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DEVELOPING IMPROVED DRYLAND CROPPING SYSTEMS FOR MAIZE IN SEMI-ARID TANZANIA. PART 1: EXPERIMENTAL EVIDENCE FOR THE BENEFITS OF RAINWATER HARVESTING

By N. HATIBU†, M. D. B. YOUNG‡§, J. W. GOWING‡,
H. F. MAHOO† *and* O. B. MZIRAI†

†*Soil-Water Management Research Group, Sokoine University of Agriculture, Tanzania and*
‡*Centre for Land Use and Water Resources Research, University of Newcastle upon Tyne, UK*

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SUMMARY

Farmers in the southern Kilimanjaro region of Tanzania have a strong preference for maize as their staple crop and have resisted attempts to introduce sorghum as an alternative in spite of the high drought risk associated with maize production. This paper presents the results of a seven-year period of field experiments to assess the benefits of a modified cropping system for maize, which aims to reduce drought risk through rainwater harvesting. *In-situ*, microcatchment and macrocatchment rainwater harvesting systems were tested against the local practice of flat cultivation as control. All were managed according to local extension recommendations, and the benefits were measured in terms of grain yield. *In-situ* rainwater harvesting provided no benefit. Microcatchment rainwater harvesting resulted in increased yield per unit area cultivated. On a total system area basis (i.e. including the uncropped catchment), however, production decreases were observed. A cost-benefit analysis, however, does show a benefit in the short rainy season. Macrocatchment rainwater harvesting provided increases in grain yield in both the short and the long rainy seasons.

INTRODUCTION

As in many parts of East Africa, population growth in high-potential upland areas in Tanzania is forcing migration into less productive semi-arid areas (Stahl, 1993). These areas are characterized by unreliable rainfall that rarely exceeds potential evapotranspiration. When rainfall does occur, it is often as short-duration, high-intensity storms, which lead to runoff and, in many cases, soil erosion. As a result of the soil moisture constraint in these semi-arid lowlands, the potential yield of even drought-resistant crops such as sorghum is achieved only 2–3 years out of every ten (Gommes and Houssiau, 1982).

The Western Pare Lowlands in the North-East of Tanzania represent such an area that has been classified as having low potential for agriculture, but which has seen increasing inward migration since the 1930s. The farmers here, many of whom have migrated to the area from the high-potential uplands in the Pare Mountains, have a strong preference for maize (*Zea mays*) and have resisted attempts to introduce sorghum

§Corresponding author, M. D. B. Young: Centre for Educational Software, The Open University, Milton Keynes MK7 6AA. Tel: 01908 659937. Fax: 01280 817457. Email: m.d.b.young@open.ac.uk

Table 1. Characteristics of the three types of RWH tested.

Characteristic	*In-situ*	Microcatchment	Macrocatchment
Flow distance	Few cm	Several m	Several km
Flow type	Sheet	Sheet/rill	Channel
Location of RPA	Within crop	Within farm	Outside farm
Typical RPA : RRA	ca. 1 : 1	$>1:1$	$\gg 10:1$
Division between RPA and RRA	Indistinct	Distinct	Distinct
Risk of erosion	Reduced	Unchanged over area as a whole	Increased
Potential problems	Produces insufficient runoff	Leaving land uncultivated	Erosion, water allocation
Typical techniques	'Ngoro' pits (Tanzania)	Meskat (Tunisia) and Negarem (Israel)	Caag systems (Somalia)

(*Sorghum bicolor*), as a drought-tolerant alternative. A series of participatory evaluation exercises (Lazaro *et al*., 1999) established that the farmers were aware of the risks, but preferred to adapt their maize cropping systems to alleviate the current production constraints.

One potential solution to their problems is rainwater harvesting (RWH). This term describes systems that collect rainfall from a runoff-producing area (RPA) for cultivation on a runoff-receiving area (RRA) (Boers and Ben-Asher, 1982; Pacey and Cullis, 1986). RWH covers a continuum of techniques that link soil-water conservation at one extreme and irrigation at the other. A number of classifications have been proposed (Critchley and Siegert, 1991; Prinz, 1995; Barrow, 1999) but the work reported here adopts a simple classification based upon the size ratio and the transfer distance between the RPA and the RRA.

At one end of the continuum, *in-situ* RWH (or soil-water conservation) comprises a group of techniques that prevent runoff over more than a few centimetres and promote infiltration (Table 1). In Tanzania, one well-documented example is the *ngoro* pit, a hand-cultivated hole some 0.3–0.6 m deep and 1.0 m in diameter (Wilcocks and Gichuki, 1996). Contour barriers of stones, crop residues (as used in Tanzania – Thornton, 1980) and earth, such as the *fanya juu* system used with such success in the Machakos district of Kenya (Tiffen *et al*., 1994) as well as tied-ridging (Jones and Nyamudeza, 1991), are classified as *in-situ* RWH techniques.

Moving up the continuum, microcatchment RWH techniques divert overland flow (sheet or rill flow) from distinct RPAs onto adjacent RRAs. The transfer distance is typically in the range of 5–50 m and both areas will typically lie within a single farmer's land (Table 1). Examples include strip catchment tillage or contour strip cropping, where strips of crop are grown alternately down a slope with strips of grass or cover crop (Critchley and Siegert, 1991), the *Meskat* system of Tunisia (El Amami, 1977) and the *Negarim* system of Israel (Evenari *et al*., 1982). The advantages of these systems include relatively high runoff efficiencies and a relatively low risk of soil erosion. In many cases, however, this form of RWH involves leaving part of a field unplanted. As a

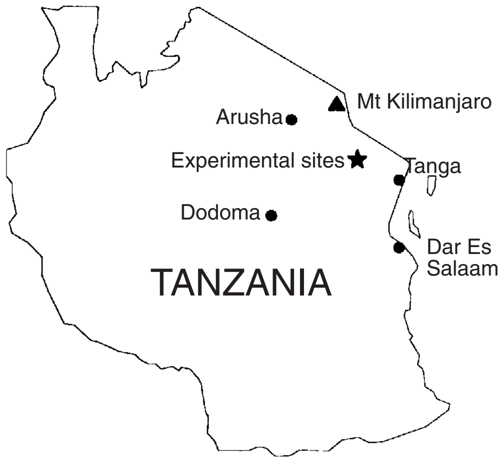


Figure 1. Location of the experimental sites.

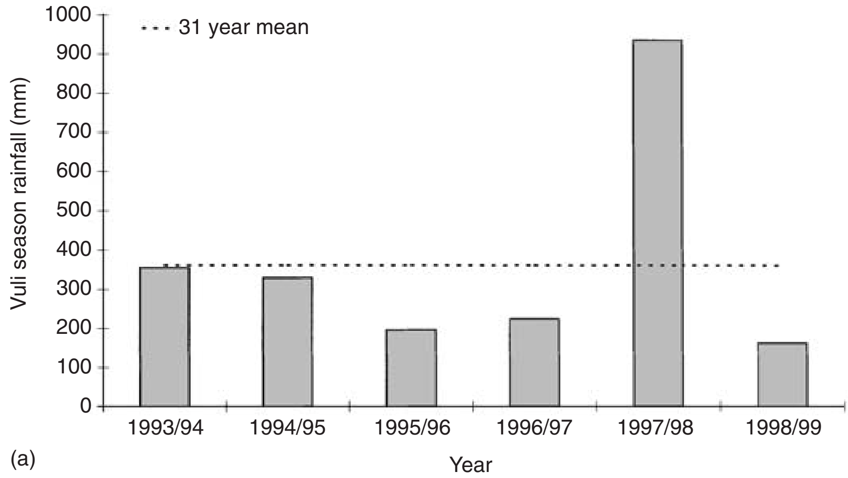
result, even though yields on the RRA may be high, overall production may decrease when measured over the total land area (RPA plus RRA).

Macrocatchment RWH techniques collect runoff from an RPA that is very much larger than the RRA; generally the two do not lie within a single farmer's land (Table 1). The RPA and RRA will often be very different in character and the transfer distance may be in the range of a few hundred metres to several kilometres. Although runoff efficiency is lower than the microcatchment systems, runoff volumes will still be large because of the size of the RPA. If the transfer distance is very large, it is also possible for the RPA to receive rain and produce runoff on days when the RRA has itself received no direct rain. Examples include: hillside systems such as the *Majaluba* system of the Lake Zone of Tanzania (Meertens *et al.*, 1999) where water is channelled into bunded rice basins by small channels constructed across the slope on grazing land; stream-bed systems that spread water flowing in ephemeral streams using permeable stone dams or earth bunds (van Dijk and Ahmed, 1993); and stream diversion systems that channel water from ephemeral streams into water-spreading structures such as the *Caag* system of Somalia (Reij, 1991). The main problems with these systems are in controlling the sometimes very high rates of runoff, and preventing erosion. Also, communal ownership of the RPA can give rise to potential problems in the allocation of water amongst users.

This paper describes work that tests the performance of these three different types of RWH for maize production in the Western Pare Lowlands of Tanzania. It aims to find the most appropriate type and design of RWH technique to tackle the soil moisture constraints of farmers in this semi-arid area.

MATERIALS AND METHODS

The experiments were located at two sites in the Mwanga district of the Western Pare Lowlands in northeastern Tanzania (Figure 1). These Lowlands lie within the



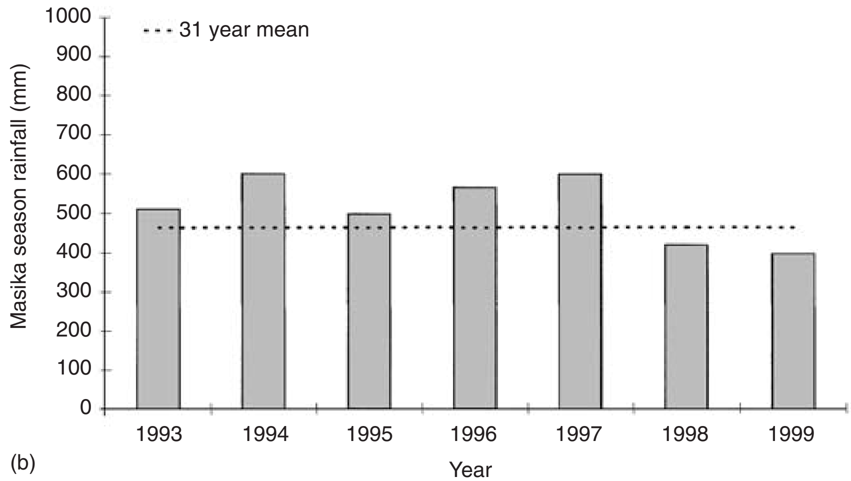


Figure 2. Comparison of (a) Vuli and (b) Masika season rainfall during the experimental period with 31-year means at Kisangara.

Massai Steppe agro-ecological zone (Land Resources Department, 1987), an area characterized by rolling plains with reddish sandy clay soils of relatively low fertility formed on basement complex rocks. The Kisangara site (3°45′S 37°35′E) is located on the western slopes of the foothills of the Pare mountain range. It is a sloping site (3–8 %) that was under sisal prior to being cleared in 1993. The soils are classified as Rhodic Lixisols (FAO, 1998). The Kifaru site is located further down the catena, closer to the Pangani river (3°29′S 37°26′E), and is a flatter site (0.5–4 %). It was previously under bush fallow. Climate in the district is semi-arid with bi-modal rainfall. The shorter rainy season (locally known as *Vuli*) lasts from October to January with a mean

Table 2. Summary of the three experiments.

	In-situ	Microcatchment	Macrocatchment
Treatments	Zero tillage (control) Flat cultivation Earth bunds Stone bunds Live barriers	i) 0 : 1, 2 : 1, 4 : 1 RPA : RRA ii) 3 % and 8 % slopes iii) Flat cultivation and staggered ridging	Flat cultivation (control) Contour earth bunds (*in-situ*) Macrocatchment
Replicates	3	3	3
Design	Randomized complete blocks	Randomized complete blocks	Partially randomized complete blocks
Maize cultivar	TMV-1	TMV-1	1997–98 TMV-1 1999 Kito
Planting density	44 000 plants ha^{-1}	44 000 plants ha^{-1}	44 000 plants ha^{-1}
Years	1993–1999	1993–1996	1997–1999
Plot size (m)	25 × 5	RRA: 5 × 10 RPA: 10 × 10 and 20 × 10	50 × 15
Fertilizer package	40 kg P ha^{-1} both at planting and 6^{th} leaf	40 kg P ha^{-1} both at planting and 6^{th} leaf	40 kg P ha^{-1} both at planting and 6^{th} leaf

rainfall of 362 mm. The longer rainy season (*Masika*) lasts from February until May with a mean rainfall of 463 mm (Figure 2).

Experimental work began in 1993 with the establishment of *in-situ* and microcatchment RWH trials. In response to feedback on the attractiveness of macrocatchment RWH, the microcatchment experiments were discontinued in 1996 and macrocatchment experiments were established in 1997. These, and the *in-situ* RWH trials, were continued until 1999.

The Kisangara site was used to test both *in-situ* RWH and microcatchment RWH. The *in-situ* RWH treatments were stone bunds, contour ridges and live barriers of *Vetiveria zizanoides* laid across the slope at 5-m intervals (Table 2). Flat cultivation (the control) was also tested against zero tillage (locally known as *kitang'anga*). The *in-situ* RWH experiments ran for a total of five Masika and five Vuli seasons (although grain yield was zero in two of the Vuli seasons).

The microcatchment RWH treatments tested the effects of slope (3 v. 8%), the RPA : RRA ratio (0 : 1, 2 : 1, 4 : 1) and RRA surface treatment (flat cultivation v. staggered ridging) on the yield of maize (Table 2). A complete randomized blocks design was used (Figure 3) with three replicates of each treatment. All RRAs were 10 m across and 5 m down the slope, with bare RPAs of 100 m^2(RPA : RRA ratio = 2 : 1) and 200 m^2 (RPA : RRA ratio = 4 : 1), and a rainfed control (i.e. zero RPA). Barriers were constructed around each conjoined RRA-plus-RPA plot and each control to prevent run-off exchange with land above and below them. The microcatchment RWH experiments ran for a total of three Masika and three Vuli seasons.

At Kifaru, the experiment assessed three replicates of three treatments (i.e. flat cultivation, *in-situ* RWH and macrocatchment RWH) on two soils in a partially randomized complete blocks design (Table 2). The macrocatchment RWH treatment involved diverting water from an ephemeral stream/gully into a brick-lined channel

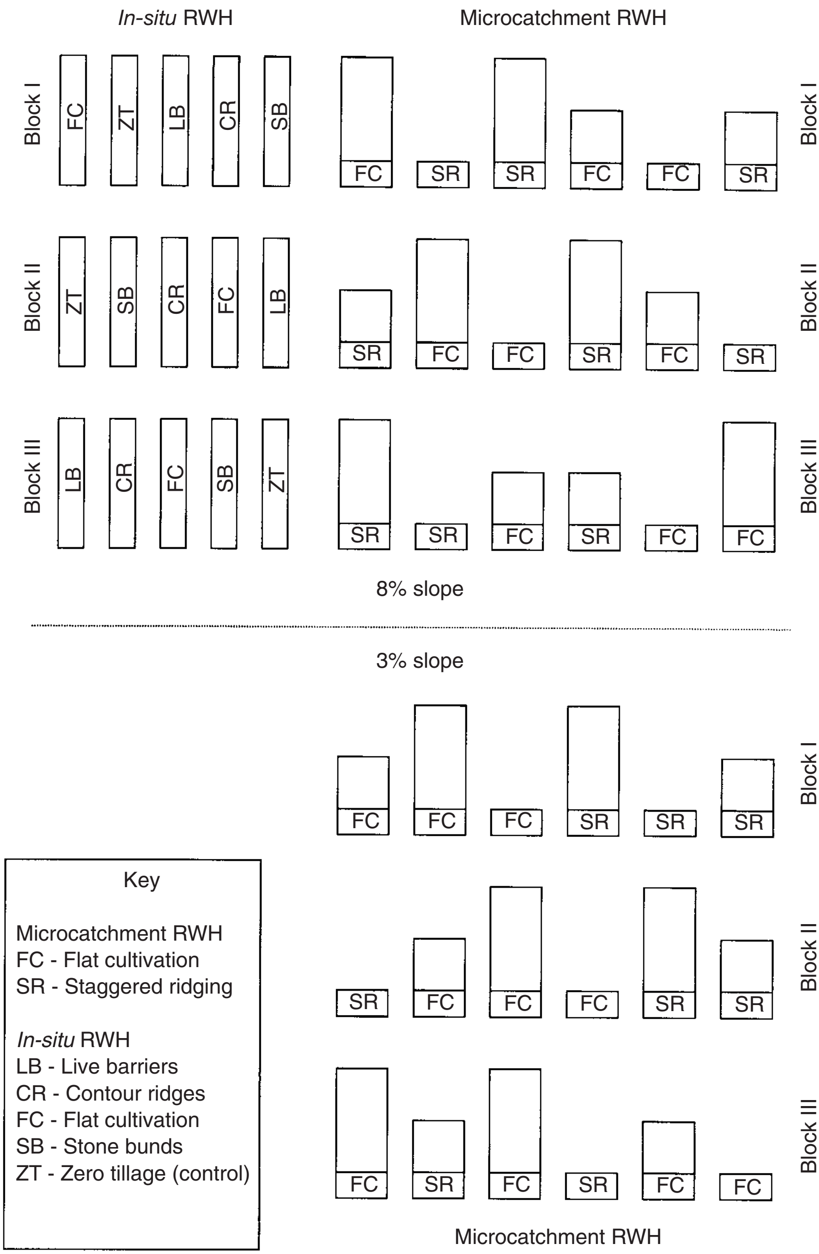


Figure 3. Layout of *in-situ* and microcatchment RWH plots at Kisangara.

from which it was distributed into the three plots allocated to this treatment on each of the two soils (Figure 4). Because of concern over losses in the distribution of the water, the macrocatchment RWH plots were excluded from the randomization within blocks based on the assumption that the majority of variation in soil properties was likely

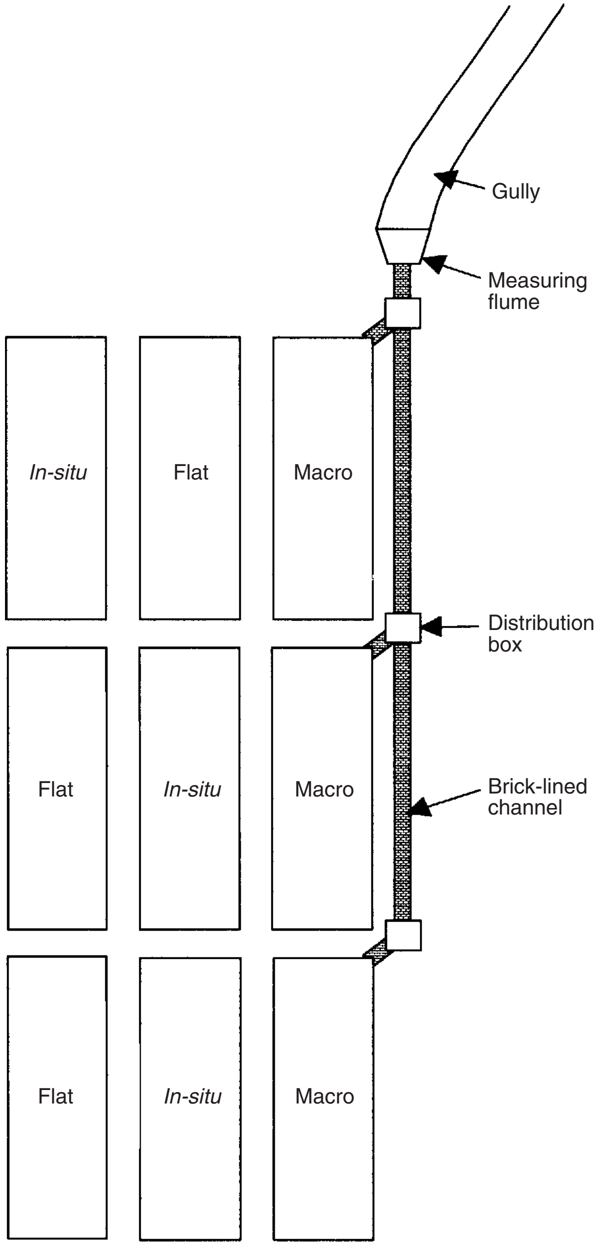


Figure 4. Layout of the upper field at Kifaru experiment site. The lower field was similar in design.

to be down the slope (i.e. between blocks). The experiments testing macrocatchment RWH ran for one Vuli and two Masika seasons from 1997 to 1999. In the first two seasons the maize cultivar TMV1 was planted but this was replaced with Kito in the final season because of a seed shortage.

Table 3. Mean grain yields and benefits over control of the five *in-situ* RWH treatments in the Masika and Vuli seasons.

Season	Treatment	Mean grain yield (kg ha^{-1})	Increase due to treatment (%)	Standard error of means (±)
Masika	Zero tillage	2463	− 20.6	279
(n = 6)	Flat cultivation (control)	3101	0	418
	Stone bunds	2686	− 13.4	451
	Contour ridges	3031	− 2.3	509
	Live barriers	3446	11.1	334
Vuli	Zero tillage	467	− 33.3	269
(n = 9)	Flat cultivation (control)	699	0	338
	Stone bunds	789	12.8	351
	Contour ridges	624	− 10.8	267
	Live barriers	644	− 7.9	299

RESULTS

In-situ *RWH*

Table 3 shows that the lower rainfall in the Vuli season was reflected in lower grain yields than were obtained in the higher-rainfall Masika season (t_{57}, $p < 0.0001$). Vuli-season grain yields were noticeably more variable than those of the Masika seasons. This is matched by greater variability in rainfall as shown in Figure 2. The 1997/1998 Vuli season had elevated yields attributable to increased rainfall due to El Niño. There were no significant differences between treatments in the Vuli season. Stone bunds appeared to show some possible benefit over the control treatment, but all standard-error values were high. In the Masika season too there were no significant differences between treatments. Zero tillage appeared to result in the lowest grain yields, and live barriers in the highest. Again, however, all standard-error values were high.

Microcatchment RWH

There were no differences in grain yield between the two slopes (t_{141}, $p = 0.15$) or the two RRA tillage treatments (t_{141}, $p = 0.43$) and, therefore, these factors are ignored in the following analysis. Table 4 gives mean grain yields per unit area cultivated for the different RPA : RRA treatments. Yields were higher in the Masika than in the Vuli season in all years (t_{121}, $p < 0.0001$). In the former, only the 4 : 1 treatment gave higher yields than the control. In the Vuli season, however, both the 2 : 1 and the 4 : 1 treatments led to large increases in yields.

The yields presented in the third column of Table 4 are expressed as grain weight per unit RRA. If land is not limiting, this is a true reflection of the benefits of microcatchment RWH. However, in some cases, land is limiting and allocation of a part of a field to act as a non-cultivated RPA reduces the total area a farmer can cultivate. This is a common criticism of microcatchment RWH because, as shown in the sixth column of Table 4, if yield is expressed per unit area occupied by the treatment as a whole, RWH actually causes a decrease in overall production regardless of season or RPA : RRA ratio. However, this analysis ignores the cost of inputs to the system. By not planting the whole area, a farmer will make a considerable saving in the

Table 4. A comparison of yields and relative benefits of microcatchment RWH at Kisangara. Results are presented with and without consideration of the area used as a RPA.

		Only cropped area			Total system area	
Season	RPA : RRA	Mean grain yield (kg ha^{-1})	Increase due to RWH (%)	Standard error of means (±)	Mean grain yield (kg ha^{-1})	Increase due to RWH (%)
Masika	0 : 1	2868	0.0	127	2868	0.0
	2 : 1	3015	5.1	144	1005	− 65.0
	4 : 1	3465	20.8	174	693	− 75.8
Vuli	0 : 1	374	0.0	52	374	0.0
	2 : 1	850	126.7	103	283	− 24.4
	4 : 1	984	162.5	96	196	− 47.5

Table 5. A comparison of yields and relative benefits of macrocatchment RWH for two Masika seasons and one Vuli season at Kifaru.

Season	Treatment	Mean grain yield (kg ha^{-1})	Increase due to RWH (%)	Standard error of means (±)
Masika	Control	2034	0.0	162
	In-situ RWH	2177	7.0	112
	Macrocatchment RWH	2483	22.1	94
Vuli	Control	1848	0.0	316
	In-situ RWH	2473	33.8	326
	Macrocatchment RWH	2736	48.1	313

costs of material inputs such as seed, fertilizer (if any), and labour inputs required for tillage, planting, weeding, and harvesting. Figure 5 presents the economic benefits of microcatchment RWH based upon the yield of the cropped area alone. Benefits of the system as a whole are also calculated, both with and without accounting for the cost of seed, and the combined cost of seed and labour inputs. The picture is much as that shown in Table 4 for the Masika season with RWH causing a reduction in benefit compared with the control. In the Vuli season, however, a different picture emerges. When seed costs alone are taken into account, there is a positive benefit with 2 : 1 RWH, despite the yield over the whole area being lower. This reflects the saving in seed made by the farmer in planting only one third of his/her land. However, 4 : 1 RWH still results in an overall reduction in benefit, as the savings in seed costs are not enough to offset the reduction in yield over the whole area. When labour is taken into account as well, all three treatments result in an overall loss but this decreases with increasing RPA : RRA ratios.

Macrocatchment RWH

Unlike the other two experiments, the data presented in Table 5 show slightly higher yields in the Vuli than in the Masika seasons. This can be attributed to the

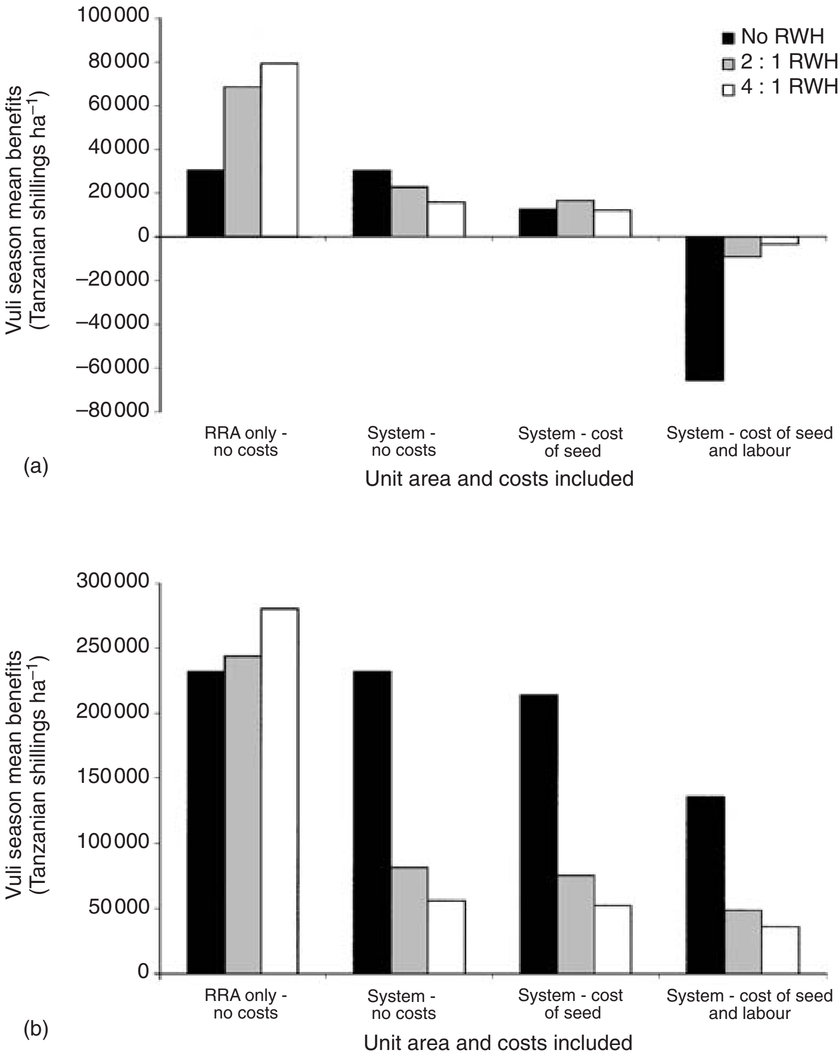


Figure 5. Cost-benefit analysis of different microcatchment RWH techniques in the (a) Vuli and (b) Masika seasons on the basis of; the cropped area alone; the system as a whole; and the system as a whole with the costs of seed, and the cost of both seed and labour subtracted. Note: labour is calculated at 0.7 of the market wage rate.

unusually high rainfall in the 1997/8 Vuli season caused by the effects of El Niño (Figure 2). As a result, there is no difference (t_{22}, $p = 0.57$) between seasons. There is also no difference (t_{51}, $p = 0.24$) between the two soils on which the experiments were located. These factors, therefore, are ignored in the analysis. The *in-situ* treatment performed erratically and in 1999, produced lower grain yields than did the control. As a result, overall yields were no different (t_{33}, $p = 0.13$) to those of the control. The macrocatchment RWH treatment produced very much higher (t_{32}, $p = 0.0035$) grain yields than were produced by the control.

DISCUSSION

In-situ *RWH*

In the absence of any consistent difference between treatments in the Vuli season, zero tillage appears to be the most efficient cultivation strategy because it demands the least labour input. In the Masika season, however, zero tillage negatively affected yields. Flat cultivation, the least labour intensive of the other treatments, performed as well as any of them. Therefore, it was the most efficient cultivation method in the Masika season. It seems that rainfall in the Vuli season is barely sufficient to produce a crop, regardless of the cultivation method. The amount and/or distribution of water are such that simply preventing runoff is not enough to ensure reliable yields. The poor performance of zero tillage in the Masika season was probably due to a combination of the loss of water through runoff and impedance of root growth in uncultivated soil. Since the other treatments performed equally well, it suggests that flat cultivation provided enough detention of surface water for infiltration to occur in amounts that satisfied plant requirements and any further detention provided by contour barriers was not used by the crop.

These results are similar to those of Maurya and Lal (1980) and Ngugi and Micheieika (1986) who found that, while minimum tillage underperformed conventional tillage in favourable seasons, in poor seasons there is little difference. In Botswana, DLFRS (1984) attributed similar experimental evidence to the fact that deeper-tilled soils allowed plants to grow rapidly and exhaust the available water while the plants in zero- and shallow-tilled soils had grown less quickly, and thus had not exploited the water so rapidly (possibly because of impedance to roots). Both Kiome and Stocking (1993) and Herweg and Ludi (1999) found similar variable benefits from *in-situ* RWH methods and highlighted the importance of site and season in determining the methods' effectiveness.

There is some evidence that the three contour methods led to the development of terraces some 0.4 m in height by preventing the movement of soil down the slope. However, unless there are problems with soil erosion, this is unlikely to justify farmer investment in contour barriers when, even after seven years, there was no discernible difference in yields. There were no observed yield benefits from *in-situ* RWH compared with existing local practice.

Microcatchment RWH

Considering only the cultivated area (i.e. when land is not limiting), the results suggest that adoption of microcatchment RWH is beneficial in the Vuli season, but existing practice performs equally well in the Masika season. The implication is that direct rainfall in the Masika season is enough to produce a crop and there is only a minor benefit to be had from additional soil-water inputs delivered by the microcatchment RWH system. In the Vuli season, however, the extra water is translated into increased grain yields more effectively.

Considering the area of the system as a whole (i.e. where land is limiting), microcatchment RWH was detrimental to overall production in both seasons. This criterion is often used to dismiss microcatchment RWH as being of little merit.

However, an (albeit simple) analysis of the economics of the different production methods presents another picture. There is still no benefit from microcatchment RWH in the Masika season but, in the Vuli season, there is a benefit from 2 : 1 RWH when the cost of seed is taken into account. Furthermore, although accounting for labour costs gives negative benefits for any form of cultivation in the Vuli season, these are lower under microcatchment RWH. The fact that analyses of this type often lead to negative calculated benefits for farmers' current practice has led to some debate over the appropriate way to cost farmer's time. In this case, the cost of labour has been calculated at 0.7 of the market wage rate (to give the so-called shadow wage rate). While this is appropriate if there are other more profitable activities to which a farmer can devote time, many subsistence farmers live in areas where there is little opportunity for alternative employment. It may be appropriate, therefore, to ignore the cost of family labour. This assumption is supported by the fact that farmers do attempt to grow maize in the Vuli season without RWH, which, if even the shadow wage rate is taken into account, results in serious losses.

Rees *et al.* (1991) carried out a similar analysis of results from catchment basin systems in Balochistan (Pakistan) and found that, although microcatchment systems with a RPA : RRA ratio of 1 : 1 significantly improved yields of wheat in the RRA, when the RPA was taken into account, total production was only 95% of normal cultivation over the full area. However, when the production costs were taken into account, net benefits equalled or exceeded those of the control by up to 23%.

The appropriateness of microcatchment RWH is thus dependent on the situation in which it is applied. On the basis of the results obtained, microcatchment RWH is not viable in the Masika season or in the Vuli season if land is limiting and the farmer's goal is yield maximization regardless of cost. If land is not limiting, however, and/or if the farmer wants to maximize return on material inputs, microcatchment RWH with a RPA : RRA ratio of 2 : 1 is the best of the tested techniques to use in the Vuli season. Given the unreliable nature of the Vuli rains in Tanzania, concentrating labour and resources within the RPA can be seen as a risk-reducing strategy that delivers more-or-less the same yield as existing extensive cultivation and may favour more intensive use of inputs (such as farmyard manure).

Macrocatchment RWH

Macrocatchment RWH was the only one of the three techniques that gave yield benefits regardless of season. Without continuous monitoring of soil moisture status in the different treatments, it is not possible to conclude if the benefit was attributable to the greater run-on volume or more advantageous timing of inputs. However, intra-seasonal dry-spells are more likely to be alleviated when direct rainfall and run-on occur non-synchronously and this was seen to occur on several occasions. The results presented here were consistent with those of Carter and Miller (1991) who, in Botswana, found that a macrocatchment system more than doubled yields of sorghum compared with a control in years with below average or poorly distributed rainfall. Imbira (1986) obtained even greater increases (more than 500%) with sorghum in the Baringo district of Kenya.

CONCLUSIONS

In Tanzania, as in most of sub-Saharan Africa, the vast majority of farmers depend on rain-fed agriculture. Future food security depends, therefore, upon developing improved dryland cropping systems. An important step towards tapping the potential of these systems will be to use the available rainfall (sometimes known as 'green water') more efficiently. Rainfall partitioning analysis by Rockstrom (2000) has shown that productive green water flow is only 15–30% of total rainfall. Adoption of RWH systems provides an opportunity to modify the natural field water balance without placing further demand on limited 'blue water' resources through introducing irrigation. The challenge is to select and apply appropriate RWH interventions that capture the unproductive green water flows.

Under the prevailing bimodal rainfall regime at this research site, no case can be made in favour of adopting *in-situ* RWH for maize production. This is also true for microcatchment RWH during the Masika season. It is apparent however, that microcatchment RWH offers benefits in the Vuli season of less-reliable rainfall. Macrocatchment RWH appears to offer the greatest benefits in both seasons. However, there are inherent difficulties with macrocatchment systems due to their scale that can be avoided with microcatchment systems. These include the erosion hazard associated with the high flow rates, and management problems in sharing runoff between a large group of farmers.

Although these experiments continued longer than the majority of such field experiments, Figure 2 indicates that, because of the effects of El Niño, the weather during the period of the experiment may not be representative of long-term means. RWH was also tested for only a limited range of environmental conditions and management practices. How it would behave under different conditions is difficult to predict from the experimental data alone. In order to overcome the problems of spatial and temporal extrapolation, this work has been used to develop the PARCHED-THIRST simulation model (Young *et al*., 2002), which can aid in the spatial and temporal transfer of these results. Its value in assessing the potential benefits of alternative RWH interventions is demonstrated in Part 2 of this paper (Gowing *et al*., 2003).

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REFERENCES

Barrow, C. J. (1999). *Alternative Irrigation: The Promise of Runoff Agriculture.* London: Earthscan Publications.

Boers, T. M. and Ben-Asher, J. (1982). A review of rain water harvesting. *Agricultural Water Management* 5:145–158.

Carter, D. and Miller, S. (1991). Three years experience with an on-farm macro-catchment water harvesting scheme in Botswana. *Agricultural Water Management* 19:191–203.

Critchley, W. and Siegert, K. (1991). Water harvesting: A manual for the design and construction of water harvesting schemes for plant production. *Report ACL/MISC/17/91, Food and Agriculture Organization of the United Nations*, Rome.

DLFRS (1984). Phase III. *Fifth Annual Report, Dryland Farming Research Scheme, Sebele, Botswana.*

El-Amami, S. (1977). Traditional technologies and development of the African environments, utilisation of runoff waters: the 'Meskats' and other techniques in Tunisia. *African Environments* 3(3/4):107–120.

Evenari, M., Shanan, L. and Tadmor, N. (1982). *The Negev: The Challenge of a Desert.* Cambridge, MA: Harvard University Press.

FAO (1998). *World Reference Base for Soil Resources.* Rome: Food and Agriculture Organization of the United Nations.

Gommes, R. A. and Houssiau, M. (1982). Rainfall variability, types of growing seasons and cereal yields in Tanzania. *Proceedings of the Technical Conference on Climate in Africa. World Meteorological Organization Publication No. 596* :312–324.

Gowing, J. W., Young, M. D. B., Hatibu, N., Mahoo, H. F., Rwehumbiza, F. and Mzirai, O. (2003). 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. *Experimental Agriculture* 39:293–306.

Herweg, K. and Ludi, E. (1999). The performance of selected soil and water conservation measures – case studies from Ethiopia and Eritrea. *Catena* 36:99–114.

Imbira, J. (1986). Runoff harvesting for crop production in semi-arid areas of Baringo. *In* Soil and Water Conservation in Kenya. *Proceedings of Third National Workshop, Kabete, Nairobi, Kenya, 1986.*

Jones, E. and Nyamudeza, P. (1991). The relationship between rainfall and the yield of cotton, sorghum and maize grown in tied furrows and on the flat in the south-east Lowveld of Zimbabwe. *Proceedings of the Second Annual Scientific Conference, Southern African Development Community-Land and Water Resources Management Plan, Mbabane, Swaziland, 1991.*

Kiome, R. and Stocking, M. (1993). Soil and water conservation in semi-arid Kenya. *Bulletin 61, Chatham, UK: Natural Resources Institute.*

Land Resources Department (1987). *Tanzania, Profile of Agricultural Potential.* Chatham, UK: Natural Resources Institute.

Lazaro, E. A., Senkondo, E. M. M. and Kajiro, G. J. (1999). A small push goes a long way: farmers' participation in rainwater harvesting technology development. *Tanzania Journal of Agricultural Sciences* 2(2):219–226.

Maurya, P. R. and Lal, R. (1980). Effects of no-tillage and ploughing on the roots of maize and leguminous crops. *Experimental Agriculture* 16:185–173.

Meertens, H., Ndege, L. and Lupeja, P. (1999). The cultivation of rainfed lowland rice in Sukumaland, Tanzania. *Agriculture, Ecosystems and Environment* 76:31–45.

Ngugi, M. N. and Micheieika, R. W. (1986). Current findings on conservation tillage in a medium potential area of Kenya. *In* Soil and Water Conservation in Kenya. *Proceedings of Third National Workshop, Kabete, Nairobi, Kenya, 1986.*

Pacey, A. and Cullis, A. (1986). *Rainwater harvesting: the collection of rainfall and runoff in rural areas.* London: Intermediate Technology Publications.

Prinz, D. (1995). Water harvesting techniques in the Mediterranean region. *In* Rainwater harvesting and management of small reservoirs in arid and semi-arid areas, (Ed. Berndtson, R.). *Proceedings of an expert seminar. Lund University, Sweden.*

Rees, D. J., Qureshi, Z. A., Mehmood, S. and Raza, S. H. (1991). Catchment basin water harvesting as a means of improving the productivity of rain-fed land in upland Balochistan. *Journal of Agricultural Science* 116:95–103.

Reij, C. (1991). Indigenous soil and water conservation in Africa. *Gatekeeper Series, International Institute for Environment and Development, London, No. 27.*

Rockstrom, J. (2000). Water Resources Management in Smallholder Farms in Eastern and Southern Africa: An Overview. *Physics and Chemistry of the Earth (B)* 25(3):275–283.

Stahl, M. (1993). Combating land degradation in eastern Africa-technical, institutional and social aspects. In *Acceptance of Soil and Water Conservation Strategies and Technologies,* (Eds Baum, E., Wolff, P. and Zobisch, M.). Witzenhausen, Germany: Deutsches Institut fur Tropische und Subtropische Landwirtschaft.

Thornton, R. J. (1980). *Space, Time and Culture among the Iragw of Tanzania.* New York: Academic Press.

Tiffen, M., Mortimore, M. and Gichuki, F. (1994). *More People, Less Erosion: Environmental Recovery in Kenya.* Chichester, UK: J. Wiley.

van Dijk, J. and Ahmed, M. H. (1993). Opportunities for expanding water harvesting in sub-Saharan Africa: the case of the teras of Kassala. *Gatekeeper Series, International Institute for Environment and Development, London, No. SA40.*

Wilcocks, T. J. and Gichuki, F. (1996). Conserve water to save soil and the environment. *Report IDG/96/15. Silsoe Research Institute, UK.*

Young, M. D. B., Gowing, J. W., Wyseure, G. C. L. and Hatibu, N. (2002). PARCHED-THIRST – development and validation of a process-based model of rainwater harvesting. *Agricultural Water Management* 55:121–140.