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DEVELOPING IMPROVED DRYLAND CROPPING SYSTEMS FOR MAIZE IN SEMI-ARID TANZANIA. PART II. USE OF A MODEL TO EXTRAPOLATE AND ADD VALUE TO EXPERIMENTAL RESULTS

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SUMMARY

Dryland agriculture is critically important to food security and rural livelihoods in Tanzania, but crop production is seriously constrained throughout the semi-arid lowlands by the rainfall regime. A major challenge is to develop improved cropping systems to alleviate the moisture constraint. Experimental evidence indicates that adoption of rainwater harvesting systems can bring benefits, but the restricted spatial and temporal extent of the experimental work leads to difficulties in extrapolation. This paper shows how the PARCHED-THIRST model can add value to the experimental results and provide important insights into their transferability. The model is seen as an aid to researchers, planners and extensionists in interpreting experimental results and designing locally appropriate interventions. Simulation based on 30 years of daily meteorological data provides an opportunity for temporal extrapolation. The long-term simulation allows an objective assessment of the risks and benefits associated with alternative rainwater harvesting systems. Simulation for different soils and modified rainfall regimes permits objective analysis of spatial transferability of experimental results to any other site for which rainwater harvesting interventions might be considered. It is shown that macrocatchment rainwater harvesting reduces drought risk within the target area, but may bring a serious risk of erosion due to excessively high flow rates. The overall assessment of the twin-track approach (experimentation + simulation) is that rainwater harvesting has potential for increasing productivity and sustainability of maize cropping systems in semi-arid Tanzania provided that the innovations are properly matched to the site-specific environmental conditions.

INTRODUCTION

In the extensive semi-arid lands of Tanzania, agriculture and the livelihoods that depend thereon, are greatly affected by the unreliable and highly variable rainfall regime. Any attempt to improve agriculture must therefore tackle the moisture constraint. However, knowledge of appropriate techniques is poor. A significant knowledge gap exists between two practices that previously have received great attention. On one hand, widespread concern about land degradation has led to a focus on soil erosion control. On the other hand, efforts to exploit water resources have led to a focus on irrigation.

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Between these two extremes, the middle ground of rainwater harvesting (RWH) has been largely neglected, despite it offering the prospect of sustainable intensification for dryland farmers (Gowing *et al*., 1999). The challenge is to identify and disseminate appropriate technologies that will reduce their vulnerability to drought. Agricultural support services are required, therefore, to identify useful innovations and to make them available to farmers at locations where they are likely to succeed. Both traditional and participatory approaches generally involve time-consuming and costly experimental work to arrive at the technology options that are most likely to work. Because of the resources involved, these experiments are undertaken at a restricted number of locations over limited periods. Extrapolation of the results and their interpretation in the context of farmer-first approaches is a problem.

Spatial extrapolation problem

The traditional approach assumed that technologies that performed well in researcher-managed experiments would also do well on farmers' fields. This ignored differences such as altitude, climate and soils. Research stations in sub-Saharan Africa are often situated in particularly favourable locations not representative of the majority of surrounding farmland. The delineation of agro-ecological zones (AEZ) within which the agricultural environment could be considered relatively homogeneous (FAO, 1978), was one attempt to tackle the problems of spatial extrapolation. More recently, it has been recognized that this approach fails to reflect the social and economic differences that influence farmers' choices of technology and management. The concept of resource management domains has therefore replaced the AEZ as a basis for the spatial extrapolation of research (Syers and Bouma, 1998).

The participatory approach has a major advantage over the traditional approach in terms of local relevance in that the technologies are actually tested out by farmers on their own fields, thus accounting for local environmental conditions and management practices. Most development projects, however, are under pressure to show impact over large areas in a short time. This would not be possible if every potential adopter was expected to carry out experiments on their fields. Once a technique has been seen to be successful in participatory on-farm trials, therefore, attempts will be made to transfer it to other farmers with different environmental conditions and management practices. At this point, the participatory approach faces the same extrapolation problem as the traditional top-down approach, which may be further compounded by the lack of control over experimental conditions, reducing the robustness of the results obtained.

Temporal extrapolation problem

In arid and semi-arid regions, variability in amount and timing of rainfall is often the primary determinant of crop performance. This variability is reflected in wide fluctuations in annual rainfall and in a wide range of dates for the start and end of the growing seasons (Mahoo *et al*., 1999). Furthermore, there may be great variability in the pattern of rainfall and the duration of intra-seasonal dry spells. For example, from 1961 to 1999 at Kisangara in Tanzania, the mean longest dry spell during the typical grain-filling period (around December) was 13 days. The maximum was 36 days and the minimum only four days. It is therefore desirable that any field research programme aimed at quantifying crop response to management factors (such as RWH) should run for a long period to ensure that results are representative. Even then it is difficult to interpret differences in performance between years, and extrapolation may be based on a crude relationship with seasonal rainfall (Jones, 1987). In general, experimental work is limited to only a few years and cannot capture this variability. Extrapolation to reflect conditions in other years is difficult (Critchley, 1989; Kiome and Stocking, 1993) and may result in misleading recommendations.

Twin-track methodology

Recognizing the limitations inherent in the experimental approach alone, a twin-track methodology – combining experimental work and modelling – was adopted for a research project in Tanzania aimed at developing improved dryland cropping systems. Field-based experiments between 1993 and 1999 tested the performance of a variety of different soil and water conservation techniques: *in-situ* RWH, microcatchment RWH and macrocatchment RWH (Hatibu *et al*., 2003). This work demonstrated both the potential and practice of RWH to farmers and extension workers in the target area. At the same time, this costly and time-consuming effort was linked to the development of a simulation model (PARCHED-THIRST) designed to permit easy spatial and temporal extrapolation of the results (Young *et al*., 2002).

PARCHED-THIRST MODEL

Any RWH system can be represented as a combination of two sub-systems:

- The catchment sub-system receives rainfall and generates runoff, which is collected (harvested) and conveyed to the cropped area. This is called the runoff-producing area (RPA).
- The cropped area sub-system receives both rainfall and runoff and stores them in the soil-water reservoir to meet crop water requirements. This is called the runoff-receiving area (RRA).

Different RHW systems are characterized mainly by differences in the RPA : RRA area ratio and in the separation distance between RPA and RRA. The PARCHED-THIRST model (Young *et al*., 2002) uses this simple conceptualization to simulate the rainfall-runoff process, soil moisture balance and crop growth in response to daily climate data. The landscape is, in effect, divided into any number of distinct or indistinct RPAs and RRAs, which are modelled as homogeneous units. The model aims to represent the important bio-physical processes within each unit using parameters that can be easily measured or estimated to represent crop, soil and site characteristics.

Experiments are necessarily limited in the number of different permutations of a system (treatments) that can be tested. With the model, however, different configurations can be simulated relatively easily by changing the parameter values representing the RPA and RRA within the model. Spatial extrapolation is made possible by use of measurable parameters that allow the model to be applied wherever the input data can be measured (or estimated using the data pre-processors). The effects of management are also simulated, enabling the model to be used to derive farmer-specific solutions. Temporal extrapolation is possible with long-term simulations, which can assess the performance of different options using available datasets of daily rainfall, for example, or by generating representative weather data (using one of the available data pre-processor utilities).

SIMULATION STUDY

To demonstrate the potential of the PARCHED-THIRST model to overcome problems of spatially and temporally extrapolating experimental results, and deliver results of direct relevance to farmers and extension services, four simulation exercises are presented here. The first three address some of the problems that might arise in attempting to extrapolate results from experimental work at Kisangara in Tanzania (Hatibu *et al*., 2003). The final exercise demonstrates the potential for modelling to assist with site-specific planning of RWH interventions.

Scenario 1 – temporal transferability

Overpopulation has forced farmers from high-potential uplands to move onto the low-potential, semi-arid Western Pare Lowlands in Tanzania. Experiments at two sites aimed to develop improved maize cropping systems with the objective of alleviating the moisture constraint. Several different RWH systems were tested, but pronounced variability in rainfall amount and timing made interpretation of the often apparently conflicting results difficult. Therefore, a computational experiment was undertaken to simulate the performance of some of these systems over a longer period.

The systems simulated were:

- rainfed control treatment
- microcatchment RWH treatment
- macrocatchment RWH treatment

In each case the simulated condition was closely matched to the experimental conditions described by Hatibu *et al*., (2003) using representative soil input data and crop parameters. The rainfed control represents the prevailing local practice of flat cultivation using hand hoe, but an alternative zero-tillage rainfed treatment (known locally as *kitang'anga*) was also included for comparison. The microcatchment RWH simulation represents the 2 : 1 RPA : RRA ratio with bare RPA surface treatment as at the Kisangara experiment site. The macrocatchment RWH simulation represents the conditions at the Kifaru site, which received three or four runoff events per season in addition to local rainfall inputs.

Simulations were based on 30 years of daily data for the experimental site. Longer simulation is possible, but a 30-year daily dataset was locally available and this provided a good indication of the range of climatic variability. Probability theory indicates that

Table 1. Simulated 30-year mean maize grain yields of the four treatments.

Treatment	Vuli grain yield ($t\ ha^{-1}$)	Masika grain yield ($t\ ha^{-1}$)	Vuli benefit over control (%)	Masika benefit over control (%)
Rainfed control	1.22	2.53	0	0
Zero tillage	1.01	1.68	−17	−33
Microcatchment RWH	1.94	2.70	60	7
Macrocatchment RWH	2.52	2.85	108	13

Table 2. Simulated mean maize grain yields for the rainfed and 2 : 1 microcatchment RWH treatments divided into five-year (pentade) periods.

Season	Pentade	Rainfed grain yield ($t\ ha^{-1}$)	2 : 1 RWH grain yield ($t\ ha^{-1}$)	Benefit over rainfed (%)
Vuli	1	1.14	1.81	58
	2	1.50	2.44	62
	3	1.10	1.37	25
	4	1.50	3.13	109
	4			
	5	1.12	1.53	36
	6	0.69	0.97	41
	All	1.22	1.94	60
Masika	1	2.48	2.72	10
	2	3.13	3.20	2
	3	2.49	2.78	12
	4	2.58	2.39	−7
	5	1.98	2.34	18
	6	2.50	2.74	10
	All	2.53	2.70	7

the probability (p) of an extreme event occurring within the 30-year period considered is given by the expression:

$$p = 1 - [1 - 1/T]^{30}$$

where T is the return period of the event considered. If, therefore, a design is based on a 10-year event (i.e. $T = 10$), there is a 96 % probability that this will be included within the 30 years simulated.

This extended analysis (Table 1) provides a clearer context for the interpretation of the relatively short-term experiments, which occurred during a period in which Masika seasons were generally wetter and Vuli seasons generally drier than the long-term means (see Figure 2 in Hatibu *et al*., 2003). To demonstrate the extent to which short-term experiments can misrepresent the long-term behaviour of systems under climatic variability, the results of the 2 : 1 RWH simulation have been broken down into five-year (pentade) means in Table 2. If five years represent the length of a field experiment, then the period during which that experiment is undertaken is critical. In this case, the benefit of 2 : 1 RWH in the Vuli season varies from 25 % to over 100 %.

Despite high climatic variability during the period of the experiment, however, the simulation results agree fairly well with the experimental results (Hatibu *et al*., 2003) and suggest that, on average, there is little benefit from RWH in the Masika season, but in the Vuli season the benefits are considerable. Similarly, zero tillage is slightly worse than flat cultivation in the Vuli season, but is considerably worse in the Masika season. There are two notable differences between the short-term observed and the long-term predicted results:

1. The benefit of 2 : 1 RWH in the Vuli season is lower than that found experimentally. While this does not detract from the technique's benefits in situations where land is not limiting, it does raise questions over its viability in situations where not cropping the RPA would reduce the overall area cropped. The same economic analysis as that carried out by Hatibu *et al*. (2003) shows two interesting differences (Figure 1). The first is that, even when debatable labour costs are considered, the higher rainfed yields mean that cropping both with and without RWH is always profitable. The second is that it is only when both seed and labour costs are considered that 2 : 1 microcatchment RWH brings an economic benefit over rainfed cropping in the Vuli season.
2. The simulated benefit of macrocatchment RWH over rainfed cropping is much greater in the Vuli season than that found experimentally. This is probably because the experimental results were heavily affected by one very wet Vuli season, which meant that even rainfed cropping performed well (Hatibu *et al*., 2003).

For resource-poor farmers, variability and risk are often at least as important as the long-term average. Figure 2 shows how long-term simulation experiments can also provide estimates of the risk of not achieving any chosen target yield. In the Vuli season, with zero tillage, there is a 50 % chance of not exceeding 0.8 t ha^{-1}. This rises to 1.1 t ha^{-1} for rainfed cropping, 1.6 t ha^{-1} for 2 : 1 RWH and 2.3 t ha^{-1} for macrocatchment RWH. In Masika, only zero tillage has a greater than 50 % chance of not exceeding 2.9 t ha^{-1}. Armed with information such as this, farmers can make a more informed judgement about whether or not to adopt proposed RWH innovations.

Scenario 2 – spatial transferability – the effect of rainfall regime

The experimental site is situated at the foot of the Pare Mountains and thus receives slightly more rainfall than many of the surrounding agricultural areas in which RWH might be of use. In order to test the extent to which experimental results are transferable to other sites in the region, simulations were repeated with generated climate datasets. The number of rainy days, and rainfall on a rainy day, were decreased and increased by one third in the Vuli season and one quarter in the Masika season to create the *Decreased* and *Increased* rainfall regimes respectively. Results of the simulation are given in Table 3. In both the Vuli and Masika seasons, the modified rainfall regimes give rise to the anticipated responses in grain yield for all treatments when compared with the simulation for Kisangara site. However, it is the relative magnitude of these changes that is of interest.

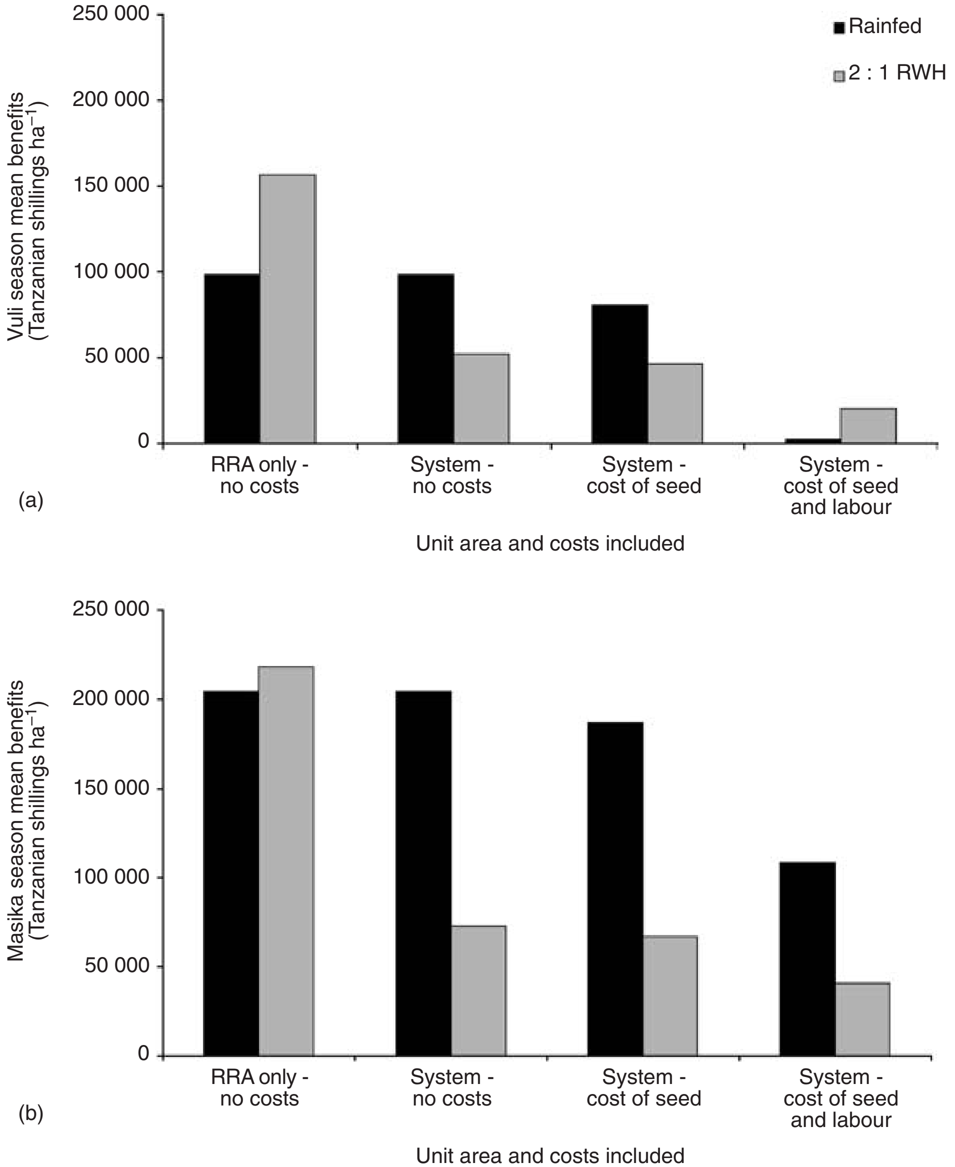

Figure 1. Cost-benefit analysis of rainfed and 2 : 1 microcatchment RWH in (a) Vuli and (b) Masika season on the basis of: the cropped area alone; the system as a whole, and the system as a whole with the costs of seed, and the cost of both seed and labour subtracted. Note: labour is calculated at 0.7 of the market wage rate.

While the benefit of zero tillage over rainfed in percentage terms remains similar for the *Kisangara* and *Decreased* rainfall regimes in the Vuli season, under the *Increased* regime, it changes from −15 % to −35 %. It seems that the greater the rainfall amounts, the greater are the effects of the compacted surface and minimal depression storage of the zero tillage plots in terms of the proportion of rainfall lost by runoff and/or the

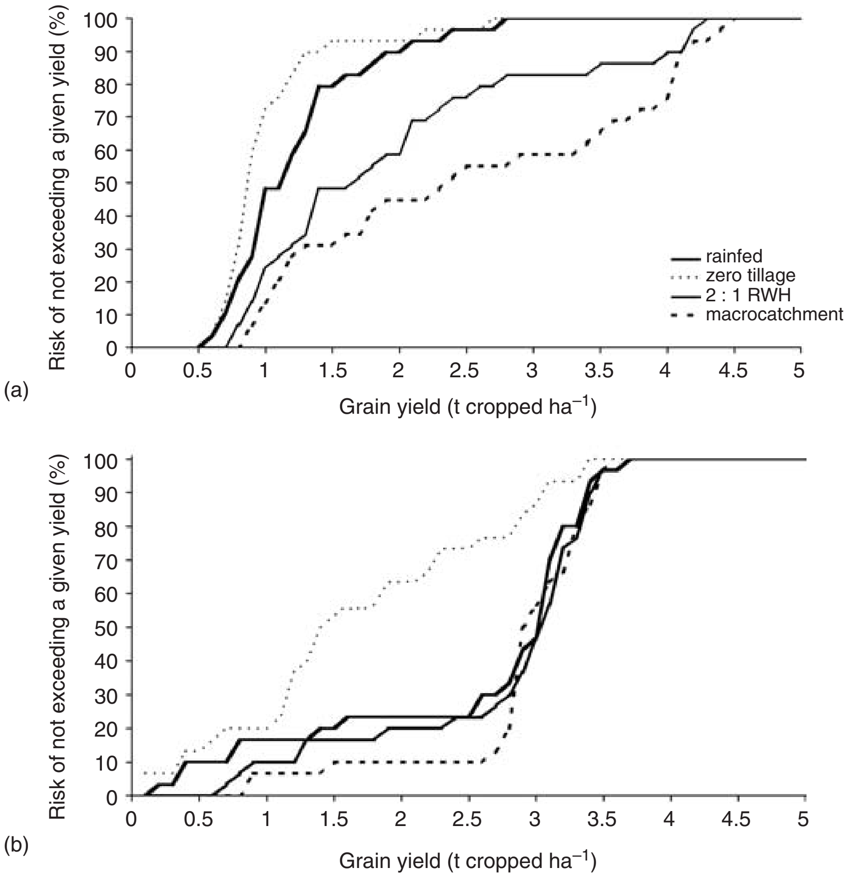

Figure 2. The risk of not exceeding a given maize grain yield in the (a) Vuli and (b) Masika season for each of the four treatments is calculated from 30-year simulations using weather data generated to match that at Kisangara.

amount of water stored in the soil profile. In the Masika season, where the number of rainy days is greater, and thus storage between events is less important, rainfall regime has less effect.

The 2 : 1 microcatchment RWH system in the Vuli season also exhibits some surprising behaviour. The benefit over rainfed cropping under the *Increased* regime is lower than under the *Kisangara* regime. This probably reflects the fact that the *Increase*d regime provides sufficient water for a reasonable rainfed crop. However, under the *Decreased* regime, the benefit is also lower. This reflects the fact that, in many years, dry spells are too long for even the RWH-augmented soil water to support a crop. In the Masika season, the opposite is true. The *Kisangara* and *Increased* regimes show very little benefit from 2 : 1 RWH, mainly because the rainfed crop does so well. Under the *Decreased* regime, however, rainfed yield is much reduced and the extra water provided by 2 : 1 microcatchment RWH brings considerable benefits to the crop.

Table 3. Simulated mean maize grain yield, under rainfed, zero tillage and 2 : 1 microcatchment RWH, as affected by three different simulated rainfall regimes.

Rainfall regime		Decreased	Kisangara	Increased
(a) Vuli season				
Mean grain yield (t ha^{-1})	Rainfed	1.08	1.22	2.01
	Zero tillage	0.91	1.01	1.31
	2 : 1 microcatchment RWH	1.29	1.94	2.82
Benefit over rainfed (%)	Rainfed	0	0	0
	Zero tillage	−15	−17	−35
	2 : 1 microcatchment RWH	20	60	40
(b) Masika season				
Mean grain yield (t ha^{-1})	Rainfed	1.39	2.53	2.99
	Zero tillage	1.10	1.68	2.26
	2 : 1 microcatchment RWH	1.98	2.70	3.04
Benefit over rainfed (%)	Rainfed	0	0	0
	Zero tillage	−21	−33	−25
	2 : 1 microcatchment RWH	42	7	2

These results indicate the risks inherent in extrapolation to sites with different rainfall regimes and the potential of simulation modelling in targeting the right technique to the particular local conditions.

Scenario 3 – spatial transferability – the effect of soil depth

Crop performance is greatly affected by soil depth (Alagarswamy *et al*., 2000) and/or the depth to which roots extend. The third simulation exercise looked at the extent to which changes in soil depth (and thus maximum rooting depth) might affect the performance of the different systems. Six depths were simulated from 0.5 to 3 m. The results, in terms of mean grain yield, are presented in Figure 3. In the Masika season, soil depth has very little effect on any of the four systems until it is reduced to 0.5 m. At this depth the soil is unable to store enough moisture for crops to survive during even the relatively short dry spells that occur in this season.

In the Vuli season, however, there is a marked increase in grain yield with increasing soil depth from 0.5 m, until the crop's maximum rooting depth is exceeded (set for maize at 1.8 m). This suggests that sufficient storage is of paramount importance if the crop is to survive the long periods without rainfall that occur in the Vuli season. In this season, macrocatchment RWH, zero tillage and, to a lesser extent, 2 : 1 microcatchment RWH all show increasing divergence from the rainfed yield with decreasing soil depth. For example, the relative benefit of macrocatchment RWH over rainfed cropping nearly doubles from 77 % at 2 m to 150 % at 0.5 m.

This exercise suggests that the relative benefits of the different systems observed on the experimental site may be very different from those which might be achieved on shallower soils or those with a restrictive layer, such as a plough-, clay- or iron pan, within the soil.

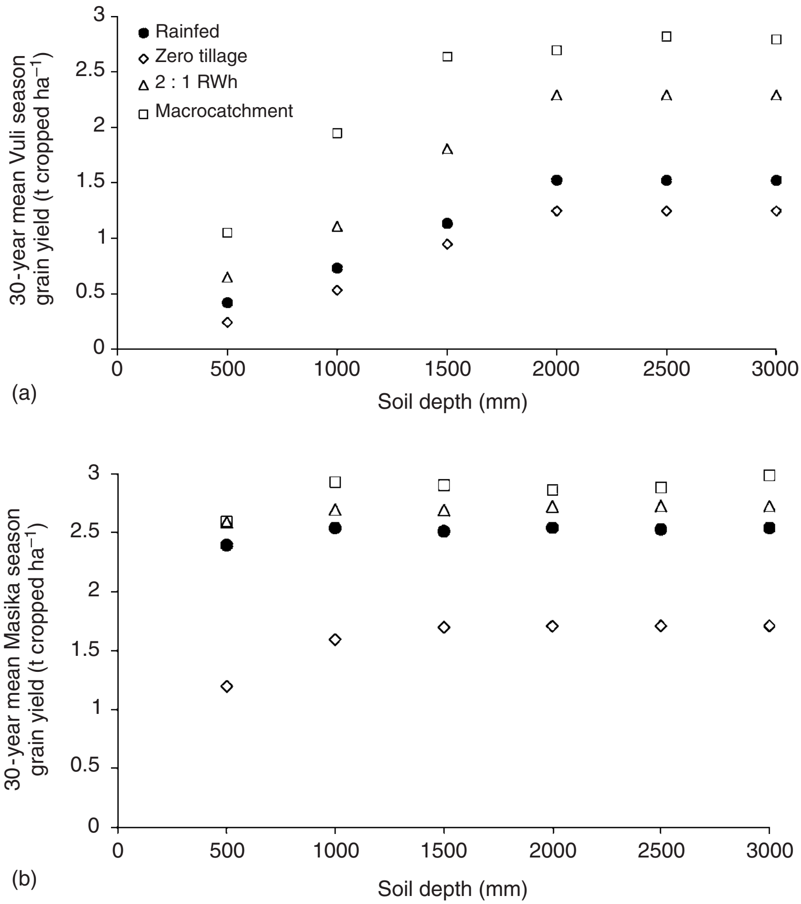

Figure 3. The effects of soil depth on mean maize grain yield in the (a) Vuli and (b) Masika season for each of the four treatments. Results are from 30-year simulations using weather data generated to match that at Kisangara. (Note: maximum rooting depth is set of 1.8 m).

Scenario 4 – water management considerations for macrocatchment RWH

Farmers in the Western Pare Lowlands have shown a growing interest in macrocatchment RWH systems, to the point of experimenting with them. In many cases, this involves diverting ephemeral streams from hillsides and road culverts onto agricultural land. In such situations, the catchment (RPA) may be ill defined and distant from the cropped field (RRA). These systems are much less predictable than microcatchment RWH and may produce runoff when there is no rain locally. The two main challenges facing farmers using these systems involve management of the captured runoff. One is that, with large catchments, runoff rates are potentially large thus presenting a serious erosion risk. This is apparent from the erosion of fields, by the uncontrolled diversion of water from gullies, which can be observed in the area. The other is that equitable distribution of the water among potential users is difficult. Simulations using PARCHED-THIRST can also provide valuable

Table 4. Simulated mean annual median of daily peak flow rates and maximum 20-year daily peak-flow rates as affected by the runoff-producing area (RPA) and season.

RPA area (ha)		1	10	40	160
Vuli	Mean annual median of daily peak flow rate ($m^3\ s^{-1}$)	0.05	0.31	1.04	3.29
	Maximum 20-year daily peak flow rate ($m^3\ s^{-1}$)	0.56	3.63	13.98	46.69
Masika	Mean annual median of daily peak flow rate ($m^3\ s^{-1}$)	0.05	0.22	0.79	2.07
	Maximum 20-year daily peak flow rate ($m^3\ s^{-1}$)	0.19	1.18	4.89	14.96

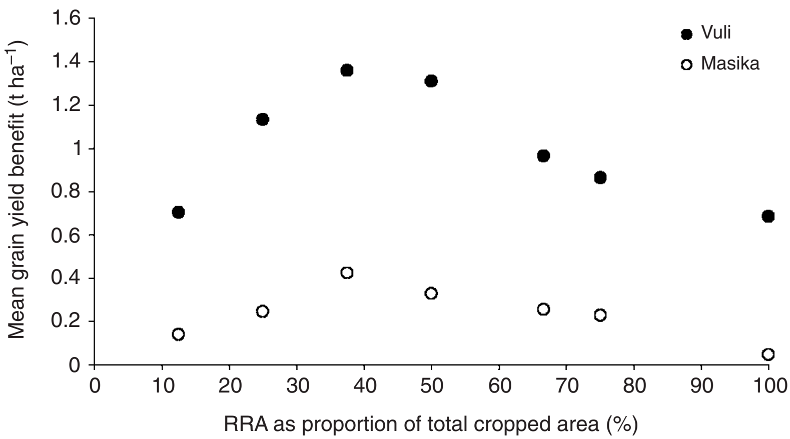

Figure 4. Effects of supplying the same amount of harvested water of runoff-receiving areas (RRAs) constituting different percentages of a total area. Results are expressed as mean maize grain yield benefit compared with rainfed cropping over the whole area.

information to help address both of these concerns. This is illustrated for conditions representative of the macrocatchment RWH experiment site at Kifaru (Hatibu *et al*., 2003).

In order to design control measures that are effective in preventing erosion, information on the amount and frequency of peak flows is required. A 20-year simulation of runoff from catchments of 1, 10, 40 and 160 ha provided this information. Table 4 gives the mean annual median of daily peak-flow rates and the maximum 20-year daily peak-flow rates during the Vuli and the Masika seasons for each RPA. In all cases, the larger the RPA, the greater the simulated daily peak flow. The maximum 20-year flow rate for the 160 ha catchment is nearly 50 $m^3\ s^{-1}$ and for the 40 ha catchment it is 14 $m^3\ s^{-1}$. Even the relatively small 1 ha catchment produced 0.56 $m^3\ s^{-1}$ once in the 20-year period. These peak flows are more than can be handled safely using earthen control structures. Simulations such as this can provide the parameters required in the design of the control structures vital to the safe management of macrocatchment RWH systems.

When planning water distribution amongst farmers, information on the effects of water sharing on system productivity and reliability is vital. In order to explore the effects of water sharing, simulations of the macrocatchment RWH system were undertaken, altering the size of the actual cropped area (RRA) to comprise different proportions of the potential cropped area (as defined in Hatibu *et al*., 2003). This is analogous to having 100 fields of the same size and diverting harvested water to different numbers of them. Figure 4 shows the benefits of macrocatchment RWH in terms of the yield increase (t ha^{-1}) over the whole area compared with rainfed cropping over the whole area. There is clearly an optimum proportion at around 40 % of the potential RRA for this case. Spreading the captured runoff over a greater area or concentrating it on a smaller area would bring smaller benefits.

Armed with information such as this, farmers' groups or other planning agencies would be in a much better position to assess best-bet solutions for site-specific interventions. This requires the dissemination of the model itself rather than dissemination of model outputs as advocated by Matthews *et al.* (2002) and raises issues of identifying end users and making the model sufficiently user-friendly.

CONCLUSIONS

The primary problem facing farmers in the semi-arid lowlands of Tanzania is the inadequate, often unreliable, supply of water in the root zone. 'Just one more good rainstorm' is the constant lament of farmers in this marginal environment. Since they cannot expect to control the rainfall process, the solution lies in increasing the productivity of the rainfall that does arrive. As 'non-productive' evaporation has been shown to account for up to 50 % of total rainfall in semi-arid tropical cropland (Rockstrom, 2000), there seems to be a large potential to improve the situation.

Rainwater harvesting systems operate on different scales (plot, field, catchment) to modify the water balance in order to increase the rainfall use efficiency. The challenge is to find ways of selecting and promoting appropriate RWH interventions that are well matched to the site-specific, biophysical and socio-economic circumstances. Research in the Western Pare Lowlands between 1993 and 1999 demonstrated the potential benefits of RWH and brought about a marked shift in perceptions. Whereas previously runoff was seen as a hazard, it is now recognized as a valuable resource. Dissemination of this simple message has been relatively easy, but providing the knowledge to meet site-specific requirements is more problematic.

The twin-track (experimentation + modelling) approach was seen as a response to this challenge. Experimental research into soil-water management, whether on a research station or on farmers' fields, is necessarily restricted to specific sites over limited time intervals, and meaningful extrapolation is a problem. Therefore, the experimental effort was linked to the development of a simulation model, designed to permit easy spatial and temporal extrapolation. Thorough validation of the model required a much greater number of crop, soil and water measurements to be taken at higher frequencies than would normally be required for agronomic experiments of this type. Nevertheless, it can be concluded that this burden was worthwhile because of the added value that accrued from the work.

The PARCHED-THIRST model is seen as a means of organizing knowledge gained from experimental effort and adding value to the results. The experience with RWH research in Tanzania supports the view of Matthews *et al*. (2002) that models have a valuable contribution to make when integrated into field-based research and extension projects. Use of the model allows exploration of a wider range of scenarios and management options than would otherwise be possible. Model outputs provide greater insight into long-term performance and overcome limitations of experiments conducted during years when climatic conditions do not reflect the full range normally encountered.

The simulations reported here have shown that the benefit of microcatchment RWH in the Vuli season, when judged on the basis of performance over a period of five years, may vary widely. Long-term simulation provides a more reliable indication of performance than would be the case for a typical five-year experiment, and also allows for risk analysis. These simulations have shown also that the uncertainty inherent in extrapolation to sites with different rainfall regimes and soils, can be reduced by modelling. This helps in targeting the right technique to local conditions. The overall assessment of the twin-track approach is that RWH has considerable potential for increasing productivity of maize cropping systems in semi-arid Tanzania provided that RWH innovations are properly matched to the site-specific environmental conditions. Sustainability of this improved cropping system then depends upon correct fertility management, but the higher productivity and reduced risk is likely to favour proper use of inputs (such as farmyard manure).

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