Performance of Maize under Micro-Catchment Rainwater Harvesting in Western Pare Lowlands and Morogoro, Tanzania

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Abstract

Micro-catchment Rainwater Harvesting (RWH) has been defined as a method of collecting run-off from a Catchment Area (CA) over short distances not exceeding 100 m and supplying it to an adjacent Cultivated Basin (CB). It is a system that is designed to concentrate rainwater so as to utilize it more effectively in areas where the seasonal rainfall amounts are frequently lower than crop water requirements. The Catchment to Basin Area Ratio (CBAR) is an important parameter in the design of micro-catchment systems. It usually varies between 1:1 and 10:1. However, methods for deciding the optimum level of CBAR for different farming systems are not available. The purpose of the experiments reported here was to evaluate the CBAR for maize production in semi-arid areas of Tanzania. The experiments were run between 1992 and 1995 in semi-arid areas of Morogoro and Mwanga Districts of Tanzania, to assess the performance of maize grown in micro-catchment systems with CBAR varying from 0:1 to 4:1. Maize var. TMV1 was grown in Mwanga District while maize var. Staha was used as a test crop in Morogoro District. Grain was harvested in five out of six experimental seasons in Mwanga (Masika 1993, 1994 and 1995 and Vuli 1994/1995 and 1995/1996). In Morogoro, grain harvest was obtained only in two seasons (Masika 1993 and 1994) out of four. The results showed that micro-catchment RWH farming is feasible during Vuli. The yield benefits due to RWH were found to be 120 – 152 % and significant at P = 0.05. The benefits during Masika were found to be very low at only 12 – 17 % and not significant at P = 0.05.

Key words: Micro-catchment, rainwater harvesting, catchment area, cultivated basin

Introduction

Rainwater harvesting is defined as a process of collecting, concentrating and stroring variuos forms of runoff for various purposes (Myers, 1975). The collected runoff can be used for several purposes such as to improve soil-moisture for plants, to supply water for livestock and domestic purposes and to recharge the groundwater (Frasier, 1994).

Depending on the storage capacity available in the root zone, the first step in the management of rainwater for plant growth is to capture it and enhance its infiltration into the soil profile.

The next step of equal importance is to prevent or reduce water losses from the root zone. The third step is to implement cultural practices to ensure that the crop makes the most effective use of the scarce water. The techniques for achieving these have been developed and promoted extensively under the subject of Soil and Water Conservation (SWC) (Tiffen et al., 1994, Thomas, 1997, Hudson, 1992).

In order to improve the productivity of rainwater in semi-arid areas it is often necessary to concentrate it into a small area of use. The focus of this paper is on micro-catchment RWH systems. A number of techniques have

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been developed in different countries (Prinz, et al., 1994, Reij et al., 1988). All techniques have two major components; a Catchment Area (CA) and Cultivated Basin (CB) (Figure 1). The CA is always directly up-slope of the CB and the water flows directly to the basin for storage in the soil. The CA is treated and managed in ways that encourage the generation of high amount of run-off.

Runoff generation and conservation

The runoff yield of a catchment is a complex function of the characteristics of land surface, soil type and rainfall (Oweis et al., 1999). Slope, length, cover and roughness are the most important characteristics. The length of a catchment has the most important effect on determining peak discharge, rise time, total runoff time and water harvesting potential. Runoff coefficient and peak runoff decreases with increasing catchment length although the total runoff from a large catchment is higher (Boers and Ben-Asher, 1982).

The vegetation cover and roughness encourage infiltration and reduce the runoff yield from a given area. This is a consequence of depression storage that provides more time and opportunity for the evaporation and infiltration of the rainwater. The nature of the soil where the rain falls is a very important determinant of how much runoff can be expected. The main controlling factors are infiltration rate, water holding capacity and hydraulic conductivity of the soil.

The rate of infiltration and therefore runoff is also greatly affected by the rainstorm amount, intensity and distribution of rainfall. A high amount will quickly saturate the soil and the excess will be released as runoff. High intensity rainstorms will lead to high runoff, because the intensity will exceed the rate of infiltration of the soil. Rain falling with long dry spells between storms will often reduce runoff yield because the catchment will dry up during the dry spell, and therefore the soil will be able to absorb more of the rainfall received during a subsequent storm.
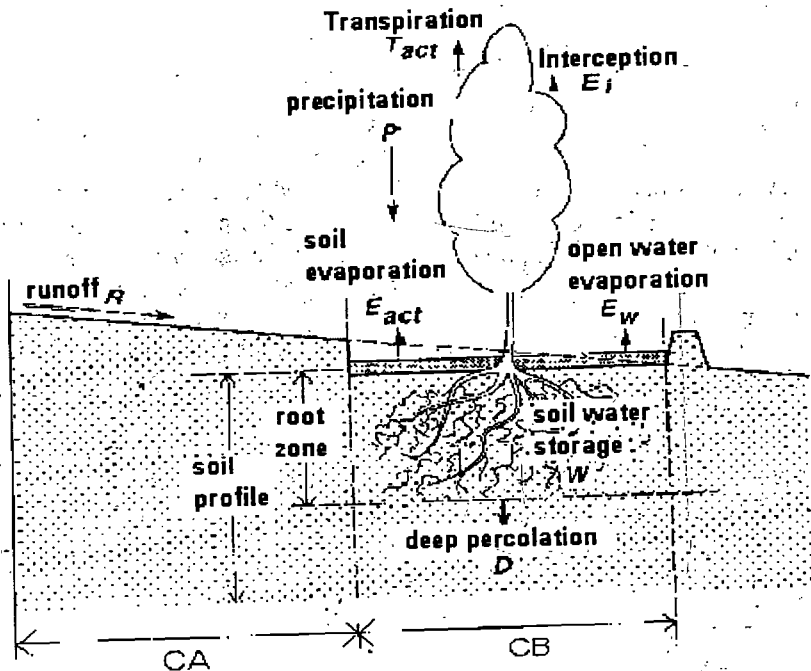

Figure 1:   Interaction between the four facets of RWH (Boers, 1994)

The Catchment to Basin Area Ratio

The key requirement in the design of micro-catchment systems is to select an optimum value of the CBAR that will allow efficient run-off yield and optimum utilization of the water added to the CB. The key parameters can be presented as shown in Figure 2.

During a rainfall event, water balance on the CA is given by:

$$R_o = R_e - E_{CA} - 1 \qquad (1)$$

where:

R_o = surface run-off

R_e = effective rainfall

E_{CA} = actual evaporation from catchment area

1 = infiltration

At the same time from the CB point of view, the most important parameter is the change of water stored in the root zone. Therefore, the water balance equation for the CB is given by:

$$\Delta_w = R_e + R_o - E_{CB} - D_p \qquad (2)$$

where:

Δ_w = change of water stored in the root zone

R_e = effective rainfall amount (assumed to be the same on both CA and CB)

R_o = run-on into the CB (= R_o from the CA)

E_{CB} = actual evaporation from the CB

D_p = water lost from the root zone due to deep percolation.

It is assumed that the water table is too low to affect this balance.

The ultimate goal is to optimize Δ_w. The approach to be taken is made clear by combining equations 1 and 2 into the following single equation assuming CA = CB (Boers et al., 1986):

$$\Delta_w = 2R_e - E_{CA} - E_{CB} - 1 - D_p \qquad (3)$$

Therefore, a micro catchment RWH system should be designed to:

(i) Minimize infiltration and evaporation from the CA

(ii) Maximize infiltration on the CB while minimizing water lost to deep percolation

(iii) Minimize evaporation from water surface or bare soil on the CB.

The calculation of the CBAR is based on the concept: *"Effective water harvested = Extra water required by the crop"*.

The Catchment to Cultivated Basin Area Ratio (CBAR) is calculated using the following
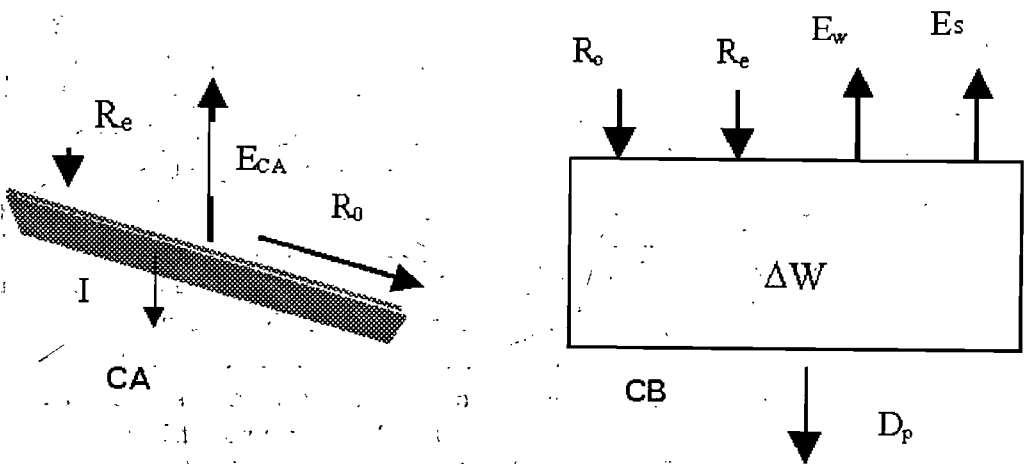

Figure 2: Water balance components of the CA and CB (Modified from Boers et al., 1986)

equation:

$$CBAR = \frac{CWR\ (mm) - DR\ (mm)}{DR\ (mm)\ x\ K\ x\ \eta} \qquad (4)$$

Where:

- Crop water requirement (CWR) is defined as the depth of water needed for evapotranspiration (ET_{crop}). The maximum value of ET_{crop} is achieved when the crop is disease free, growing in large fields under non restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Doorenbos and Kassam, 1984). Crop water requirement is influenced by climate, crop type and stage of growth. It is estimated that the crop water requirements for maize cultivar TMV1 grown in Kisangara is 590 mm in *Vuli* and 500 mm during *Masika*. However, it is not possible for a crop in a farmers' field to meet the conditions for maximum ET_{crop}. This is why an efficiency factor (η) is introduced.
- Design rainfall (DR) is defined as the total amount of rain during the cropping season at or above which the catchment area provides sufficient runoff to satisfy the crop water requirement (Critchley and Siegert, 1991).
- Runoff coefficient (K) for a given period is calculated as:

$$K = R_o/R_e \qquad (5)$$

An analysis of the rainfall-runoff relationship and subsequent determination of runoff coefficients should be based on actual, simultaneous measurements of both rainfall and runoff. For example, parallel micro-catchments experiments carried out in Kisangara showed that runoff coefficient of 30% can be expected in bare compacted catchments.

- The efficiency factor (η) represents the proportions of water the plant can actually utilize, it varies from 0.5 to 0.75. The efficiency factor depends on the distribution

of water in the field and considers all losses due to evaporation and deep percolation.

For Kisangara, the CBAR can be estimated as follows, using rainfall amount expected to be exceeded 70 % of the seasons, as design rainfall:

CBAR (*Vuli*) = (590 – 257)/(257 x 0.3 x 0.75)
= 6:1

CBAR (*Masika*) = (500 – 318)/(318 x 0.3 x 0. 75)
$\cong$ 2.5:1

The main objective of this paper is to assess the effectiveness of micro-catchment systems in the performance of maize grown in semi-arid areas.

Materials and methods

Location

The experiments were conducted in the semi-arid zones of Morogoro and Mwanga Districts. In Morogoro, the experiments were located within the Sokoine University Farm on longitude 37°39'E and latitude 6° 30'S and at an altitude of about 500 m above mean sea level (masl). The site was close to the footslopes of the Uluguru mountains which descend abruptly to the gently undulating dissected peneplain extending north and west of Morogoro. The site was formally under maize cultivation for several years before being left under fallow for two years prior to start of the experiments in 1993. In Mwanga District, the experiments were located at Kisangara within the semi-arid Western Pare lowlands (WPLL). The site was located at 37°35'E and 3° 43'S at an altitude of 870 masl. The area was under sisal production since 1975. The sisal plants were cleared in 1993 by a front mounted shear blade bulldozer, before setting up the experiments.

Soils

The soils of the Morogoro sites are reddish brown sandy clay loam. The bottom soils are sandy clay, said to originate from metasediments of Uluguru Mountains. The soils are fairly deep (>100 cm), well drained and are classified as *Typic Ustorthent* (USDA soil taxonomy system) and *Eutric Regosols* (according to FAO/UNESCO system) (Kaaya, 1989).

The dominant soil occurring in the Kisangara experimental site is *Luvisol*. *Ferric Luvisol* occupies nearly 90% of the experimental site (Ngatoluwa *et al.*, 1995). These soils occur intensively on the middle and the lower slope position. *Ferric Cambisol* and *Plinthic Luvisol* cover approximately 8% of the experimental area. The remaining 2% is occupied by small pockets of *Chromic Luvisol*.

Experimental design, layout and treatments

The experimental layout was similar for both sites and in both cases was split into two different slopes of 3 and 8 or 6%. Randomized Complete Block Design (RCBD) with three replicates was used. The treatments were as elaborated in Table 1, and the layout was as shown in Figure 3. The Cultivated basins were 50 m^2 and were 10 m long and 5 m wide. The catchments were also 5 m wide, and the different CBAR were achieved by varying the length of the catchment. Maize (*zea mays* var TMV1) was used as a test crop for Kisangara and (*zea mays* var Staha) for Morogoro.

The crop was sown at a rate of two plants per hill. At sixth leaf growth stage, the crop was thinned to one plant/hill giving a plant population of 45,000 plants/ha with the spacing of 0.75 m between rows and 0.3 m between plants. Fertilizer TSP at a rate of 40 kg P/ha was applied at sowing, and N fertilizer was applied at rate of 40 kg N/ha at six-leaf growth stage. Tillage was implemented by hand hoe to a depth of 10 cm. A "U" shaped bund was constructed around each cultivated basin to a height of 15 cm. Ridges were constructed with staggered openings, for spreading harvested water.

Table 1: Description of treatments

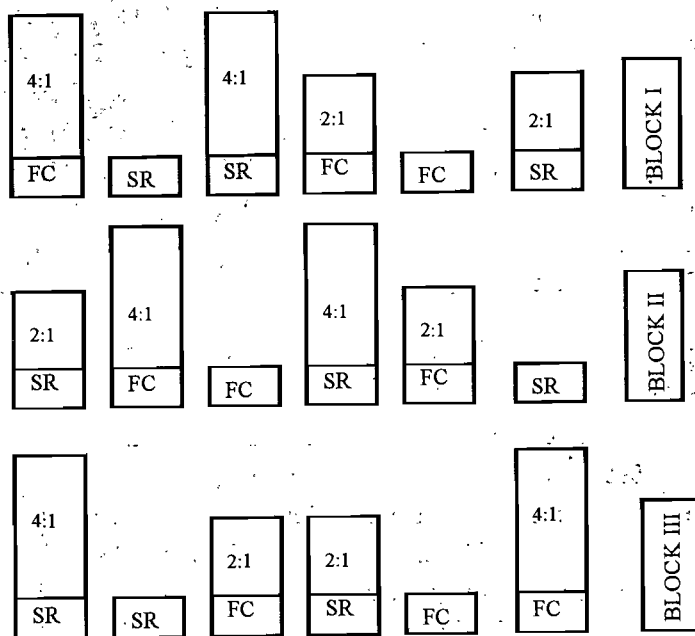| Tillage practice on the CB	CBAR	Treatment
Flat cultivation (FC)	0:1	T1
	2:1	T2
	4:1	T3
Staggered Ridging (SR)	0:1	T4
	2:1	T5
	4:1	T6

Figure 3: An example of treatments layout

Data collection and analysis

Data collected included daily rainfall (continuous and total), maximum and minimum daily temperature, pan evaporation, soil moisture content to a depth of 1.5 m, runoff from adjacent micro-catchments, agronomic data, such as biomass at six leaves and at silking stage and crop final harvest (biomass and grain yield).

Rainfall data was collected using a recording raingauge located at the Morogoro Meteorological station, about 0.5 km from the Morogoro site and at Kisangara, the recording raingauge was located 1.5 km from the site. This may have created some problems, as the rainfall in these areas is known to vary substantially over short distances (Ngana, 1991). To overcome this problem a non-recording raingauge was also used at the Kisangara site. Evaporation and temperature data was also collected for both sites. Moisture content was monitored using a neutron probe through an

access tube in the centre of each CB. Crop growth was monitored through biomass harvest at 6th leaf and at silking stages. Stover and grain yields were determined by harvesting 15 m² of well-bordered sample plots. All stover and grain were dried at 60°C until constant weight was obtained.

Descriptive analysis was used to compare long-term means and seasonal effect on grain yield. Analysis of variance (ANOVA) was used to test the effect of treatments on both biomass and grain yields.

Results

Effect of catchment to basin area ratio (CBAR) on grain yield

The grain yields as affected by the CBAR are presented in two different ways. First by considering only the cultivated basin. This is a valid approach in situations where land is not a

constraint and the aim is to enhance productivity of labor and other inputs. Secondly, yield was calculated by taking into account the total mobilized land including the catchment area. This would be necessary in areas where land is a limiting factor. When only the cultivated basin is considered the yields generally increased with increasing CBAR ratio (Tables 2 a and b).

In Kisangara, for example, there was an increase of 17% for CBAR of 4:1 over the control, during *Masika*, while the increase during *Vuli* for the same CBAR was 152%. For Morogoro, during *Masika* there was a decline in yield probably due to too much water in the CB thus causing waterlogging problems.

When presented from the point of view of land productivity, the yield per unit of mobilized land decreased with increasing CBAR (Tables 2 a and b). In this case the total harvest from the cultivated area is expressed per ha of the land occupied by the RWH systems (i.e. CA

+ CB). The long term reduction in yield compared to control, during *Masika* in Kisangara was 53% and 77% for CBAR of 2:1 and 4:1, respectively. During *Vuli* in Kisangara the long term mean reduction of yield is only about 27 and 50% for CBAR of 2:1 and 4:1, respectively, compared to increase of 120 and 152 %. Therefore, during *Vuli* a net increase in long term mean of yields per unit inputs by about 100% was obtained in Kisangara. The yield from RWH treatments was significantly (P = 0.05) higher than from the control.

Cultivated basin management

At Kisangara, the management of the cultivated basin had some effect on the grain yield. The mean grain yield from flat cultivation was 2,683 kgha^{-1} and staggered ridges being only 2,401 kgha^{-1} (Table 3). The difference in yield was significant (P = 0.05) during only a few of the seasons.

Table 2a: Effect of RWH on long-term grain yield means at Kisangara

		CB area only		Total mobilized land	
	CBAR	Mean grain yield (kgha^{-1})	% Increase due to RWH	Mean grain yield (kgha^{-1})	% Decrease in yield
Masika	0:1	2,324.1 a		2,324.1	
	2:1	2,593.0 a	12	864.3	63
	4:1	2,709.8 a	17	542.0	77
Vuli	0:1	385.4 b		385.4	
	2:1	847.8 a	120	282.6	27
	4:1	970.1 a	152	194.0	50

Table 2b: Effect of RWH on long-term grain yield means at Morogoro

		CB area only		Total mobilized land	
	CBAR	Mean grain yield (kgha^{-1})	% Increase due to RWH	Mean grain yield (kgha^{-1})	% Increase due to RWH
Masika	0:1	4,436.0 a		4,436.0	
	2:1	4,580.1 a	3.2	1,526.7	65.6
	4:1	4,087.6 a	- 7.9	817.5	81.6

Figures followed with similar letters are not significant at P = 0.05

Seasonal effects

Season effects on grain yield was observed for both Kisangara and Morogoro sites. In Kisangara the grain yield was high during *Masika* with an average of 2,542 kgha^{-1} as compared to *Vuli* season with average yield of 734 kgha^{-1}. There was both significant difference between the season and treatment at P = 0.05 (Table 4). In Morogoro, grain yield was only harvested during *Masika*, where the average grain yield obtained in *Masika* season was 4,368 kgha^{-1} (Table 4).

Effect of slope

The effect of slope on grain yield was observed in Kisangara between 8 % and 3 % slopes and in Morogoro between 6 % and 3 % slopes. In both sites the grain yield was slightly higher in the 3% slope (Table 5). This may be explained by the difference in fertility due to removal of nutrients from the upper area and their deposition on the lower area. Another reason may be that the plots on 3% received water through subsurface flow from the upper part.

Table 3: Effect of tillage practice on the grain yield

Site	Tillage Practice	MASIKA 1993	1994	1995	Mean	VULI 1993/94	1994/95	1995/96	Mean
Kisangara	FC	1844.3	3047.0	3159.0	2683.4	-	865.7	769.3	817.5
	SR	1209.7	2902.3	3091.3	2401.1	-	671.2	631.5	651.3
Morogoro	FC	4135.6	4990.1	-	4562.9	-	-	-	-
	SR	3980.3	4366.8	-	4175.6	-	-	-	-

Figures followed with similar letters are not significant at P = 0.05

Table 4: Seasonal effects on grain yield (kgha^{-1}) for Kisangara and Morogoro sites

Treatments	Kisangara [1] Masika	Vuli	Morogoro Masika	Vuli
T1	2502.3	361.3 b	4645.1	-
T2	2145.8	409.5 b	4228.7	-
T3	2779.2	1079.5 a	4512.1	-
T4	2406.8	616.0 ab	4648.1	-
T5	2768.8	1011.8 a	4531.4	-
T6	2650.7	928.5 a	3643.9	-
Mean	2542.3	734.4	4368.1	-

Figures followed with similar letters are not significant at P = 0.05

[1] At Kisangara, all treatments had significantly (P = 0.05) higher grain yield during *Masika* than the corresponding treatment in *Vuli*
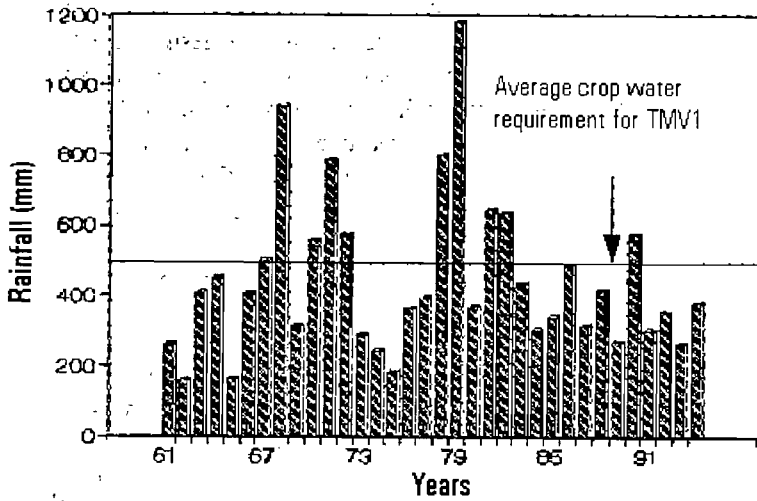
Table 5: **Effect of slope on grain yield**

Slope	Kisangara		Morogoro	
	Masika	*Vuli*	*Masika*	*Vuli*
8% (6%)[1]	2664.8	954.0	4355.3	-
3%	2866.0	514.1	4381.2	-
	**	**	**	

[1] Slope 6% was used in Morogoro experiments
** Not significant at P = 0.05
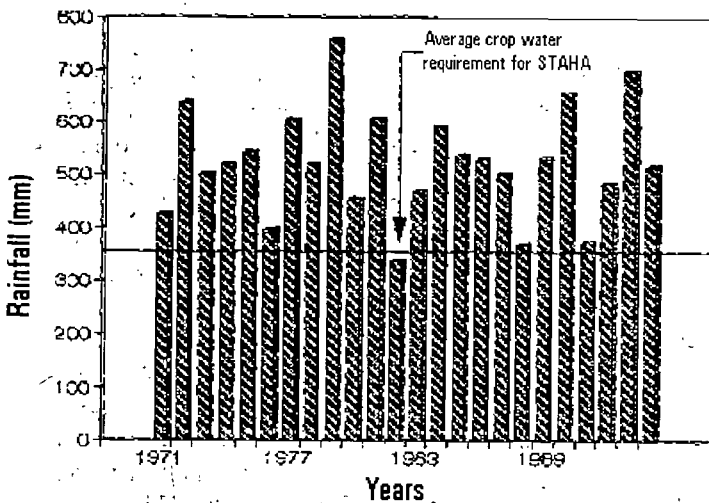
(a)   Kisangara

(b)   Morogoro

Figure 4:   Comparison of historical *Masika* rainfall and average maize water require-
ment, in Morogoro and Kisangara

Combined effect

At Kisangara during *Masika*, overall highest yield was observed in treatment T3 (4:1 CBAR, Flat Cultivation) with a long-term mean grain yield of 2,779 kgha⁻¹ (Table 5). There was a significant difference (P = 0.05) between the treatments during *Vuli* in Kisangara. The highest grain yield was obtained in treatment T5 (2:1, Staggered Ridges). In Morogoro there was no significant difference of the treatments.

Discussion

This study has shown that the yield increase benefits obtained from micro-catchment RWH are low during *Masika* season on both sites. The main explanation is that the crop water requirement is adequately met during this season (Figure 4). This explains the minimal effect obtained from addition of water. This is also made clear by estimation of CBAR illustrated in equation 7. During *Vuli*, the benefits from RWH were large indicating that soil-water available to plants is limiting as illustrated in equation 6. However, the low overall yields compared to *Masika* indicate that the CBAR used in this study were too low. The difference between *Vuli* and *Masika* in relation to the performance would be as expected. Similar trends have been observed in experiments in Kenya (Critchley, 1989; Kilewe and Ulsaker, 1984).

The total failure of the crop to yield grain in Morogoro during *Vuli* requires some explanation. An analysis of the long-term rainfall patterns of both Kisangara and Morogoro may provide the explanation (Mahoo *et al.*, 1999). In Morogoro the *Vuli* season starts very late, as indicated by monthly rainfall amounts. Rainfall expected 70% of the time during the months of October, November, December and January, is 10 mm, 37 mm, 59 mm and 48 mm, respectively. In Kisangara, the trend is 8 mm, 78 mm, 52 mm and 18 mm. Therefore, rainfall

during the first two months of the season in Morogoro was only 50% of what was obtained in Kisangara. This means that there was less rainwater to harvest in Morogoro at the beginning of the *Vuli* season, which reduced the benefits of RWH. This is an important factor in determining the potential of RWH as discussed by other researchers such as Fraiser (1990) and Perrier (1988), as quoted by Oweis *et al.* (1999). These findings show the importance of using shorter durations (such as monthly or even 10-day periods) in assessing the rainfall characteristics. It is emphasized that the total seasonal or mean rainfall amounts are often misleading in designing RWH systems. This is exactly what is demonstrated by the findings of this research. At the same time the difference in varieties grown on the two sites may also explain the large difference in crop performance between the sites.

The increase in yield from the small-cultivated basin especially during *Vuli*, means that RWH assist in improving productivity of labour and other inputs. For example, in Kisangara the productivity of cultivated basin was increased by a factor of 2.5 through RWH. This means that labour and inputs expended on this small area become more productive. The implication of these findings is that a farmer with a RWH system with a CBAR of 2:1, cultivates and uses inputs on only 33% of the field. During *Vuli*, the cultivated area will produce more by a factor of 2.5, almost compensating for what would be obtained from the area left as catchment. However, the farmer would benefit by the fact that all the inputs were cut down to only 33% with only a small reduction in total harvest. On this basis, RWH leads to improved productivity of inputs such as labour and fertilizer.

However, the increase was not large enough to compensate for the land used as catchment area. This means that using micro-catchment RWH for maize production may cause reduction in land productivity. This may not be acceptable in areas where there is scarcity of good land for cultivation.

Conclusion

Micro-catchment RWH for maize production would significantly improve the productivity of labour and other inputs in an area of very low rainfall (less than 300 mm per season) or *Vuli* seasons. However, the benefits of the system can only be realised if the rainfall distribution is such that a high proportion is obtained during the beginning of the season. At the same time, the system does not give significant benefits during *Masika* seasons. In general, micro-catchments for maize production can be justified and would be accepted only in areas where there is no scarcity of good land for cultivation, to allow for the requirement to have a catchment area adjacent to the crop basin.

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