This example corresponds to an average wheat line sown on 25th of June 2007 at Halhale (Eritrea) in a deep silt soil with heading occurring on 20th September and harvesting on 7th November. The figure shows how water stressed occurred during grain filling while there could be enough rain in June to cover the early needs of the crop. In fact, rainfall pattern in the project zones is bimodal with some rain occurring between March and June, which in some cases represent a significant amount (e.g. 370 mm at Tekondae or 120 mm at Wekerti in 2006 corresponding to 40 and 27 % of total amount, respectively). Target sowing date should be revised with historical weather data to explore best used of stored soil water of early rains.

For comparative purposes, water productivity will be calculated as grain yield (or biomass yield) divided by ET_c, seasonal or total rainfall.

Figure 1. Soil water deficit in a wheat crop at Halhale (Eritrea) in 2007.



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Climate change impact on crop productivity in the semi-arid tropics of Zimbabwe in the 21st century

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Abstract

The Intergovernmental Panel for Climate Change (IPCC) projections for Southern Africa (based on the outputs of 21 Global Circulation Models (GCM), using the A1B greenhouse gas emission scenario) suggest average annual temperature increases of 3.1°C and changes in annual rainfall of between -12 and +6%. Atmospheric carbon dioxide levels for this scenario are expected to increase to around 700ppm from the current 370ppm. How might these changes impact on crop productivity in the drier semi-arid cropping systems of the region? This paper reports an analysis of the combined positive (CO_2 fertilization) and negative (higher temperature, lower rainfall) impacts of these projected climate changes on crop productivity using the crop systems simulation model APSIM with its climate change module, together with the long-term daily climate data from Bulawayo (1951–2001). In undertaking these simulations, the effects of the climate change scenarios on the potential grain and stover yields of maize, sorghum, pigeonpea and groundnut was examined.

APSIM output shows that increasing CO_2 concentrations will increase crop yields by around 6–8%. Similarly, reduced rainfall had the expected negative impact on grain yield. However, it is increasing temperature (and not reduced rainfall) that has the most dramatic impact on grain yields; reductions of 16% for the two cereals and 31% for groundnut, but only 3% for pigeonpea. Hence, for the combined effects of climate change, it appears that pigeonpea will be the least affected crop, incurring an 8% reduction in potential grain yield compared to the current potential yield. In contrast, groundnut can be expected to incur a 30% reduction, sorghum a 22% reduction, and maize a 25% reduction. Model outputs on crop duration, water productivity and stover yield were further analyzed to explain the differences between crop species in response to climate change and their implications for animal feed production.

An important implication of this analysis is that adoption of longer duration rather than shorter duration germplasm would seem the more appropriate response in dealing with the main effects of climate change. Another is the preliminary indication that opportunities for increased cropping intensity and increased use of legumes in the farming system could emerge under climate change. However, the largest scope for dealing with reduced crop yields and food insecurity under future climate change is to raise the productivity of smallholder rainfed cropping systems through improved management, and especially through the use of N fertilizer.

Key words

APSIM, sub-saharan Africa, maize, ground nut, pigeon pea

Introduction

In 2002, the Intergovernmental Panel for Climate Change (IPCC) provided strong evidence of accelerated global warming. In Paris in February 2007 they released the most recent assessment that reinforced the link between human activity and global warming beyond any reasonable doubt (IPCC 2007). Since then, many key investors and stakeholders in agricultural development in the developing world have recognized that, while the exact nature and extent of the impacts of climate change on temperature and rainfall distribution patterns remain uncertain, it is the poor and vulnerable who will be the most susceptible to changes in climate. This is especially true for those communities who live in the drylands of Africa and who rely largely or totally on rainfed agriculture for their livelihoods. It is they who are currently most vulnerable to existing climate variability and shocks.

While climate change predictions point with a high degree of certainty to a warming world within the next 50 years, the impact of rising temperatures on rainfall distribution patterns in Africa remains far less certain (IPCC 2007). However, climate change is likely to make matters worse with increases in rainfall variability being predicted for the semi-arid tropics (SAT) region. The prognosis for rainfall in Southern Africa is particularly poor, with almost the entire region having a reduction in rainfall (unlike India for example where the predictions are for areas of increase and decrease and in equal proportions), and up to 20% reduction in length of growing season with consequent effects for cropping area, distribution, productivity and ultimately food production in a region that consistently experiences food deficits (Scholes 2008; Bwalya 2008; Ager 2008). At the same time, Conservation Agriculture is being strongly promoted as an appropriate response to climate change in rainfed cropping systems because of its better management of the rainfall resource for crop production (Bwalya 2008; Nyagumbo 2008).

What has been less forthcoming is quantitative information on the likely extent of crop yield reductions. This is to be expected given the uncertainty in how rainfall patterns will change with rising temperatures, but also because there are likely to be positive (e.g. CO_2 fertilization) as well as negative impacts on crop productivity with climate change, and how the interaction of these effects will play out is difficult to analyze.

In this study we have applied a soil-crop simulation model in conjunction with actual and modified long-term historical climate data to assess the potential impacts of climate change on crop productivity in semi-arid regions of Zimbabwe. The soil-crop modeling tool is APSIM (Keating et al. 2003) which contains well-tested algorithms that deal with temperature effects on crop growth and development as well as soil water and nitrogen dynamics (including in Zimbabwe, Ncube 2007). The model includes a 'climate change' module that allows temperature and rainfall data to be adjusted by nominated amounts and, for some crop modules, includes carbon assimilation algorithms that respond to increased CO_2 concentrations.

In the analysis we disaggregate the effects of increased temperature, reduced rainfall and increased CO_2 concentrations on crop productivity as well as investigate the combined effects. The focus of the analysis is assessment of the impacts of climate change on crop productivity at the field level, with the aim of identifying the main mechanisms by which climate change will impact on crop yields and the magnitude of such impacts. The analysis does not attempt to extrapolate the findings to national or regional levels and does not make inferences for future food security.

Materials and Methods

Climate change scenario examined

We used the climate change scenario for the greenhouse gas emission scenario associated with Storyline A1B considered in the IPCC deliberations and analysis. The A1 storyline and scenario family describe a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source on the assumption that similar improvement rates apply to all energy supply and end-use technologies). The expected climate change impacts of this scenario across the 21 Global Circulation Models (GCM) used by IPCC are given for southern Africa in Table 1.

Table 1. Predicted effects of climate change on temperature and rainfall in southern Africa by the end of the 21st century using the A1B scenario with 21 Global Circulation Models (IPCC 2007)

Season	Temperature Response (°C)					Precipitation Response (%)				
	Percentiles					Percentiles				
	Min	25	50	75	Max	Min	25	50	75	Max.
DJF	1.8	2.7	3.1	3.4	4.7	-6	-3	0	5	10
MAM	1.7	2.9	3.1	3.8	4.7	-25	-8	0	4	12
JJA	1.9	3.0	3.4	3.6	4.8	-43	-27	-23	-7	-3
SON	2.1	3.0	3.7	4.0	5.0	-43	-20	-13	-8	3
Annual	1.9	2.9	3.4	3.7	4.8	-12	-9	-4	2	6

For Zimbabwe, we have taken the 50% percentile values for temperature change (3.1°C) in the growing season (DJF+MAM) and explored a 10% reduction in rainfall, even though the prediction is that rainfall in the growing months will, on balance, be unchanged. We have also examined the impact of increased greenhouse gas emission. For the A1B storyline, CO_2 levels will increase from the current 350 ppm to 700ppm by the end of the 21st century.

Cropping scenarios examined.

We used the 'climate change' module associated with the cropping systems model APSIM, together with the long-term daily climate data from Bulawayo (1951–2001) for this analysis. A summary climatic description is given in Table 2. At Bulawayo the cropping season rainfall falls predominantly between November and April. Bulawayo has an altitude of 1350 masl.

Table 2. Summary climatic characteristics of Bulawayo, Zimbabwe (Numbers in parenthesis are CV's of the mean rainfalls)

Location	Bulawayo (1951- 2001)	
Season	Nov-Apr	Annual
Average rainfall (mm)	548 (40%)	597 (30%)
Average max T°C	27	26
Average min T°C	16	13
Average T°C	22	19

The legume growth modules in APSIM are able to respond to increased carbon dioxide levels by modifying the transpiration efficiency coefficient and the N concentration optimum for photosynthesis. Neither the sorghum nor maize modules currently have this capability; hence different scenarios were simulated for the cereal and legume crops.

Based on the climate change predictions given in Table 1, we examined the following scenarios through APSIM simulations:

1. Baseline. This scenario looked at simulations derived from the unmodified current climate data.

Grain legumes

2. Carbon dioxide fertilization. This scenario examined the impacts of increasing the CO_2 level from 350 to 700ppm, keeping all other parameters constant.
3. Increased temperature. This scenario examined the impacts of increasing the maximum and minimum temperatures by 3.1°C, keeping all other parameters constant.
4. Reduced rainfall. This scenario examined the impacts of decreasing daily rainfall by 10%, keeping all other parameters constant.
5. Combined effects – carbon dioxide, plus temperature plus % rainfall changes.

Cereal crops

6. Increased temperature. This scenario examined the impact of increasing the maximum and minimum temperatures by 3.1°C on cereal production, keeping all other parameters constant.
7. Reduced rainfall. This scenario examined the impact of decreasing rainfall by 10%, keeping all other parameters constant.
8. Temperature plus rainfall. This scenario looked at the combined impact of increased temperature and reduced rainfall for cereal production.

We examined these scenarios for sorghum (early hybrid cultivar), maize (early hybrid), short-duration pigeonpea and short-duration groundnut varieties.

Simulation details

A common planting moisture criterion (20mm rainfall over 5 days, 15mm plant available water in profile) during the window (Nov 20 to Jan 10) was used to trigger sowing in all simulations. Input plant populations (plants m^{-2}) for the respective crops were: sorghum – 6 , maize – 3.7 and groundnut – 10. The soil was shallow sand (1m rooting depth, PAWC = 59mm), the curve number for runoff was set to 85, and crop residues were removed after harvest. The soil water balance was simulated with accumulated effects of crop growth and rainfall across years (i.e., there were no resets).

In undertaking these simulations, we examined the effect of the climate change scenarios on *potential* crop yield. In other words, we ran the simulations under nutrient non-limiting conditions, with no pest occurrences or weed infestation. Soil mineral N supply was maintained at 75kg N ha^{-1} distributed throughout the profile for each day of crop growth. A low N treatment for maize was also simulated, and in this case soil mineral N was re-set to 16kg N ha^{-1} at each crop sowing.

If water balance conditions for planting within the nominated window were not met, a sowing was simulated to take place on the last day of the window regardless of water availability (i.e., a 'dry sow' on Jan 10^{th}). As reliable information is not available on how climate change will affect distribution of rainfall within the cropping season, the forced sowing rule ensured all available rainfall distribution patterns were sampled in quantifying the effects of climate change on plant growth. A consequence of this rule is that crop failures due to lack of sowing rains are not included in the simulated yield distributions in this analysis.

Results

Grain yield, crop duration and water use.

Simulated average potential grain yield of sorghum, maize, groundnut and pigeonpea at Bulawayo are presented in Table 3, along with the average main effects of the climate change scenarios. APSIM output shows that increasing CO_2 concentrations will have a positive effect on crop yields, on average 8% and 6% for the two legume test crops. Similarly, a reduction in rainfall amount had the expected negative impact on grain yield, although with 6–8% yield reduction across species, it is a lower reduction than the 10% reduction in rainfall. This suggests some improvement in water use efficiency with reduced rainfall in this environment, probably as a result of less runoff.

Clearly, the scenario of increasing temperature has the most dramatic impact on crop grain yields, at least for the two cereals, which had a reduction of 16%, and particularly for groundnut, which had a 31% reduction. Interestingly, pigeonpea yield was little affected by the temperature increase – its 3% reduction in yield was even less than the reduction due to rainfall. Hence, for the combined effects of climate change, it appears that pigeonpea will be the least affected crop, incurring an 8% reduction in potential grain yield. In contrast, groundnut can be expected to incur a 30% reduction compared to current potential, sorghum a 22% reduction and maize a 25% reduction. However, it must be noted that of the four test crops, short-duration pigeonpea has by far the lowest current yield potential at Bulawayo.

Table 3. APSIM simulations of the impact of climate change scenarios on average potential grain yield of sorghum, maize, groundnut and pigeonpea at Bulawayo, Zimbabwe.

Crop	Potential** grain yield kg ha^{-1}	CO_2 effect on yield	Rainfall effect on yield	Temperature effect on yield	CC* effect on yield
Sorghum	2753	n/a	-6%	-16%	-22%
Maize	2125	n/a	-8%	-16%	-25%
Groundnut	1979	+8%	-7%	-31%	-30%
Pigeonpea	1230	+6%	-7%	-3%	-8%

* Climate change – combined effects of increased temperature and reduced rainfall, and increased CO_2 in the case of groundnut and pigeonpea, and of increased temperature and rainfall in the case of sorghum and maize
** Potential yield of the current rainfall, CO_2, temperature and radiation environment averaged over 50 seasons, with no nutrient, pest or disease constraints.

What explains these differences in response to climate change between crop species? It is primarily related to a shortening of crop development phases with increased temperatures and consequent change in plant use of available resources, namely, solar radiation and soil water?

Under the combined effects of climate change, all crops have large reductions in days to maturity (13–18%), and all have a large reduction in total biomass (18–27%) except pigeonpea, which shows a 4% increase (Table 4). For maize and groundnut, there is also a decrease in average harvest index (HI) and water-use efficiency (WUE) because the grain filling period for these two crops suffers a larger reduction (19 and 14%) compared to the vegetative phase (17 and 11%). Sorghum, on the other hand, experiences greater shortening of the vegetative phase (18%) relative to the grain filling phase (14%), resulting in increased HI while retaining a WUE of 6.7 kg ha^{-1} mm^{-1}. The higher HI for sorghum thus results from much lower total biomass, resulting in the 22% reduction in grain yield shown in Table 3.

In contrast, pigeonpea has the largest reduction in crop duration (18%), yet shows an increase in total biomass and an increase in WUE. A more favourable soil water balance for the pigeonpea explains this result. Under the current uni-modal rainfall conditions (and latitude), the crop has a very long duration such that grain filling takes place under declining rainfall and increasing water stress. Higher temperatures under climate change shorten the crop duration so that it matures when the wet season is still active. This is particularly so for the duration of the grain filling period, which is reduced by 31% on average.

In terms of relative change, sorghum and pigeonpea grain yield demonstrated the most resilience of the four test crops under climate change (Table 3) as a consequence of increased HI and WUE. However, it can be seen in Table 4 that WUE itself is dependent on crop duration and in-crop rainfall, both of which are reduced by climate change. An important associated result is an increase in residual soil water under climate change, from 8–22mm (current climate) to 11–34mm across species. If, under climate change, the length of the rainy season is assumed to be unchanged (as in this analysis), then the predicted shortening of crop duration and higher residual soil water are indicative of opportunities for increased cropping intensity, especially on soils of higher water holding capacity.

Table 4. APSIM simulations of the impact of the combined effects of climate change on potential total biomass, crop duration, in-crop rainfall, harvest index and water-use efficiency of sorghum, maize, groundnut and pigeonpea at Bulawayo, Zimbabwe.

Crop	Baseline					Climate Change				
	Total biomass (kg ha^{-1})	Duration (d)	In-crop rain (mm)	HI	WUE* (kg ha^{-1} mm^{-1})	Total biomass (kg ha^{-1})	Duration (d)	In-crop rain (mm)	HI	WUE* (kg ha^{-1} mm^{-1})
Sorghum	6398	107	396	0.41	6.7	4663	88	320	0.44	6.7
Maize	6403	129	433	0.29	4.3	4747	107	352	0.28	3.9
Groundnut	4628	122	416	0.42	4.5	3782	106	345	0.37	3.8
Pigeonpea	4288	165	463	0.27	2.3	4445	136	397	0.24	2.4

*WUE was calculated as kg of grain / (soil water at sowing – soil water at harvest + in-crop rainfall)

Stover production.

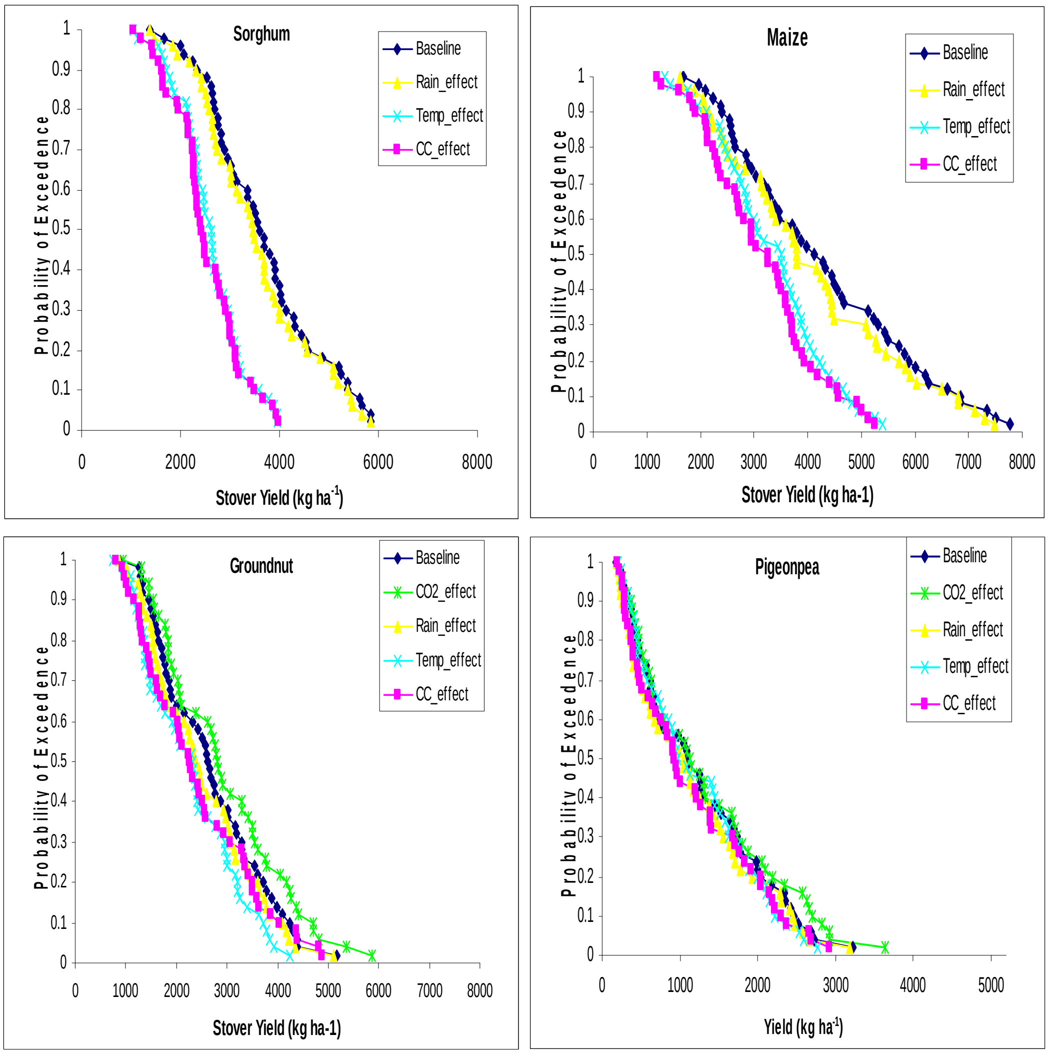
In extensive mixed farming systems in SAT regions, grain production is important for food security purposes. However, in these systems, crop stover is of equal or higher value as a feed source for livestock during the long dry season. Cereals provide the bulk of this feed source because there are limited plantings of legumes, typically less than 10% of croplands. This is the situation even though legumes have a higher stover N content and therefore higher nutrient value than the cereal crops.

The probability distributions for crop stover yields (Figure 1) show that, under current conditions (and with non-limiting N supply), cereal crops compared to the legumes potentially produce more stover. However, under conditions of climate change, the cereal stover yields are more sensitive to the shortened crop duration than the legumes, and show dramatically reduced stover yield distributions, especially in the more favorable seasons. Under climate change, the 50 percentile yield for groundnut stover is similar to that of maize and sorghum, and because of its higher N content, may become a more attractive crop as a source of animal feed under the climate change.

Climate change and farmer yields.

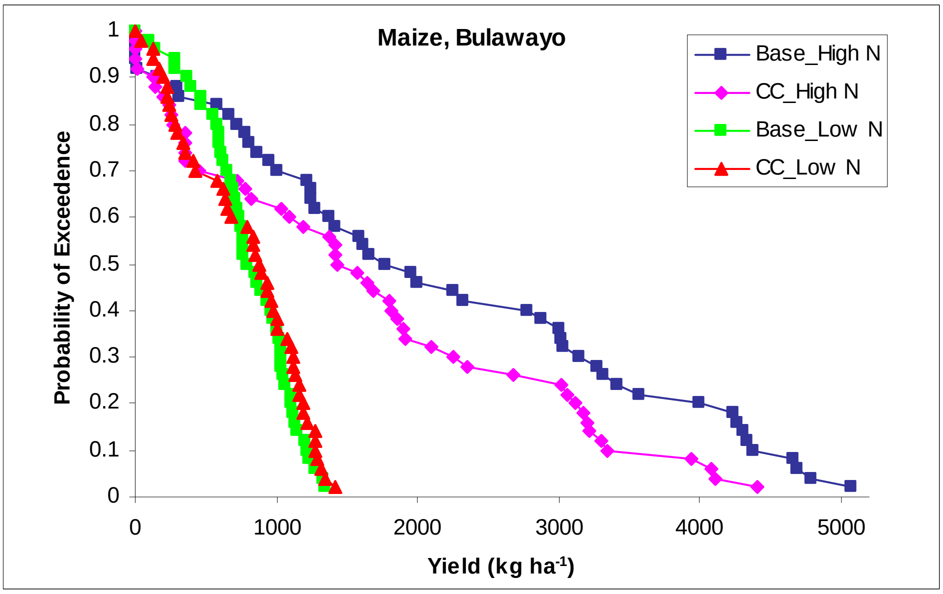
A comparison of simulated maize grain yield probability distributions at the low levels of N fertility typical of farmer management in the SAT and at non-limiting N is shown in Figure 2, along with the respective responses under climate change conditions. The distributions show that in the drier 15% of years, maize yields at low N are higher than with N non-limiting, illustrating the strong interaction of N supply and water supply in determining grain yields in these environments (Bongani 2007). Also evident is the fact that for N constrained crops, climate change will adversely affect yields in the driest 30% of seasons, but will have no or a slight increase in yield for the majority of seasons (the simulated small increases in yield with climate change are probably related to more favorable plant N balance as a result of shortened crop duration, smaller biomass production and higher soil N mineralization with higher soil temperatures). In other words, if farmers in the SAT maintain their current management practices and yield levels, climate change will be largely inconsequential due to the over-riding constraint of fertility on crop yield.

Figure 1. Cumulative probability distributions of exceedence for stover yields of sorghum, maize, groundnut and pigeonpea under various climate change scenarios at Bulawayo, Zimbabwe.



For the potential yield scenario (high N), climate change substantially reduces maize yield for the better 85% of the seasons. However, for almost all of these better seasons the potential yield under climate change still exceeds yields of current farmer practice (low N) by a much larger margin than the reduction in potential yield due to climate change. This highlights the large yield gap that smallholder farmers in these rainfed farming systems are forgoing in the better seasons, and points to the large scope that exists for dealing with future climate change impacts on food production if we could only find solutions to the chronic low productivity of these farming systems under current climate conditions, especially solutions to the low use of N fertilizers.

Figure 2. Cumulative probability distributions of exceedence for maize grain yield under current (Base_) and climate change scenario (CC_) for high (non-limiting) and low (farmer fields) levels of N at Bulawayo, Zimbabwe.



Summary

The crop simulation analysis has shown that for the chosen climate change scenario (A1B), potential crop yields in the Zimbabwe SAT will be substantially reduced under climate change: by 8–30% for the crop cultivars used in this analysis. The results also point to increased temperatures (the aspect of climate change that is seemingly most certain) as the main mechanism by which climate change will have a significant impact on crop productivity (through reduced crop duration, radiation interception and biomass accumulation). By comparison, the effects of predicted reductions in rainfall or increased CO_2 concentrations are relatively small in this analysis. This could be an important insight because much current thinking points to a need to breed shorter duration crop cultivars to deal with assumed shorter growing periods and increased moisture stress under climate change. This analysis suggests that the easy and readily available solution would be to adopt current longer duration germplasm under climate change conditions. At the same time, the simulation output on soil moisture, crop duration and stover yields is indicative of possible opportunities for increasing productivity under climate change, for example, an increased opportunity for relay cropping and increased use of legumes in the cropping system.

However, it should not be overlooked that this analysis has considered the effects of a climate change scenario that is predicted to take place at the end of the 21st century. The analysis also adopted potential grain yield (in relation to rainfall, temperature and radiation conditions of the test environment) in assessing the impact of the climate change scenario. The yield levels for the analysis are therefore much higher than those which smallholder farmers are typically producing, especially in the SAT where soil fertility is generally poor and investment in fertilizer by farmers is very low. While the analysis has shown that future climate change could have significant impact on crop productivity in the SAT, and there is need to prepare for this outcome, the research agenda should not lose sight of the fact that there is much that can be done now to help smallholder farmers increase their current crop productivity. Doing this in the context of current climatic risk is perhaps the best way of providing smallholder farmers with appropriate strategies for coping with future climate change (Cooper et al. 2007).

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Assessing water supply and demand for dry season rice in coastal polders of Bangladesh

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Abstract

Salinity intrusion prohibits the use of river water for irrigation of dry season (boro) rice in the coastal zone of Bangladesh. This can be overcome by using water stored in the canal networks within the polders for irrigation when the river water becomes saline. It is not yet known, however, whether this technology can be adopted on a large scale. By using systems approaches, this study compared the water demand of boro rice with the storage capacity of the canal networks to assess the area of boro rice that can be grown in the polders. A two-season field experiment was carried out in a typical coastal polder to quantify responses of crop growth, yield, and irrigation water demand to different planting dates. Experimental results were used to calibrate and evaluate the model ORYZA2000, which was then used to quantify the probabilistic yields and water demand of boro rice over a 20-year period. Rice crops planted in October suffered from low temperature during the reproductive period, resulting in low harvest index (HI). Delaying planting after 10 November did not result in yield gain but increased the water requirement from the canal storage substantially. Oryza2000 simulated satisfactorily the total rice biomass, and water requirement, but needs to be improved to take into account the effects of low temperature on HI to enable it to satisfactorily simulate yields of boro rice. The optimum planting time for highest productivity with respect to storage water was from 1 to 10 November. The area of boro rice that can be irrigated from water storage was about 15% of the rice area of the polder in at least 50% of years. This can be increased to 40% of the area if the canals are dredged according to the plan by the Bangladesh Water Development Board. The potential of large-scale adaptation of boro rice warrants the investment to increase the water storage capacity of the polder. Development of cold-tolerant rice varieties can further increase the potential area because they can be planted earlier and hence reduce water requirements.

Key words

Oryza, boro, sowing date, water use, irrigation, salinity

Introduction

Bangladesh faces an enormous challenge in trying to achieve food self-sufficiency for its growing population. The coastal zone of Bangladesh, covering an area of 2.83 million ha, is the least productive agricultural zone. Because of salinity intrusion in the dry season, rice cultivation is limited to a single rainy season crop (aman rice). The area, however, has potential for development. Mondal et al. (2006) showed that with proper water management an additional rice crop could be grown in the dry period after the aman rice in the coastal polder areas. Growing dry season (boro) rice in the area involves two distinct stages of irrigation. The first stage (when river water salinity is low, with electrical conductivity EC < 4 dS m^{-1}, usually before mid February) is gravity irrigation by letting river water in through sluices at high tides. The second stage starts when the river water EC > 4 dS m^{-1}. Just before the river water becomes saline, it could be taken into and stored in the internal canal networks of polders (old river channels). The stored water could be used to irrigate the dry season rice by pumping onto the fields until shortly before harvest time. The possibility of out-scaling the technology, i.e. for wide scale adoption of boro rice cropping, has not been systematically investigated. This is hampered by the lack of data on: (1) the water requirement of the boro rice crop; (2) the optimal planting time for high yield and water productivity with respect to the amount of water pumped from the canal network; (3) the storage capacity of the internal polder canal networks; and (4) the time when river water becomes too saline for irrigation.

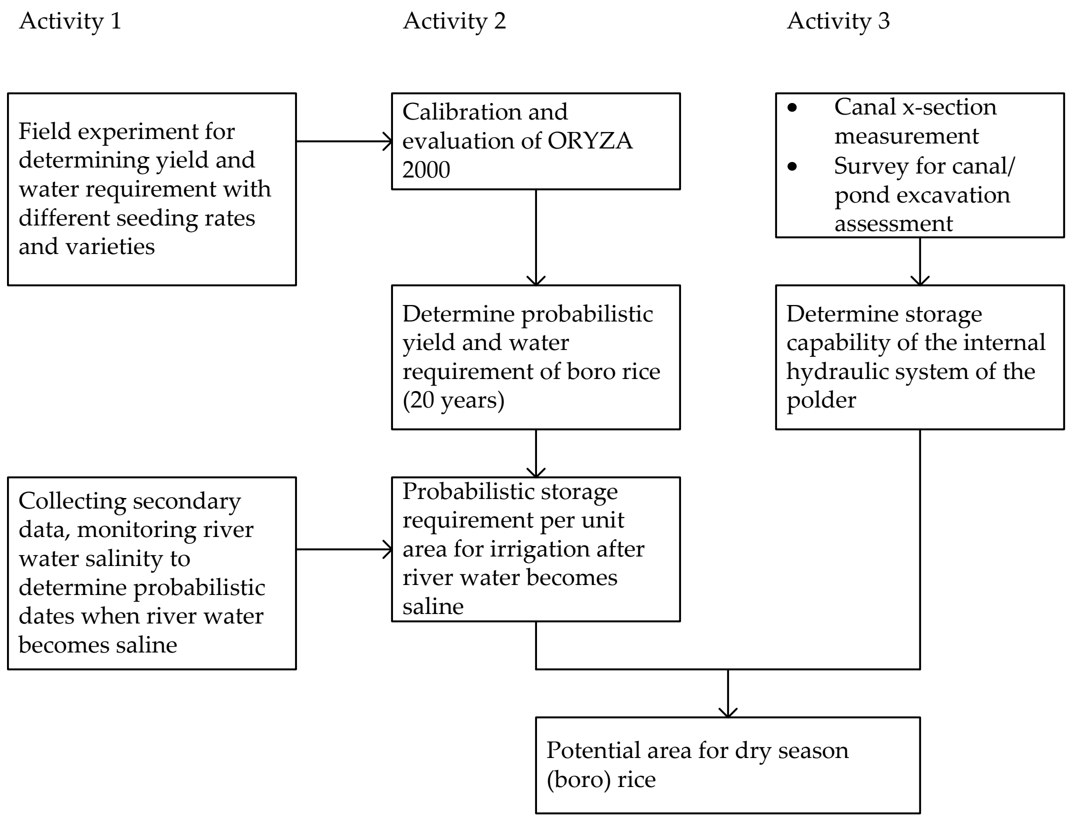
The main objective of the study was to determine the potential for increasing boro rice production in the polder areas in the coastal zones of Bangladesh through effective utilization of the available land and water resources. This was achieved through a systems approach, combining field activities and crop modeling using ORYZA2000 (Bouman and van Laar 2006). This approach was used to quantify probabilistic yields and water requirements of boro rice crop for different times of establishment and varieties, and to balance the water requirement with storage capacity of the internal canal networks of a typical polder in the coastal zone.

Methods

The study site (Polder 30, between 22° 37' and 22°46' North and 89°27' and 89°33' East) is located in Batiaghata Upazila in Khulna district, southwestern Bangladesh. The gross area of the polder is about 7725 ha with a net cultivable area of about 4867 ha (IPSWAM 2007). The polder is protected from high tides by an embankment 40 km long and 4.3 m wide at the crest. The hydraulic system of the polder is controlled by a system of sluices. The water level of the surrounding rivers fluctuates daily due to tidal effects. During high tide, the water level can rise from 1 to 2.8 m above land level, creating opportunities for gravity irrigation when the water river is not too saline.

The research was organized in three activities as schematically shown in Figure 1.

Figure 1. Key research activities in the coastal zone of Bangladesh



Field experiment

An experiment was carried out in the 2005–06 and 2006–07 dry seasons (DS) with a split plot design. The main plots were four dates of seeding (D1 = 22nd Oct, D2 = 1st Nov, D3 = 7th Nov, and D4 = 15th Nov). The subplots were two cultivars (BRRIdhan 28, a popular variety also known as BR-28 and PVS B8).

The seedlings were transplanted when they acquired four leaves, at three to four seedlings per hill and spacing of 20 cm x 20 cm. All plots were irrigated until 2 weeks before harvest. The amount of irrigation water applied to each plot was measured using a V-notch weir. This amount was checked against daily subsidence of the water level in the fields, measured by a staff gauge. The subsidence was equivalent to total field water requirement (evapotranspiration (ET) + percolation (P) + seepage (S)). Two 1 m x 1 m GI tanks (0.4 m height, installed to depth of 0.25 m) one with a bottom and one bottomless, were installed in the four main plots. Subsidence of water level in the tanks was monitored daily for the measurement of ET and P (calculated by difference). A rain gauge and a class A evaporation pan were installed in the field.

Urea was applied at 120 kg N ha^{-1} in four equal splits (basal, 25 days after transplanting (DAT); 5 to 7 days before panicle initiation (PI), and heading). Basal incorporation at last harrowing also included 60 kg P_2O_5 ha^{-1}, 40 kg K_2O ha^{-1}, 10 kg $ZnSO_4$ ha^{-1}, and 60 kg $CaSO_4$ ha^{-1}.

Crop phenology, biomass, its partitioning and leaf area index (LAI) at critical growth stages, grain yield, and yield components were monitored following standard procedures. Water and crop data were analyzed with standard split-plot analysis of variance (ANOVA) techniques.

River water salinity measurement and data collection

The EC of the river water was monitored daily to check its suitability for irrigation. When river water EC approached 4 dS m^{-1}, the sluice gates were opened at high tide to fill the canals with river water to their maximum capacity. Storage water was used for irrigation from this time until the end of the season. The daily recorded EC of the river water at the study sites did not differ significantly from those recorded at Khulna, a national permanent water quality monitoring station. Daily Khulna EC data were subjected to frequency analysis to determine the 50% probability of exceedence (P_{excd}) of the date when EC = 4 dS m^{-1}, beyond which (cut-off date) the river water cannot be used for irrigation.

Crop growth modeling

Crop data from the third seeding of the 2006–07 DS crop were used to generate variety- and site-specific parameters required by ORYZA2000. They were the crop development rate, percentage partitioning of biomass into its components, indigenous nitrogen uptake, and S&P. The model was then evaluated using data from 2005–06 and other seeding dates of the 2006-07 crops, according to the procedure described by Bouman and van Laar (2006). The third step involved scenario analysis over a period of 20 years (using climatic data from Khulna) of the effects of eight different seeding dates (every 5 days from 15 October) on crop yield and water requirement of the two varieties.

Storage capacity

Total hydraulic storage within the polder was determined from the length and cross-sections of the canal networks and other small water bodies (ponds/ditches) within the polder. Since most of the canals in the study polder were silted, the Bangladesh Water Development Board (BWDB) developed a plan to dredge and widen the canals (IPSWAM 2007). This plan was consulted to determine the future storage capacity of the water bodies of the polder.

Results and discussion

In both years, grain yields varied with seeding date and variety. Grain yields of the first two seeding dates were significantly lower than those of the later seeding dates (Table 1). The lower yields of the earlier seeding dates were mainly attributed to their lower number of spikelets m^2 and lower percentage of filled spikelets (data not shown), resulting in significantly lower harvest index (HI) than those of the last two seeding dates (Table 1). Earlier seeding dates exposed the reproductive stage of the crop to low temperature, affecting the spikelet formation processes. This is supported by the linear correlation between HI and the average daily minimum temperature from panicle initiation (PI) to the flowering stage of the crop (Figure 2, for BR 28 – similar results were obtained for PSV-B8).

The average ET increased from 1.7 mm d^{-1} in November to 3.5 mm d^{-1} in March; and the average S&P rates from 2.1 mm d^{-1} to 3.6 mm d^{-1} over the same period. The total irrigation amount of D1 was significantly lower than those of other treatments in 2006-07 (Table 1). There was no significant difference in total irrigation water among the last three seeding dates. The effects of higher daily ET and S&P of the later seeding dates on water requirement were balanced by their shorter duration (due to higher temperature during their crop period), resulting in equivalent water requirements. The amount of irrigation taken from canal storage increased as the seeding dates were delayed. The difference of maturity period for the first and last seeding dates was about 15 days; however, almost twice the amount of irrigation water was taken from the canal storage for the last seeding than for the first seeding (Table 1, for the 2006–07 DS season). In the experiment, river water remained suitable for irrigation until the end of January, and most of the irrigation for the D1 crop came directly from the river because the crop matured at the beginning of March, while the D3 and D4 plots had a higher dependency on canal storage water to meet the irrigation water demand after January until they matured in April.

The long-term salinity data analysis indicated that the cut-off date corresponding to P_{excd} = 50% for using river water was the second week of February.

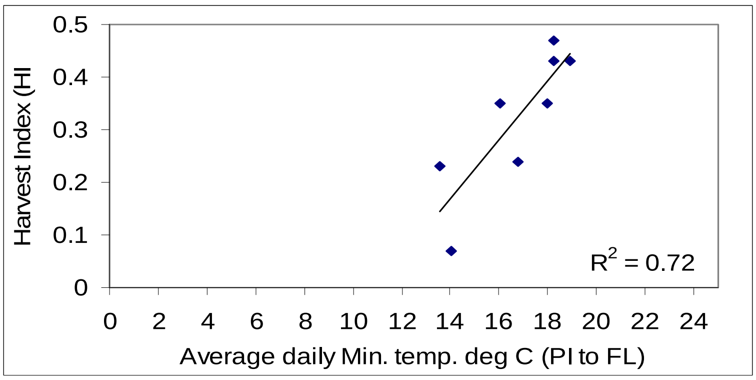
Table 1. Yield, harvest index (HI), total irrigation water, and irrigation from canal storage for two rice varieties seeded in different dates in 2006-07 DS crop. 2005-06 DS crop had similar results.

Seeding dates	Yield (kg ha^{-1})			HI		Irrigation water (mm)	
	BR-28	PVS-B8	Diff.	BR-28	PVS-B8	Total	Canal storage
D1 = 22 Oct	703 d[a]	940 d	ns	0.07 c	0.08 c	621 b	143 c
D2 = 1st Nov	2394 c	2878 b	*	0.24 b	0.34 b	722 a	223 b
D3 = 7 Nov	5036 a	5218 a	ns	0.47 a	0.49 a	759 a	268 a
D4 = 15 Nov	4501 b	5111 a	*	0.43 a	0.47 a	761 a	278 a

[a]In each column means followed by the same letter are not significantly different at 5% level by LSD. Mean values are averaged over four replications.
* = significant at 5% level by LSD and ns = not significant.

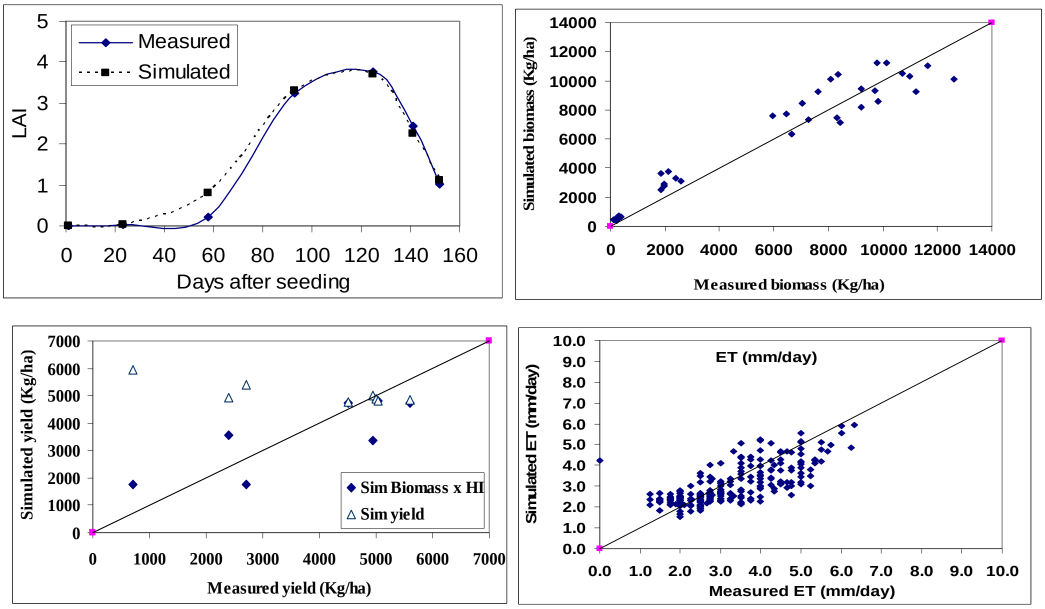
The storage capacity of the canal system was about 2,592,164 m^3. After subtracting the "dead volume" and the volume needed for fisheries, the extractable volume was 2,137,445 m^3. If the canals are dredged and widened according to the plan of BWDB, the extractable volume for irrigation will increase to 5,575,118 m^3.

Figure 2. Relationship between HI and the average daily minimum temperature from panicle initiation (PI) and flowering (FL) for cultivar BR-28.



The simulated LAI, total biomass, and ET (Figure 3a, b, and d) satisfactorily agreed with the measured values. In Figure 3c, the simulated yields that exceeded the measured values corresponded to the early seeding dates (15-31 October). The poor agreement between measured and simulated yields for the early sowing dates is because ORYZA2000 does not adequately taken into account the effects of low temperature on spikelet formation and pollination. Rice yields obtained by multiplying the simulated biomass by HI (which was obtained from Figure 2) agreed well with the measured values. This method of yield simulation was used in the scenario analysis.

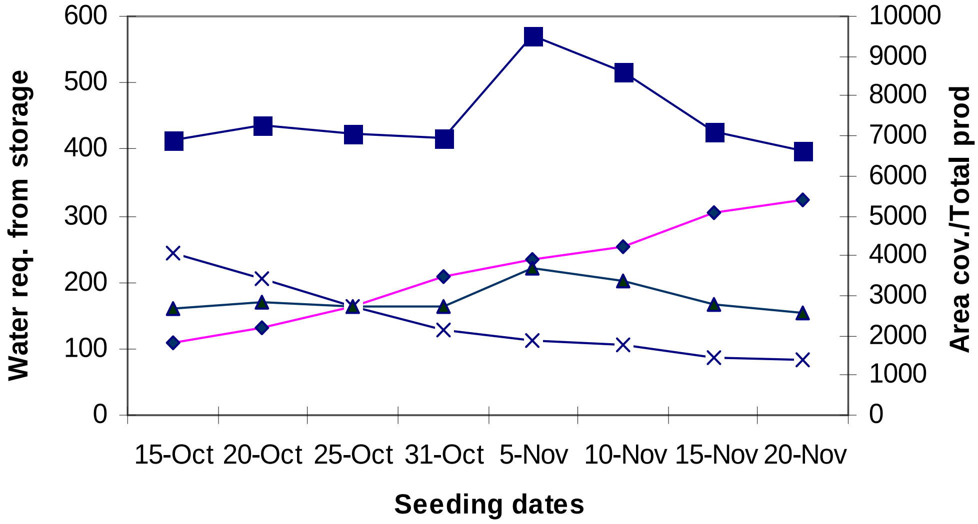
Figure 3. Oryza2000 simulated vs. measured (a) LAI, (b) total above-ground biomass, (c) grain yield, and (d) ET (mm/d) for cultivar BR28, in four seeding dates of 2005-06 and 2006-07 dry season crops. The simulated grain yields (c) were from simulation using Oryza2000 (Sim yield Δ) or calculated from simulated biomass multiplied by HI calculated from the relationship in Figure 2 (Sim Biomass x HI ♦). Similar results were obtained for PSV-B8. The solid line is the 1:1 relationship.



Simulation using 20 years of climate data showed that rice yield increased steadily from about 2,000 to 5,000 kg ha^{-1} as the seeding date was delayed from 15 October to 10 November at all probabilities of exceedence. Seeding later than 10 November did not increase yield but increased considerably the amount of irrigation water taken from the canal storage (Figure 4). As a result, the maximum water productivity with respect to irrigation from canal storage was obtained when seeding was carried out on 5 November. At P_{exd} = 50% the maximum water productivity was 2.2 g kg^{-1}.

The area that can be brought into boro rice cultivation declined steadily as the seeding date was delayed (Figure 4, showing the future scenario when canals are dredged according to the BWDB's plan). The total boro rice production, however, maximizes at a seeding date of 5 November (Figure 4), corresponding to the seeding date with maximum water productivity (with respect to irrigation water from canal storage). With this seeding date and at P_{exd} = 50%, the boro rice area that can be irrigated from the storage of the present canals (i.e. silted) is 740 ha (15% of the rice area). This can be increased to 1,924 ha (40% of the rice area) if the canals are dredged. These will bring an additional 3,700 t (present canal conditions) and 9,600 t (dredged canals) of rice to Polder 30, compared with 13,000 t presently produced by the aman rice crop.

Figure 4. Irrigation water requirement from canal storage (♦mm); the predicted area of boro rice (x, in ha) that can be irrigated when canals are dredged according to the plan of BWDB; total predicted boro rice production (■ tons) when canals are dredged; and total predicted boro rice production (▲ tons) in the present (i.e. silted) canal condition. All values correspond to the probability of exceedence of 50%, using 20-year simulation.



Conclusions and recommendations

The time of seeding had contrasting effects on the two components of water productivity of boro rice grown in the south western coastal region of Bangladesh. Seeding before November resulted in very low yields due to cold stress at the critical reproductive stages of boro rice. Late-seeding required more water to be taken from the limited storage capacity of the canal network, and therefore will reduce the area that can be irrigated. A systems approach, using crop modeling, allowed us to analyze the trade-offs between the two components over a 20-year period. With the optimum dates of seeding around 1–10 November, and with proper water management, 15% of the rice land can be planted with boro rice after the aman season. The percentage can be increased to 40% with some investments to improving the conditions of the canals. Developing cold-tolerant varieties that can be planted early, hence reducing water required from the canal storage, can also increase the area of boro rice.

Acknowledgments

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SECTION 3

Downstream impacts of increasing water productivity in rainfed cropping systems

Methodologies and case studies for investigating upstream-downstream interactions of rainwater water harvesting in the Limpopo Basin

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Abstract

Rainwater harvesting (RWH) is a promising technology for increasing water availability for crop production of smallholder farmers in the semi-arid regions of the Limpopo Basin. A few studies on rainwater harvesting have been conducted in the basin at small plot and farmer field scales. Results from Mozambique, Zimbabwe and South Africa indicate substantial benefits to crops grown using a range of rainwater harvesting techniques. However, there have been no catchment and basin level studies to investigate the impacts of wide scale adoption at these levels. A methodology flow chart is proposed for systematically investigating the impacts of out-scaling of these in-field and ex-field rainwater harvesting techniques. The method proposes an analysis of levels of adoption to help identify optimum levels that will maximize land and water productivity while minimizing negative hydrological and ecological impacts at catchment or basin scales.

Key words

hydrological model, methodology flow chart, smallholder farmers, technology, out-scaling

Background and Introduction

Introduction

The Limpopo Basin is one of the benchmark sites of the Consultative Group of International Agricultural Research (CGIAR) Challenge Program on Water and Food Crop (CPWF). The basin has low annual rainfall (530 mm) and it covers most semi-arid regions of Southern Africa (Harrington *et al.* 2004). Crop production is one of the major activities in the basin, but farmers face many challenges, especially smallholder farmers. The low rainfall and frequent droughts that are experienced during the growing season make rain-fed farming a risky business (Butterworth *et al.* 1999; Twomlow and Bruneau 2000; Unganai and Mason 2002). There is competition for water among countries and communities within the region (Basson and Rossouw 2003; Mazvimavi 2004; Mugabe *et al.* 2007; Nyabeze 2004; Vörösmarty *et al.* 2000). The CPWF program in the Limpopo Basin is therefore addressing issues of improving the productivity of rainfed cropping systems by introducing drought resistant varieties, suitable crop and soil management practices, appropriate water policies and governance, and adopting a basin approach to water management (Harrington *et al.* 2004). Smallholder rainfed farming remains the dominant economic activity for a large part of the southern African population. Given the constraints on availability of blue water for full-scale irrigation, which are likely to remain the case for the medium term future, the improvement of smallholder rainfed farming must be a priority (Love *et al.* 2006). Green water use efficiency (that proportion of rainwater that is converted to transpiration) is very low in sub-Saharan Africa (15 %, Stroosnijder 2008). The need for technologies that increase the efficiency of use of the limited water in both crop production and domestic use is therefore very clear (Ngigi 2003). Rainwater harvesting (RWH) is one of these technologies.

Rainwater harvesting is broadly defined as the collection and concentration of runoff for productive purposes (crop, fodder, pasture or tree production, livestock and domestic water supply etc.) (Ngigi 2003) or the process of concentrating rainfall as runoff for use in a smaller target area (Botha *et al.* 2003). The rainfall harvested can either be in-field (tillage techniques, pits etc.) or off-field (micro-catchment or runoff farming and supplementary irrigation). The advantages of RWH include increases in infiltration and groundwater recharge, and the potential to harvest water from small rainfall events that do not always produce increased stored water for irrigation (Li 2008). Field scale studies in the Limpopo basin have so far looked at some of the RWH technologies (Woltering 2005; Magombeyi and Taigbenu 2008, Mupangwa *et al.* 2007 and 2008; Mwenge-Kahinda *et al.* 2007), but the impacts of up-scaling the techniques are not known and are not easy to quantify.

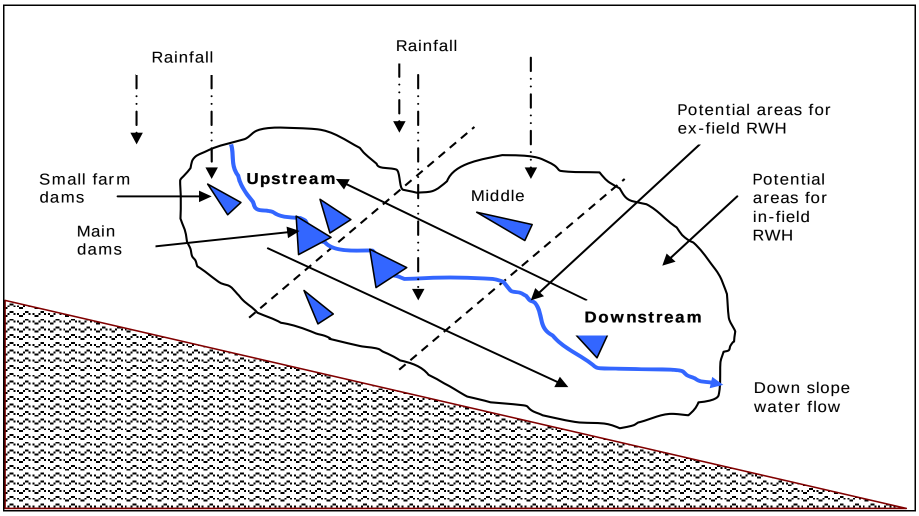
Rainwater harvesting may have a substantial downstream impact if it results in: (i) diverting significant amounts of rainwater or soil moisture from recharge, overland flow or stream runoff into transpiration, (ii) diverting rainwater from one micro-catchment to another micro-catchment, or (iii) both. Where RWH diverts incoming rainwater that would otherwise have been lost through interception or soil evaporation it does not exert a demand on the terrestrial water balance and can be said to have minimal downstream impact.

Water regulations governing the management of upstream-downstream impacts

Water tends to build asymmetrical relationships between people and communities within river basins because of water flow down slope (Figure 1). The activities of upstream users impact on the downstream users but not vice versa. To equitably share blue and green water resources in a catchment implies that upstream users have to forego some potential water benefits (van der Zaag 2007). Under the international water laws (Thompson 2006) that deal with equitable and reasonable allocation of water in trans-boundary river basins (in this study the Limpopo River Basin), upstream states support rules that give them control of the waters that originate in their territory, in line with the absolute territorial sovereignty doctrine, while downstream states/communities on the other hand appeal to the doctrines of prior appropriation and absolute territorial sovereignty that would provide them with unaltered flow quantity of the waters that enter their states/ catchments.

Helsinki Rules would consider the water that falls on the drainage basin and used before flowing into a common river as beneficial water use (e.g., rainfed agriculture, in-field RWH, natural forest and groundwater use) for the state/user having benefit of the water, whereas the UN Convention (United Nations 1997) would not consider any water use from outside the watercourse as part of the water to be equitably used (Thompson 2006). In the future the water to be shared in Southern Africa will change from actual water flowing in the river (SADC Revised Protocol on Shared Watercourses Systems), as required by UN Convention, to rainfall over the basin (Thompson 2006). Under such circumstances the impacts of in-field RWH would need to be assessed to avoid tensions and conflicts between upstream and downstream users at local or basin level.

Figure 1. Upstream-downstream catchment relationship with water flux (partly adapted from van der Zaag 2007)



Different RWH techniques influence hydrological processes at different spatial scales in a non-linear mode. Processes governing rainfall and runoff partitioning operate at a variety of scales (Blöschl and Sivapalan 1995). At the micro-catchment and field scales (approximately 10^{-3} to 10^{1} km^2), factors such as infiltration (which is spatially variable) and the length of the slope (distance of overland flow before entry of runoff into a stream) control the proportion of site runoff that is discharged from that scale as runoff and the proportion that is redistributed to become soil moisture (van de Giesen *et al.* 2000). At the meso-catchment scale (approximately 10^{1} to 10^{3} km^2), processes after runoff generation operate upon streams, for example the transfer of water between streams and groundwater or redistribution and re-infiltration in wetlands. This has been shown to sometimes lead to the estimation of (apparently) less conversion of rainfall into runoff at larger scales. Flow monitoring in a semi-arid area at different spatial scales showed that the runoff coefficient varied from 46 % at field scale to 12 % at basin scale in Kenya (Ngigi *et al.* 2005) and from 6.3 % for a 41 km^2 catchment to 0.7 % for a 1,386 km^2 catchment in Zimbabwe (Love *et al.* 2007). Due to this scale dependent complexity, the estimation of (apparent) diversion of rainwater from runoff generation to transpiration can be affected by the scale at which water balance measurements are made. These complex scale relationships and the potential for changes to downstream stream and groundwater flow make it important to assess the hydrological and socio-economic impacts (positive and negative) of out-scaling of RWH.

Despite the anticipated socio-economic impacts related to farm decision-making and farmer actions, out-scaling of RWH techniques, beyond a certain limit, may lead to hydrological and environmental impacts (Ngigi *et al.* 2005; Woyessa *et al.* 2006). Therefore, it is important to know the impacts of in-field and ex-field RWH techniques at catchment and basin scales. Furthermore, an understanding of the optimum level of adoption at catchment or basin scale that maximizes land and water productivity while minimizing negative hydrological and ecological impacts is important for sustainability of RWH technologies. This paper seeks to present small plot and farmer field scale case studies of RWH technologies conducted in the

Limpopo River Basin, and to propose an approach for systematically investigating the impacts of out-scaling such technologies to catchment and basin levels.

Rainwater harvesting case studies within the Limpopo Basin

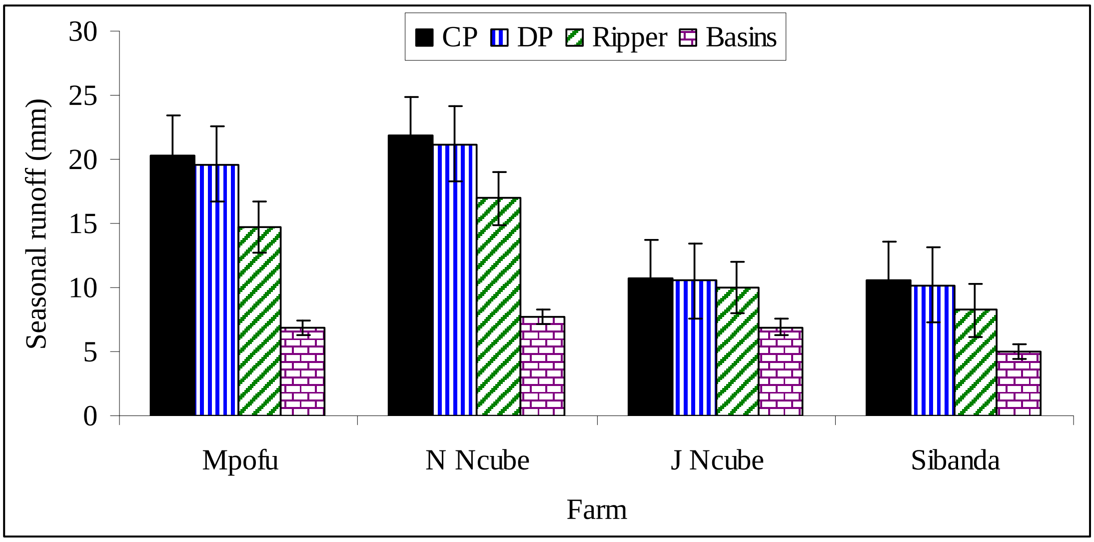
In-field RWH field experiments were conducted at several locations in Zimbabwe, Mozambique and South Africa. All experiments included treatments with 'Planting Basins'. Planting basins systems, with a variety of basin size and spacing, are practised in various part of Africa under a variety of names such as the Z*ai* system in Mozambique, Mali and Burkina Faso, the Chololo system in Tanzania (Mati 2005), the *Trus* system in Sudan, and the *Tassa* system in Niger. Crops are planted in the basins, often with small amounts of organic and/or inorganic fertilizers. The objectives of the basins are to reduce runoff and increase infiltration through breaking the surface crust and creation of a depression/pit/hole, and to increase soil fertility through reduction in erosion. Modelling studies were also conducted to evaluate RWH options. Some of the rainwater management techniques increase demand for labour, and their suitability for adoption will depend on economic viability and other factors such as acceptability to farmers. Another relevant issue is the required land versus land availability for these practices, as well as the need to coexist with other farming techniques such as inter cropping.

In-field rainwater management techniques: Mzingwane Catchment, Zimbabwe

The effect of planting basins and ripping on surface runoff and soil water storage in cropped fields was assessed over two cropping seasons in the semi-arid Mzingwane Catchment in Zimbabwe (Mupangwa 2009). The planting basins were dug using a hand hoe and each basin measured 0.15 m (length) × 0.15 m (width) × 0.15 m (depth). The basins were dug at 0.9 m × 0.6 m spacing. The rip lines were created at 0.9 m inter-row spacing using a commercially available ripper tine (ZimPlow) attached to the beam of a donkey-drawn mouldboard plough. The planting basins gave the lowest seasonal runoff losses regardless of soil type and field slope (Figure 2). Despite the below average rainfall of 328-353 mm during the period of experimentation (2006/07 and 2007/08 seasons), planting basins consistently gave the highest soil water content particularly during the first half of the cropping period. Despite the higher soil water content and lower surface runoff in the planting basin system, there were no significant ($P > 0.05$) maize yield differences between the four tillage systems regardless of the different rainfall distribution each season.

The results from the two year study indicate that planting basins have the potential to: i) promote infiltration of rainwater, ii) minimize soil, water and nutrient losses from the field, iii) reduce siltation and pollution (by agrochemicals) downstream of the fields, and iv) increase groundwater recharge as soil water is lost through deep drainage especially on sandy soils. However, during high rainfall seasons water logging (the severity depending on the soil type) can occur and affect yield. High surface runoff from each tillage system is likely during seasons with above-normal rainfall on the predominantly sandy soils of Gwanda and Insiza districts.

Figure 2. Seasonal runoff measured under each tillage treatment at Mpofu, N Ncube, J Ncube and Sibanda farms in Insiza and Gwanda Districts (adapted from Mupangwa, 2009). Data are means of 11 rainfall events that generated measurable runoff from each tillage treatment during the 2007/08 cropping period. Vertical bars indicate standard error of means. CP = conventional practice; DP = double ploughing.



Rainwater harvesting in Chokwe, Mozambique

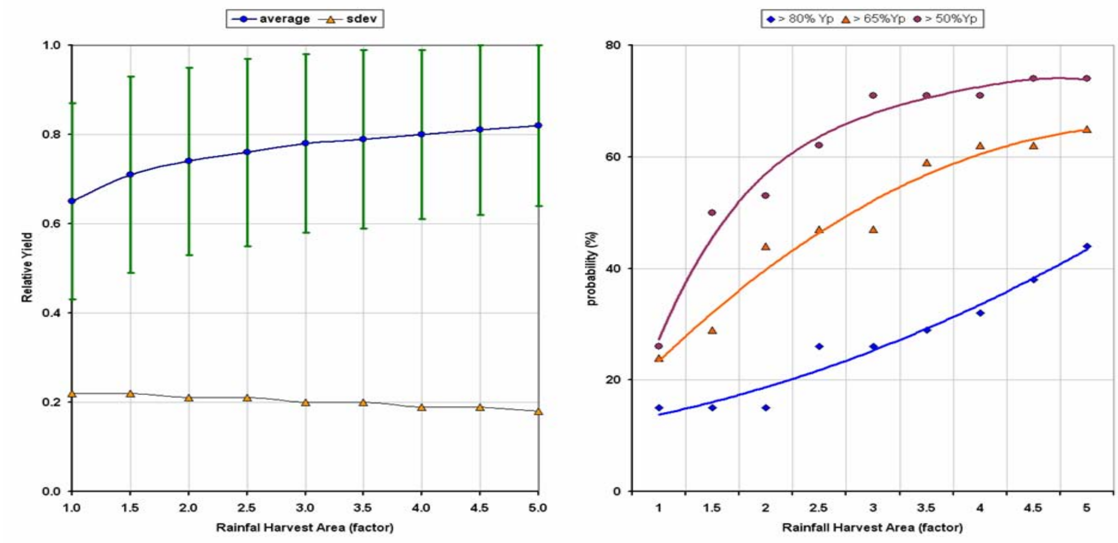
Modelling rainwater harvesting

Modelling studies were carried out to assess the potential for in-field RWH in the semi-arid region of Chókwè in Mozambique (Niquice 2006). The studies examined planting date, RWH, and storage of water in the root zone for rainfed maize. The main objective of these modelling studies was to maximise the use of rainwater captured by plants by looking at the effects of catchment area (through changing planting density) on final grain yield. Other effects such as soil texture and type, different RWH techniques, agronomic management and varieties were not considered. There were some limitations in the models in that they simply estimated the runoff to the plants with the assumption that no runoff from the field is generated.

The results indicated that total seasonal evaporation always exceeds rainfall in this part of the Limpopo River Basin near the coast, despite the relatively large rainfall here. Figure 3 shows the effect of "rainfall harvest area" factor (horizontal axis) on relative grain yield. The "rainfall harvest area" factor is the ratio of the area of runoff collection per plant to the runoff area per plant for the recommended planting density. A factor of 1.0 means using the recommended planting density, and a factor of 3.0, for example, means that the area per plant is three times larger than with the recommended density, increasing the area (three-fold in this case) of for runoff collection per plant (Niquice 2006).

Moving from the recommended plant density with a "rainfall harvest area" factor of 1.0 to lower planting densities with a factor of 5.0, the expected relative yields increased from 65 to 82% of potential yield (with water non-limiting), as shown on the left hand graph in Figure 3. The standard deviation tends to decline slightly due to limited increment of yield as the factor increases, determined by the soil water storage capacity within the root zone. The right hand graph shows that as the runoff area for RWH increases, the chances of getting certain threshold of relative yields increases (Niquice 2006).

Figure 3 Effect of "rainfall harvest area" factor (the ratio of the area of runoff collection per plant to the runoff area per plant for the recommended planting density) on predicted relative potential yield for maize in Chókwè (adapted from Niquice 2006). A factor of 1 means recommended planting density. (left) Average and standard deviation (sdev) of yields. (right) Probability of potential yield (Yp) for different factors



Rainwater harvesting trials using zai pits

Studies were carried out in three locations within Chókwè District to assess maize and cowpea yields grown using Zai Pits (planting basins), in comparison with the same crops produced under farmers' practice (control), i.e. mixed cropping systems (maize intercropped with cowpea, cassava etc.) using conventional tillage. The dimensions of the Zai pits were about 0.6 m diameter and 0.3 m in depth. Four to eight seeds of maize or cowpea were sown in each pit, and the seeds were evenly distributed within the pit. The planting density in the Zai treatment was half that of the control.

The maize grain yield was 14 and 111 kg ha^{-1} for the control and pits respectively. Although the yields were very low in both treatments due to low rainfall, the pits increased yield 8-fold. Grain yield of cowpeas was increased from 92 kg ha^{-1} to 131 kg ha^{-1} by the pits.

The Zai pits tended to increase water availability in the root zone, especially in loam-clay soils . On sandy soils, the technique has some limitations due to poor soil structure (low water holding capacity). Although the study has shown a potential for increased RWH, its effectiveness depends on rainfall patterns, soil type, crops and other agricultural practices like planting date and density, and mulching. Further work is required to identify situations where Zai pits are likely to be beneficial and to develop associated crop management guidelines. The surprising result from these studies was that 21% of farmers (including those who were already implementing Zai pits before these studies) in the study area have adopted the pits despite the need for further study (Momade 2006).

Rainwater harvesting in the Olifants Catchment, South Africa

Rainwater harvesting studies were also conducted at the field level in the Olifants Catchment, South Africa. In-field RWH techniques (Chololo pits or ridges) were compared with conventional tillage at 2 locations. The potential benefits of ex-field RWH for supplementary irrigation were also studied in separate experiments.

In-field rainwater harvesting experiments

The dimensions of the Chololo pits were 0.22 m in diameter and 0.3 m in depth. The pits were spaced 0.6 m apart within rows and 0.9 m between the rows, which ran along the contour. Conventional tillage involved ploughing then levelling and sowing in lines 0.9 m apart with 0.40 m between plants within rows. Three maize seeds were sown per pit, and plant density was 4 plants m^{-2} in both treatments. There were two replicates of each treatment at each site, and plot dimensions were 6 m x 13 m. Deep drainage *(D) was* determined from volumetric soil water content (θ, measured) and soil hydraulic conductivity, using Darcy's equation (Stephens, 2000; Reshmidevi et al. 2008). Van Genuchten's (1980) equation was used to estimate soil hydraulic conductivity, $K(\theta)$, and crop evapotranspiration (E_c) was calculated as the residual term in the water balance equation:

$$E_c = P - (R + D + \Delta S)$$

where *P* is precipitation, *R* is runoff (measured), *D* is deep drainage below root zone and ΔS is change in soil water content (harvest soil moisture minus sowing soil moisture).

Table 1 shows the maize crop water balance components, yield and cost of each technique from the two sites. Precipitation during the crop season was very low at both sites, and the RWH treatments made the difference between no yield and yields of 585 or 335 kg ha^{-1} at Worcester and Enable, respectively. Yields with Chololo pits at Worcester were higher than yields with tied ridges at Enable, despite the lower rainfall at Worcester. Good results (yield tripling) under Chololo pits have also been reported in East Africa (Mati 2005). The water harvesting treatments reduced runoff, and increased deep drainage slightly. There was much greater soil drying in the Chololo pits at Worcester than in the other treatments, reflecting the better crop growth at that site. However, during high rainfall seasons, leaching and water logging could adversely affect crop yield.

The Chololo pits required much more labour than conventional tillage, and they cost almost 5 times as much to implement (Table 1), but the technique produced grain yield in a low rainfall year when conventional methods produced no grain yield. Farmers have shown enthusiasm for the technique, with a number of them adopting the pits in their small vegetable gardens. The pits also reduced runoff by 100% in small to moderate rainfall events (Magombeyi *et al.*, 2008; Botha *et al.*, 2003). The ridges required about one third of the labour of the Chololo pits, and at about one third the cost, but were also more labour demanding and expensive than conventional tillage. However, they also made the difference between no yield and some yield during this low rainfall year.

Table 1 Maize water balance components, grain yield and water productivity at the 2 study sites in 2007/8, and the cost of preparing Chololo pits compared to other techniques, in Olifants catchment.

	Worcester		Enable	
	Chololo pits	Conventional tillage	Ridges	Conventional tillage
Precipitation (P, mm)	268	268	361	361
Change in soil moisture between harvest and sowing (*ΔS*, mm)	-111	-36	-24	-17
Runoff (R, mm)	21	69	46	129
Drainage[a] (*D*, mm)	22	11	19	8
Crop evapotranspiration[b] (*Ec*, mm)	336	224	320	241
Maize crop grain yield (kg/ha)	585	0	335	0
Grain water productivity (kg grain/ha/mm of *Ec*)	1.74	0	1.05	0
Labour requirement (person days)	43	10	15	10
Cost (ZAR* ha^{-1})	1,512	316	521	316

*ZAR = South Africa Rand (1 US$ = ZAR 10)

Ex-field rainwater harvesting for supplementary irrigation

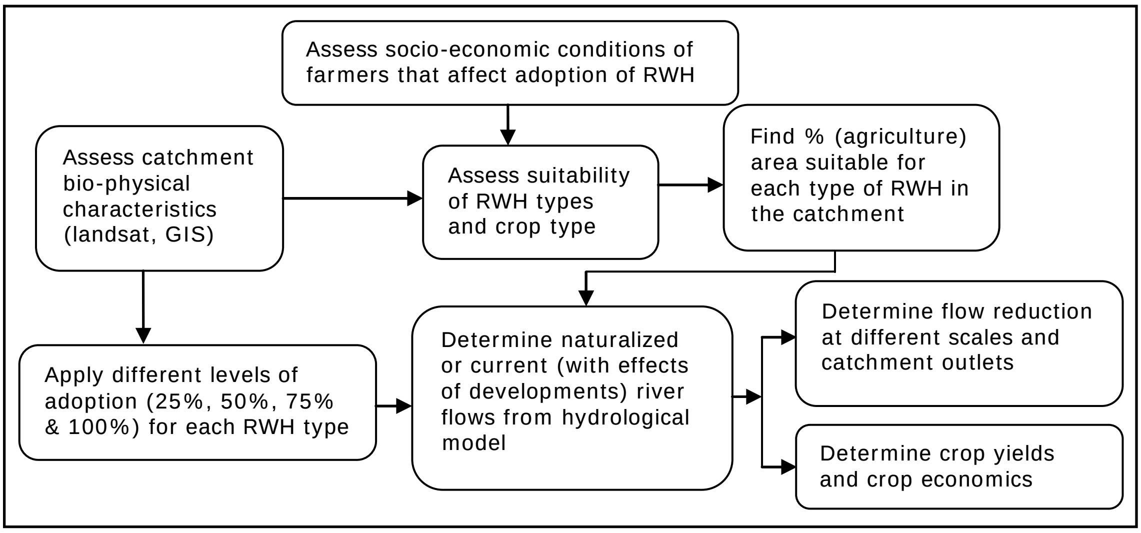
Components of the water balance and yield were compared in rainfed plots and plots receiving supplementary irrigation over 3 seasons (2005-2008) at 2 sites in the Olifants catchment (Magombeyi et al. 2008). Ex-field RWH by means of a weir across a stream was used to create the water supply for supplementary irrigation to 1 ha plots in farmers' fields. Plant density was 3 plants m^{-2} in all plots. Supplementary irrigation increased water productivity with respect to evapotranspiration from an average of 2 kg mm^{-1} ha^{-1} under rainfed conditions to 4 kg mm^{-1} ha^{-1} with supplementary irrigation. This was associated with an increase in average maize grain yield from 0.7 t ha^{-1} under rainfed to 1.7 t ha^{-1} under supplementary irrigation, an average increase of 143 % when compared to exclusive rainfed maize farming. Huge benefits of supplementary irrigation were realised when the crop growing period rainfall was below average and unevenly distributed throughout the season, as in the 2006/7 and 2007/8 seasons, when supplementary irrigation increased yields more than 4-fold. The study concluded that timely and adequate supplementary irrigation could be fundamental in ensuring farming families' food security and improved livelihoods by bridging the frequent intra-seasonal dry spells characteristic of semi-arid areas. However, extraction of water for supplementary irrigation reduces downstream flows. Hence, there is need for hydrological studies to estimate the crop area that can be brought under supplementary irrigation in the catchment without causing adverse impacts on downstream users and the environment.

Proposed approach for up-scaling the impacts of adoption of RWH technologies to catchment level

Model structure

The few small plot and farmer field studies presented above indicate that there is considerable potential for RWH technologies to increase yield and water productivity within the Limpopo River Basin. However, there are no studies showing what impacts these technologies will have upstream or downstream, both at catchment and basin levels. There is a need to find ways of up-scaling these techniques to catchment level and to understand what impacts these technologies will have. We want to answer questions such as: at catchment or basin scale what is the impact of these in-field and ex-field RWH techniques?; what level of adoption will maximize land and water productivity while avoiding unacceptably adverse hydrological and ecological impacts at these scales?; how to define "unacceptably adverse" impacts? A methodology model (flow chart) (Figure 4) is proposed for a systematic approach to assessing the biophysical and economic impacts of RWH to inform policy formulation and institutional reform processes regarding adoption of RWH practices that may promote integrated water resources management (IWRM).

Figure 4 Proposed flow chart for assessment of the impacts of up-scaling rainwater harvesting technologies in the Limpopo River Basin. RWH is rain water harvesting.



Indicators that could be used to assess the environmental impacts of increased RWH include relative reduction of runoff and river flows for average, high and low flows; irrigation water demands due to adoption of RWH systems (if more water is captured in the soil profile under in-field RWH, less irrigation water is required); and increased crop yields and income from crop sales.

The RWH techniques could be classified according to factors such as: agronomic productivity, riskiness, economic viability, and attractiveness of the technology to farmers. Social acceptability of the technology is also important for up-scaling to catchment level, and the socio-economic aspects which shape the water demand and ability to adopt the RWH technology by the farmers need to be included.

Use of a hydrological model to assess the hydrological impacts of rainwater harvesting

A spatial hydrological model is needed to answer questions such as:

- What are the potential areas where RWH technologies could be applied in the catchment?
- If you implement RWH what is the impact on flows downstream and sediment yields?
- What is the limit of out-scaling a particular RWH technology in the catchment?

Scenarios on the different levels of adoption for different RWH techniques such as: in-field soil storage systems (in situ water conservation: conservation tillage, bunds, micro-basins, mulching), micro-catchment (overland flows) and macro-catchment (diversion of an ephemeral stream by a weir into cropland e.g. in Olifants)

- What percentage of the area is suitable for RWH in the catchment? Studies on the suitability of RWH using land slope, rainfall, land cover, soil type and depth/texture structures are needed in Mozambique and Zimbabwe to complement work done in South Africa (Mwenge-Kahinda 2008).
- What percentage of land can be put under RWH so that the water requirements for downstream users and environment are still met (the level of adoption that is sustainable).
- Do the farmers accept the RWH techniques (acceptability)? Work on modelling farmer adoption of RWH and supplementary irrigation adoption was reported in He et al. (2007). Is there a need for it? What's the current level of water supply in the catchment? Do they have money to build the RWH facilities or structures (affordability of the RWH techniques)?

Hydrological implications of up-scaling RWH in a river basin

It will be important to know what amount of runoff (overland flow) is retained by farmers. This is important because cumulative effects of hydrological processes at the field scale influence and regulate what happens at the larger catchment scale. The level of reduction in river flow that results from overland flow retention upstream will also be important. The impacts of reduced surface land flow could become significant as the RWH is adopted by a larger population in the catchment. Possible sources of data for up-scaling would include Landsat and remote sense images.

Possible Challenges

Hydrological models are only as good as the available input data. Hence, it is paramount to validate and verify input data. There is an increasing degree of uncertainty and complexity in water fluxes when moving from field scale to catchment scale hydrology, meaning that it is not valid to directly extrapolate or interpolate results from one spatial scale to another. The dynamic socio-economic conditions (family annual income and labour) of the farmers also pose challenges in setting up the integrated impact model (Figure 4).

Conclusions

In-field and ex-field rainwater harvesting technologies are promising technologies for the semi-arid regions such as the Limpopo River Basin. Field scale studies have shown substantial crop yield benefits to smallholder farmers. However, RWH technologies often require more labour and additional cost to implement than normal farmer practice, and the magnitude of the yield gains varies depending on seasonal and site conditions. There is a need to systematically identify under which situations RWH technologies are likely to increase productivity and profitability. There is also a need to find ways of out-scaling the technologies for a greater impact on the livelihoods and food security of the very large numbers of poor farming families in the Basin. However, as we find ways of out-scaling, there is also need to understand the up-stream and down-stream impacts of out-scaling in-field and ex-field RWH at catchment and basin levels. Development of a decision support tool in the form of an integrated model presented in this paper could answer several questions on the impacts and sustainable levels of RWH adoption and aid policy makers.

Acknowledgments

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Micro watershed to basin scale impacts of widespread adoption of watershed management interventions in the Blue Nile Basin

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Abstract

High population pressure, inappropriate agricultural policies, improper land-use planning, over-dependency on agriculture as a source of livelihoods and extreme dependence on natural resources are inducing serious problems in many parts of the Blue Nile River Basin. These problems include deforestation, overgrazing, expansion of agriculture to marginal lands and steep slopes, declining agricultural productivity, and resource-use conflicts. Poor agricultural and other practices affect runoff characteristics and result in increased erosion and siltation and reduced water quality in the basin. The result is a downward spiral of poverty and food insecurity for millions of people both within the upper catchment and downstream across international borders. Quantification of erosion and sedimentation and evaluation of the impacts of interventions are difficult tasks. We studied rainfall-runoff and sediment-runoff relationships in the Gumera watershed, and calibrated the SWAT model for this watershed. The analysis shows that rainfall, runoff and sediment load are highly variable in both time and space. The amount of sediment in the river systems is strongly related to the onset of rainy season. The hydrographs show that the peak sediment concentration occurs first, followed by the peaks for rainfall and then runoff. Furthermore, the cumulative sediment load curve shows that most of the sediment enters the river in the first three months of the rainy season. The results show that both runoff and sedimentation can be reasonably simulated using the SWAT model (R^2=0.82 and 0.79, respectively). The study demonstrated, that by undertaking spatial analysis using topographic, soil and land use parameters with the SWAT model, that it is possible to identify the high sediment risk sub-watersheds. The modelling studies showed that use of vegetative filters with widths of 5 and 10 m in high erosion risk watersheds reduced sediment yield by 52% and 74% respectively.

Key words

erosion, sedimentation, rainfall-runoff, degradation, SWAT

Introduction

Soil erosion is a major watershed problem in many developing countries, causing significant losses of soil fertility and productivity, and environmental degradation. Generally, soil erosion and the ensuing sediment transport are functions of many processes. Erosion from the land surface takes place in the form of sheet, rill and inter rill, and gully erosion, and part of the eroded soil is delivered to rivers. This, together with in stream bed and bank erosion of rivers constitutes the sediment load in the river. The Blue Nile River (Abay) contributes up to 62% of the Nile River flow measured at Aswan, and a similar proportion of the sediment in the Nile. The upper Blue Nile River is heavily affected by watershed management problems caused by overpopulation, poor cultivation and land use practices, deforestation and overgrazing. This results in significant loss of soil fertility, rapid degradation of natural systems, significant sediment deposition in lakes and reservoirs, and sedimentation of irrigation infrastructure such as canals. Unofficial data describes that 70% of the cost of operation and maintenance in the Blue Nile part of Sudan is spent on sediment related and canal maintenance. A massive surface water harvesting effort is being undertaken in the dry lands of Ethiopia to supplement rainfed agriculture with irrigation. However, most of the water harvesting schemes are under serious threat due to siltation (Tamene et al. 2006). Sedimentation is a serious problem that reduces the economic life time of reservoirs. In many places the sediment erosion rate is higher than the soil formation rate, and many small reservoirs and micro dams have lost their dead storage capacity in a short period of time.

The use of filter strips is one of the most effective of many watershed interventions to reduce erosion and sediment yield in rivers.. This method has been tested in micro watersheds in Ethiopia, and soil loss was reduced by grass strips by 55 %, 73%, 72 %, 57, 84% and 81% at five soil and water conservation research stations at Maybar, Andit Tid, Anjeni, Gununo, and Dizi , respectively (Tenaw 2008).

Modeling erosion and sedimentation, and evaluation of the impacts of watershed management interventions on the sediment budget, is a difficult task. The most widely used empirical model for predicting erosion is the universal soil loss equation (USLE). The USLE model estimates average annual soil loss by sheet and rill erosion on those portions of landscape profiles where erosion but not deposition is occurring. However the model does not predict single storm loss, nor does it predict gully erosion (Dilnesaw 2006). Both the USLE and the Modified/Revised method (M/RUSLE) estimate erosion in small catchments based on relationships established using soil conservation site data. Applying such relationships in basins such as the Blue Nile is difficult, as such models are not primarily designed for such large scale systems, and obtaining pertinent data for calibration, validation and impact evaluation is also difficult.

SWAT is the acronym for Soil and Water Assessment Tool, a model developed by United State Department of Agriculture, Agricultural Research Service (USDS-ARS). SWAT is a physical process-based model that simulates processes at a catchment scale (Arnold, et al. 1998; Neitsch, et al. 2005). The objective of SWAT model development was to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. SWAT has been applied in catchments ranging in size from a few to thousands of hectares. Currently, SWAT is used widely in many watersheds of the world and has been evaluated in a range of environments. For example, in the 932.5 km^2 Upper North Bosque River Watershed in north central Texas, SWAT-predicted monthly sediment losses matched measured data well, but prediction of daily output was poor (Saleh, et al. 2000). In the Thur River basin (area 1700 km^2) in Switzerland, SWAT simulations of sediment transport processes at the catchment scale provided good results (Abbaspour, et al. 2007).

This paper presents a typical case study watershed used to analyse rainfall-runoff relationships, sediment-runoff relationships, and the sensitivity and accuracy of the SWAT model in a catchment in the Gumera watershed of the Blue Nile River. Using the calibrated model, we then analysed the impacts of vegetation filter strips on the sediment budget.

Methodology

Data acquisition, erosion, sediment and interventions impact modeling

The wider scope of the study related to this paper schematizes the Blue Nile as in Figure 1 below and also shows how sediment modeling is addressed at various scales in the entire Blue Nile basin. These scales include: a) micro watershed, b) watershed c), sub-basins and major lakes, basin outlets and large reservoirs, and d) downstream of outlets and large reservoirs. The Basin level sediment predictions were earlier addressed by Steenhuis et al (2008) and will not be repeated here. Currently, we are also testing a revised version of a rainfall runoff model to improve the distributed runoff predictions without changing the discharge predictions at the outlet (White et al., 2008). This paper presents the results of using the SWAT model based on extensive work reported in Tenaw (2008) in one of the selected catchments known as the Gumera watershed. The study was intended to model runoff and sediments, and to evaluate the impacts of interventions. Thus, it is focusing only on scale b) of the larger study. Figure 2 shows Gumera watershed and the 29 micro watersheds within the boundary of Gumera.

Figure 1. Map showing the BNB and schematization for erosion and sediment modeling using various tools. The specific study area corresponding to this picture is a tributary to Lake Tana, shown at the head water

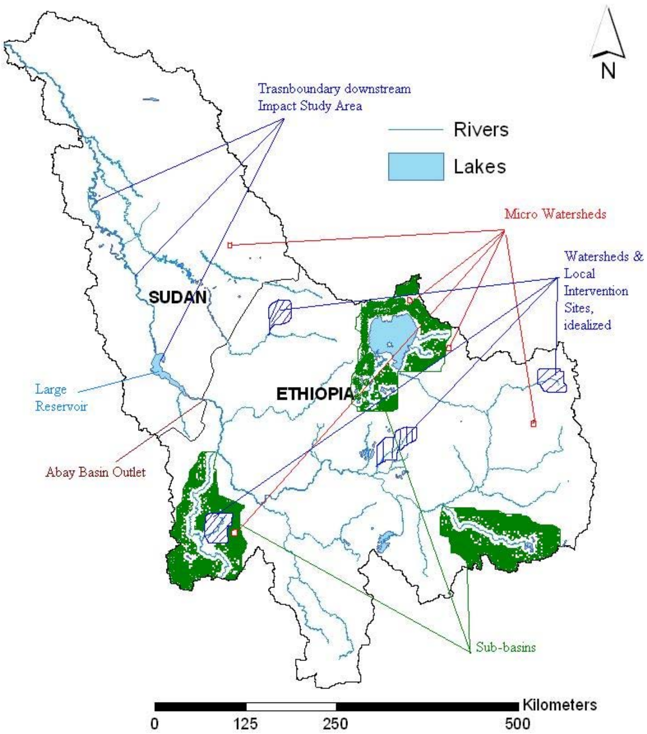
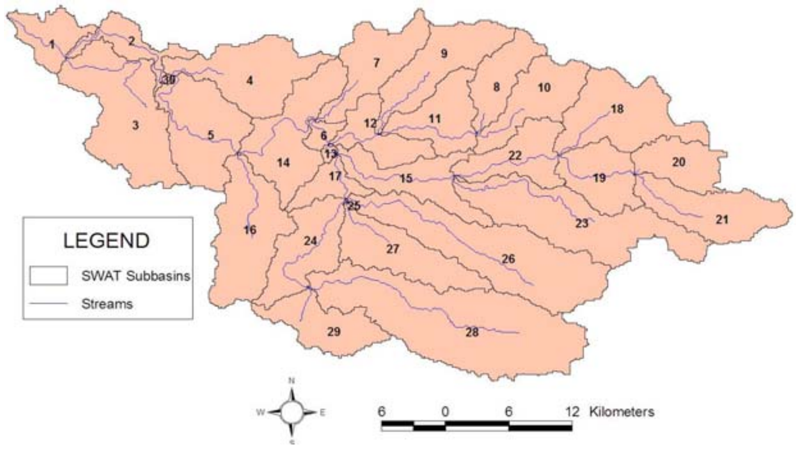


Figure 2. Gumera watershed, one of the BNB small watersheds and sub-watersheds under SWAT.



We used water balance-based rainfall-runoff and runoff-sediment relationships at the watershed outlet according to the Modified Universal Loss Equations (MUSLE) after Williams (1995), and actual measured data for Gumera watershed. For detailed discussions, refer Tenaw (2008). Sensitivity analysis was carried out to identify which model parameters are the most important in flow modeling. From this analysis, ten parameters, including initial curve number, available water capacity, average slope steepness and hydraulic conductivity, were identified as the most sensitive parameters that significantly affect surface runoff and base flow generation.

The calibration and validation of SWAT were carried out using data measured at the outlet of the watershed at Gumera bridge on the main road of Bahir Dar to Gondar. To evaluate the efficiency of the model, three measures were employed: the Nash–Sutcliffe simulation efficiency (ENS), the correlation coefficient (R^2), and the mean deviation of errors (D). In the model, we also used filter strips of 5m and 10m width to estimate the impact on the potential reduction in sediment delivery. The filter strip trapping efficiency for sediment, nutrients and pesticides was calculated as $Tef = 0.367\ (WF)^{0.2967}$ (Neitsch et al 2005), where Tef is the fraction of the constituent loading trapped by the filter strip, and WF is the width of the filter strip (m).

Data requirements for the model flow and sediment calibration and validation related to digital elevation, land use and soil properties were obtained from previous studies of the Ministry of Water Resources, Ethiopia, such as the master plan studies BCEOM (1998) and MOARD (2004). Daily river flow and sediment discharges at the gauging station, obtained from the Ministry of Water Resources, Ethiopia, were used for discharge and sediment yield calibration and validation of the modeling work.

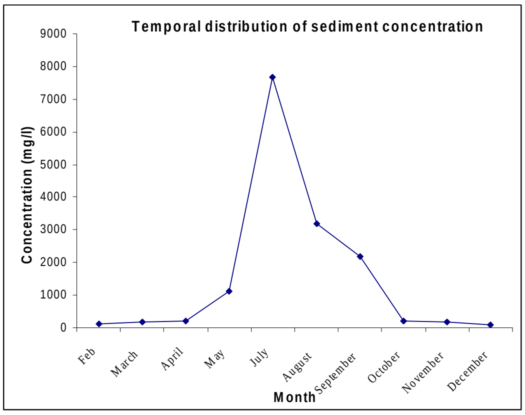
Results and discussion

Sedimentation and runoff observations

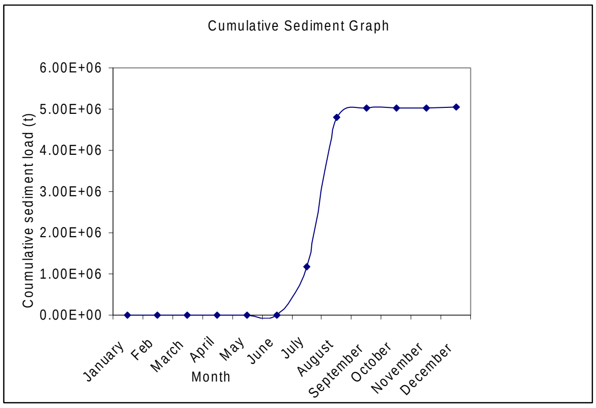
Analysis of rainfall and runoff shows that, in the rainfall season, the peaks of sediment concentration and sediment load come before the peaks of rainfall and runoff. The annual sediment concentration (sediment weight per volume of water) measured in mg/l shows that sediment load distribution is concentrated in June to September, with the highest peak is in

July, while the rainfall and runoff peaks occur in August. Figure 3 is a typical example of Blue Nile tributaries, in terms of the long term monthly average sediment concentration of Ribb river at Addis Zemen. The river is a medium-sized watershed tributary with a catchment area of 1592km² draining to Lake Tana.

Figure 3: a) Typical monthly sediment concentration, and b) cumulative sediment load over time, in the Ribb River at Addis Zemen station, a tributary of the Blue Nile



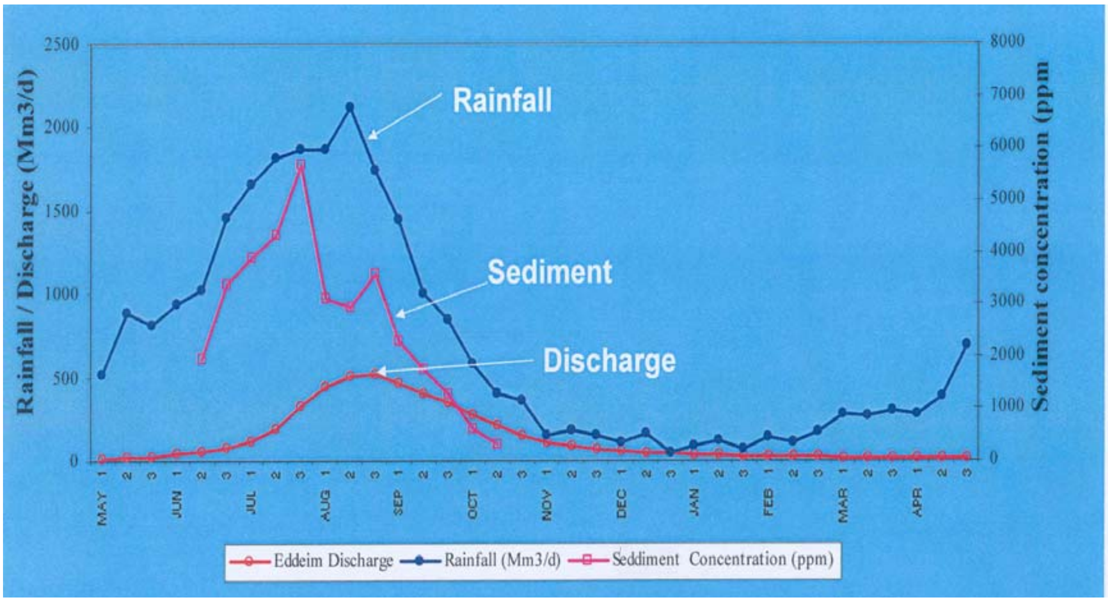
a



b

The cumulative consequence at the downstream end within the watershed and across the boundary is problems such as aggradation of river beds, difficulty of operation of hydraulic infrastructures, loss of storage capacity and heavy cost of operation and maintenance for sediment management. Figure 4 (Awulachew et al 2008) shows the consequential sediment concentration at the downstream end in Sudan, at the border with Ethiopia. Note that Figures 3a and 4 are comparable figures in terms of concentration distribution and magnitude of concentration.

Figure 4. Rainfall, discharge and sediment yield at El diem (Source: Ahmed, 2003)



Detail investigation and modeling of Gumera Watershed

Physical setup of the catchment: under the SWAT modeling environment, we developed a Digital Elevation Model (DEM), and land use, soil, area rainfall, crop land management factors. The 90m DEM provided a reasonable baseline for characterization of the watershed in terms of physical characteristics.

Flow modeling

Calibration resulted in a Nash–Suttcliffe simulation efficiency (ENS) of 0.76, correlation coefficient (R^2) of 0.87, and mean deviation (D) of 3.29 %, showing a good agreement between measured and simulated monthly flows (e.g. Figure 5). Similarly, the validation results also show good agreement between measured and simulated values, with ENS 0.72, R^2 0.82 and D 5.4%.

The erosion predictions showed good agreement between calibrated monthly sediment and measured sediment yields with ENS 0.74, R^2 0.85, and D 14.2% (e.g. Figure 6). Validation results also showed good agreement between measured and simulated values, with ENS 0.62, R^2 0.79, and D 16.9%.

Spatial pattern of sediment source

The spatial distribution of annual sediment generation for the Gumara River watershed shows that 18 out of 29 sub-watersheds (micro-sheds) produce average annual sediment yields ranging from 11-22 t/ha/yr, while most of the low land and wetland areas in the north west region produce 0-10 t/ha/yr.

Figure 5: Calibration results of average monthly measured (--♦--)and simulated flow (–■–) at Gumera gauge

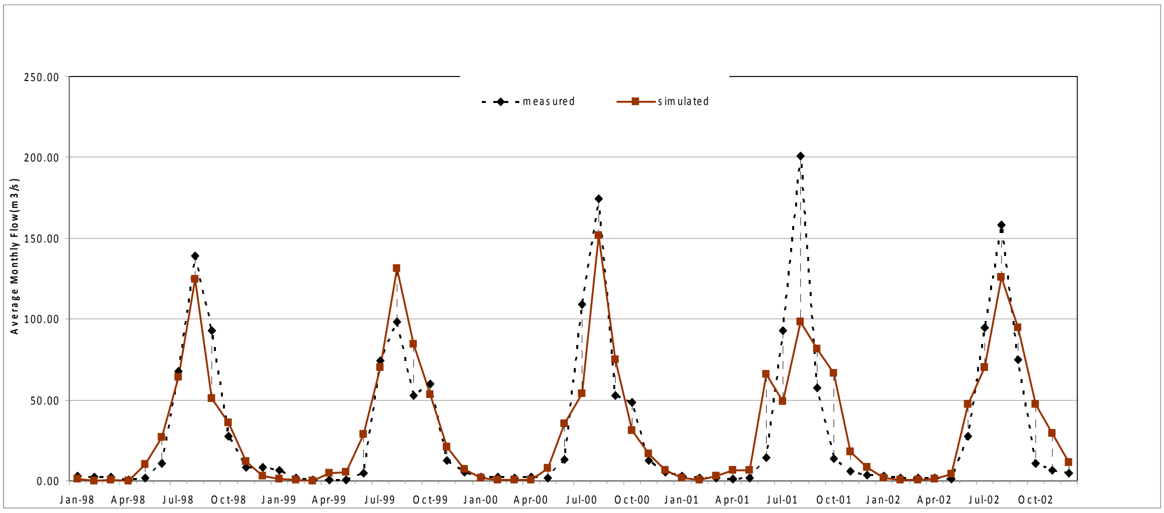
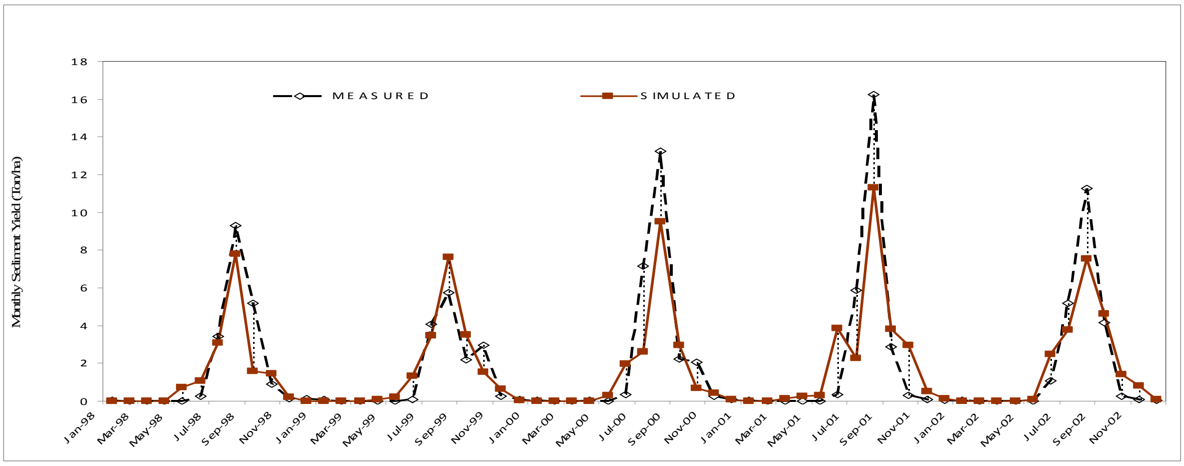


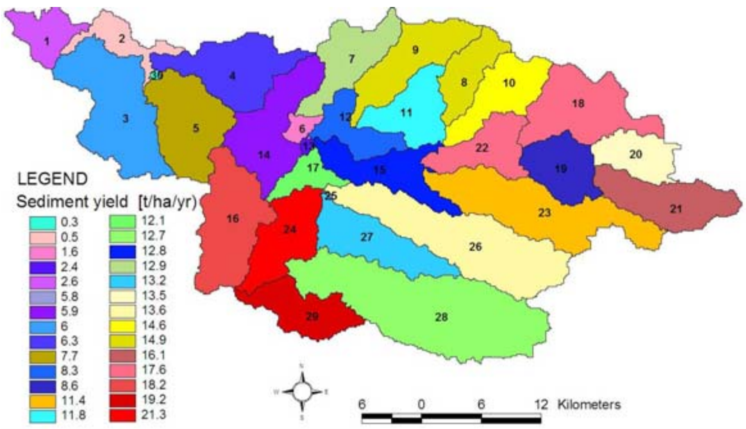
Figure 6. Calibration results of monthly measured (--♦--)and simulated (–■–) sediment yield at Gumera gauge



Watershed intervention impact analysis

Simulation showed that implementation of vegetation strips in 7 high erosion sub-watersheds reduced average annual sediment yields by 52 % to 62 % using a 5m buffer strip width, and by 74.2 to 74.4% for 10m strip width. This shows that it is possible to reduce the amount of sediment yield effectively by employing watershed management interventions such as vegetative strips. Such measures at micro watershed levels can have significant cumulative effects at sub-basin and basin levels, and can reduce sedimentation problems in lakes, man made reservoirs and natural river systems.

Figure 7. Spatial distribution of average annual sediment yield by sub- watershed(t ha^{-1} yr^{-1}) simulated using SWAT. Numbers (1-29) are sub-watershed numbers in Gumera watershed



Conclusion

Erosion, sediment transport and sedimentation are critical problems in the Blue Nile Basin. The current levels of degradation leading to erosion, sediment transport and sedimentation are causing considerable loss of soil, and deposition in rivers and reservoirs, and can cause irreversible soil degradation, loss of livelihoods, and significant canal and reservoir sediment cleaning costs. The Basin is providing significant flow but also a heavy sediment load. The analysis of data at various stations shows that seasonal sediment distribution is highly variable, and that the highest sediment concentration occurs in July, when most of the land is cultivated using traditional practices that lead to significant loss of soil and nutrients from agricultural fields in the form of erosion and sediment. The consequence is rapid accumulation and losses of capacity of small reservoirs built for agricultural or other water supplies, and rapid filling of the dead storage of large reservoirs and natural and man-made lakes. This paper also demonstrates the usefulness of modeling tools such as SWAT to model a complex and data scarce basin. Through modeling of the Gumera watershed we showed that runoff and sediment can be simulated with reasonable accuracy. This also indicates that long term data can be generated for ungauged basins in the Basin. As demonstrated by the vegetative filters, the impact of similar interventions can be quantified and the results suggest that vegetative filters can provide a significant reduction in sediment load to the upper Blue Nile. Actions taken at the farm, field or irrigation scheme level have broader basin-wide impacts. Application of the vegetative filter and other interventions throughout the basin could help to reverse land degradation and improve the livelihoods of the people upstream, and at the same time reduce the cost of operation and maintenance of hydraulic infrastructure and other sedimentation damage downstream.

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Assessment of potential supplemental irrigation impacts on downstream flows in the Karkheh River Basin of Iran

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Abstract

Supplemental irrigation (SI) is applied in rainfed systems to alleviate soil moisture stress for improved crop yields and water productivity. However, SI developments upstream impact on the amount and quality of water flowing downstream. Runoff in the upper Karkheh River Basin in Iran was assessed using a simple water balance in a GIS framework. The potential flow changes under SI strategies were assessed at the upstream sub-basin scale. Water demand and runoff maps were then simulated for a range of rainfall and irrigation scenarios. Three runoff/flow scenarios were considered: average rainfall, average rainfall with an environmental flow allocation (15% of the mean annual runoff) and low rainfall. The water requirement for SI was assessed under two irrigation scenarios: a single irrigation for early sowing (75 mm in autumn); two irrigations in spring (150 mm total). A FORTRAN program was prepared to calculate the water allocations for the upstream sub-basins. The impacts of the different scenarios on stream-flow were evaluated for each sub-basin and subsequently at the basin scale by comparing the flow with and without the SI scenarios, for the three flow/runoff situations,. The results indicated that early sowing SI allocation in an average rainfall year will decrease downstream flow by about 15% annually, while full spring SI under dry conditions will reduce the amount by about 10%, if all potential areas for SI are developed.

Keywords

supplemental irrigation, rainfed, environmental flow, runoff mapping

Media grab

A methodology has been developed enabling assessment of the potential for supplementary irrigation (SI) in upper catchments, and the impacts of adoption of SI on downstream flows

Introduction

The Karkheh River Basin (KRB) covers about 43000 km^2 in southwestern Iran. The basin has a semi-arid to arid climate. Most of the agricultural area in the upper KRB is rainfed, where livelihoods depend mainly on dryland farming. Iran's agricultural strategy identifies water productivity improvement as a top priority. Annual precipitation in the upper catchments of the KRB ranges from 350 to 500 mm. GIS-based methods have been developed to better geographically target areas suitable for various water productivity (WP) enhancing practices such as SI. Supplemental irrigation is applied essentially to rainfed crops during dry spells to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields. Results from SI research show substantial increases in crop yields in response to the application of relatively small amounts of SI (Oweis, et al., 1998). Supplemental irrigation (SI) is strongly recommended to increase crop and water productivity in rainfed systems of upstream KRB (Tavakoli and Oweis, 2003). The optimal SI amount and timing, the economic feasibility of investment, and the presence of biophysical limitations are the major issues for investigation. The objective of this work is to examine the potential for SI implementation in rainfed areas of the upper KRB and the consequences on downstream flow. The assessment is made in 3 stages: 1) Iso-potential mapping suitable lands for SI; 2) Water resource requirements for SI and environmental flow; and 3) Flow allocation and assessment of different scenarios of SI.

Methodology

Runoff mapping

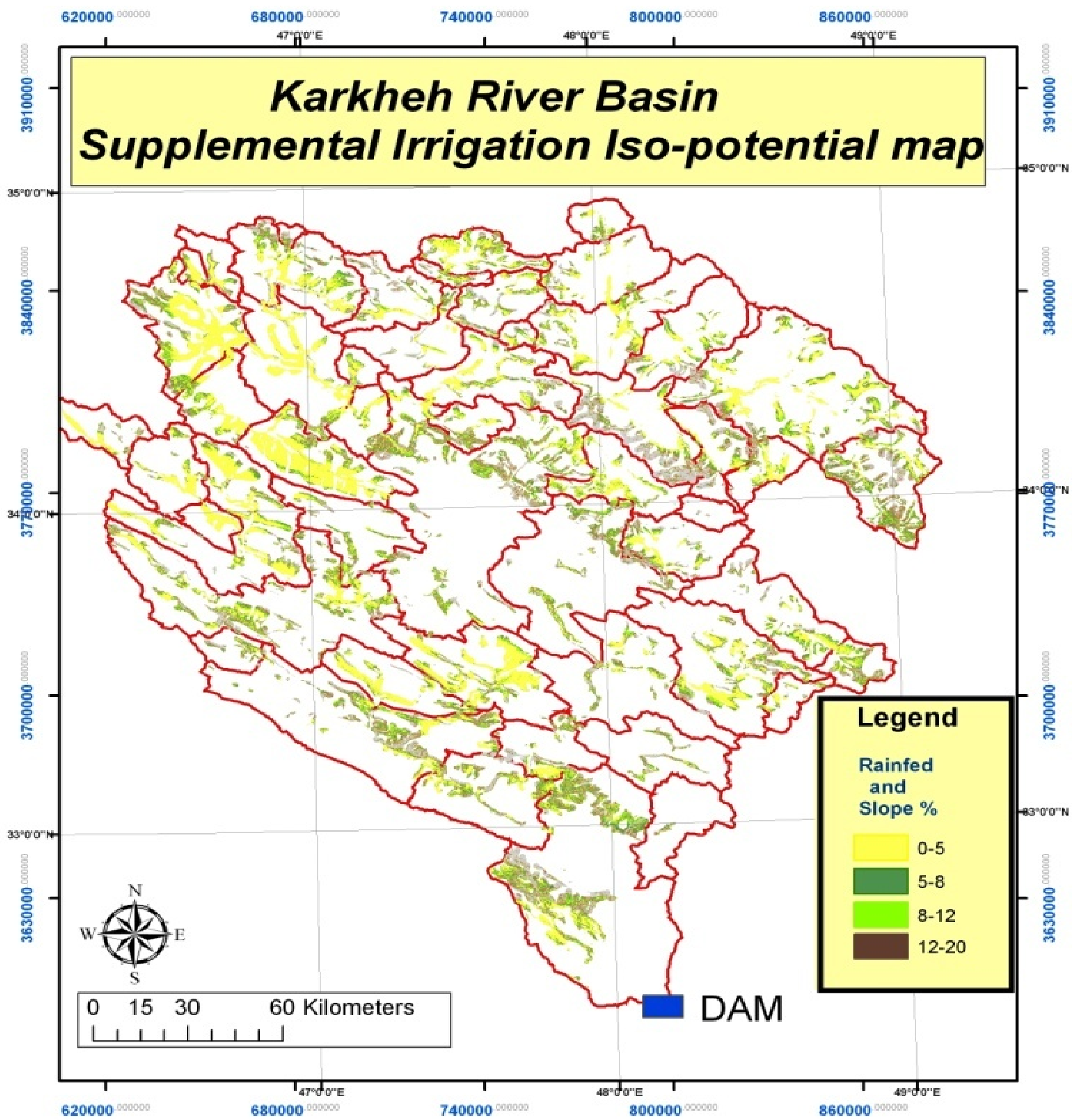
Monthly flow records for the years 1975 - 2004 were extracted from the Tamab Database. Gauging stations operating over the entire period were selected, yielding a set of 53 stations. The ArcHydro extension (Maidment 2002) in ArcGis9 was used to derive the drainage patterns of the Karkheh catchments from the digital terrain model. Raster analysis was performed to delineate the gauged watersheds. Some watershed boundaries were corrected manually using 1:25,000 topographic maps. Given a grid of precipitation values and a grid of watersheds (defined with the same cell size), a table of the mean precipitation in each watershed was determined. Based on computed 30 year mean flows for each station, the net measured inflow for each of the 53 watersheds was computed, and then the net measured inflow was normalized by the watershed area and expressed in mm/year. The average runoff per unit area (mm) versus average rainfall (mm) for all delineated watersheds was calculated. Information from the outlying points was used to create a map of actual runoff. Using the inference of scale-independence, the expected runoff function was applied to the precipitation grid to create a spatially distributed map of expected runoff. A grid of actual runoff was created by combining net runoff information at the watershed scale.

Supplemental irrigation iso-potential mapping

De Pauw et al. (2008) presented a methodology for using GIS tools and expert criteria to identify potential areas for SI in Syria. The assumptions used are that such areas: are basically rainfed; are characterized by the presence of arable soils; have non-constraining slopes; and are within the proximity of existing irrigation schemes that do not require substantial investment in irrigation infrastructure. The method is based on the assumption that the irrigation water discharge (from either surface or groundwater) available in existing irrigated schemes, that is currently used to fully irrigate summer crops, could instead (or in addition) be used fully or partially in winter for SI of winter crops. Since the water requirements for SI of winter, rainfed crops are a fraction of that for non rainfed fully irrigated summer crops, the areas that could be irrigated in winter, using same amount of water, are much larger than the areas currently used for summer full irrigation. The method uses a simple model to calculate the additional rainfed area that can be irrigated by shifting from spring/summer fully-irrigated crops to supplementally-irrigated winter/spring crops. The potential SI area is identified by combining with a water allocation procedure for the surrounding rainfed areas based on suitability criteria. In this research, the method used in Syria was applied to the KRB.

Slope classes determine the suitability land for different types of irrigation. Figure 1 shows slope classes in two sub-basins of the KRB. The slopes used for different irrigation methods are: surface (less than 5%), sprinkler (5-8%), and trickle (8-12%). River surface flow is assumed to be the sole source of water for irrigation. Potential rainfed areas for SI were considered within buffers of 1000 m around the streams lines. The buffer is based on expert knowledge of the maximum distance that is feasible for conveying water away from water source. The stream buffer area layer is overlayed on that of the slope classes of the 53 sub-basins, from which the iso-potential map for SI is derived. The monthly irrigation requirement for each sub-basin is calculated based on the SI map. In this research, the long term monthly streamflow data of gauge stations along the river were considered as the available water for allocation to SI.

Figure 1. Rainfed cultivation areas with different slope class in two sub-basins of KRB



Water resource requirements (system, SI and environmental flow)

Available stream flow is allocated for SI in autumn and spring. Water requirements include: existing needs (irrigation, industry, domestic), new supplemental irrigation and environmental flow requirements (EFR). At each gauge station flows in excess of the domestic, industry and environmental needs are recorded. Thus the recorded stream flow data assumes all existing needs are satisfied. The available water was considered for SI with the following strategies: (i) applying a single irrigation of 100 mm in autumn; (ii) applying two irrigations of 75 mm each in the spring.

Available water in each sub-basin is based on daily and monthly base flow of the stream in addition to available groundwater resources. Discharge data variation and the wet and dry thresholds of surveyed sub-basins and base flow in sub-basins determine the water available for allocation. The challenge is to determine the amount of water, and its quality, that should be allocated for the maintenance of the ecosystems through an "environmental flow allocation" and water that can be allocated for agriculture, industry, and domestic services (Ramsar Convention Secretariat 2007). Methods for estimating EFR include: hydrological methods, hydraulic rating, habitat simulation and holistic methods (Mazvimavi et al. 2007). In this research, 15% of the mean annual runoff was used as an EFR. By subtracting EFRs from monthly flow data, available water for allocation to SI areas of all sub-basins was determined.

Water allocation

Allocation of water is made according to location, planting calendar and available water in sub-basins. In this study, long term monthly flow data of gauge stations along the river were used to estimate the available water for SI in suitable rainfed areas. One scenario of allocation water for SI will be drought situation. A higher level of water stress was considered, with the (river) resource availability set at 80% of the occurrence probability as a drought condition. A FORTRAN program was developed to calculate the available and required water volumes for each sub-basin based on the suitable area for each slope class and to route the remaining water from the upper sub-basins to the Karkheh dam. The program first calculates the potential available flow for each sub-basin by subtracting all current downstream uses computed from the observed incoming and outgoing flows (gauge data) of each sub-basin.

Results and discussion

The outflow estimation before and after applying SI strategies allowed evaluating: i) the impacts of different SI strategies on stream flow; ii) assessment of the water demand at each sub-basin; iii) the water allocation pattern; iv) the response of each sub-basin to SI intervention; and v) the available and allocated water based on each strategy. Tables 1 and 2 present the impacts of implementing the three SI scenarios on the areas and the flows downstream, respectively. Allocations of water may be adjusted based on water availability and priorities and the comparative benefits among various uses within the basin. The critical factors affecting water management are the temporal and spatial characteristics as associated with the national objectives of the upstream-downstream development. Figure 2 shows results of comparison of the 3 rainfall/flow conditions and the potential supplemental areas. Expected reductions in the downstream flows under the average, average with environmental flow and dry conditions are 9-15%, 9-16% and 5-10% of the available flow, respectively. Thus the results indicate that implementation of SI in the rainfed areas does not substantially reduce the average annual flow to the Karkheh reservoir significantly. At the same time, SI provides considerable benefits for yield and water productivity in the upper

KRB according to ongoing research on selected sites. In addition to environmental flow there is surplus flow from most subbasins (Tavakoli and Oweis 2003).

Table 1. Suitable irrigation areas and developable irrigated areas of SI scenarios

Scenario	Areas (km²) in different slope classes			
	0-5%	0-8%	0-12%	0-20%
	Suitable SI areas (km²)			
	3559	4802	5945	7361
	Actual SI areas (km²)			
Average streamflow	1259	1572	1833	1945
Average streamflow with environmental flow	827	1053	1234	1362
Dry conditions (low streamflow)	432	628	793	975

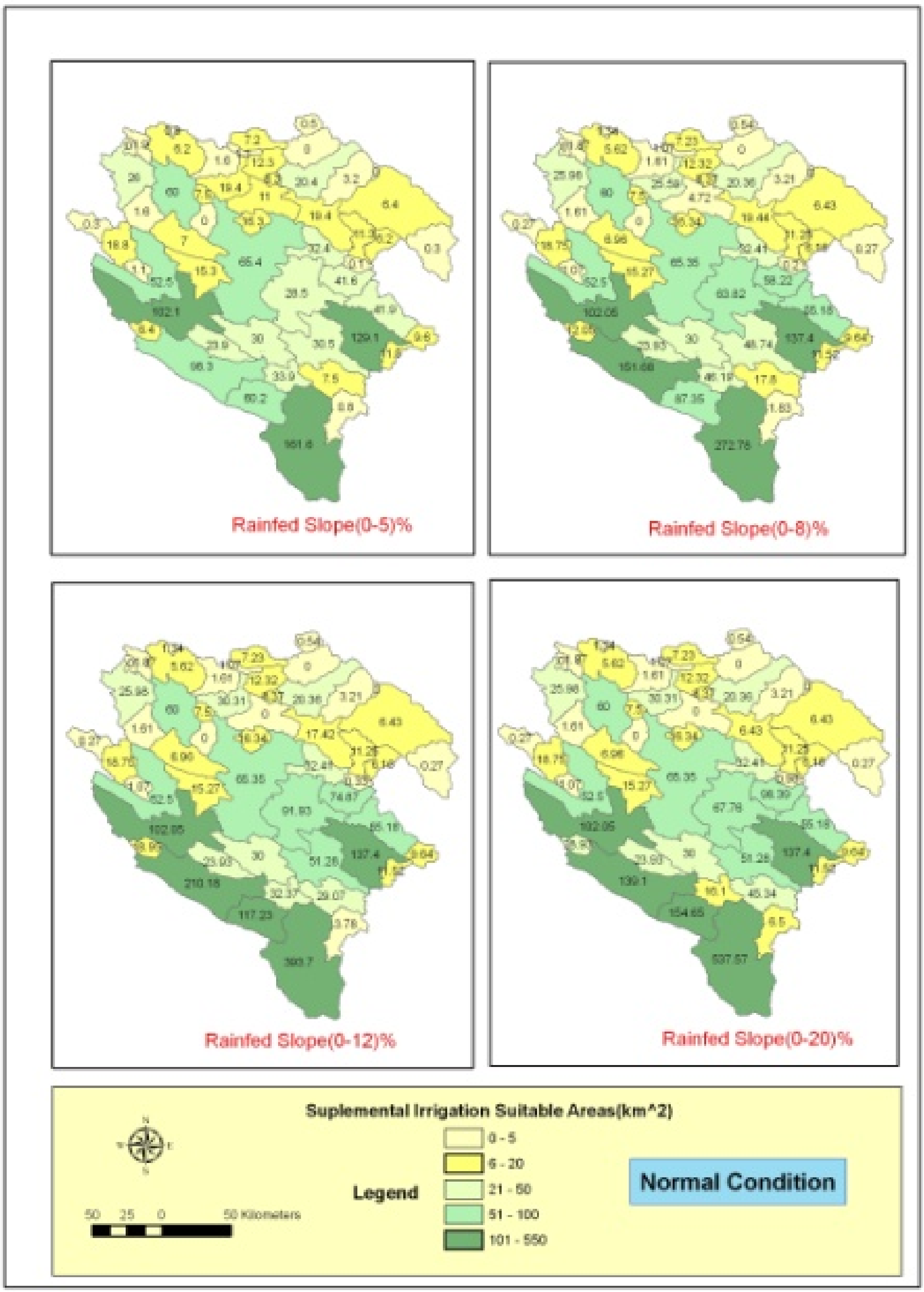
Table 2. Available flow and outflow after implementation of SI scenarios

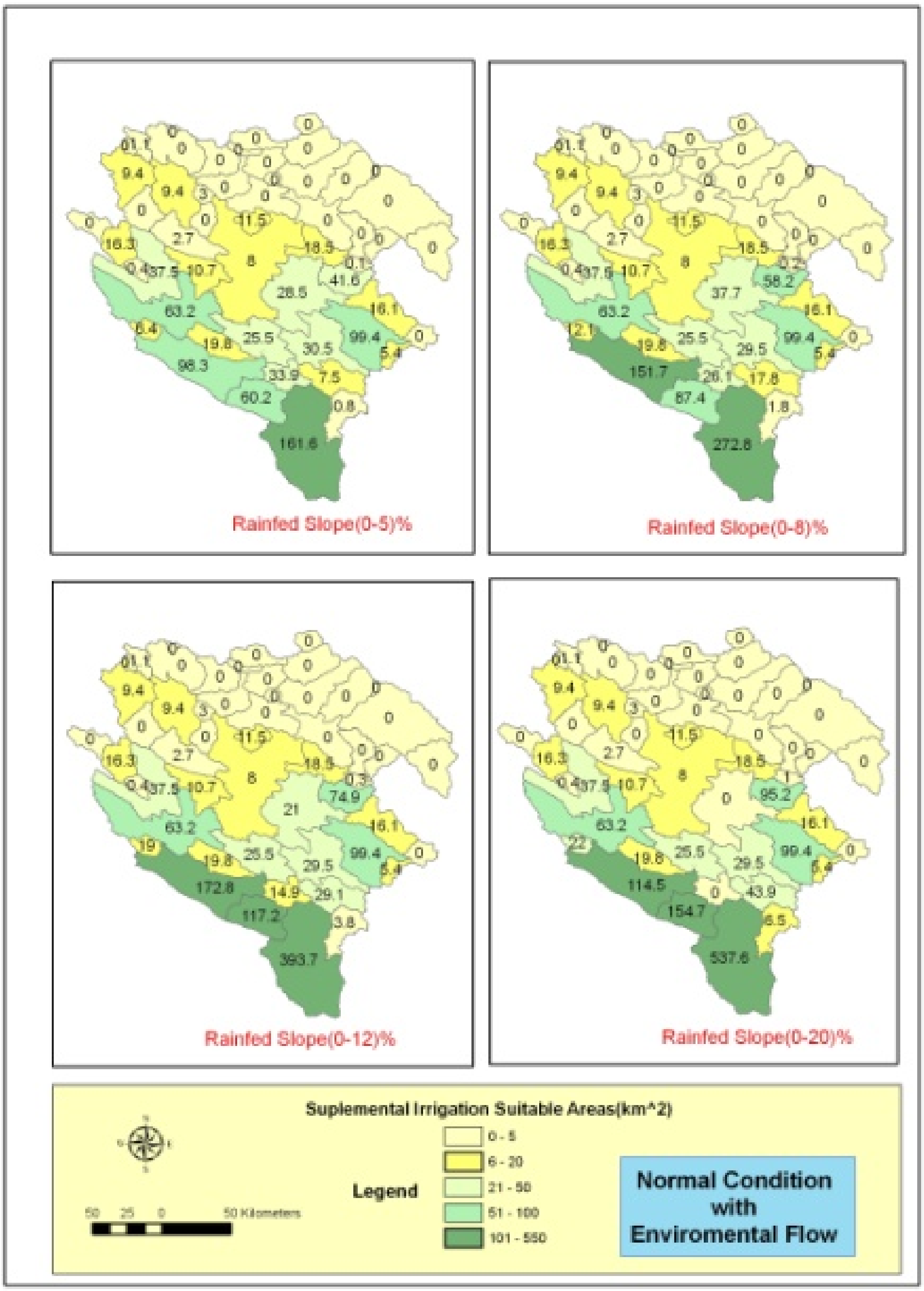
Slope %	Conditions	*Average streamflow*					*Average with env. flow*					*Dry*				
		Oct	Nov	Apr	May	Ann.	Oct	Nov	Apr	May	Ann.	Oct	Nov	Apr	May	Ann.
	available flow (m³/s)	57	115	421	284	177	30	89	394	257	151	42	67	205	225	90
0 -5	Outflow with SI (m³/s)	17	107	408	167	162	6	80	381	144	137	28	59	205	212	86
	Reduction of downstream flow (%)	-71	-7	-3	-41	-9	-79	-10	-3	-44	-9	-33	-13	-6	-11	-5
0 -8	Outflow with SI (m³/s)	10	101	400	133	158	3	75	373	113	133	26	53	205	204	85
	Reduction of downstream flow (%)	-82	-12	-5	-53	-11	-90	-16	-5	-56	-12	-38	-21	-9	-13	-6
0 -12	Outflow with SI (m³/s)	6	96	391	106	154	2	69	364	86	130	26	48	205	195	83
	Reduction of downstream flow (%)	-90	-17	-7	-63	-13	-93	-22	-8	-67	-14	-39	-29	-13	-15	-8
0 -20	Outflow with SI (m³/s)	6	88	380	82	150	2	62	354	72	127	26	41	205	184	82
	Reduction of downstream flow (%)	-90	-23	-10	-71	-15	-93	-30	-10	-72	-16	-39	-40	-18	-15	-10

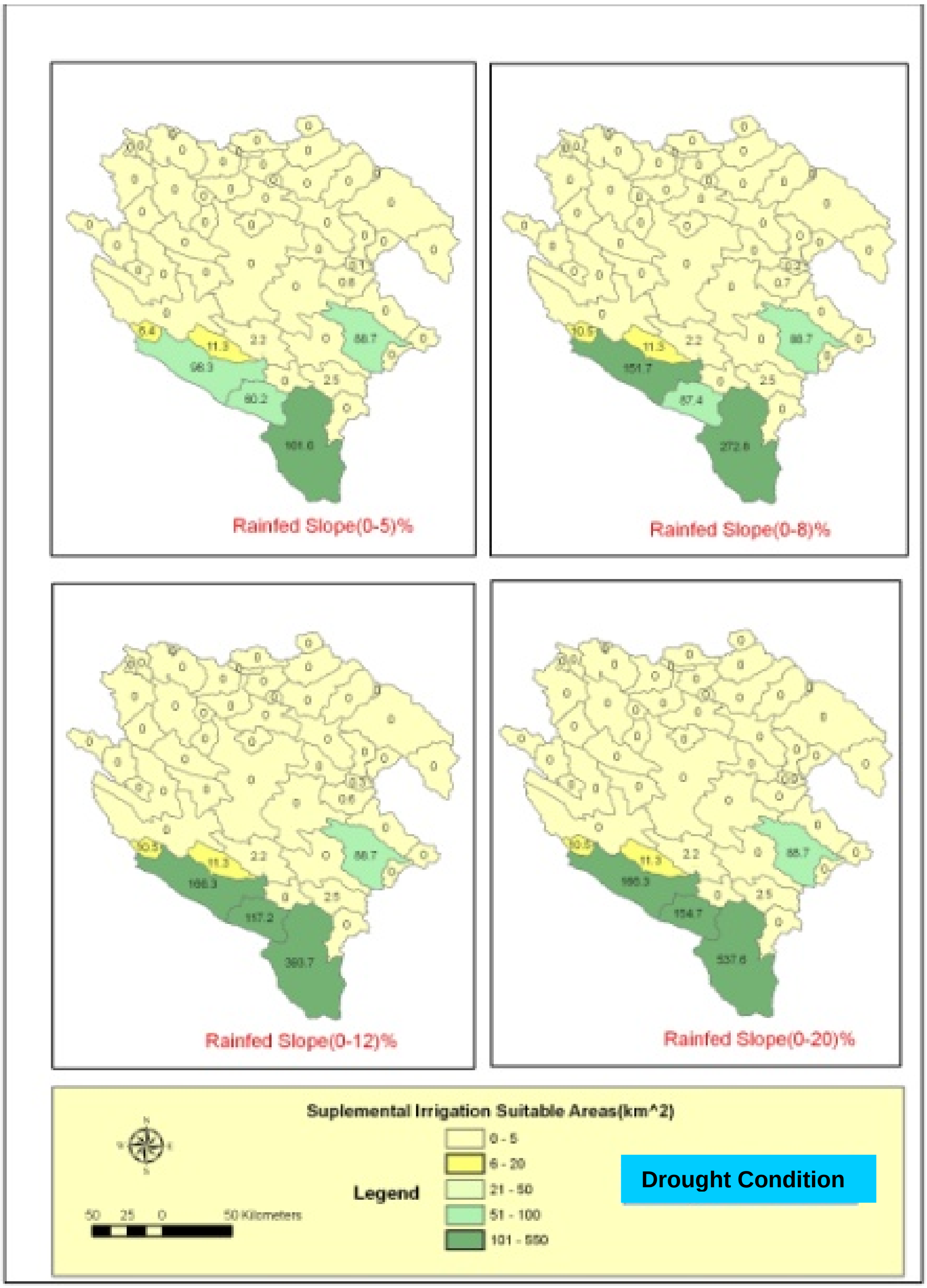
Conclusions and recommendations

The results indicate that implementation of SI in the rainfed areas does not substantially reduce the average annual flow to the Karkheh reservoir, while providing considerable yield and water productivity benefits. We recommend the use of SI in spring, or a single irrigation in autumn with early sowing, to maximize water productivity in upstream KRB. Further research should be made to evaluate EF allocation with surplus water from the KRB system of 53 sub-basins. A complex detailed soil map could help allocate SI water more precisely to more suitable lands. The methodology, the criteria and the scenarios may be refined further by including socioeconomic factors. In particular, the predicted changes in farm incomes under the proposed options may help influence policies for the reallocation of available water resources.

Figure 2: Potential supplemental irrigation areas (km2) for Average (normal), Average with env. Flow, and Dry (drought) conditions in KRB of Iran




Rainfed Slope(0-5)%
Rainfed Slope(0-8)%
Rainfed Slope(0-12)%
Rainfed Slope(0-20)%
Suplemental Irrigation Suitable Areas(km^2)
Legend
0 - 5
6 - 20
21 - 50
51 - 100
101 - 550
50 25 0 50 Kilometers
Normal Condition with Enviromental Flow



Acknowledgments

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SECTION 4

Adoption constraints and opportunities

Agricultural water management and poverty in Ethiopia

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Abstract

A significant part of Ethiopia and its agricultural production are affected by prolonged dry spells, recurrent drought, land degradation and consequential low productivity, resulting in extreme poverty and highly vulnerable rural communities. Traditional rainfed agriculture predominates, and *in situ* and *ex situ* Agricultural Water Management (AWM) technologies are used on less than 10% of the cultivated land. Among the *in situ* technologies, measures to reduce runoff and erosion, such as terracing, stone bunds and trash lines, are common. However, evaluation of their use and impacts on crop production and productivity is difficult and not well established in Ethiopia. The *ex situ* technologies used in Ethiopia include rain water harvesting for supplementary or full irrigation – most commonly from ponds, river diversion, micro dams and wells. Nearly forty types of technologies are used, in a range of combinations with respect to water control, lifting, conveyance and field application. Based on key informant interviews, 6 categories of technologies related to water source/control that have been successful and are widely used by small holders were identified. The poverty impacts of the AWM technologies were determined, based on extensive data collected from 1,500 households using these technologies and control households (non-users) in four major Ethiopian regions. The evaluation showed that the incidence, depth and severity of poverty is significantly lower among AWM technology users than non-users. AWM technology users are 22% less poor than non-users. Deep wells, river diversion and micro dams, were associated with poverty reductions of 50%, 32% and 25%, respectively. The difference was mostly attributed to the scale effects, such as larger plots and more reliable water sources.

Key words

rain water harvesting, irrigation, crops,

Introduction

General

With a human population estimated at 77 million in 2007, and which grows by some 2.8% annually, Ethiopia is the second most populous country in sub-Saharan Africa after Nigeria. Its economic mainstay is agriculture, which contributes about 45% and 85% to the GDP and national export earnings, respectively. Largely dependent on highly variable rainfall, and coupled with rampant land degradation, agricultural productivity continues to decline or stagnate and thus perpetuate poverty and food insecurity. Recurrent drought is one of the major threats to food security and sustainable use and conservation of natural resources in Ethiopia. The country's rural poor are often trapped in a vicious cycle between poor access to resources (poverty), land degradation and recurrent drought. In the face of currently soaring food prices in international markets, importing agricultural products through purchase or aid is becoming more challenging than ever before, calling for substantial increases in agricultural productivity. Thus, the widespread implementation of improved land and water management systems that ensure sustainable increases in agricultural productivity is urgently needed.

Crop Production in Ethiopia

About 10 million hectares are cultivated in Ethiopia, some 20% of the total arable land. The land that is under improved AWM irrigation is less than one million hectares, of which only about a quarter of a million hectares are under formal irrigated agriculture. The irrigation potential of the country is about 3.7 million hectares, thus the current level of irrigation is about 6% of the potential. Although there is some large-scale commercial irrigation, producing mainly industrial or export crops, semi-subsistent and traditional rain-fed farming together with limited small-scale traditional irrigation contribute the largest share of total agricultural production. Further details about irrigation in Ethiopia are provided in Awulachew et al. (2007).

The major crops grown in the country are cereals - bread wheat (*Triticum aestivum* L), durum wheat (*T. durum* Desf), tef (*Eragrostis tef*), maize (*Zea mays*) and barley (*Hordeum vulgare*) - plus various other crops such as pulses, oil seeds, root crops, fruit crops, sesame (*Sesamum indicum*), cotton (*Gossypium sp.*), sugar cane (*Saccharum*), chat (*Catha edulis*) and coffee (CSA, 2006). Cereals, pulses and oil seeds cover about 95% of the total cropped area. Cereals alone cover 75% of the cropped area, out of which tef covers the largest area followed by maize, sorghum, wheat and barley in that order. In terms of production, however, maize contributes the largest tonnage, followed by wheat, tef, sorghum and barley. All these crops are largely cultivated as rain-fed crops. Coffee, cotton, sesame and sugar cane - which have high export earning potential - constitute a small proportion of the total crop production.

Rainfed System

Rain-fed agriculture contributes the largest share of total Ethiopian agricultural production. Its contribution is expected to increase in the foreseeable future as indicated in the sustained increase in land area under rain-fed farming. According to CSA (2006), the area of agricultural land occupied by rain-fed agriculture increased from 9.5 M ha to 10.4 M ha between 2003/04 and 2005/06, a 9.5% increase (average 4.7% per year), while production increased by 12 to 15% every year. The yield increase can be attributed to the increased use of improved inputs such as fertilizers, and to favorable weather conditions during that period. Rainfed production increases have not, however, kept pace with population growth in the past, and production can be substantially increased.

Irrigated Systems

Irrigation is among the technological interventions believed necessary to achieve a major increase in agricultural productivity to meet the growing demands for agricultural products in Ethiopia. The major crops commonly grown under irrigation are sugar cane, cotton, sesame, fruit and vegetables. These crops are grown under small and traditional as well as medium to large-scale irrigation schemes. While the major food crops are under the rain-fed system, irrigation has been seen as a means to provide employment opportunities and increase the livelihoods of rural people by enabling them grow cash crops. Most Ethiopian farmers can develop access to small scale or traditional irrigation, which is inexpensive, and which can be easily integrated into rain-fed and livestock farming systems. These initiatives are, however, at very small scales, and the contribution of irrigation to the economy is insignificant. According to Hagos et al. (2008), irrigated agriculture contributed only 5.7% and 2.5% of Ethiopian agricultural output in 2005 and 2006, respectively. This is despite the relatively high efficiency of smallholder managed irrigation systems. The latter generate an average income of about USD 323/ha compared to an average income of USD 147/ha obtained under rain-fed system (Hagos et al. 2008). Expanding the use of irrigation systems will, it is thought, increase the incomes of smallholders and thereby stimulate rural development and system intensification. Also, its increased contribution to agricultural and overall GDP will fuel the overall economic development efforts of the country.

Objectives of the paper

Various *ex* situ and *in* situ AWM technologies are practiced in Ethiopia. Huge resources are being allocated to develop and promote diverse low cost technologies in many developing countries including Ethiopia. In the last few years, many low cost AWM technologies have been developed for use by smallholders. In spite of these huge investments, their impacts remain unknown. The main objective of this paper was, hence, to explore whether adoption of selected AWM technologies has led to a significant reduction in poverty, and if so, to identify which technologies have higher impacts.

Review of AWM technologies and suites

Widely used technologies

The overall objective of this section is to review the use and suitability of AWM technologies and to identify promising technologies for scaling up. The method of collecting data and information included a literature review from both local and international sources, and key informant interviews at federal, regional, and, in some instances, at zonal and woreda levels. In addition, a questionnaire was designed and distributed to relevant experts in various institutions (government and non-government organizations, UN agencies, private, etc.) to capture diversified information on AWM practices, ranking of technologies and associated constraints. Where feasible, site observations were made and discussions with individual farmers were also held. In total, 38 different types of AWM technologies for rainfall and water conservation/control were identified which are practised at both micro catchment (e.g. stone terraces, trash lines) and macro catchment (e.g. ponds, small dams, diversions) scales. The list of these technologies are provided in Loulseged et al. (2008).

Technology suites

Very often, AWM technologies are advocated in isolation, for a particular function. While this is applicable for most *in situ* soil and water conservation technologies, *ex situ* systems require more than one combination of technologies. This usually includes all or some of the technologies used for water control/storage, lifting, conveyance and field application, yielding a 'suite' of technologies. The factors that influence which technologies are included in the optimum suite include: affordability, experience, availability, and awareness. The most commonly used technology suites in Ethiopia are shown in Table 1

Table 1: Major AWM technologies and their suites in Ethiopia

Water storage	Lifting and conveyance	Field application
Rainwater harvesting suites		
Pond	bucket/watering can/pulley/siphon	flooding
	bucket/ pressure treadle pump	drip/sprinkler
	suction treadle pump/rope and washer pump➔Channel	flooding
Hemi-spherical tank (mortar)	channel	flooding
Dome shaped tank (concrete)	channel	flooding
Spate irrigation (gully plugging, stone bund)		water spreading
Roof rain water tank (surface or underground)		watering can
Excavated dam	hand/motorized pump	flooding
Micro irrigation suites		
Shallow well	bucket/hand/(motorized pump + drip) storage drum	drip/sprinkler
	treadle/motorized pump➔Canal	furrow/flooding
Deep well	motorized pump	drip/sprinkler
Small scale irrigation suites		
Earth dam	canal	furrow/flooding
Diversion weir	canal	furrow/flooding
River	motorized pump➔Outlet chamber➔Canal	furrow/flooding

Based on this inventory, interviews and ranking exercises, the most promising AWM technologies in the four major regions of Ethiopia were identified (Table 2).

Table 2. Major AWM technologies used in the four major regions of Ethiopia

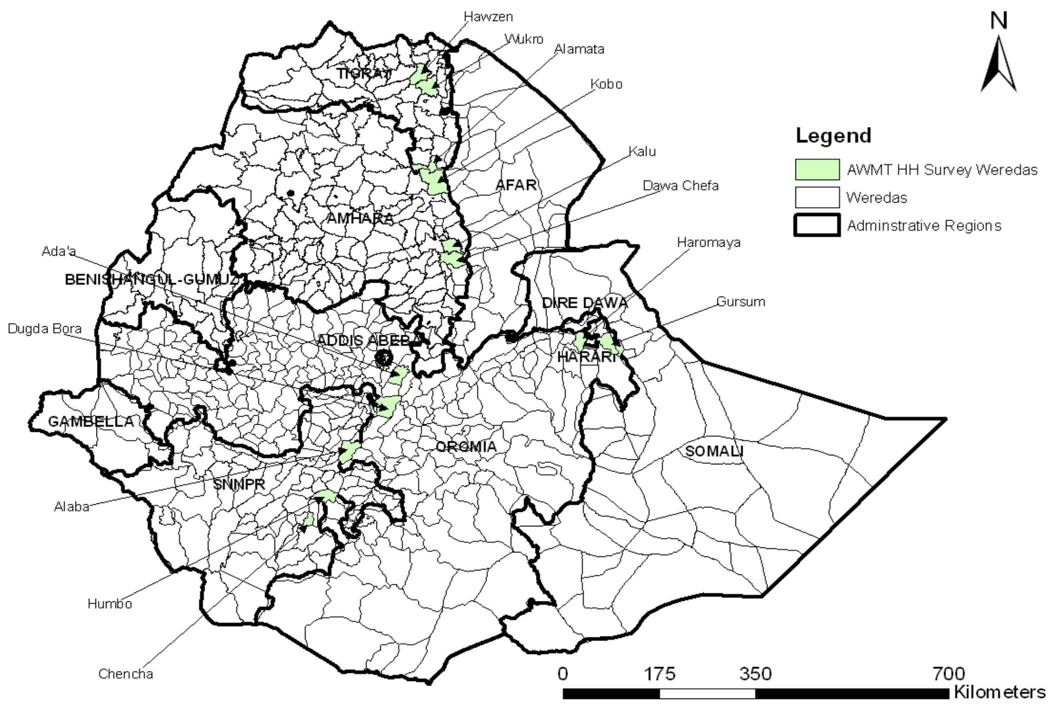
Rank	Tigray	Amhara	Oromia	SNNPR[1]
1	River diversion	River diversion	Wells	River diversion
2	Micro dams	Micro dams	River diversion	Pump irrigation (from perennial river)
3	Wells	Wells	Ponds	Dams
4	Ponds	Ponds	Spates	Ponds
5	Water tanks/cisterns		Terraces	Soil bunds

Poverty Impact of AWM technologies

Method and data

The socio-economic survey data, on which this study is based, were gathered from 1517 households from 29 Peasant Associations (PAs) in four Regional states (Fig. 1). The PAs were selected based on the presence of the above promising technologies. For more details on the identification of promising technologies through key informant interviews, see Loulseged et al. (2008). The households from each PA were selected randomly, and stratified into those with and without access, following a non-proportional sampling approach. Details of the sample households by type of technology from the four regions are given below in Table 3. The data were collected for the 2006/2007 cropping season.

Figure 1. Location of the study sites



[1] SNNPR is Southern Nations Nationalities and People's Region

The poverty impacts of AWM technologies were assessed using standard poverty analysis techniques (Foster et al. 1984) to explore whether those with access to AWM technologies have higher consumption expenditure per adult equivalent than those without access (for details see Hagos et al., 2008)

Table 3. Number of sample households using each AWM technology in each of the 4 study regions

Region	Agricultural water management technologies						
	None - purely rainfed	Pond	Shallow wells	Deep wells	River diversion	Micro dams	Others
Amhara	281	8	45	10	28	13	5
Oromia	219	12	23	68	68	1	2
SNNPR	217	68	55	0	14	25	0
Tigray	143	47	91	1	40	35	18
Total	860	657					

The poverty analysis followed six steps. First, we chose household consumption expenditure as a welfare measure, and adjusted this for the size and composition of the household. Second, the consumption poverty line was set at 1821 Ethiopian Birr (ETB) per annum (1USD=9.2 ETB), an inflation-adjusted poverty line using the baseline poverty line of ETB 1075 set in 1995/96 corresponding to some minimum acceptable standard of living in Ethiopia (MOFED 2006). We also used an inflation-adjusted poverty line of 1096 Birr as the absolute food poverty line based on the corresponding 1995/96 food poverty line. These lines were chosen to enable meaningful comparison of poverty levels in Ethiopia between various groups and over time. Third, poverty indices such as the number of poor (incidence), poverty gap (depth) and poverty gap squared (severity) were calculated. Fourth, we constructed poverty profiles showing how poverty varies over population subgroups (for example, users vs non-users of different AWM technologies) or by other characteristics of the household (for example, level of education, age, asset holding, location, etc.). This type of poverty profiling is particularly important as what matters most to policymakers is not so much the precise location of the poverty line, but the implied poverty comparison across subgroups or across time. Fifth, we did ordinal poverty comparisons using stochastic dominance to test the robustness of the poverty orderings. This is important because the estimate of the poverty line could be influenced by measurement error. Lastly, we explored the determinants of poverty using multivariate regression analysis. We analyzed the correlates of poverty against household and demographic factors, specific individual/household head characteristics, asset holdings including adoption and use of AWM technologies, village level factors, and policy related variables (access to services). By doing so, the marginal impacts of access to AWM technologies on poverty were assessed while controlling other possible covariates.

Poverty analysis results and discussion

Summary and separation tests

We report the results of the mean separation tests of important variables for users and non-users. The results of this statistical test provide an indicative measure of the differences in important variables between users and non-users, which may be considered as indicative measures of the impact of access to AWM technologies. However, a more systematic analysis of impact is needed before drawing definite conclusions on the impacts of access to AWM technologies (next section).

There were statistically significant differences in mean values of important variables (Table 4). There are highly significant differences ($p < 0.0001$) in agricultural incomes (both crop and livestock) among users and non-users of AWM technologies. Those with access to AWM technologies used more farm inputs and supplied a significantly higher share of their produce to the market ($p \leq 0.0001$) implying increased market participation. Accordingly, the value of fertilizer, seed, labor and insecticide used and the size of loans received from microfinance institutions were significantly higher for users of AWM technologies compared with non-users. This may imply that because of access to AWM technologies, there is increased intensification of agriculture. This is expected to have wider effects on the economy e.g. on input and output markets. Not surprisingly, users of AWM technologies also had significantly higher asset endowments such as male adult labor, oxen, livestock and land holding, which may imply that those with access to AWM technologies have managed to build assets. On the other hand, it may also mean that households with better resource endowments were targeted by the program (or were self-selected) to secure access to AWM technologies, factors that we may not be able to separate in the absence of baseline data. However, the mean separation test indicated that there are no significant differences in mean consumption expenditure per adult equivalent, incidence of food shortage and size of non-farm income between those with and without access to AWM technologies.

The problem with such mean separation tests is non-comparability of the two sub-samples and that we did not control for the effects of other covariates. Hence, the need to systematically analyze whether access to AWM technologies has led to significant effects on income and poverty using matching (by creating comparable groups) and more advanced poverty analysis techniques, below.

Average treatment effects

Of the 1517 households, only about 946 are comparable. When the treated (ATT) and control households were matched on the basis of their similarity scores using nearest neighbor, kernel and stratification methods, there was a significant effect on household income of using AWM technologies for all three matching methods (Table 5). For details of the methods see Hagos et al. (2008). The estimated average annual income of the AWM users is about ETB 780 (USD 82) higher than income of the non-users using all methods. This indicates that access to AWM technologies has lead to a significant increase in household income.

Table 4. Results of separation tests of some important variables of households with access and without access to AWM technologies

Variable name	Non-users (n= 641) Mean (SE)	User (n= 876) Mean (SE)	p-value*
Value of fertilizer used (ETB/year)	274.9 (27.0)	399.5 (32.7)	0.005
Value of seed used (ETB/year)	272.1 (31.1)	698.1 (204.1)	0.076
Value of labor used (ETB/year)	600.9 (34.7)	1114.3 (67.6)	0.0001
Value of insecticide used (ETB/year)	19.6 (3.1)	75.4 (19.7)	0.016
Loan size (cash, ETB/year)	1293 (108)	1689 (103)	0.008
Crop income (ETB/year)	302.3 (16.4)	682.5 (57.0)	0.0001
Livestock income (ETB/year)	51.6 (5.37)	67.3 (4.25)	0.020
Agricultural income (ETB/year)	352.9 (7.2)	749.7 (57.2)	0.0001
Non-farm income (ETB/year)	63.7 (4.36)	67.0 (4.95)	0.628
Consumption expenditure per adult equivalent (monthly, ETB)	39.2 (4.46)	40.8 (3.71)	0.774
Face food shortage (%)	37.3 (1.9)	35.4 (1.6)	0.448
Market share (%)	7 (1)	15 (1.2)	0.0001
Oxen (number)	1.18 (0.047)	1.71 (0.055)	0.0001
Livestock units (TLU[1])	3.27 (0.113)	4.64 (0.15)	0.0001
Land holding in (timad[2])	5.12 (0.163)	7.143 (0.19)	0.0001
Total labor endowment (number of adult laborers)	2.961 (0.059)	3.054 (0.051)	0.234
Male labor endowment (number of adults male laborers)	1.446 (0.039)	1.568 (0.035)	0.021
Female labor endowment (number of adult female laborers)	1.496 (0.037)	1.476 (0.029)	0.665

[1] TLU = tropical livestock unit. 1TLU =250 kg
[2] 1 timad = 0.25ha
* Two-sided test of equality of means

Table 5. The impact of AWM technologies on household income (ETB) after matching households (bootstrapped standard errors, see Hagos et al. (2008) for details)

Treatment (n)	Non-users (n)	ATT (se)	t-test
Kernel Matching Method			
699	394	788 (219)	3.605***
Nearest Neighbor Matching Method			
699	247	760 (256)	2.972***
Stratification Method			
699	394	785 (228)	3.451***

We now turn to poverty analysis using consumption expenditure per adult equivalent.

Poverty profiles and decomposition

Using the absolute overall poverty line of ETB 1821, about 48% of the AWM technology user households are poor. On the other hand, about 62% of the non-users are poor. The test results also show that there is significant difference in poverty levels between users and non users. There is about 22% lower poverty among users compared to non-users. In other words, households with access to AWM technologies are in a better position to meet their consumption requirements, both food and non-food. There are also significant differences in the poverty gap and severity of poverty between users and non-users, implying that AWM technologies are effective instruments to narrow the poverty gap and inequality (see Table 6). However, the results also suggest that the overall level of poverty has increased compared to the baseline poverty of about 39% in 2004/05 (MOFED 2006; p. 23) calculated based on poverty line of ETB 1,075. However, this apparent increase in poverty may be due to failure to adjust the poverty line to properly account for other factors affecting poverty such as unemployment and devaluation.

Table 6. The effect of irrigation on incidence, depth and severity of poverty, see Hagos et al (2008) and Duclos et al. (2006) (poverty line = ETB 1821)

Category	Incidence[1] (proportion) ($\alpha = 0$)[4]		Depth[2] ($\alpha = 1$)		Severity[3] ($\alpha = 2$)	
	value	SE	Value	SE	Value	SE
Access to AWM Technology						
Users (n= 876)	0.478	0.017	0.198	0.009	0.1110	0.007
Non-users (n= 641)	0.623	0.018	0.282	0.011	0.167	0.009
z-statistic[5]	-484.2***		-381.6***		-282.0***	
Type of AWM Technology[6]						
Pond (n= 196)	0.561	0.035	0.218	0.017	0.107	0.011
z-statistic	-193.5***		-170.8***		-146.2***	
Shallow wells (n= 251)	0.565	0.031	0.266	0.019	0.168	0.016
z-statistic	-233.0***		-172.3***		122.1***	
Deep wells (n=93)	0.312	0.048	0.113	0.021	0.0550	0.013
z-statistic	-109.2***		-107.8***		-98.0***	
River diversion (n= 291)	0.403	0.029	0.1440	0.013	0.071	0.009
z-statistic	-258.0***		-235.5***		-189.0***	
Micro-dams (n= 63)	0.484	0.063	0.1910	0.032	0.101	0.022
z-statistic	-71.6***		-63.0***		-53.3***	
In-situ AWM technologies[7]						
Users (n= 368)	0.614	0.025	0.253	0.014	0.141	0.0110
Non-users (n= 373)	0.521	0.0148	0.2300	0.008	0.134	0.007
z-statistic	-296.2***		-220.9***		-150.5***	
Water application technologies[8]						
Flooding (n= 533)	0.429	0.021	0.159	0.010	0.079	0.007
Manual (n= 284)	0.567	0.029	0.274	0.018	0.171	0.015
Water withdrawal						
Treadle pump (n=101)	0.524	0.049	0.183	0.023	0.088	0.014
z-statistic	-111.0***		-103.4***		-63.4***	
Motor pump (n=127)	0.228	0.037	0.068	0.0135	0.027	0.007
z-statistic	-155.7***		-172.7***		-171.0***	
Water input						
Supplementary (n= 270)	0.56	0.030	0.262	0.18	0.16	0.15
z-statistic	-245.0***		-24.5***		-17.4***	
Full irrigation (n= 579)	0.437	0.020	0.16	0.009	0.077	0.006
z-statistic	-322.7***		-287.0***		-231.7***	

[1] poverty head count (proportion)
[2] income or consumption shortfall relative to the poverty line
[3] takes into account the shortfall and inequality
[4] the Foster-Greer-Thorbecke (FGT) poverty measures are defined as $P(z;\alpha) = \int_0^1 \left(\frac{g(p;z)}{z} \right)^{\alpha} dp$ where z denotes the poverty line, and α is a nonnegative parameter indicating the degree of sensitivity of the poverty measure to inequality among the poor
[5] The z-statistic is derived using Kwakani's (1993) formulae to test for equality of poverty measures. The critical value for the test statistic is 1.96 at 5% level of significance
[6] We compared those using AWM technologies with non-users
[7] Note that the *in situ* technologies used here are terraces and soil bunds. However, there are much more effective technologies such as zai pits, mulching, etc. which can make more substantial productivity impact, e.g. Amede et al (2008)
[8] We compared those using different water application technologies against non-users

We disaggregated users by the type of AWM technology to measure the poverty impact of specific technologies. All the *ex situ* AWM technologies considered in this study had significant poverty reducing impacts. However, deep wells, river diversions and micro dams had higher poverty impacts compared to ponds and shallow wells, perhaps largely due to scale benefits such as larger plots and more reliable water sources. Deep wells, river diversions and micro dams led to approximately 50, 32 and 25% reduction in poverty levels compared to rainfed systems. On the other hand, the *in situ* AWM technologies (terraces and soil bunds) had no significant poverty reducing impacts. Those using *in situ* AWM technologies had higher poverty levels in terms of incidence, poverty gap and severity of poverty indices. We do not have any *clear* reason for this counter intuitive result. However, the *in situ* technologies were only soil conservation (erosion reduction) measures with little immediate impact on productivity growth; at the same time they may divert labor from direct agricultural crop production to conservation that contribute to household welfare directly.

We also disaggregated poverty levels by type of water withdrawal and application technologies. The most common withdrawal and application mechanisms included gravity flooding (63.3%), manual (cans) (33.7%), treadle pump (6.7%), and motor pump (8.4%). Sprinkler (0.2%) and drip (0.2%) are hardly used, although there are signs of households gradually adopting these technologies. Those using motor pumps had a significantly lower poverty level than treadle pump users. In fact, as a result of using motorized pumps, there was more than a 50% reduction in the incidence of poverty mainly due to scale benefits. As far as water application technologies are concerned, households using gravity had significantly lower poverty levels than those using manual application. We also disaggregated poverty by the type of water use - that is, whether the water was used for supplementary or full irrigation. Those who used AWM technologies for full irrigation had significantly lower poverty levels compared to those using supplementary irrigation and non-users. This implies that supplementary irrigation could contribute to poverty reduction; a significant contribution comes, however, from full irrigation. This will have an important implication on technology choice for effective poverty reduction.

We also estimated poverty profiles using an absolute food poverty line of ETB 1096. Accordingly, 23% of the users and 34% of the non-users are identified as food poor. These indices could be taken as food security indices. This implies that the level of food security has increased compared to 38% in 2004/05 (MoFED 2006; p. 27) calculated based on the poverty line of ETB 647.8 (no adjustment for inflation or devaluation). However, we feel that the food poverty line used should have been adjusted to account for price changes to make meaningful comparisons.

When disaggregated by type of AWM technology, as in the case of overall poverty, deep wells, river diversion and micro dams are associated withthe highest reductions in food poverty. Ponds and wells, however, have also led to significant poverty reduction compared to non-users. However, *in situ* AWM technologies have not led to significant reduction to food insecurity. On the contrary, those using *in situ* AWM technologies had higher poverty levels in terms of the head count, poverty gap and severity of poverty indices.

Table 7. The effect of irrigation on incidence, depth and severity of poverty (poverty line = ETB 1096)

Category	Incidence ($\alpha = 0$)		Depth ($\alpha = 1$)		Severity ($\alpha = 2$)	
	value	SE	Value	SE	Value	SE
Access to AWM Technology						
Users (n= 876)	0.2340	0.015	0.086	0.007	0.049	0.005
Non-users (n= 641)	0.349	0.018	0.137	0.009	0.081	0.007
z-statistic*	-286.4***		-231.3***		-181.8***	
Type of AWM Technology						
Pond (n= 196)	0.275	0.032	0.071	0.011	0.028	0.006
z-statistic[2]	-116.2***		0.00		-144.9***	
Shallow wells (n= 251)	0.311	0.029	0.143	0.017	0.094	0.014
z-statistic	-137.0***		0.0		-69.7***	
Deep wells (n= 93)	0.151	0.037	0.0380	0.0130	0.017	0.008
z-statistic	-3.8***		0.0		-73.2***	
River diversion (n= 291)	0.158	0.021	0.047	0.008	0.023	0.006
z-statistic	-179.6***		0.0		-128.9***	
Micro-dams (n= 63)	0.234	0.053	0.081	0.022	0.039	0.014
z-statistic	-47.0***		0.0		-39.7***	
In-situ technologies						
Users (n= 368)	0.302	0.024	0.111	0.012	0.062	0.009
Non-users (n= 373)	0.279	0.013	0.109	0.007	0.064	0.005
z-statistic	-156.7***		-117.2***		-85.1***	
Water application technologies						
Flooding (n= 533)	0.176	0.016	0.056	0.006	0.027	0.005
Manual (n= 284)	0.341	0.028	0.144	0.015	0.091	0.0128
Water Withdrawal technologies						
Treadle pump (n=101)	0.227	0.042	0.062	0.013	0.020	0.005
z-statistic	-490.7***		0.1		-104.6***	
Motor pump (n= 127)	0.0470	0.019	0.014	0.007	0.006	0.003
z-statistic	-490.8***		0.0		-149.3***	
Water input						
Supplementary (n= 270)	0.333	0.028	0.138	0.016	0.086	0.013
z-statistic	-496.6***		0.1		-75.8***	
Full irrigation (n= 579)	0.174	0.0158	0.053	0.006	0.025	0.004
z-statistic	-490.7***		0.1		-155.8***	

Furthermore, households using AWM technologies for full irrigation have relatively lower food poverty compared to those using water for supplementary irrigation. We consider that the lower poverty with full irrigation reflects greater reliability and adequacy of water supply as well as availability of labor for water management.

Conclusions

Our results show that there was significant reduction in poverty due to adoption and use of *ex situ* AWM technologies. There was about 22% less poverty incidence among users compared to non-users of *ex situ* AWM technologies. We found the poverty orderings between users and non-users are statistically robust. Furthermore, from the poverty analysis (severity indices), we found that AWM technologies were both poverty-reducing and also equity-enhancing technologies. While poverty analysis techniques do not have in-built

* Critical statistics

[2] We compared those using different AWMT against non-users.

mechanisms of creating comparable groups, and hence could lead to attribution bias[3], our results from the propensity score matching indicated that the average treatment effect of using AWM technologies is significant and has led to an income increase of, on average, USD 82/household. The magnitude of poverty reduction was technology specific. Deep wells, river diversions and micro dams were associated with 50, 32 and 25% reductions in poverty incidence, respectively, compared to the purely rain fed system. The use of modern water withdrawal technologies (treadle pumps and motorized pumps) was also strongly related to lower poverty. The use of motorized pumps was associated with more than a 50% reduction in poverty incidence. Similarly, households using gravity irrigation had significantly lower poverty levels than those using manual (cans) application because of scale benefits. These results suggest that the promotion of modern water withdrawal and application technologies can enhance poverty reduction. While access to AWM technologies seems to unambiguously reduce poverty, our study also indicated that there is a host of factors that can enhance this impact. The most important determinants include asset holdings, educational attainment, family labor and access to services and markets. To enhance the contribution of AWM technologies to poverty reduction, there is, hence, a need to: 1) build assets; 2) develop human resources; and 3) improve the functioning of labor markets and access to markets (input or output markets).

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[3] The baseline situation of users and non-users is unknown. One could argue that the difference in estimated poverty levels may have to do with differences in initial conditions.

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Irrigation options in the upper east region of Ghana

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Abstract

Irrigation is used for year-round cropping to sustain economic livelihoods in the Upper East region of Ghana, which experiences a long dry season and erratic rainfall during the rainy season. The sources of irrigation water are a few medium-size reservoirs (e.g. Tono and Vea) and a large number of small reservoirs scattered across the region. Other approaches include the application of shallow groundwater for vegetable cultivation. In recent times, pumping from rivers has increasingly been used to irrigate areas close to rivers to cultivate high value crops. Dry season irrigation cropping helps to increase household food security and also provides off-season employment for the many youths who are idle during this time of the year. This paper examines the different irrigation approaches in relation to the economic benefits to farmers, amidst growing concern for water availability for alternative uses. Net financial returns to land were similar for irrigation from small reservoirs and medium-sized reservoirs for vegetable production. Most of these smaller systems face problems, which include partial or complete drying-up of the reservoir in the dry season, high input costs (e.g. pumps and accessories), lack of access to credit facilities, and rapid deterioration and low profitability of medium scale schemes. The choice of irrigation water source such as dams (medium or small), or river pumping must be based on location specific criteria that maximise profitability, efficiency and sustainable use of the scheme.

Key words

dry season, pump irrigation, small dams, water productivity, water use

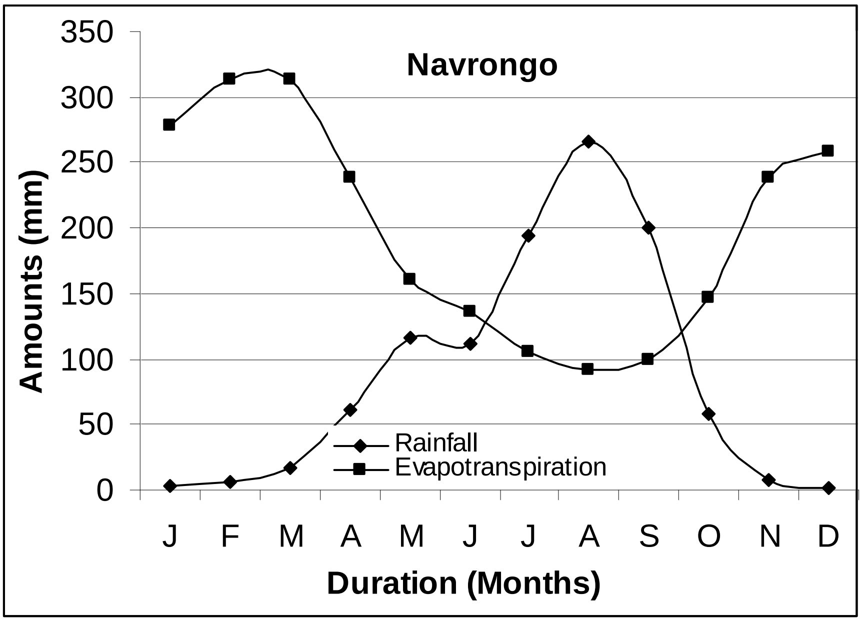
Introduction

The Upper East Region of Ghana is heavily dependent on agriculture with over 65% of the working population having agriculture as their main occupation. Despite being the main economic activity, agriculture barely sustains many households in the Region. The Region also experiences erratic rainfall for a period of about five to six months (see Figure 1) resulting in persistent seasonal food shortages. Often the yields of the main growing (rainy) season are not enough to guarantee a household's livelihood. With high rainfall variability and a limited rainy period in the region, 65 % of the working population is without work for most of the year where there is no form of irrigation.

As a coping strategy, households engage in off-season economic activities to supplement their incomes. The youth migrate to southern Ghana to seek often non-existing economic opportunities at the end of the growing season, and return to till their farmlands during the farming season. Dry season farming, which involves the use of various types of irrigation systems, has become an increasingly important source of livelihood for a greater number of people in the area. It also helps to keep most of the migrating young men and women at home.

A vital ingredient for the modernisation of agriculture in Ghana is irrigation. Unfortunately, the total area under irrigation is tiny - estimated at 11,000 ha in 1996, only 0.44 % of the total land area (Memuna and Cofie 2005) or just 0.26 % of the area under cultivation. This has barely changed over the years (Kyei-Baffour 1994; FAO 2005; Memuna and Cofie 2005) thereby supporting the fact that agriculture is mainly rainfed, and thus subject to the vagaries of the weather. It is, however, noteworthy that through the Ghana Irrigation Development Authority (GIDA) and the Ministry of Food and Agriculture (MoFA), a draft national irrigation policy is currently available.

Figure 1. Monthly mean rainfall and evapotranspiration at Navrongo in the Upper East Region [Derived from Meteorological Services Agency (MSA) data (1961-2004)]



Irrigation is needed because of the occasional dry year such as the one that occurred in 1983, when total rainfall was 719 mm compared to mean annual rainfall of 990 mm from 1961 to 2004 at Navrongo. The seasonality of rains is another issue that seriously affects agricultural operations. For example, the rainfall pattern in Navrongo (Figure 1) shows a unimodal rainfall pattern of short duration and rainfall is exceeded by evapotranspiration in all but 3 months. The duration of the dry season in these areas tends to be distinct and long (nearly 6-7 months). The implication is that under rainfed agriculture farming is possible only for a period of 4-5 months each year, and the cultivation of long-duration crops is impossible or risky without irrigation.

Past policies on irrigation management, lessons learnt and present policy direction

In the past, the government owned and managed the irrigation schemes with farmers seen as beneficiaries with little or no voice in the day-to-day operations and management of the schemes. Profitability of the schemes was not a priority. The government paid salaries of staff and provided money for maintenance work with farmers contributing little or nothing for using the schemes (Ayariga 2008). In most cases the choice of crops was dictated by irrigation staff and they were also responsible for land and water allocation.

This management system certainly has had its own problems. With an increasing number of schemes, the government could no longer afford the budgets associated with maintaining the irrigation schemes. This led to rapid deterioration of most schemes with farmers not assured of continued access to land under the schemes.

Currently, the government's intention is to construct and/or rehabilitate the irrigation schemes but leave the management and maintenance of the medium-scale schemes to District Assemblies (DA) and farmers. Small schemes are to be completely farmer-managed through their democratically run Water Users Associations (WUA) with the DA providing public interest regulatory functions.

Irrigation resources of Upper East Region

Historical accounts trace irrigated agriculture in Ghana to a little over a century ago (Smith 1969) but the practice on a small scale dates back to as early as 1880 in the Keta area on land above flood level between the lagoon and the sandbar separating it from the sea. The first scheme that the government conceived was in 1920 as part of the then Winneba Water Supply Project (Smith 1969).

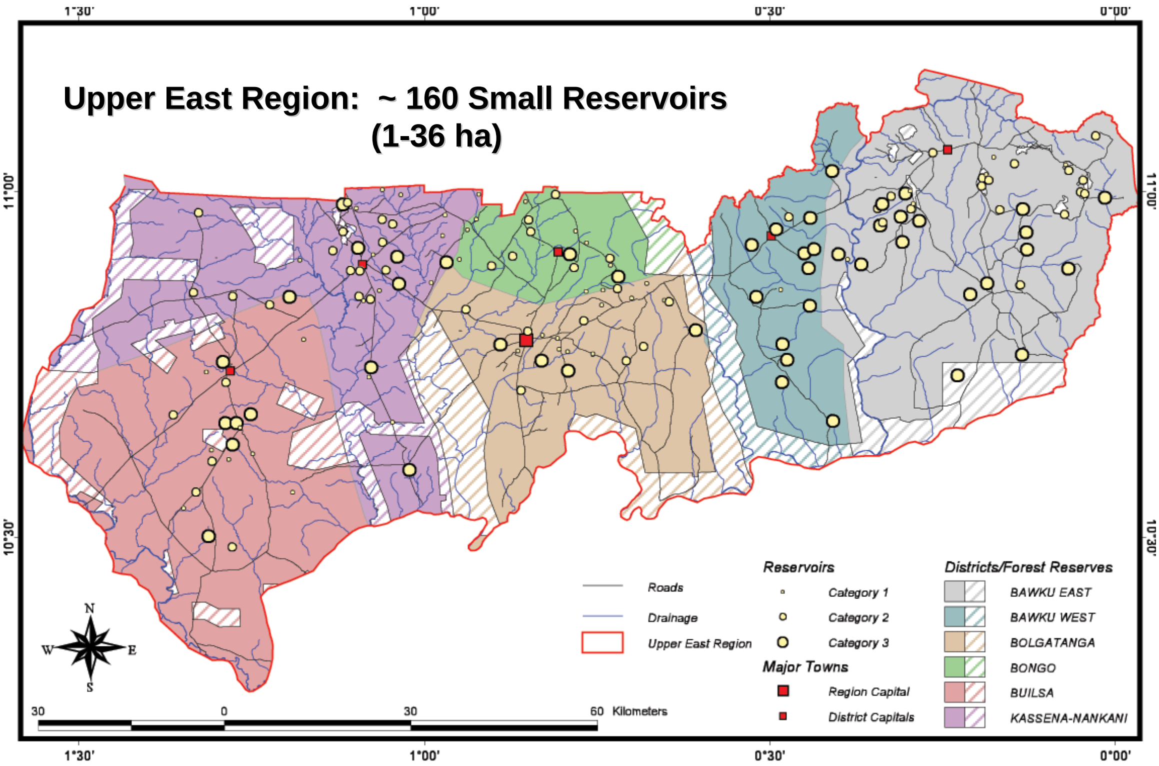
Formal irrigation was introduced to the Upper East Region in the early 1950s when small dams were built for livestock watering, vegetable production in the dry season and for soil conservation. The responsible government agency, GIDA, built and operated these schemes on behalf of government. At present, there are two medium-scale irrigation schemes, namely Tono and Vea in the Region. The Tono and Vea dams have irrigable areas of 2,638 ha and 1,417 ha but operate far below their capacities at about 30% and 28 % utilisation capacity, respectively (Table 1).

Table 1. Irrigation capacity utilisation of Tono and Vea projects.

Irrigation Project	Irrigable Potential (ha)	Net Irrigated (ha)	Capacity Utilisation (%)
Tono	2,632	800	30.4
Vea	1,417	400	28.2
TOTAL	**4,049**	**1,200**	**29.6**

The Upper East Region has numerous small dams that are basically the conventional clay earth-fill dam walls connecting two sides of a valley and retaining rainfall run-off. There are about 160 such dams with irrigable area in the range of 1-36 ha as shown in figure 2 (Liebe 2008). Their reservoir capacities range from 1.0 million down to 50,000 m^3. The dams usually have an inlet-outlet structure for water delivery from the reservoir. Also, there are more than 70 dugouts usually constructed by borrowing earth material from the adjacent relatively flat terrain to form an embankment for the purpose of harvesting rainfall run-off. Dugouts are constructed mainly for livestock watering rather than for irrigation, and do not have inlet-outlet structures.

Figure 2. Small-scale reservoir distribution in the Upper East Region of Ghana [Source: Liebe 2008]



There are also indigenous, traditional or informal irrigation methods involving crop production on small plots fenced off with thorn bushes or stalks along valley bottoms, seasonal rivers and other water bodies for the purpose of producing vegetables (mainly tomatoes, onions and peppers) at the end of the rainy season. Irrigation water is obtained from shallow wells dug within the fenced area or fetched with buckets, gourds or calabashes directly from the water body. In some cases the wells are dug within dried river beds or lowland areas. This system is possible because of the shallow groundwater table. Though the number of farmers and acreage involved in this practice are yet to be documented, preliminary studies by Laube *et al*. (2008) indicate that it is predominantly carried out in the Kasena Nankana District with farmers creating about 100-200 ha of vegetable gardens. This is made up of gardens with sizes of about 0.06 ha and 0.2 ha for farmers using buckets and pumps to lift the water, respectively. There has also been a rapid increase in the adoption of shallow groundwater irrigation over the past 5-15 years as a result of population increase and the increasing unreliability of rainfed farming which is attributed to climate change (Laube *et al*. 2008).

In addition to the formal (modern) gravity fed irrigation systems (medium- and small-scale irrigation systems based on gravity using lined canals) and traditional or indigenous irrigation systems, the use of pumps to draw water directly from the White Volta River is on the ascendancy (Table 2). In response to the need for irrigation facilities to aid dry season farming activities, the Ministry of Food and Agriculture (MoFA) and some NGOs are leading efforts towards the promotion of riverine pump irrigation in the region.

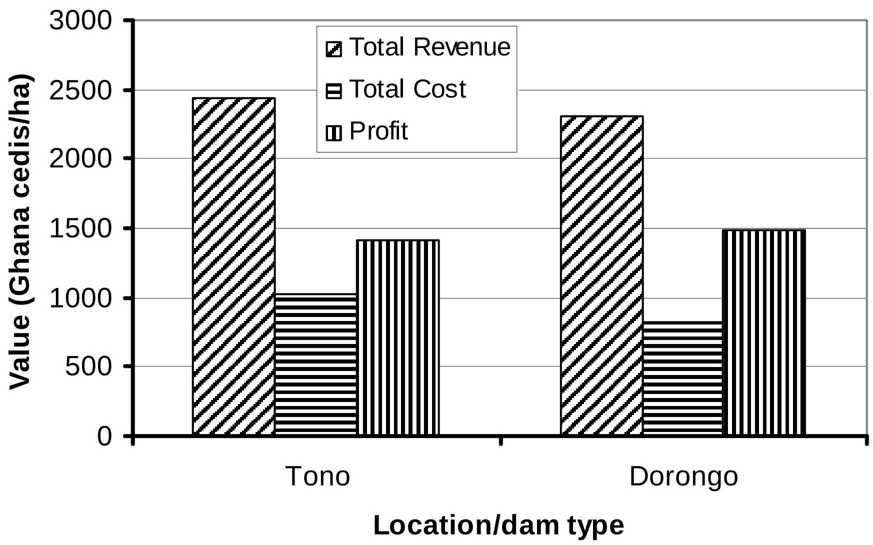
Table 2. Trends in number of farmers using pump irrigation in five communities along the White Volta River

Year Community	1999	2000	2001	2002	2003	2004	2005	2006
Bansi					7	18	41	51
Kugri				1	3	18	32	43
Googo		16	23	42	147	47	72	43
Yarigu	2	4	30	70	122	209	245	304
Adaboya			3	7	12	16	22	27

Financial performance of irrigation as affected by system scale

Mdemu (2008) and Laube et al. (2008) compared the profitability of different irrigation options per unit area (medium- and small-scale reservoirs) in the Upper East Region (Figure 3). There were 59 farmers with a mean plot size of 0.7 ha and 60 farmers with a mean plot size of 0.2 ha involved at Tono and Dorongo, respectively. Their work showed that small-scale reservoir irrigation at Dorongo had similar land profitability (LP) compared to the medium-scale reservoir of Tono.

Figure 3. Irrigation economics per unit area (ha) of a medium-scale reservoir (Tono) and a small-scale reservoir (Dorongo) in Upper East Region [1 Ghana cedi = 1.11US$] [Source: Mdemu 2008]



The financial return to water was about 58% and 64% of the mean total revenue with an estimated value of water at 0.20 US$ m^{-3} and 0.31 US$ m^{-3} at Tono and Dorongo, respectively (Mdemu 2008). The contribution of water to the total return was much higher than that of other inputs (Figure 4), indicating the importance of water to dry season tomato production.

Figure 4. Percentage contribution of production factors to total revenue [Source: Mdemu 2008].

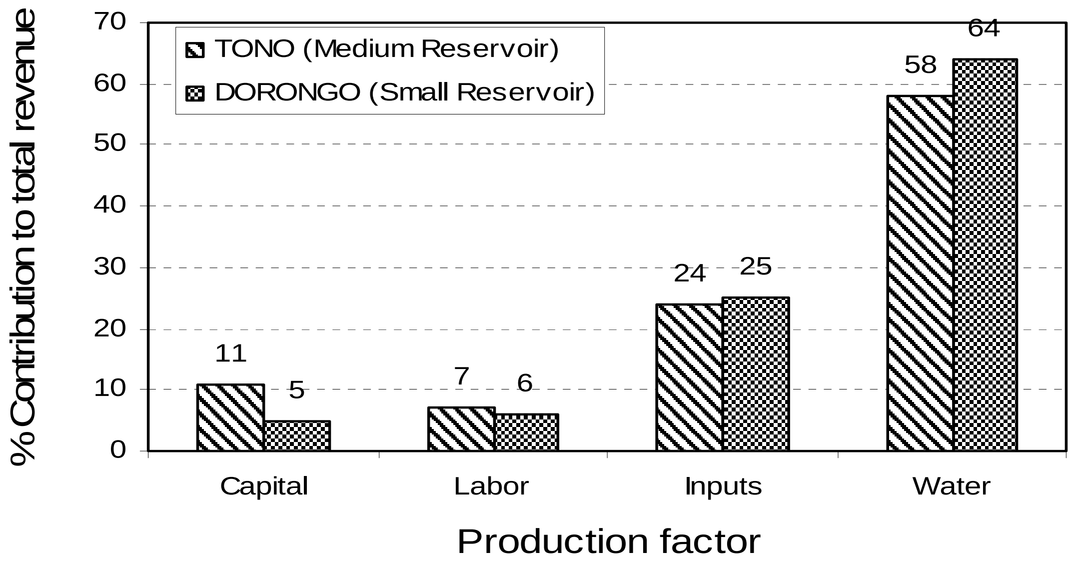


Table 3. Selected economic performance parameters for pump irrigation in the Upper East Region (N = number of Sampled farmers)

Productivity factor	N	Mean	Std. Dev.	C.V
Total factor productivity (GH¢/ GH¢)	186	1.09	1.32	1.21
Labor productivity (GH¢/man-day)	186	3.31	5.34	1.61
Water productivity (GH¢/cm^3)	186	3.76	7.70	2.04
Fertilizer productivity (GH¢/kg)	178	7.32	9.24	1.26
Income per man-equiv. (GH¢/man-equivalent)	186	272	574	2.11
Consumption capacity (GH¢/consumer)	186	212	422	1.99

Source: Agyare *et al*. (2008)

In analysing the economic performance of the pump irrigation system, Agyare *et al*. (2008) considered production factors such as labor, water and fertilizer productivities as the main factors constraining production in the dry season. The observed mean return to labor of GH¢3.31 per man-day (Table 3) was more than twice the mean daily wage for labor at the time of the study.

Agyare *et al*. (2008) also observed performance as affected by age, gender and education (Table 4). The productivity factors were classified as low if less than one and high if greater than one. The estimated productivity indicators were highest for the age group 41-50 and also for men. This was attributed to the fact that people in this age group tend to be both mature and experienced and could improve productivity on their fields by taking the right farming decisions. In the study area, dry season farming is largely dominated by men because they have easier access to farm lands and also could cope with the drudgery associated with pump irrigation itself. It is evident from Table 4 that people with formal education (Basic, Secondary or Post Secondary) have higher total factor productivity and water productivity, with Basic education being the most important.

Table 4: Production performance by age, gender and educational level in percentages under river pump irrigation in Upper East Region

Character		Number	Productivity			
			Water		Total Factor	
			Low	High	Low	High
Age group	<30	31	41.9	58.1	61.3	38.7
	30-40	74	35.1	64.9	64.9	35.1
	41-50	52	30.8	69.2	50.0	50.0
	51-60	18	61.1	38.9	88.9	11.1
	>60	11	81.8	18.2	100.0	0.0
Total		186	40.3	59.7	64.5	35.5
Gender	Male	175	38.9	61.1	64.6	35.4
	Female	11	63.6	36.4	63.6	36.4
Total		186	40.3	59.7	64.5	35.5
Education	No Education	93	46.2	53.8	71.0	29.0
	Basic	113	15.0	85.0	54.0	46.0
	Secondary	19	42.1	57.9	57.9	42.1
	Post Secondary	2	50.0	50.0	50.0	50.0
	Non formal	9	66.7	33.3	88.9	11.1
Total		186	40.3	59.7	64.5	35.5

Challenges in irrigation farming

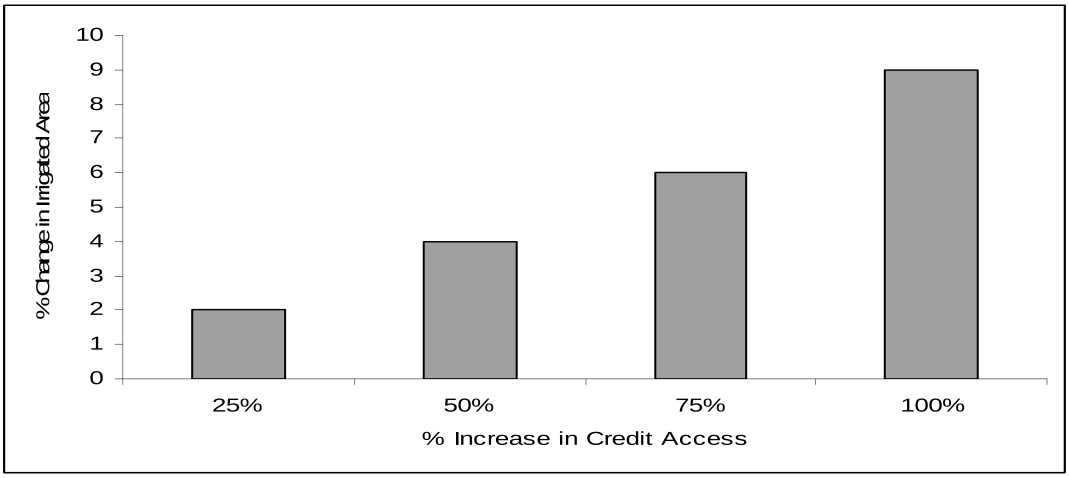
Irrigation management

Irrigation management has two major components, namely management of the scheme as a business entity and irrigation water management.

The business managerial function is the overall direction and coordination of the decision-making process which usually involves monitoring those factors which influence the irrigation system performance, namely resources (i.e. finance, manpower and equipment), skills (i.e. technical, management and communication know-how) and the motivation of staff (i.e. salaries, bonuses, material and non-material incentives, promotions, job satisfaction and recognition of exceptional contributions by individuals). This function is generally performed by Ghana Irrigation Development Authorithy (GIDA), but as a government agency with limited budget and staffing, it is not able to maintain adequate technical expertise in all departments of irrigation and so cannot ensure higher productivity on projects. Political interference and lack of timely release of project funds are serious constraints.

The adoption of appropriate water management policies will lead to substantially increased crop production with regards to yield, which on the average is higher than under rainfed conditions. This includes water distribution (i.e. system operation), systems maintenance and irrigation extension. Simple moisture sensing and flow measuring devices to give an indication of how much and when water is required, so as to improve on irrigation efficiency, are usually lacking. Proper land preparation needed to ensure efficient water management to enhance even water flow is usually not well done. Therefore the problem of low or high spots affecting water distribution is a common feature. There is high wastage leading to problems such as rise of water table, water logging, leaching of nutrients, erosion, as well as water-borne and water-related diseases.

Figure 5. Impact of credit access on irrigation by commercial farmers [Source: Dessalegn 2005]



Dessalegn (2006) highlighted the importance of access to credit in increasing the area cultivated under irrigation (Table 5). This emphasizes the fact that farmers are willing to expand the irrigated area if the necessary resources are provided.

A key production constraint that came out of the focus groups discussions held with dry season pump irrigation farmers in five communities in the Upper East Region is the high cost of pumps and accessories (Agyare *et al*. (2008). However, the issue of access to credit, pests and diseases, fertilizer and agrochemicals cost and fuel are equally important. Other constraints such as the lack of fences to keep livestock out of the fields, the undulating nature of the land, maintenance problems, and theft were of lower importance.

Conclusions and recommendations

What is very Important for achieving agricultural industrialization in Ghana is not only focusing all efforts on expanding the area under irrigation but also improving on the water productivity or yield per unit water use of existing structures and future irrigation schemes to an appreciable level. Also, there is the need to support farmers with adequate credit facilities to enable them expand their farm sizes and use the necessary inputs to increase productivity. The choice of irrigation option must take into consideration social and economic factors as well. However the key factors that must be considered are profitability, efficiency and sustainable use of the schemes. Whether the choice is for dams, underground abstraction or river pumping it must be based on these criteria.

Acknowledgement

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Fertilizer microdosing for the prosperity of resource poor farmers : a success story

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Abstract

Fertilizer microdosing is the application of tiny doses of fertilizers in the planting hole at sowing, or next to the plant two to three weeks after planting. The technology increases fertilizer use efficiency and yield while minimizing the cost of inputs. The results reported here show that solving the soil fertility problem unleashes the yield potential of improved crop varieties, roughly doubling yield. Two crucial advantages of microdosing are its adoptability and profitability. High rates of fertilizer have been recommended to farmers for a long time to maximize yields, but farmers could not afford to do so. By using much lower rates of fertilizer than the recommended rate, in more efficient ways that deliver economically optimum returns, farmers are much more able and inclined to adopt the practice, and are increasingly doing so. Once fertilizer microdosing is adopted, it establishes a pattern for future productivity as farmers become accustomed to increasing their investments in inputs in order to generate increased returns. Microdosing is thus a strategic first step on a sustainable development pathway, in addition to generating large benefits itself. The microdosing technology has been demonstrated and promoted in Burkina Faso, Mali and Niger during the past few years with very encouraging results. Sorghum and millet yields increased by 45 to 120 % in comparison with farmer practice while farmers' incomes went up by 50 to 130 %. This paper highlights these outstanding past results and the on-going efforts to further scale-up the technology.

Key words

Fertilizer microdosing, West Africa, capacity building, net gains, productivity

Introduction

Poverty and food insecurity continue to create suffering across the semi-arid Sudano-Sahelian zone of West Africa. Unpredictable droughts cause food shortages for both humans and the livestock on which they depend. The predominantly sandy soils in this zone are of very low fertility, particularly in phosphorus (P) and nitrogen (N), with P being more limiting to crop growth and yield than N (Bationo et al. 1998a, b). It was reported that crop response to nitrogen was minimal when crop phosphorous requirements were not met (Traore 1974).

Sivakumar (1992) reported that the limited arable land in the Sudano-Sahelian zone is gradually decreasing due to the southward creep of the 400 mm isohyet as a consequence of land degradation, drought and other human activities. In addition, the high population growth rate (3.4% per annum) and resultant increasing population density have put a lot of pressure on the cultivated lands, which leads to a significant decrease, and disappearance in some cases, of fallow lands. Because of this, farmers are increasingly being forced to cultivate marginal and degraded lands where moisture and nutrient stress significantly constrain crop yields, and which also results in further land degradation. Stoorvogel and Smaling (1990) reported that because of these problems, increases in crop production have resulted more from the expansion of the cultivated area than from increased crop yield.

It is widely believed that the only real cure for hunger in the West African Sahel is the intensification of agriculture and in increased productivity of the arable land through the use of external inputs, mainly inorganic fertilizers (Van Keulen and Breman 1990; Breman 1990). Soil fertility enhancement technologies have been developed over the years for the main staple food crops in West Africa, such as sorghum and millet. However, these technologies have not been adopted by resource-poor farmers due to the high cost and unavailability of the inputs. Consequently, yields of the major staple food crops such as sorghum and millet have continued to decrease.

To address these constraints and increase the productivity of these major staple food crops, various national and international research institutions working in the Sahel joined forces and developed an effective technique to increase fertilizer use efficiency and reduce investment costs for resource-poor small scale farmers (Bationo et al., 1998a, b; Buerkert and Hiernaux, 1998). This resulted in the development of the fertilizer microdosing technology, which involves the application of small doses of fertilizer in the hill of the target grain crop at planting rather than broadcasting it all over the field. The amount applied is typically 60 to 80% of the recommended rates for maximum yield. Microdosing is affordable to the poor because of the reduced investment cost, and it results in more rapid early growth, thus avoiding early season drought, and an earlier finish, avoiding or reducing the impact of end-of season drought while increasing crop yields (Tabo et al. 2006, Tabo et al. 2007). A vigorous plant with a large root system is able to exploit moisture at greater depth later in the season when soil moisture at the surface of the soil is low.

This paper reports the results of on-farm evaluation trials and demonstrations of the microdosing technology in three countries in West Africa, Burkina Faso, Mali and Niger.

Materials and Methods

Demonstrations and on-farm trials involving microdosing technology were conducted in Burkina Faso, Mali and Niger between 1998 and 2004. These field experiments were designed by researchers but were managed by the farmers, with training and technical backstopping from extension agents, NGOs, and scientists. Experimental plots and types of fertilizers used varied across the study sites depending on the local conditions and the availability of inputs.

On-farm field experiments

The on-farm field experiments consisted of three adjacent plots per farmer, each plot measuring approximately 300 m^2. Three treatments were compared in Mali: (1) farmers' practice, using their normal sowing method (often broadcast), and fertilizer practice (usually none), (2) the recommended fertilizer application (about 100 kg NPK (15:15:15) per ha broadcast before sowing), and (3) fertilizer microdosing at 4 to 6 g per hill of NPK (15:15:15) (40 to 60 kg NPK per ha), or 2 grams of diammonium phosphate (DAP) per hill (20 kg DAP per ha), or 2 g of DAP (20 kg DAP per ha) at sowing + 1 g of urea (10 kg urea per ha) at thinning, 3 to 4 weeks after sowing. Farmers were asked to plant the fields when they felt that soil moisture was adequate for germination of the seeds. There were usually two farmers who applied the microdosing technique, with one person digging the hole and the second placing the measured quantity of fertilizer and seeds into the planting hole and closing it. Weeding was done at least twice during the cropping season. Thinning to 3 plants per hill was done two to three weeks after sowing. Harvesting was done by farmers in each plot under the supervision of field technicians, who collected the yield data. The panicles were weighed and then threshed for grain yield measurement.

In Burkina Faso and Niger, only treatments 1 and 3 were compared. In Niger the test crops used were millet and sorghum. Plant density under farmer conditions ranged from 5,000 to 6,000 hills per ha while plant density in the microdose plots ranged from 10,000 to 20,000 hills per ha.

In Burkina Faso, 30 villages and 210 farmers in the Central North Zone were involved in these studies from 2002-2004. In Mali the on-farm trials were carried out in 44 villages in the region of Mopti, Segou, Koulikoro, Mande and Beledougou, with 321 farmers, in 2002 and 2003. In Niger, approximately 1,536 demonstrations and field experiments were established in 254 villages in five departments in southern Niger, namely Tillabery, Dosso, Tahoua, Maradi and Zinder, from 1998-2004.

Economic assessment

In addition to the field trials, an economic evaluation was carried out to assess the performance of fertilizer microdosing. Net gain was calculated as the difference between the revenues from the grain using the prevailing price at harvest each year and the total cost of fertilizer as:

$$NG = R - C$$

where, NG = net gain; R = revenue from sale of grains; and C = cost of fertilizer

Net gain was expressed in FCFA (Franc Communauté Financière Africaine) per ha. The cost of labour was not included as the data were collected from plots that are not large enough and the data were not reliable. The value of the straw (used for animal feed) was not included in the revenue.

Capacity building activities

Field technicians, extension agents and farmers in all the three participating countries were trained in the laying out of the demonstration plots and in applying fertilizer microdosing. This included demonstrations in the field of how to measure the recommended amount of fertilizer per plant (microdose), how to apply it correctly, and how to manage the field after sowing. Emphasis was also put on the best way of collecting agronomic as well as economic data from the trials set up.

Results

Burkina Faso

Grain yields

Throughout the study period (2002 to 2004), average yields with microdosing were higher than yields of the farmers' traditional practice. The yield advantage of microdosing for millet ranged from 44 % in 2002 to 75 % in 2003, while sorghum grain yield increase with microdosing ranged from 47 % in 2002 to 82 % in 2003 (Figures 1 and 2).

Figure 1. Millet grain yield (kg ha^{-1}) [Control, Micro-dose (MD), Recommended Rates (RR), and Zai] Burkina Faso, 2002 and 2003; Vertical bars are standard errors of means

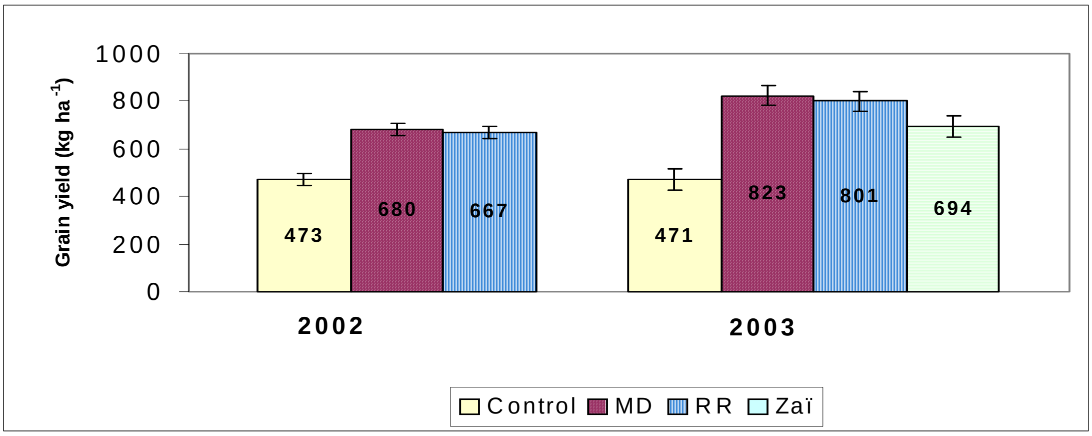
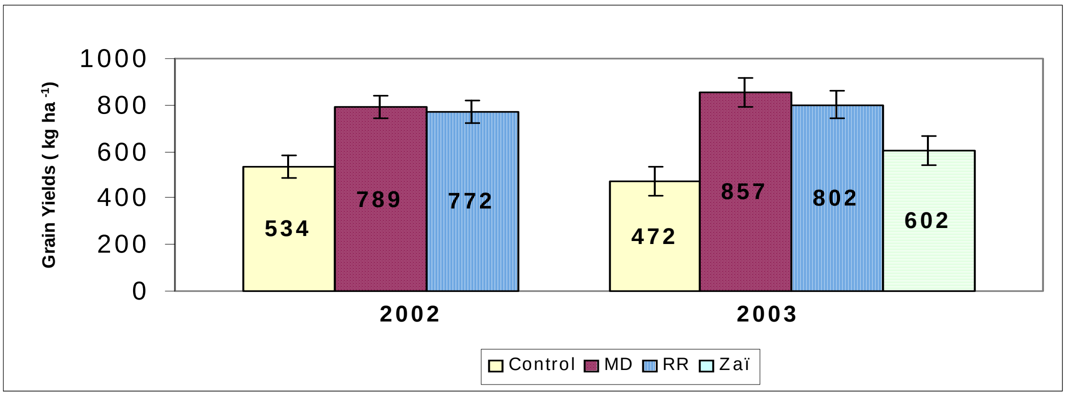


Figure 2. Sorghum grain yield (kg ha^{-1}) [Control, Micro-dose (MD), Recommended Rates (RR), and Zai], Burkina Faso, 2002 and 2003. Vertical bars are standard errors of means



Net gains from microdosing

Farmers obtained net returns from their millet with microdosing that were three times higher than the revenue with the recommended rate with fertilizer broadcast (12575 FCFA ha^{-1} as compared to 5175 FCFA ha^{-1}). The net gains for sorghum were approximately 2.5 times higher with microdosing (22780 FCFA ha^{-1} vs. 9255 FCFA ha^{-1})

Mali

Grain yields

Sorghum and millet performed better with microdosing than with the recommended practice and farmers' practice. Average millet and sorghum grain yields with microdosing were 61-90 % and 69-107 % higher, respectively than the control (Figures 3 and 4).

Figure 3. Millet Grain Yields (kg ha^{-1}) for Demonstration Trials [Farmers' practice (control), microdosing (MD), and recommended rates (RR)] in Mali, 2002 and 2003. Vertical bars are standard errors of mean

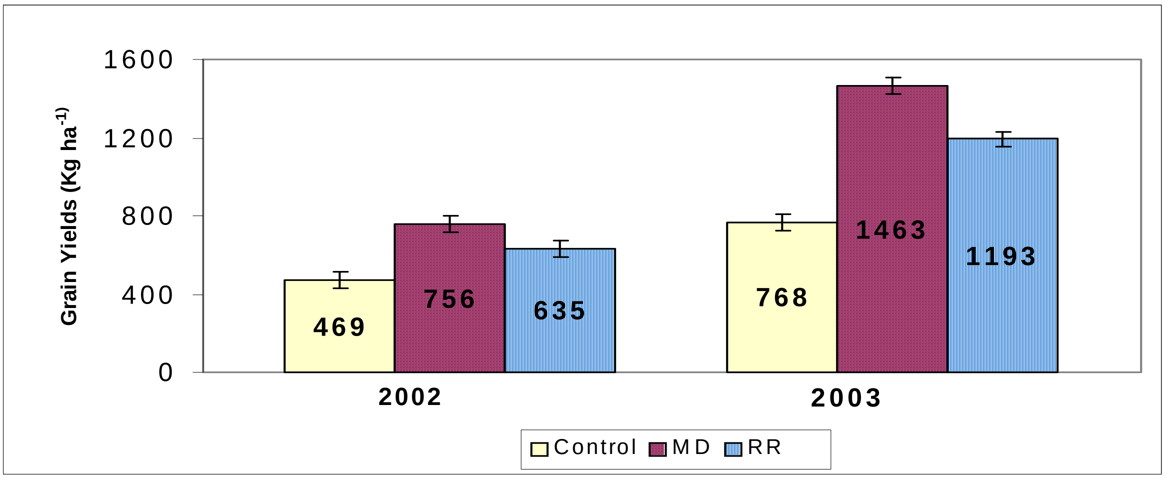
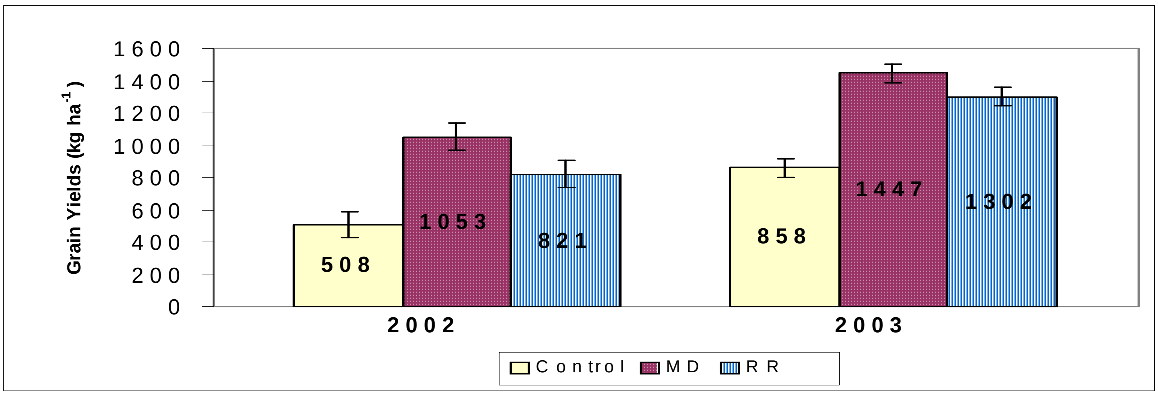


Figure 4. Sorghum Grain Yields (kg ha^{-1}) for Demonstration Trials [Farmers' practice (control), microdosing (MD), and recommended rates (RR)] in Mali, 2002 and 2003. Vertical bars are standard errors of means.



Net gains from microdosing

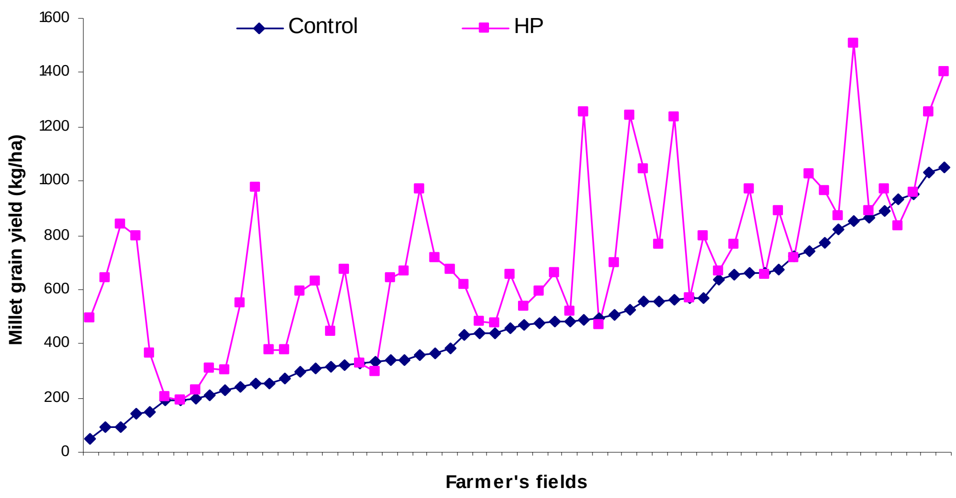
Millet under microdosing gave net monetary gains of 119690 FCFA (US$200.00) ha^{-1} which were 68 % higher than the net returns from the traditional practice with 71167 FCFA (US$119) ha $^{-1}$ and 33 % higher than the net gain from the recommended practice (89959 FCFA ha^{-1} = US$150)

Niger

Grain yields

In all the 58 fields, over 3 seasons, microdosing resulted in similar or higher (by up to 89%) grain yield compared to farmers' practice (Figure 5). The yield increase with microdosing averaged 44% or about 300 kg ha^{-1}, and in approximately half (44%) of the fields yields were at least doubled.

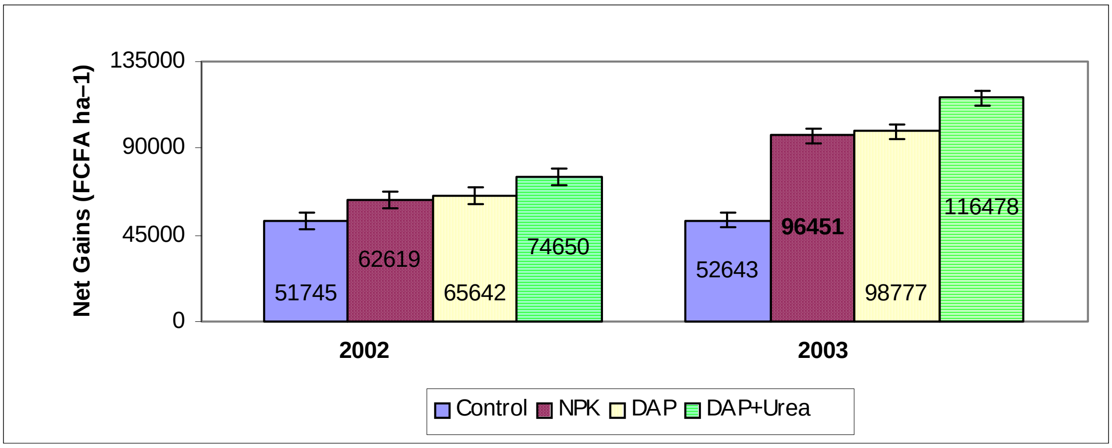
Figure 5. Pearl millet grain response (kg ha^{-1}) to microdosing (hill placed – HP) compared with farmers' practice (control) in 58 fields in Niger, 1998-2000.



Net returns from microdosing

In 2002, net returns were 74650 FCFA (US$124) per ha for DAP + Urea, 65642 FCFA (US$109) per ha for DAP, 62619 FCFA (US$104) per ha for NPK and 51745 FCFA (US$86) per ha for farmers' practice (Figure 6). Net profits were, on average, 44 % and 121 % higher with microdosing than with farmers practice in 2002 and 2003, respectively.

Figure 6. Net gains (FCA ha^{-1}) from millet grown under fertilizer microdosing and farmers' practice, Niger 2000 and 2003. Vertical bars are standard errors of means.



Discussion

The results show that fertilizer microdosing has great potential to improve crop yields and profitability, in a range of environments and rainfall situations. Overall grain yield increases using microdosing were double the yields obtained from the farmers traditional practice. The technology offers the resource poor small scale farmers a good opportunity to reduce risks to investment under the unpredictable environment of the semi-arid tropics while it enables a significant increase in crop yield. Because of the low rates of fertilizers used, farmers can reduce greatly their costs of production. As farmers see the benefits obtained from these small quantities of fertilizer, they are more willing to invest in fertilizers and increase fertilizer use. The fertilizer microdosing technology is therefore an entry point for increased use of fertilizers in farmers fields, which can lead to sustainable development.

As with any promising technology there is a need to build the capacity of various stakeholders including extension agents, NGOs and researchers to enhance the dissemination of the technique as well as ensuring the sustainability of the systems. Demonstrations and farmers field schools approach have proven to be an effective means for the promotion of this technology.

An issue that requires further investigation is the possibility of soil mining arising from using the fertilizer microdosing technology. As grain yields increase and very little organic matter (OM), including crop residues, are returned into the soil there is the likelihood that nutrient imbalances will develop with time. There is therefore a need to ensure that organic matter is added and incorporated into these soils to improve their structure so that their capacity to store adequate moisture and nutrients even after crops are harvested is enhanced.

Conclusions and recommendations

Our results suggest that fertilizer microdosing has the potential to greatly increase yields across a range of agro-ecological zones in West Africa, from the drier Sahelian zone to the wet Sudano-Guinean environment. Overall, millet and sorghum grain yields were 50 to 120 % higher with microdosing than with the earlier recommended fertilizer broadcasting rates and farmers' traditional practices. This simple technology is affordable to resource poor small scale farmers in the semi-arid tropics as it enables them to reduce the risk to investments and increase crop yields. As this technology requires two people to implement, there is a need to further look into various strategies to reduce labor input, such as the use of mechanical seeders and fertilizer application equipment.

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Institutional innovation: the potential of the warrantage system to underpin the green revolution in Africa

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Abstract

The warrantage or inventory credit system was developed to address the liquidity constraints that farmers encounter while trying to intensify their production systems. The scheme removes barriers to the adoption of soil fertility restoration technologies by ensuring that farmers have access to cash, technical advice, and inputs. Farmers use the credit to purchase external inputs, such as fertilizers and seeds, and to invest in dry season income-generating activities, such as fattening of small ruminants, vegetable growing, trading, and groundnut oil extraction. In an earlier study funded by USAID, it was found that the incomes of farmers using the warrantage system, along with use of the fertilizer microdosing technology increased by 52 to 134 %. In a project funded by the Challenge Program on Water and Food (CPWF), farmers are responding positively to the implementation of warrantage in two communities in the villages of Ziga and Saala in Burkina Faso. This scheme is getting increasing support from donors for its wider promotion in Sub-Saharan Africa. The constraints to the development and implementation of warrantage include lack of capital for Decentralized Financial Systems (DFS) to grant loans and for supervising bodies to provide guarantees, government interference through dumping imported commodities onto the market, lack of infrastructure at the village level, and lack of well-organized farmer associations. An analysis of the constraints to the implementation of the scheme as well as the factors underlining the promotion and use of the warrantage system are also discussed.

Key words

farmer organizations, markets, credit, net benefits, inputs, crops

Introduction

Countries in the West Africa semi-arid tropics (WASAT) are among those designated by the United Nations as the least developed countries in the World on the basis of low national income, weak human assets and high economic vulnerability. The majority of the inhabitants of these countries live and work in rural areas and depend on agriculture for their livelihoods. The fast growing human population in these Sahelian countries is placing enormous demands on the food production systems. Given that more than 90% of the food consumed in the WASAT comes from local production, the economic and physical well-being of poor people in these countries will depend on stabilizing and increasing agricultural productivity through more effective and efficient practices and technologies. Growth in agricultural productivity is critical because it means more food and higher incomes, and thus improved ability to purchase food and other basic necessities, for the many food-insecure, poor people who earn their livelihoods through agricultural production. Growth in agricultural productivity also translates into increased food supplies and lower food prices for consumers. However, increased in agricultural productivity must be achieved and sustained without jeopardizing the productive capacity of the natural resource base

In these semi-arid regions of sub-Saharan Africa, agricultural productivity is low and stagnating due to low and erratic rainfall and the long term decline in soil fertility, compounded by limited use of inputs (such as fertilizer and seeds of improved varieties). Socio-economic factors like lack of access to credit and inputs are major constraints to the use of inputs. Crop yields and net returns to inputs can be significantly increased through the adoption of improved technologies, and especially through the use of fertilizers in a more efficient manner (i.e. fertilizer microdosing, Tabo *et al*., 2009), and through improved soil-water-crop-nutrient management techniques and improved high yielding varieties (Fosu et al. 2008; Sawadogo et al., 2008; Twomlow et al., 2009) . However, liquidity constraints often prevent farmers from intensifying their production systems, and it is clear that credit systems are needed to help remove barriers to the use of fertilizer and improved seeds.

The warrantage or inventory credit system has been practised in Asia for many years, but was recently introduced in the Sudano-Sahelian region of West Africa. Farmers in the region are aware of the benefits of fertilizers, but they usually cannot afford them. Thus, recognizing the widespread low crop productivity in the region as a result of the slow adoption rate of improved soil management technologies, the Food and Agriculture Organization (FAO) in collaboration with ICRISAT and other partners initiated the “warrantage” system to solve farmers’ liquidity constraints.

The warrantage system allows farmers and producer organizations to mortgage their cereals at harvest time to secure a loan in order to meet their daily needs and to carry out income-generating activities during the off-season, without selling their grains into a glutted market at a lower price. These cereal grains and grains of other crops are kept in a clean store with a double lock - representatives of the Farmers Organization and the Decentralized Financial Systems (DFS), which are the village level credit and savings schemes, each place a padlock on the doors thus ensuring that both partners are present and agreeable to open the doors. The products are sold by farmers 6 to 7 months later when the supply of grain declines in the market and prices are higher. The establishment of this credit scheme allows households to smooth their consumption patterns, thus reducing the risk of food shortage. The credit system is being popularized with the assistance of farmers’ organizations, FAO, some commercial banks, NGOs and donors.

The warrantage system can be used as a link between credit, cereal grain markets, and input markets, and can help remove the inaffordability barrier to the adoption of fertilizers and other inputs. To make inputs accessible to farmers, farmer-based business enterprises and cooperative organizations are developed, storage facilities and input shops (boutique d' intrants) are built, and credit and savings schemes are established. These facilities are managed by members of the cooperatives**.** Linking farmers to input or product markets, and the vertical integration between these, are believed to be prerequisites to the uptake of agricultural technologies. Efforts to develop institutional arrangements likely to improve the linkages of rural households to major markets are often major development challenges.

The issue of potential surplus in the Sahel and Sudanian zones of West Africa is also important. In most years, since farmers need cash, a glut of grain goes on the market at harvest time, causing prices to collapse. It is important to manage the surplus by storing it and dispersing it to the market in a gradual and orderly way, including perhaps through the expansion of national and regional emergency grain reserves.

This paper reviews the findings of studies that were conducted in West Africa with financial support from USAID and the Challenge Program on Water and Food (CPWF) (Tabo et al. 2005; Tabo et al. 2007). The USAID funded project on microdosing and the warrantage system was implemented in Burkina Faso, Mali and Niger from 2002 to 2004 while the CPWF funded project was executed in Burkina Faso and Ghana from 2004 to 2009. In the paper we also review the socio-economic, political and cultural conditions under which this system works, identify gaps in understanding that need to be filled to help the implementation of the system, and suggest mechanisms for promoting the adoption of the scheme by resource poor farmers in Sub-Saharan Africa.

Methods

USAID Target project on microdosing and warrantage

The warrantage system was evaluated in Burkina Faso, Mali and Niger from 2002 to 2004, during which approximately 60 farmer organizations were involved in the study, with a total credit of 73. 6 million FCFA (Franc Communauté Financière Africaine) or about US$150 000 from the DFS.

The Farmer Organizations (FOs) stored their excess production in their warrantage stores. The excess grains were used to guarantee the cash loans that the farmers took from the Savings and Credit Scheme (CREP) /bank/micro credit system. The credit was for short duration (maximum of 6 months) and was intended only for carrying out income generating activities. The amount of credit which could be granted to the producer was equal to 75% of the value of the stock which he/she put into the store. The remaining 25% was the guarantee for the risks. The interest rate was 15%. At the end of the loan period, in agreement with the farmer, the store keeper sold the entire or part of his stock to pay the capital and the interest of the loan. This sale was done through the organization of a cereal sale or through contracts signed with cereal traders, processors, etc. At the same time, for the storage period, the farmer paid overhead charges to the co-operative. The additional value of the stock above the loan, loan interest and overhead charges was paid to the farmer.

Burkina Faso

The warrantage credit system was initiated in 2003 in Burkina Faso with only 8 farmer organizations in the targeted areas. Some villages were already receiving financial assistance from the DFS, that were affiliated to the NGOs operating in the villages, to undertake income-generating activities. In 2004, 176 farmers in the targeted areas participated in the micro-credit program (Table 1).

Table 1. Warrantage credit system in Burkina Faso, March 2004.

	Zone Centre	Zone Nord			Total
	Malgrétenga	**Kaïn**	**Thiou**	**Oula**	
Product Stocked (kg)					
Sorghum	1,000	1,400	1,600	400	4,400
Millet	2,600	4,300	200	50	7,150
Rice	100	0	2,500	250	2,850
Maize	700	0	0	0	700
Cowpea	900	1,900	1,200	450	4,450
Gorundnuts	2,400	4,284	3,200	10,700	20,584
Sesame	0	0	100	0	100
Voandzou	100	50	0	0	150
Bissap	400	0	0	0	400
Graines d'oseille	0	0	0	250	250
Total farmers	30	44	35	67	176
Loan: Amount Requested (FCFA)	700,000	700,000	749,000	724,000	2,873,000
Loan: Amount Granted (FCFA)	0	700,000	749,000	0	1,449,000

Mali

In Mali, the farmers in the targeted areas benefited from the credit system established with the help of several NGOs including Sasakawa Global 2000 (SG2000), ADAF/Galle, and Winrock International that funded the savings and credit services during the 2002-2003 and 2003-2004 cropping seasons. Producers placed large quantities of millet, sorghum, and rice paddy (54.3 tons in 2002-2003) in stock, and were granted 5.429 million FCFA (US$ 10911) in 2002-2003 and 16.351 million FCFA (US$ 32700) in 2003-2004 (Tables 2 and 3). The farmers were charged a loan fee of about 2.5% of the loaned amount.

Table 2. Warrantage credit system in Mali, 2002-2003

NGO Partners	Villages	Products Stocked	Quantity Stocked (kg)	Value of Stock at Storage (Nov/Dec 2002) (FCFA x 1000)*	Value of Stock 6-7 Months after Storage in 2003 (FCFA x 1000)**	Management Fees (FCFA x 1000)***	Net Benefits (FCFA x 1000)****
SG2000	Kondogola	Millet	4,000	400	600	4	196
	Niamabougou	Millet/ Sorghum	28,500	2,850	4,275	13.2	1,412
	Sélinkégny	Maize/ Millet	3,800	380	570		190
	Tioribougou	Sorghum	4,000	400	600	10.5	190
ADAF/ Gallé	Kénioroba	Millet/ Sorghum	6,885	689	1,033		344
Winrock International	Tissala	Millet/ Sorghum	6,200	620	930	46.5	264
	Sofara	Sorghum	902	90	135		45
TOTAL	7 villages		54,287	5,429	8,143	74	2,640

*Value of stock (FCFA) at storage = Price of 1 kg of grains (100 FCFA) x quantity of grains (kg)
**Value of stock (FCFA) 6 to 7 months after storage = Price of 1 kg of grains (150 FCFA) x quantity of grains (kg)
***Management fees (FCFA) = fees paid by the producers to keep their products in the store (maintenance, cleaning)
****Net benefits (FCFA) = value of stock 6 to 7 months after storage (FCFA) – value of stock at storage (FCFA)– management fees (FCFA)

Table 3. Warrantage credit system in Mali, 2003-2004

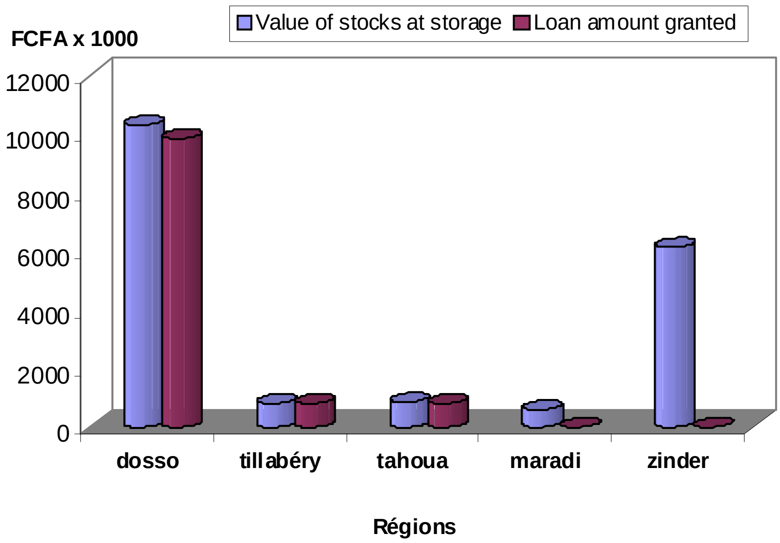
NGO Partners	Products Stocked	Value of Stock at Storage (Nov/Dec) (FCFA x 1000)*	Value of Stock 6-7 Months after Storage (FCFA x 1000)**	Management Fees (FCFA x 1000)***	Net Benefits (FCFA x 1000)****
SG2000	Millet Sorghum Maize Rice Paddy	6,629	8,339	326	1,385
ADAF/ Gallé	Millet Sorghum	2,850	3,135		285
Winrock International	Millet Sorghum Rice Paddy	6,873	7,979	96	1,010
TOTAL		16,351	19,453	422	2,680

*Value of stock (FCFA) at storage = Price of 1 kg of grains (100 FCFA) x quantity of grains (kg)
**Value of stock (FCFA) 6 to 7 months after storage = Price of 1 kg of grains (150 FCFA) x quantity of grains (kg)
***Management fees (FCFA) = fees paid by the producers to keep their products in the store (maintenance, cleaning)
****Net benefits (FCFA) = value of stock 6 to 7 months after storage (FCFA) – value of stock at storage (FCFA)– management fees (FCFA) of stock at storage (FCFA)– Management fees (FCFA)

Niger

In Niger, 40 farmer associations were involved in the warrantage credit scheme in 2003-2004 compared to 23 in 2002-2003. In 2002-2003, the DFS financed about 34.1 million FCFA (US$ 68,150), or approximately 93 % of the value of the stored grains under the warrantage system. Income generating activities that were pursued by farmers using this credit included groundnut oil extraction, vegetable gardening, sheep fattening, small trade, etc. In 2003-2004, the local DFS was able to raise 11.5 million FCFA (US$ 23,000) for the warrantage activities in the targeted areas (Figure 1). However, these funds were not sufficient to meet the demands of the producers at the opportune time. The acuity of the problem was particularly severe in the regions of Zinder and Maradi, where no financing was available. Farmers from regions that received some credit undertook various income-generating activities (i.e., small trade) and purchased inputs.

Figure 1. Warrantage credit system in Niger, 2003-2004



Challenge Program on Water and Food (CPWF) – PN 5 Volta Basin

Burkina Faso

The warrantage system was tested in Saala and Ziga villages using Participatory Learning and Action (PLA) methods in 2005 and 2006. Participatory Rural Appraisal (PRA) and a literature review were undertaken to determine the farmers' capacity to carry out this activity. Sensitization sessions with the target public and training sessions were organized so as to develop a Memorandum of Understanding (MOU) with partners in each village. The sensitization sessions were undertaken through meetings with the target groups, financial institutions, development partners, NGOs and project manager groups. The training curriculum included a description of the warrantage credit system, its functionality and how it should be monitored, identification of income generating activities, and market management and organization.

Results

USAID Target project on microdosing and warrantage

Burkina Faso

Producers, for the most part, stored millet, sorghum, and groundnuts. Because of the lack of cash from the DFS during the year, out of the 2.873 million FCFA (US$ 5,774) loan amount requested, farmers were granted only 1. 4 million FCFA (US$ 2,900), or about 49 percent of the amount asked (Table 1). Furthermore, only farmers in the north zone of the country were granted credit, as requests for credit in the center and middle-center zones were denied due to lack of liquidity in the banks. The lack of credit in those areas was a great impediment to the conduct of income-generating activities during the dry season. This situation did not, however, eliminate the advantages of the warrantage system since farmers got higher prices for the stored products later in the season when the supply of grains had decreased in the market. The profit margins could have been higher if the farmers had been able to obtain cash loans and engage in dry season income generating activities. The lesson to be drawn from this situation is that efforts should be made to link the DFS with commercial banks that could make cash available to the village banks, thereby enabling the farmers' organizations to provide cash loans to the farmers against their stored products.

The amount of the loan depends on the liquidity in the banks. However, even without receiving a loan farmers can store their products and make profits later when prices go up. The lack of a loan is mainly an impediment for the conduct of income generating activities.

Mali

The net benefits obtained by farmers' associations from the sales of their products 6 to 7 months after storage were about 2.64 million (US$ 5,305) in 2002-2003 and 2.68 million FCFA (US$ 5,360) in 2003-2004 (Tables 2 and 3). The farmer associations involved in warrantage activities used the credit to undertake income-generating activities (i.e., steaming and trading of rice, sheep fattening, small business, groundnut oil extraction, etc.). The farmers also used the profits realized under the warranting schemes to purchase fertilizer and seeds of improved varieties for the next cropping season.

Niger

Figure 1 shows an example of the variation in how the system functioned in different regions in Niger during 2003/2004. In some regions such as Dosso and Tillabery the system performed well as the farmers were given the equivalent amount of cash loan against their warranted products. This was an indication that the DFS had enough liquidity because of a good linkage to the commercial banks and their own savings and credit systems. These two regions are closer to the capital city of Niamey, where there are large commercial banks that provide loans to the DFS, than the other regions in the study. Because of the close proximity with the villages where the warrantage systems are operating, the representatives of the commercial banks are able to visit the warrantage infrastructure and determine their credibility. These visits offer an opportunity to the banks to have more confidence in the warrantage system. In addition, the presence of several projects funded by GTZ, FAO and the European Fund for Development near these two regions provided an opportunity for training and financial support to the DFS. Due to this enabling environment, farmers organizations were able to have better access to credit and also to save more money in the banks. In contrast, the warrantage system did not work well in Maradi and Zinder where there was not enough cash in the DFS to give cash to the farmers for their stored grains. These two regions are farther away from the capital city of Niamey and do not have much contact with the large commercial banks. In such cases, efforts are needed to link the DFS to commercial banks to ensure that funds are available for loans to the farmers who are willing to place their products as collateral and get some credit to enable them meet their daily needs and undertake income generating activities.

Challenge Program on Water and Food (CPWF) – PN 5 Volta Basin

Burkina Faso

Participatory Rural Appraisal (PRA) studies conducted in 2005 in Burkina Faso enabled us to characterize the 2 project sites (Saala and Ziga) in terms of socio-economic status including infrastructure, internal and external relationships between farmer organizations, and development partners (public, private and NGOs). Infrastructure included the farmers' capacity for product storage to secure the warranted products. In each village, warehouses that can contain up to 30 tons of products were identified. Overall, partnerships between the various stakeholders were poorly developed due to lack of consultation and lack of financial means to meet and engage in common activities. The project had to develop a Memorandum of Understanding (MOU) between the decentralized financial institution, namely the "Direction Régionale des Caisses Populaires", farmers' organizations and the Project 5 (PN 5) in each village. The protocols described in detail the role of each partner in the warrantage system as well as the conditions for farmers to access credit and to repay the loans.

Table 4 shows the quantities of warranted products in 2005-2006 (year 1) and 2006-2007 (year 2). There was a higher number of product types stored in Saala compared to Ziga because of greater diversification of the cropping systems in Saala which had higher annual rainfall and better soil fertility than Ziga. In the second year (2006-2007), the quantity of products used in the warrantage system increased by 34% in Ziga and 493% in Saala as there was increasing interest of farmers in the warrantage system following their experiences with it in the first year (2005-2006). Farmers saw the merits of storing their harvest safely until prices go up before selling them.

Table 4. Nature and quantity (kg) of products in 2005-2006 (year 1) and 2006-2007 (year 2) for warrantage

Village	Year	White Sorghum	Red Sorghum	Millet	Maize	Rice	Groundnut	Cowpea	Soybean	Sesame	Total	Rate of Increase in Total Quantity
Ziga	1	1,312	-	-	-	-	5,600	656	-	-	7,569	
	2	2,112	-	96	-	-	6,776	1,168	-	-	10,154	34
Total		*3,424*	-	*96*	-	-	*12,376*	*1,824*	-	-	*17,720*	
Saala	1	-	256	-	944	30	-	64	-	-	1,295	
	2	-	384	-	3,296	2,340	1,260	272	32	96	7,682	493
Total		-	*640*	-	*4,240*	*2,370*	*1,260*	*336*	*32*	*96*	*8,974*	

Capacity Building

Under the USAID TARGET project, a training workshop on the warrantage credit scheme was held from 9 to 10 October 2002, in Kamboinsé, Burkina Faso, at the Agricultural

Environmental Formation and Research Center (CREAF) of INERA. Eighteen (18) participants from several institutions including ICRISAT, Projet Intrants FAO, INERA, Federation Nationale des Groupements Naam (FNGN), Association pour le Développement de la region de Kaya (ADRK) and Hunger project took part in this workshop. The objectives of the workshop were to acquaint the partners in Burkina Faso with the warrantage credit system, to draw from the experiences of Nigerien farmers with the system, and to assess the feasibility of starting the credit system in some villages of Burkina Faso. The participants interacted to define the action plan and the framework within which the USAID TARGET Project was to launch the warrantage credit system in Burkina Faso. The participants also visited the demonstration of fertilizer microdosing trials in the Kaya and Malgrentega regions, and interacted with farmers in these regions.

Under CPWF PN 5, approximately 100 farmers were trained in the various aspects of credit and market management in 2005-2006. This resulted in the capability of the farmers to make informed decisions and to better manage the credit and income generation activities. Each village formed its own management committee comprising a credit manager, a stock manager and a warehouseman/store keeper.

Discussion

There is general agreement in the agricultural research, policy and development community that enhancing farmers' access to more efficient and equitable markets is a crucial pathway out of widespread poverty in sub-Saharan Africa. Ndjeunga and Bantilan (2005) concluded from their case studies in Mali and Burkina Faso that farmers who are close to markets are likely to apply more fertilizer to derive more surplus for sales. They further stated that farmers located in environments with better access to the main roads are more likely to invest in fertilizer because they incur less transport cost in bringing their products or purchasing inputs and other consumption goods from the markets. They recommended that policy makers should foster investment in road infrastructure to reduce transport or transaction costs and provide an enabling environment for the development of input and product markets. Successful agricultural development, and in fact any rural development strategy, must target and address the challenges (such as poor access to both input and output markets) that the millions of small farmers face. The number of poor living on small farms in Sub-Saharan Africa continues to increase at an alarming rate along with a reduction in average farm size and degradation in land quality, posing a daunting challenge to research and development efforts in the region. Research and development are particularly essential if the strategy of introducing improved technologies that increase smallholder farmer productivity is to lead to better farmers' income, family health and improved well-being for those rural populations. Wider uptake of improved agricultural technologies is often inhibited by lack of inputs, finance (credit and loan) and output markets, important pre-conditions for effective input demand and to increase in surplus production by farmers.

Potential of warrantage to help enhance adoption of improved technologies

Linking farmers to inputs like fertilizer and seeds and product markets, as well as effective coordination and integration of these two markets, are important prerequisites for the adoption of agricultural technologies. Although in these case studies, data have not been collected or fully analyzed to demonstrate the link between warrantage and the adoption of new and improved technologies, we hypothesize that as farmers have better access to credit, inputs and markets through the warrantage system, they are more likely to increase their investments in intensifying their production systems and to take additional risks in trying improved technologies. As more functional warrantage systems are established in the villages and as the DFS become better linked to larger commercial banks which can provide some with needed capital, future efforts will focus on studying and strengthening the connection between the warrantage system and the adoption of improved technologies.

Constraints, lessons learnt and solutions

Some of the major constraints to the development of warrantage systems include: i) the lack of sufficient capital for the DFS to grant loans and for supervising bodies to provide guarantees; ii) interference of the government through the dumping of imported commodity onto the market; iii) lack of storage infrastructure at the village level, and iv) the lack of well-organized of farmer associations (Table 5).

These constraints can be addressed through: i) support to the DFS to source funds with commercial banks and to negotiate good interest rates; for example, in Niger the Credit Rural du Niger (CRN) and la Banque Regionale de Solidarite (BRS) help to identify banks and advise and assist in linking the DFS to commercial banks; ii) sensitization of people to mobilize savings; iii) negotiation with the DFS to value stocks of products; iv) diversification of products to be stored; v) sourcing information to anticipate the de-stocking of products; vi) negotiation with government for the purchase of products covered by the warrantage system; vii) establishment of secondary warehouses in new villages; viii) sensitization of farmers' organizations to the construction of warehouses; ix) seeking support from other projects providing assistance for the establishment of community infrastructure; x) training of farmers organizations in warehouse management; xi) training of farmers organizations in management bodies and their roles, and xii) training of farmers organizations in the keeping of management documents (Table 5).

Key interventions that will drive change

The key interventions that will lead to adoption of improved technology and reduction of poverty include the following:

(i) Institutional changes: The warrantage or inventory credit system is critical to enhance farmers' access to inputs at reasonable and affordable prices and to offer them the opportunity to sell their outputs at good prices. Key ingredients of the institutional changes needed include: input-output market development and efficient coordination to ensure access to credit and availability of inputs; establishment of linkages between farmers' organizations and DFS. The provision of small packs of fertilizers (1, 2, 5, and 10 kg) in input shops provides the opportunity for small poor farmers to be able to afford to start using fertilizers (Simpungwe et al., 2008). This is first step towards the intensification of production through increased use of fertilizers (Tabo *et al*. 2009).

Government policy is also critical for viable farmer input-output market linkages that would enhance returns to investment in integrated soil fertility management. According to Doss (2003), institutional factors, such as the policy environment, also affect the availability of inputs and markets for credit and outputs and, thus, the profitability of a technology. Ajayi et al. (2003) note that adoption of soil fertility management options cannot happen in a policy vacuum. The promotion of high-value agricultural enterprises is one policy direction that is likely to generate increased income and investment in integrated soil fertility management (Place et al. 2003).

(ii) Capacity building: to foster the emergence of farmer-leaders and agro-dealers, strengthen credit systems, train managers of DFS, train extensionists and farmers in crop technologies and warrantage, build capacity to supply fertilizers, diversify fertilizer supply sources (input shops) and build capacity of farmer organizations.

(iii) Provision of infrastructure: Construction and renovation of roads to facilitate movement of goods and inputs such as fertilizers; construction of - stores for keeping grains and inputs under safe conditions, workshops for construction and repairs of farm equipment; mechanization of farm operations to reduce labor costs and improve efficiency; establishment of input shops to keep fertilizers, seeds, chemicals and other inputs that will be accessible to farmers at the right times and at affordable prices; establishment of micro-finance institutions to make credit available to poor smallholder farmers; establishment of a good communication infrastructure that will deliver market information to producers.

Table 5. Summary of constraints to the implementation of the warrantage system and possible solutions

Constraints	Solutions
Lack of capital - for Decentralized Financial Systems (DFS) to grant loans - for supervising bodies to provide guarantees	- Support DFS to source funds with commercial banks and to negotiate good interest rates - Sensitize people to mobilize savings - Negotiate with DFS to value stocks of agricultural products (depreciation of the value of the product)
Interference of the government through the dumping of imported commodities onto the local market	- Diversification of products to be stored - Seek information to anticipate the de-stocking of products - Negotiate with the government for the purchase of products covered by the warrantage system
Lack of infrastructure at village level	- Establishment of secondary warehouses in new villages. - Sensitize Farmers Organizations to the construction of warehouses - Seek support from other projects providing assistance for the establishment of community infrastructure
Lack of well-organized farmers' organizations	- Training of FOs in warehouse management. - Training of FOs in management bodies and their roles. - Training of FOs in the keeping of management documents.

Conclusions and recommendations

The warrantage or inventory credit system has shown its potential in enhancing farmers' access to credit and cash, inputs and output market. This scheme is gaining increasing support from donors for its wider promotion in Sub-Saharan Africa. Constraints to the development and implementation of warrantage systems include the lack of capital for the decentralized financial systems (DFS) to grant loans and for supervising bodies to provide guarantees, the interference of the government through the dumping of imported commodities onto the market, the lack of infrastructure at the village level, and the lack of well-organized farmers' associations. These constraints should be taken into account when promoting the scheme. Five major priorities for intervention to facilitate adoption of the warrantage system are: (1) Capacity building (of farmers, farmers' associations, and other service providers) for effective production, marketing and decision-making; (2) Creating innovative production and marketing ventures and strengthening market information systems; (3) Identification and mitigation of policy constraints, and creation of incentives; (4) Dissemination and promotion to farmers and farmers associations; and (5) Monitoring and evaluation of the performance and impacts. In the future, efforts are needed to study and demonstrate the link between the warrantage system and the adoption of improved technologies.

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Agricultural technology adoption successes and failures in Ghana and Kenya

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Abstract

Technology involves the application of science and knowledge to manipulate the environment to the benefit of humans, ideally without prejudice to sustainability or harm to any stakeholder. While many technologies have been introduced to Sub-Saharan African farmers, the adoption rate of the majority of these technologies has been minimal and with only modest successes. Using the model of Exploratory Literature Review, this study examined case studies of technology transfer and the problems associated with their adoption by small-scale, resource poor farmers in Ghana and Kenya. Technologies selected for the synthesis cover issues essential to improvements in productivity and poverty alleviation. Data used for the studies came mainly from on-farm sources and thereby introduce readers to actual on-farm situations. On-farm data sources included PRA, questionnaires and experimental procedures, which were analyzed using statistical procedures, empirical logistic correlation. The data included estimates of technology performance, profitability and rates of adoption. The purpose of the review was to highlight specific factors that contribute to technology adoption or non adoption by small-scale producers in Sub-Saharan Africa. The results indicate the generally cooperative attitude of farmers in adopting technologies, but also show that the causes of non-adoption result from both farmer and non-farmer sources. The review shows that many of the causes of non adoption could be avoided through appropriately designed and executed strategies that fit the needs of farmers, their circumstances and their diversity.

Key words

Sub-Saharan Africa; technology transfer; resource poor farmers; poverty alleviation; non adoption.

Introduction

About 60 – 85% of the rural populations of Sub-Saharan Africa engage in agriculture as a means of livelihood. However agricultural productivity, especially in the food sector, is low and at subsistence levels. The situation results in severe poverty and stagnant rural economies, low labor productivity and under-employment. According to John W. Mellor (1966) "a dynamic contribution to economic development from the agricultural sector and significant improvement in rural welfare depend upon the modernization of agriculture through technological change". Recent experiences in countries like Malaysia, India, Thailand and Vietnam also suggest that the adoption of improved technologies in agriculture is one of several necessary conditions for the development and modernization of rural economies. Technology improvement is the process by which humans modify nature to meet their needs and wants. It involves the application of science, knowledge and tools to manipulate the environment for the benefit of humans, ideally without damaging the environment.

Two types of technologies have been identified. The first consist of hard technologies which are science based and improve the technical coefficients of production and processing. Hard technologies impact on technical relationships (input/output). These technologies can have faster pay-offs to the producer or processor by reducing cost per unit, thereby reducing the amount of inputs for the same level of output, or by increasing output for the same level of inputs. Returns on these types of investment, which normally occur over the short term, could be high if well adopted. The second type, known as soft technologies, involves changes in market or other environmental requirements and result in improvements in productivity. Examples are changing demand in food quality, food safety, product certification, product traceability as in beef and milk for instance, market information (pricing efficiency), forward contracting agreements, business skills, and access to credit. The returns on investment for many of these technologies may be harder to measure and take a longer time to materialize than for the hard technologies.

Even though several technologies of both types have been introduced to farmers in developing countries, the adoption rate of the majority of these technologies have been minimal and most often unproductive or short lived. This paper highlights some experiences of technology transfers to small-scale resource poor farmers in Ghana and Kenya using case studies. The purpose of the review is to acquaint readers with work on some technology developments in agriculture, the dispersion procedures used, and the extent of adoption and causes of non adoption. Such information can assist decision makers in selecting technologies for promotion, and methods for achieving higher adoption and productivity.

Methodology

The methodology for the review was adopted from Taylor (1998) in her paper "Efforts to Help the Small-Scale, Resource Poor Farmer in International Agricultural Development". Using the model of Exploratory Literature Review, she highlighted important issues essential to improving in small-scale farm productivity. Likewise, this paper reviews the evaluation of efforts made to introduce agricultural technologies to resource poor farmers, their successes and failures as well as the constraints hindering their adoption.

The review covered six cases of technology promotion, summarizing each promotion by focusing on the title, objectives, methodology, results and the main conclusions (Table 1).

The review covered the following studies:

1. Adoption and Impacts of Improved Maize Production Technology: A case Study of the Ghana Grains Development Project
2. Technology Adoption by Small-Scale Farmers in Ghana
3. Learning About a New Technology: Pineapples in Ghana.
4. Bridging Knowledge Gaps between Soils Research and Dissemination in Ghana
5. Ensuring Better Technology Transfer in Less Developed Countries: Indigenous Mud Silo Promotion in Northern Ghana
6. Economic Analysis of Non-Conventional Fertilizers in Vihiga District, Western Kenya.

1 **Table 1: Synthesis of Technology Evaluations.**

Title	Objectives	Successes and causes of non adoption
Adoption And Impacts of Improved Maize production Technology: A case Study of the Ghana Grains Development Project.	▪ To evaluate the success of the Ghana Grains Development Project (GGDP) in developing improved maize production technologies and transferring the technologies to farmers; ▪ To assess the impact of the technologies at the farm level; and ▪ To draw lessons from the GGDP that may be useful in the design and implementation of similar future projects.	The results show that GGDP succeeded in meeting its primary objectives of raising productivity, increasing incomes, and improving nutrition for resource-poor households in the country. However, the characteristics of the technology, the farming environment into which the technology is introduced, the circumstances of the farmer making the adoption decision and the effective extension service, efficient inputs distribution system and appropriate economic incentives have been found to be capable of militating against the long-term adoption of the technologies.
Technology Adoption by Small-Scale Farmers in Ghana	▪ A review the aims and strategies pursued by rural-development projects, such as NORRIP, in their attempt to diffuse improved technology among the peasants of the Mamprusi area; ▪ Conduction of preliminary survey of the area's farming community to outline the factors relevant to the adoption of technologies in this district; ▪ Conduction of formal and quantitative surveys to test hypotheses suggested by the preliminary survey, and ▪ To suggest to decision-makers ways to facilitate the adoption of technology by rural farmers.	The results show that essential ingredients are normally missing in technological packages introduced to small-scale farmers. For instance while prices of fertilizes are too high, the situation is compounded by the untimeliness and inadequacy of its supply and difficulties in its accessibility since depots are normally few and far from many farming areas. Secondly the large number of NGOs controlling technology dissemination with different strategies, negative competition, and ineffective government supervision creates confusion and makes technology adoption more evasive for farmers.
Learning About a New Technology: Pineapples in Ghana	To test whether farmers adjust their inputs to align with those of their information neighbors who were surprisingly successful in previous periods.	Social information was found to flow through information networks, conditional on physical, economic and demographic factors including common growing conditions, credit arrangements, clan membership, gender, wealth, family ties and religion. The results indicate that a farmer is willing to increases his dosage of fertilizer after someone with whom he shares information achieves higher than expected profits with more fertilizer than he used and decreases his dosage when the reverse occurs.

Title	Objectives	Successes and causes of non adoption
Bridging Knowledge Gaps Between Soils Research And Dissemination In Ghana	▪ To explore the reasons for low adoption of outputs from soils research in Ghana; ▪ To develop effective dissemination strategies; and ▪ To suggest ways to bridge a perceived knowledge gap between soils research, dissemination and adoption.	The results indicated that low use of inorganic fertilizer could be caused by unfavourable Value -Cost Ratios as well as a limited effectiveness of the research and extension system in the development and dissemination of soil fertility management technologies. The study also revealed a lack of traditional management of the soil in the use of animal manure and leguminous crops.
Ensuring Better Technology Transfer In Less Developed Countries: Indigenous Mud Silo Promotion In Northern Ghana	▪ To identify the weaknesses and strengths of the promotion process; ▪ To examine the opportunities offered and the challenges of the new storage structure to beneficiaries; and ▪ To identify the experiences of the technology transfer, which may serve as guidance for future promotional campaigns.	Although the new technology offered numerous advantages and was highly demanded by beneficiaries, the study revealed serious violations of baseline study recommendations during the promotion and this led to quality control limitations and a setback to the long-term adoption of the technology.
Economic Analysis Of Non-Conventional Fertilizers in Vihiga District, Western Kenya.	▪ To carry out an economic analysis of some non-conventional fertilizers	Though the technology was acceptable, farmers complained about the lack of seeds of the recommended agroforestry shrubs. Increasing availability of the seeds through production for use by farmers can improve the adoption rate of the profitable technologies and enhance food production in the study area ((Kenya) and related areas in Sub-Saharan Africa.

Adoption and impacts of improved maize production technology: a case study of the Ghana Grains Development Project

This case study was one of a series of adoption evaluations coordinated by the Impact Assessment and Evaluation Group (IAEG) of the Consultative Group of International Agricultural Research (CGIAR). It examined the adoption of improved maize production technologies developed by the Ghana Grains Development Project (GGDP), a subsidiary of the Crops Research Institute (CRI), which operated from 1979 to 1997 (Michael et al. 1997).

The study sought to achieve the following objectives:

1. To evaluate the success of the GGDP in developing improved maize production technologies and transferring the technologies to farmers.
2. To assess the impacts of the technologies at the farm level.

Three of the most important technologies studied were:

1. Improved maize varieties (germplasm)
2. Fertilizer recommendations
3. Plant configuration recommendations

Data on the adoption of these technologies were collected through a nationwide survey of maize farmers. A sample of 420 farmers was drawn for interview by a three-stage clustered, randomized procedure. Questions centered on maize production, consumption and marketing practices, preferences for maize varietal characteristics, knowledge and access to inputs such as seeds and fertilizers. Analytical procedures consisted mainly of statistical inferences including the estimation of percentages, frequencies and standard deviations.

The results of this study indicated that the GGDP adopted an extremely effective research strategy. By extensively testing experimental technologies at the farm level, researchers were able to foster the active participation of farmers in the technology development process; this helped ensure that the recommendations developed through the project were appropriate for farmers' circumstances. The GGDP was able to link its research component with an effective extension strategy. During the technology development phase, considerable efforts were made to familiarize extension officers with the technologies by involving them in on-farm testing activities. Once farmer recommendations had been formulated, the same extension officers played a key role in implementing a national program of demonstration trials that served to widely publicize the technologies.

However, the following prevailing key factors affected adoption of the technologies.

- Characteristics of the technology, including the complexity of the technology, and its profitability, riskiness, divisibility and compatibility with other technologies or practices.
- Characteristics of the farming environment into which the technology is introduced, including agro-climatic conditions, the nature of prevailing cropping systems, the degree of commercialization of the cropping enterprise, factor availabilities, farmers' knowledge and access to technical information, availability of physical inputs.
- Characteristics of the farmer making the adoption decision, such as the farmers' personal circumstances, including ethnicity and culture, wealth, education, gender, and security of access to land.
- Institutional and policy factors, including the existence of: effective extension services, efficient inputs distribution systems, and appropriate economic incentives which could enable a technology to make a meaningful impact at the farm level.

Technology Adoption by Small-Scale Farmers in Ghana

This study focused on technology adoption by small-scale farmers in the Mamprusi area of the Northern Region of Ghana. The central hypothesis was that the strategies used for diffusion of improved technology to small-scale farmers in the north have been inadequate or inappropriate and that this is why the aims of development agencies have not been realized in this region (Owusu-Baah 1995).

The objectives of the study included the following:

1. a review of the aims and strategies pursued by rural-development projects, such as the Northern Region Improvement Project (NORRIP), in their attempts to diffuse improved technology among the peasants of the Mamprusi area;
2. conduct of a preliminary survey of the area's farming community to outline the factors relevant to the adoption of technologies in this district;
3. conduct of formal and quantitative surveys to test hypotheses suggested by the preliminary survey;
4. suggestions for decision-makers of ways to facilitate the adoption of technology by rural farmers.

After a preliminary survey of official and farm sources, detailed interviews were conducted with a sample of 69 randomly selected farmers to obtain information on farm households and farming practices and to identify some of the constraints to increased food production.

Results indicated that essential ingredients are missing in technological packages introduced to small-scale farmers. For instance, while prices of fertilizes are too high, the situation is compounded by untimely and inadequate supply and poor accessibility since fertilizer depots are normally few and far from many farming areas. Other problems include the multitude of NGOs controlling technology dissemination and competing with each other with little government supervision.

The study recommendations included:

- The Government of Ghana should take control of agricultural-technology policies and play a leading role in achieving their objectives.
- NORRIP should be restructured to coordinate the activities of the development agencies and eliminate duplication in their work.
- The development agencies should come up with strategies to advance loans in the form of cash or agricultural inputs to farmers.
- Canals and dams should be built to conserve excess water from the heavy rains since modern technologies cannot rely on rains only.
- The development agencies operating in the Mamprusi area should take advantage of the government's new policy on fertilizer imports to import their own fertilizers and other agricultural inputs for farmers in their catchment areas.
- Ministry of Food and Agriculture should team up with the development agencies to solve the marketing and storage problems of producers.

Learning about a new technology: pineapples in Ghana.

This study investigated the role of social learning in the diffusion of new agricultural technologies in Ghana (Conley et al. 2004). The role of social learning in promoting growth and technology diffusion has been featured in the endogenous growth literature (Romer 1986;

Lucas 1988; Aghion and Hewitt 1998). Social learning is also an integral part of current practice in agricultural research and extension systems in developing countries. New technologies are introduced either by farmers' own experimentation or through formal sector intervention and the process of social learning encourages their diffusion (Bindlish and Evenson 1997; Rogers 1995).

Data for the study were drawn from a two-year survey (1996-98) of approximately 240 households in southern Ghana. The sample was constructed in two stages. The process began with the purposive selection of four 'villages' near the towns of Nsawam and Aburi, the center of the recent growth of intensive vegetable cultivation in the Eastern Region. The second stage was a random sample of married individuals: 60 couples (or triples when there are two wives) were chosen by a simple random sample in each village. Two enumerators lived in or near each village and interviewed each respondent in 15 rounds at intervals of approximately six weeks.

Data on farmers' communication patterns were used to define each individual's information neighborhood and the set of others from whom he/she might learn. A basic form of the model used states that farmers are trying to learn about the responsiveness of output $y_{i,t+1}$ on plot (*i*) to a discrete-valued input $x_{i,t}$ which is fertilizer (Equation 1)

$$y_{i,t+1} = w_{i,t} f(w_{i,t}) + e_{i,t+1} \qquad (1)$$

where,

$e_{i,t+1}$ is an expectation zero productivity shock across farmers and at time $t+1$;

$w_{i,t}$ is a positive, exogenous growing conditions variable influencing the marginal product of $w_{i,t}$ that is correlated across farmers at time t.

Empirical logistic correlation is applied to test whether farmers adjust their inputs to align with those of their neighbors with whom they share information.

The results indicated that farmers adopt unusually successful neighbors' practices, conditional on physical, economic and demographic factors including common growing conditions, credit arrangements, clan membership, gender, wealth, family ties and religion. The relationship of these input adjustments to farmers' experiences further supports their interpretation as resulting from social learning. Although no evidence of learning was found when the methodology was applied to a known maize-cassava technology, indicating strong traditional experience in these crops, social learning was found to play a significant role in the cultivation decisions of pineapple, a relatively new enterprise requiring the use of fertilizers and perhaps chemicals. Looking at the magnitude of innovations in fertilizer use, results indicate that a farmer is willing to increase his dosage of fertilizer after someone with whom he shares information achieves higher than expected profits with more fertilizer than he used, and decreases his dosage when the reverse occurs.

Bridging knowledge gaps between soils research and dissemination in Ghana

Since the 1980s the problem of soil degradation in Ghana has been on the ascendancy. Apart from international climatic factors like CO_2 emissions and associated erratic rainfall patterns which are beyond our control, a myriad of local causal factors have been blamed. Some of these are bushfires which deplete the land of humus accumulation, especially in the northern sector, the shortening of the fallow period, and population pressure with associated fragmentation of land and migration. The resulting manifestations are declining food production per capita and poverty. The future livelihoods of farmers continue to be threatened and effective dissemination of soil management technologies, many of which have been developed and used, is therefore crucial to help reverse the situation.

Although soil fertility improvement technologies have been successful in increasing long-term yields, becoming widely adopted in some areas where farmers are investing in soil fertility in response to increasing rural population density, the uptake of soils research outputs has mostly been low in Ghana. It had also been established that technically proficient and participatory research does not necessarily produce appropriate outputs, and that dissemination of research outputs in packages, rather than as targeted advice in terms of agro-ecological concepts already known to farmers, may impede uptake and adaptation (Thorne et al. 1999). Innovations where outputs of soils research were presented as decision trees had began to address this (Palm et al. 1997), and the need for gender specific dissemination of soils research outputs in Africa had also been demonstrated (Gladwin et al. 1997). The collaborating target institutions (FORIG, MOFA and IITA) have expressed the need for a methodology for disseminating soils research outputs which could be used by international research centers, and by local and international NGOs working directly with farmers throughout West Africa. A *Soil Management Action Plan for Ghana had* already been produced (Bonsu et al. 1996), as well as a *National Soil Fertility Management Action Plan* (MOFA 1998) which recognized the low inherent fertility of soils in Ghana and the low uptake of soils technologies. It sets out a diverse range of projects (recommendations) aimed at improving soil fertility management in Ghana.

The study sought to achieve the following objectives :

1. to explore the reasons for low adoption of outputs from soils research in Ghana;
2. to develop effective dissemination strategies; and
3. to suggest ways to bridge a perceived knowledge gap between soils research, dissemination and adoption.

The project was therefore aimed at addressing the identified fact that technically feasible outputs from participatory soil fertility research have not enjoyed high adoption rates (NRSP Workshop in Reading 1997 and ICAR Workshop Bhopal 1998).

The research started with an initial in-country workshop followed by a review of available information on soil fertility research outputs (Fergus et al. 2001).

The analysis involved use of statistical inferences, evaluation matrices, generation and flows of knowledge and the development of a methodological framework and tools for soil fertility research and dissemination strategies.

The results indicated general reasons for low adoption of techniques to improve soil fertility and crop yield in Ghana which were already well understood and recognized by government. They included the high price of inorganic fertilizer, lack of availability of organic material, and a low level of dissemination activity within the context of a relatively low level of investment in soils research. There is need to undertake effective soils research and dissemination to overcome these constraints. A more essential constraint is the absence of an effective means of focusing research and dissemination on farmers with different circumstances. The available soil fertility technologies were found to be suitable for only a fraction of rural farmers, predominantly those male farmers producing high value cash crops, while technologies directly relevant to women farmers and other marginalized groups were not in place. This mismatch between the technology options being made available and the circumstances of poorer farmers in the forest savanna transition zones of the country were due to (i) lack of understanding of the different sets of constraints and opportunities faced by rural farmers, and (ii) absence of an effective means to focus research and extension activities on farmers' circumstances.

In line with the terms of reference, a framework and tool kits were designed to increase the relevance of soils research and dissemination. The tools which are used within the framework comprise of:

- a set of knowledge bases including farmers' understanding of soil fertility in five contrasting locations in Ghana and comprehensive knowledge from a range of sources about cover crop technology;
- a diagrammatic livelihood description tool for disaggregating rural households in terms of common constraints and opportunities relating to adoption of soil fertility interventions; and
- a technology choice tool for matching interventions to rural livelihoods.

Options were provided for wide application of the vital aspects of the framework and tools, with appropriate national and local adaptation. Where there is limited market development, few opportunities exist for profitability, and with poor access to highly priced inorganic fertilizers the process of agricultural intensification can become blocked since marketing issues are highly significant to the profitability of different food crops in the country. In some areas market inaccessibility is a problem, whereas in others seasonally low prices or markets flooded by crops (glut) reduce profitability. Improvements in post-harvest storage technology, agricultural credit and farmers' ability to manage cash flow in conjunction with the adoption of improved soils technologies could contribute to more profitable farming. Strategies to improve soil fertility management should not therefore focus on soils technologies alone. Another aspect of technology development and adoption failure is that international and national scientific knowledge is not fully utilized during the development of technologies, and that there is insufficient documentation within the National Agricultural Research Services (NARS) about research activities (Moss 2001). Nor is there adequate information about the livelihoods of rural people for researchers to draw upon, even at the district level. Indications are that the socio-economic and national policy environment is not sufficiently taken into account in the design of research and dissemination activities.

Moreover, research results do not always reach farmers due to poor functioning of the extension services. Both the research and extension systems over-rely on external sources of funding for maintaining activities (MOFA 2001). This approach commonly leads to a breakdown in services when sources of funding are finished and are not sustainable.

Ensuring better technology transfer in less developed countries: indigenous mud silo promotion in Northern Ghana

This study evaluated the adoption of a modified traditional high grade mud silo storage technology horizontally transferred to districts where farmers had been using a low grade type that is easily attacked by termites and rodents (Bediako et al. 2005). The initial promotion campaign on the merits of the technology had been very successful in view of the frequent storage loses farmers endure with their traditional inferior structures. The transfer process started with a baseline study in Gushegu/Karaga, the beneficiary district. The use of a bottom-up approach was recommended to ensure community participation in decisions specific to beneficiaries including choice of villages in view of local material availability for construction and maintenance (Stevenson 1999). Farmers were to be informed to procure and prepare local construction materials well in advance of constructions as artisans moved from village to village. Some farmers in each community were to be trained during the construction to ensure sustainability of the new technology.

The impact assessment, three years after the installation of the storage structures, had the following objectives:

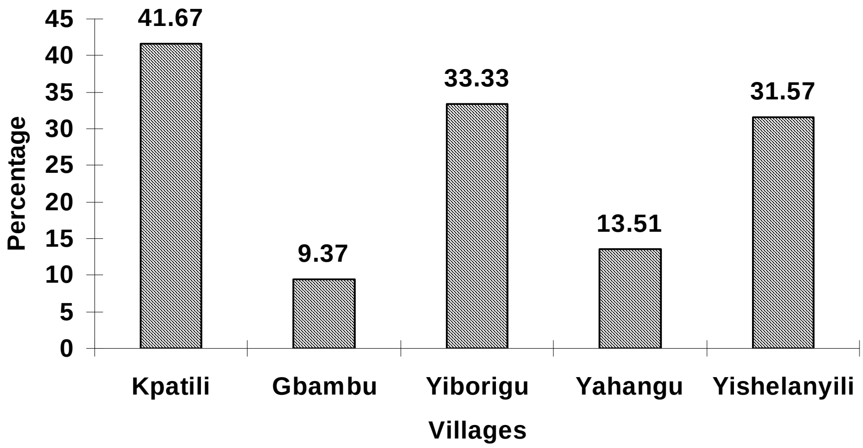
1. to identify the weaknesses and strengths of the promotion process;
2. to determine the opportunities offered and the challenges of the new storage structures to beneficiaries; and
3. to examine the experiences of the technology transfer, which may serve as guidance for future promotional campaigns.

The methods used consisted mainly of Participatory Rural Appraisals (PRA) procedures with limited questionnaire administration and analysis by statistical inferences and matrices. Results of the study indicated that violations of the baseline study recommendations lead to quality control limitations and a setback to the long-term adoption of the technology. In an attempt to satisfy the unprecedented high demand and huge rush for the technology, the following errors resulted.

- The know-how, skills and experiences of many of the appointed builders were inadequate, while in many villages 'alternative' building materials were used in place of those recommended leading to the provision of weak structures with wrong designs.
- The payment of the artisans was on a 'piece-work' basis, (i.e. payment on number constructed) which led to undue haste and shoddy workmanship.
- The scale of the promotion within the stipulated period, which had itself induced considerable demand by farmers, prevented adequate supervision of the artisans.
- The recommendation to train community members for future construction and repair works were overlooked.

Thus, in spite of its usefulness to farmers and the highly positive response for its adoption, the high rate of breakage (Fig. 1) deterred continued interest in the technology.

Figure 1. Percentage of collapsing mud silos in villages



Economic analysis of non-conventional fertilizers in Vihiga District, Western Kenya

The socio-economic situation of farmers in the study area are similar to those in many other Sub-Saharan African countries where most farmers are faced with the problem of low income, high population pressure, small land size, and low availability and therefore high cost of labor. In addition, the present economic policy of liberalized markets due to globalization has led to the prices of conventional fertilizers and other farm inputs like hired animal traction and tractor services to rise faster than farm produce prices which are controlled by seasonal local demand forces with only a marginal external demand. Consequently, the adoption of any soil fertility technology option is rationally subject to farmers' perceptions of its economic benefits and limitations. The importance of such requirements makes this study of particular significance for small-scale farmer technology adoption.

The overall objective of the study was to carry out an economic analysis of some non-conventional fertilizer materials (agroforestry shrubs) used to improve food production in Vihiga district in Kenya (Kipsat et al. 2001). The results of the study, however, have a wide range of implications for technology adoption in Sub-Saharan Africa.

The primary data source was a random sample of 150 farmers selected from three of the six divisions of Vihiga district with official source secondary data. Gross-margins and cost to benefit ratios were used as the main tools in data analysis.

The primary results confirmed the supremacy of conventional fertilizers over non-conventional organic counterparts by their higher levels of productivity for both maize and beans. However, results obtained for phosphate rock (PR) fortified organic fertilizers, like fortified *Crotalaria*, fortified compost, fortified farmyard manure and others (Table 2) show significant increases in yield for both crops compared to organic fertilizers without fortification with PR, and compared to the control (or no application of any type of fertilizer) as practiced by some farmers.

Table 2. Yield Increases with Use of Fortified Organic Materials in Vihiga District

Soil Fertility Management Technology	Increase in grain yield over the control (%)	
	Maize	Beans
Zero fertilizers added (control)	0	0
Use of *Tithonia diversifolia* alone	72	65
Use of fortified farmyard manure	109	82
Use of fortified Compost manure	117	80
Use of fortified *Tephrosia vogelii*	124	85.5
Use of fortified *Tithonia diversifolia*	134	93.7
Use of fortified *Crotalaria grahamiana*	157	112

Source: *Economic Analysis of Non-Conventional Fertilizers in Vihiga District, Western Kenya* (Kipsat et al. 2001)

Based on crop yield responses, fortified *Crotalaria* was the best of the organic matter technologies in improving yields of both maize and beans in Vihiga by on average 157 and 112 % respectively, followed by fortified *Tithonia* by 134, and 93.7 % respectively. The results suggest that PR fortified organic materials are capable of serving as alternatives to inorganic materials in crop production in the study area as well areas with similar conditions.

However, the use of organic materials is labor intensive and leads to significant increases in cost where labor is limited, as in areas suffering from rural-urban migration in Sub-Saharan Africa. Economic analysis indicated that there are indeed significant profitability differences between the non-conventional fertilizers, and that the use of fortified *Crotalaria* and *Tephrosia* on maize and bean production gave the best profitability in relation to the other non-conventional fertilizers considered (Table 3).

Table 3. Results of Economic Evaluations of Organic Matter Technologies

Soil Fertility Management Technologies	Net Present Value NPV ha^{-1} in (Ksh ha^{-1})	Benefit to Cost Ratio	Rank
Fortified Crotalaria	33568	1.27:1	1
Fortified Tephrosia	13746	1.13:1	2
Fortified Tithonia	11045	1.08:1	3
Fortified Compost Manure	6020	1.05:1	4
Fortified Farmyard Manure	4592	1.04:1	5
Tithonia alone	-2130	0.87:1	6
No Fertilizer (control)	-11719	0.61:1	7

Source: Source: *Economic Analysis of Non-Conventional Fertilizers in Vihiga District, Western Kenya* (Kipsat et al. 2001)

Although fortified *Tithonia* gave higher crop yield than fortified *Tephrosia*, the net value was lower (Table 3) due to high labor demands and thus high cost. Fortified farmyard and compost manures had relatively low crop yields plus high labor costs, lowering the returns to their use. The Net Present Value) of using unfortified *Tithonia* and production under conditions of no fertilizers are negative. This means that farmers who produce under these two systems are incurring losses in maize and bean production and should be advised to find alternative use of the invested labor, land and capital. These two technologies resulted in very low Benefit Cost Ratios (<1) while the rest of the soil fertility management technologies under consideration had favorable BCR values. The results show that farmers can achieve positive returns by using the other non-conventional fertilizer technologies, whichever is more convenient to her/him in maize-bean production, although the relative returns vary from technology to technology. Through participatory studies, farmers, scientists and agricultural extension agents should consider profitability differences in the choice of technologies to promote in Vihiga district and in areas of similar soil and environmental conditions in Sub-Saharan Africa. Based on complaints about the lack of seeds of agroforestry shrubs, increasing availability of the seeds to farmers can improve the adoption rate of the profitable technologies and enhance food production in the study area and related areas.

Conclusion

Even though farmers' cooperation in adopting technologies is essential, the causes of technology non-adoption in Sub-Sahara Africa result from both farmer and non-farmer sources. The study reveals non adoption causes originating from the technology promoters themselves, and that many of these causes could be avoided through properly designed and executed strategies that fit the needs of farmers, their circumstances and their diversity.

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