Trends of productivity of water in rain-fed agriculture

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Abstract
In Sub-Saharan Africa, rain-fed agriculture is the dominant source of food production. It is likely to remain so for the foreseeable future. However, yields from rain-fed agriculture are often very low. But there is an enormous opportunity to raise crop yield of rain-fed agriculture especially by focusing on the aspect of increasing productivity of water. In order to formulate and adopt appropriate and adequate options for increasing productivity of water in rain-fed agriculture, there is a need to have an understanding of the trend of productivity of water in rain-fed agriculture. In this paper, an analysis of the trend of productivity of water (PW) for five crops cultivated under rain-fed conditions in Mbarali District, Mbeya Region, Tanzania, was carried out using secondary data. The crops included maize, sorghum, beans, potato, and groundnut. The $PW_{(eta)}$ *for maize, sorghum, potato, beans and groundnut had peak values of* $0.49 kg/m^3$ *in 1993/94,* $0.47 kg/m^3$ *in 1994/95,* $3.07 kg/m^3$ *in 1993/94,* $0.33 kg/m^3$ *in 1996/97, and* $0.20 kg/m^3$ *in 1994/95 cropping seasons, respectively. Evapotranspiration deficit caused by either mid cropping-season dry spell or early cessation of rainfall and low rainfall utilization efficiency were the primary drivers of the PW in rain-fed agriculture in the area.*

Key words: Productivity of water, Crop yield, Crop water requirement, Evapotranspiration deficit

Introduction

About 95% of current world population growth occurs in tropical developing countries with rural economies based on rain-fed agriculture (Rockstrom et al., 2003*)*. In Sub-Saharan Africa, rain-fed agriculture has been the dominant source of food production. It is likely to remain so for the foreseeable future, since more than 95% of the agricultural farmland is under rain-fed agriculture (Parr *et al*., 1990; Rosengrant *et al., 2000)*. The common characteristics of rain-fed agriculture, especially in the tropical and the semi-arid agroecosystems are low crop yields far below potential yields attainable in the regions, and high on-farm water losses. For example, in tropical and semi-arid Sub-Saharan Africa, cereal yields from rain-fed cultivation have been reported to be generally around 1 t ha^{-1} *(*Rockstrom et al., 2003*)* as against potential yields attainable in the region, which are reported as 3-5 t ha^{-1} *(Barron, 2004)*.

This wide yield gap suggests that there is an enormous opportunity to raise crop yields of rain-fed agriculture. According to McCalla (1994) and Young (1999), new lands that can be put under agriculture are limited, contrary to the last three decades, where the bulk of food production in Sub-Saharan Africa came from expansion of agricultural lands. The opportunities to increase crop yields under rain-fed agriculture strongly rest on focusing our attention on maximizing yield per unit of water applied. In order to formulate and adopt appropriate and adequate options for increasing productivity of water in rain-fed agriculture, it is worthwhile to have an understanding into the performance of this sector from trends analysis of the productivity of water of crops cultivated under rainfall. Such insight will enable us to identify possible factors that dictate productivity of water in rain-fed agriculture and their magnitude.

The primary objective of this paper therefore is to show the trends of productivity of water (PW) for some selected crops commonly cultivated under rain-fed agriculture and identify the forces dictating PW. The crops include: maize, sorghum, beans, potato, and groundnut. The case study is that of Mbarali District of Mbeya Region, Tanzania.

Methodology

The location of the study area

The Mbarali District, which lies between latitudes $7^0$48' and $9^0$25' South, and longitudes $33^0$40' and $34^0$09' East, is one of the districts of Mbeya Region in Tanzania. The district lies in the heart of the plains of the Great Ruaha River Basin. The economy of the district is agrarian based, with more than 80 % of the adult population involved in farming. Crop production in the district relies largely on rainfall. Beside paddy rice that is cultivated within the formal and indigenous irrigation schemes in the district under supplementary irrigation, other corps cultivated in the district under rain-fed agriculture include maize, sorghum, potato, beans, and groundnut. The study reported here was focused on the trends of productivity of water for these crops.

Sources of climatic and crop yield data

In order to develop the trends of productivity of water for the rain-fed crops, weather data comprising rainfall, temperatures, relative humidity, sunshine hours and wind speed were obtained from two weather stations within the district. These stations are the Kapunga and the Igurusi weather stations. Weather data for a period of 11 years (agricultural years of 1989/90 to 1999/2000) were used. The crop yield and area cultivated to these major rain-fed crops were obtained from the archives of the Mbarali District Agricultural Office. Annual records of the crop yields and the total area cultivated to each crop during a cropping season are kept in the District Agricultural Office.

Simulation of crop water requirements and water use

The weather data (rainfall, maximum and minimum temperatures, relative humidity, wind speed and sunshine hour data) obtained from the weather stations was input into the FAO CROPWAT model version 4.2 to generate the crop water requirements and crop water use (actual evapotranspiration) for each crop and for each cropping seasons from 1989/90 to 1999/2000. The FAO CROPWAT model was adopted for this study because it is simple to use and the default crop input parameters are widelyapplicable.

For the crops under study, the crop parameters required as input data in the model, which include crop coefficient (Kc), rooting depth and depth of moisture extraction, were taken as the default data for the respective crops in the CROPWAT model. The other crop parameters, which include planting dates and length of crop growing period for each crop, were adjusted to the cropping calendar in the study area. The cropping calendar for the crops, especially planting dates was dictated by the period of the onset of rains, which varies from third decade of November to second decade of January. For the purpose of simulation, the planting dates for the crops were assumed to be from the period when the rainfall is established. In general, most of the rain-fed crops are planted between the first decade of December and the first decade of January in the district, depending on when rainfall is established and the soils soft enough for tillage. Assumption on date of planting had to be made because there were no records on exact dates the crops were planted.

Computation of productivity of water

The Productivity of Water (PW) was calculated for each crop for each cropping season. The productivity of water under rain-fed condition (PW_{rf}) was expressed as:

$$PW_{(rf)} = \text{crop yield (kg)/ rainfall in the cropped area (m}^3\text{)} \quad (1)$$

The productivity of water use (also referred to actual evapotranspiration) (PW_{eta}) was expressed as:

$$PW_{(ETa)} = \text{crop yield (kg)/crop water use (m}^3\text{)} \quad (2)$$

Evapotranspiration deficit is the difference between the crop water requirement and crop water use (actual evapotranspiration)

Results and Discussion

Rainfall

Table 1 shows the average of the two stations' monthly mean weather data (except rainfall, which were average monthly total) for the years under study. Table 2 shows the average of the two stations' rainfall data from 1989/90 to 1999/2000 agricultural years. The least annual rainfall was 422 mm in the 1996/97 and the highest was1460mm in 1989/90 agricultural years. The mean annual rainfall for the years under study was 736.7mm. The high record of rainfall in 1989/90 cropping year was due to torrential rainfall in some few days in the month of March as observed from the daily weather records. The rainfall recorded in March alone was 868mm, which was higher than the total rainfall of the other months in the cropping season put together.

Table 1. Mean monthly climatic data for Mbarali District

Month	Rainfall mm	Max. Temp °C	Min Temp °C	Rel. Hum %	Wind Speed km/day	Sunshine hr
November	33.6	30.9	19.5	61.2	217	9.6
December	122.4	30.6	18.6	76.3	138.2	7.3
January	169.1	28.3	18.4	78.9	79.6	5.8
February	165.4	29.8	17.3	85.8	71.3	5.1
March	168.8	30.2	16.2	78.5	70.6	7.7
April	67.5	30.4	16.3	74.3	102.9	8.9
May	6.7	29.5	13.5	65.8	91.3	9.4
June	0.4	28.5	11.2	56.8	68.1	10.7
July	0	28.9	9.2	55.9	119.6	10.7
August	0	29.7	11.2	59.7	177.9	9.7
September	0.7	30.9	12.1	58.3	174.7	10.5
October	2.1	32.3	16.9	58.9	183.2	9.8

Table 2. Total monthly rainfall for Mbarali District

Season	89/90	90/91	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00
November	63	5	9	40	17	15	0	0	0	0	55
December	136	105	151	40	26	61	189	98	245	49	154
January	152	275	102	202	156	138	161	131	229	116	98
February	129	137	215	172	158	140	217	132	120	46	114
March	868	90	110	146	197	85	79	19	40	153	163
April	104	205	47	32	14	15	67	44	77	87	40
May	0	2	34	10	2	0	0	0	23	0	1
June	0	0	3	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0
September	0	7	0	0	1	0	0	0	0	0	1
October	9	10	2	0	0	0	0	0	0	0	0
Total	1460	836	673	642	570	454	714	422	734	451	625

Crop yields

Table 3 shows the crop yields for the cropping seasons under study. Cropping season here referred to the period from planting to harvesting of the crop. The grain yield for maize varied from 0.67 t/ha in 1996/97 cropping season to 3.0 t/ha in 1995/96 cropping season. The grain yield for sorghum varied from the least value of 0.80 t/ha recorded in first the three cropping seasons under review to 1.85 t/ha in 1993/94 cropping season The yield for potato varied from 5.00 t/ha in 1999/2000 cropping season to 16.00 t/ha in 1993/94 cropping season The grain yield for beans and groundnut varied from 0.4 t/ha in 1999/2000 cropping season to 1.11 t/ha in 1996/97 cropping season and 1.20 t/ha in 1997/98 cropping season, respectively.

Although the peak values of the crop yields may not be within the range of the potential yields attainable in the sub-Saharan Africa, they could be regarded as appreciably good bearing in mind that these values represent a pooled (or aggregate) yield for the entire district. It is well known in the study area that the larger population of the farmers plant different kinds of local and composite varieties, not hybrids, because the local varieties and composites are more tolerant to moisture stress and common diseases in the area, but the genetic yield potential of these local varieties are not as high as the hybrids.

Table 3. Crop yield for rain-fed crop in Mbarali District (t/ha)

Cropping Season	Maize	Sorghum	Potato	Beans	G/nut
1989/90	2.30	0.80	9.00	0.80	0.70
1990/91	1.80	0.80	7.00	0.80	0.90
1991/92	2.00	0.80	12.00	0.80	0.90
1992/93	1.56	1.34	5.50	0.84	0.91
1993/94	2.40	1.85	16.00	1.00	0.80
1994/95	1.20	1.62	6.00	0.80	0.70
1995/96	3.00	0.90	6.70	0.96	0.50
1996/97	0.67	0.91	7.10	1.11	0.70
1997/98	2.60	1.26	10.00	1.00	1.20
1998/99	0.90	1.36	5.94	0.75	0.52
1999/2000	1.50	1.00	5.00	0.40	0.40

Crop water requirements and water use

Table 4a and 4b shows the total rainfall for each crop growing season, the crop water requirements, crop water use (actual evapotranspiration), and evaptranspiration deficit for the crops under study. Crop water use was found to be appreciably lower than crop water requirement for all the crops in all the cropping seasons under consideration except in 1995/96 cropping season where the differences were quite small. The crop water use was within the range of 180 mm to 375 mm/season for maize; 160mm to 360 mm/season for sorghum; 320mm 450 mm/season for potato; 220 mm to 320 mm/season for beans, and 175mm to 430 mm/season for groundnut. The values in the lower range were experienced in the 1994/95 cropping season. This may have been attributed to low amounts of rainfall in March and April that season. The values in the upper range were experienced in the 1995/96 cropping season, which experienced early on-set of rains and good amount of rainfall throughout the cropping season. The average crop water requirements for rain-fed maize, sorghum, potato, beans, and groundnut were: 378mm, 359mm, 484mm, 344mm, and 471mm per season, respectively.

Table 4a. Seasonal rainfall (TRF), crop water requirement (CWR), actual evapotranspiration (ETa), and evapotranspiration deficit (ETd) for rain-fed maize, sorghum and potato.

Crop Season	Maize TRF (mm)	CWR (mm)	ETa (mm)	ETd (mm)	Sorghum TRF (mm)	CWR (mm)	ETa (mm)	ETd (mm)	Potato TRF (mm)	CWR (mm)	ETa (mm)	ETd (mm)
89/90	1226.2	378.9	310.7	68.2	1270.4	360.3	311.2	49.1	1264.0	461.0	363.0	98.1
90/91	631.8	379.0	316.8	62.2	685.5	360.3	319.5	40.8	645.7	461.0	390.6	70.4
91/92	578.4	379.0	339.9	39.0	571.4	360.3	320.7	39.6	607.3	461.8	415.1	46.7
92/93	530.7	387.6	264.3	123.3	519.8	369.3	244.7	124.6	570.9	461.4	375.4	86.0
93/94	487.5	389.4	248.3	141.1	487.5	369.3	234.3	135.0	521.6	517.4	372.9	144.4
94/95	360.0	389.4	186.8	202.6	342.7	372.5	166.0	206.5	392.2	517.4	317.4	200.0
95/96	756.6	380.1	374.5	5.6	757.5	361.8	357.3	4.5	662.3	517.4	442.9	74.5
96/97	347.6	383.6	195.5	188.0	354.5	363.6	197.2	166.4	382.5	489.4	278.0	211.4
97/98	587.9	379.0	261.8	117.2	599.4	359.2	263.4	95.8	543.6	484.8	307.2	177.6
98/99	370.3	388.2	276.5	111.7	365.9	369.3	271.5	97.8	378.8	476.1	311.4	164.8
99/00	509.3	378.3	319.5	58.9	491.9	360.3	324.7	35.6	467.5	484.7	347.1	137.6

Table 4b. Seasonal rainfall (TRF), crop water requirement (CWR), actual evapotranspiration (ETa) and evapotranspiration deficit (ETd) for rain-fed beans and groundnut

Crop Season	Beans TRF (mm)	CWR (mm)	ETa (mm)	ETd (mm)	Groundnut TRF (mm)	CWR (mm)	ETa (mm)	ETd (mm)
89/90	935.7	310.4	237.5	72.9	1271.6	473.6	371.7	101.9
90/91	552.7	310.4	286.1	24.3	771.3	473.6	396.9	76.7
91/92	520.3	310.4	304.3	6.1	587.3	473.6	354.2	119.4
92/93	502.4	315.3	263.0	52.3	532.3	484.2	269.5	214.7
93/94	510.5	430.8	410.3	20.5	487.5	486.8	252.4	234.4
94/95	375.1	340.8	279.0	61.8	342.7	491.2	176.0	315.3
95/96	575.3	344.3	315.2	29.1	813.4	473.6	430.0	43.6
96/97	339.5	340.8	224.3	116.4	359.2	478.6	211.4	267.2
97/98	523.0	344.3	265.8	78.5	636.9	471.8	308.4	163.4
98/99	333.2	333.7	243.9	89.8	370.8	485.1	284.7	200.3
99/00	419.4	346.5	274.2	72.3	541.8	470.6	365.5	105.1

Evapotranspiration deficit ranged from 5.61 mm to 202.56 mm for maize; 4.46 mm to 206.5 mm for sorghum; 5.66 mm to 192.66 mm for millet; 74.46 mm to 199 mm for potato; 29.06 mm to 61.8 mm for beans; 75.26 mm to 258.78 mm for sunflower and 43.58 mm to 315.26 mm for groundnut, respectively. These deficits were associated with low rainfall, midseason dry spell or early cessation of rainfall. The 1994/95 cropping season was characterised by late on-set of rains, with only 60mm recorded in December, low rainfall in March recording 84.6mm, and early withdrawal or cessation of rains in April. The late take-off of rains may have delayed land cultivation and planting till late December to early January. Low rainfall in March and early withdrawal of rains in April led to high evapotranspiration deficit, and consequently low yields. The same trend was noticed in the 1996/97 and 1989/99 cropping seasons, which also recorded very high evapotranspiration deficits and low crop yields.

The drought in February 1999 may have been responsible for the crop failure (and low yields) in the 1998/99 cropping season. The season experienced late onset of rains so that planting was done in late December and early January. The drought spell met the crops at their full vegetative and early flowering growth stages and had severe impact on crop yields. It may also be noticed that when there is early onset of rains (when rainfall starts in late November and becomes established in the first and second decade of December) and planting was done in first and second decade of December, drought spell in March or early cessation of rains in April have little impact on crop yield, even though evapotranspiration deficits may be high. This is because grain crops like maize; sorghum, millet and beans would have entered into their maturity growth stages at this period. This may explain the good yields in the 1997/98 cropping season despite fairly high evapotranspiration deficit.

Although, poor yields in rain-fed crops in the area is commonly attributed to farmers not planting high yielding crop varieties and not using fertilizers, high evapotranspiration deficits as noticed across the years and for all the crops may be the true cause of poor yields. When the rains are established early in the cropping season and farmers are able to plant early, and carry out other recommended farming operations on time, which help to improve rainfall utilization efficiency, high crop yields can be obtained even with local crop varieties, as noted for maize and sorghum in 1997/98 cropping season. With high yielding varieties and adequate fertilization, crop yields will still turn out to be poor if crop water requirements are not met. In many cases the local crop varieties are more adaptable to moisture stress than the improved, high yielding crop varieties.

Crop Water Productivity Trend of Rain-fed Crops

Table 5 shows the productivity of water in terms of rainfall (PW_{rf}) and evapotranspiration (PW_{ETa}) for maize, sorghum, potato, beans and groundnut. $PW_{(rf)}$ varied from 0.19kg/m^3 in 1989/90 to 0.49kg/m^3 in 1993/ 94 cropping season for maize; and from 0.06kg/m^3 in 1989/90 to 0.47kg/m^3 in the 1994/95 cropping season for sorghum. The $PW_{(rf)}$ for potato, beans and groundnut varied from 0.712 kg/m^3 in 1989/90 kg/m^3 to 3.07 kg/m^3 in 1993/94, 0.09 kg/m^3 in 1989/90 to 0.33 kg/m^3 in 1996/97, and 0.06 kg/m^3 in 1989/90 to 0.20 kg/m^3 in 1994/95, respectively.

Figures 1(a-e) show the trend of crop water productivity (kg/m^3) for each crop across the cropping seasons under review. The trends did not show close similarities among the crops. This implies that the circumstances that may induce the crops to attain peak PW were not the same for all the crops. However, the least values of $PW_{(rf)}$ for the five crops were recorded in 1989/90 cropping season; maize and potato attained peak PW $_{(rf)}$ in 1993/94 cropping season, while sorghum and groundnut attained peak $PW_{(rf)}$ in 1994/95 cropping season. Sorghum and groundnut also attained peak $PW_{(ETa)}$ in the same cropping season. The 1989/90 cropping season experienced the highest amount of rainfall with some torrential rainfall in March. These torrential rainfalls only generated runoff, and were not beneficially used by the crop to increase yield or water use. More so, since there was early on-set of rains, planting would have started in the first or second decade of December. From late March, crops would be attaining maturity. High rainfall in April may not necessarily increase crop yield. The implication of torrential rainfall *vis-à-vis* low PW is that such high values of rainfall only increased the denominator of the PW expression, without any added value to the numerator, the crop yield,. hence low PW. Therefore, low values of $PW_{(rf)}$ may not necessarily be due to poor crop yield but low rainfall utilization efficiency.

Table 5. Productivity of water in terms of rainfall (PW_{rf}) and evapotranspiration (PW_{ETa}) for maize, sorghum, potato, beans and groundnut.

	Maize		Sorghum		Potato		Beans		Groundnut	
Crop season	PW_{rf}	PW_{eta}	PW_{rf}	PW_{eta}	PW_{rf}	PW_{eta}	PW_{rf}	PW_{eta}	PW_{rf}	PW_{eta}
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3
89/90	0.19	0.74	0.06	0.26	0.71	2.48	0.09	0.34	0.06	0.19
90/91	0.29	0.57	0.12	0.25	1.08	1.79	0.15	0.28	0.12	0.23
91/92	0.35	0.59	0.14	0.25	1.98	2.89	0.15	0.26	0.16	0.26
92/93	0.30	0.59	0.26	0.55	0.96	1.47	0.17	0.32	0.17	0.34
93/94	0.49	0.97	0.38	0.79	3.07	4.29	0.20	0.24	0.16	0.32
94/95	0.33	0.64	0.47	0.98	1.53	1.89	0.21	0.29	0.20	0.40
95/96	0.40	0.80	0.12	0.25	1.01	1.51	0.17	0.30	0.06	0.12
96/97	0.19	0.34	0.26	0.46	1.86	2.55	0.33	0.50	0.20	0.33
97/98	0.44	0.99	0.30	0.48	1.84	3.26	0.19	0.38	0.19	0.39
98/99	0.24	0.33	0.37	0.50	1.57	1.91	0.23	0.31	0.14	0.18
99/00	0.30	0.47	0.20	0.31	1.07	1.44	0.10	0.15	0.07	0.11

The trends showed that high PW were obtained under high evapotranspiration deficit. This was the case with groundnut and sorghum in the 1994/95 cropping season, beans and maize in the 1996/97 and 1997/98 cropping seasons respectively. In the case of groundnut and sorghum, crop yields obtained during the cropping seasons were not at their peaks, but PW were high. This may be due to the fact that the local varieties of crops planted by the farmers in the area being stress tolerant, were able to maximize production per unit of water. This implies that in some instances, though high crop yields may be obtained, planting moisture stress tolerant varieties that can maximize productivity per unit of water can be employed to improve crop water productivity. This may be the reason why the indigenous farmers continue to insist on planting their local varieties, beside their tolerance to diseases and pest.

Maize and beans also recorded the highest values of $PW_{(ETa)}$ in the 1997/98 and 1996/97 cropping seasons, respectively, despite the dry spell recorded in March in these cropping seasons. Due to early onset of rains, planting could have been done early in December. Since crop growth duration of beans is short, the dry spell did not have much impact on bean production. Early planting associated with early onset of rains may also have contributed to better yield and higher $PW_{(ETa)}$ for maize in the 1997/98 cropping season. Therefore, early onset of rains is one of the factors that influence the productivity of water in irrigated agriculture in the study area.

Conclusion

The trend of productivity of water under rainfed agriculture is influenced by evapotranspiration deficit, which is caused by mid-cropping season dry spell and early cessation of rainfall. Early planting facilitated by early onset of rains may also have contributed to better yields and higher PW in rain-fed cropping. It is therefore one of the factors that influence the productivity of water in irrigated agriculture in the study area. Planting of moisture stress tolerant varieties also helped maximized productivity of water. Poor rainfall utilization efficiency also dictates the trend of productivity of water. High PW may not necessarily mean high crop production but an improvement in efficiency of water utilization.

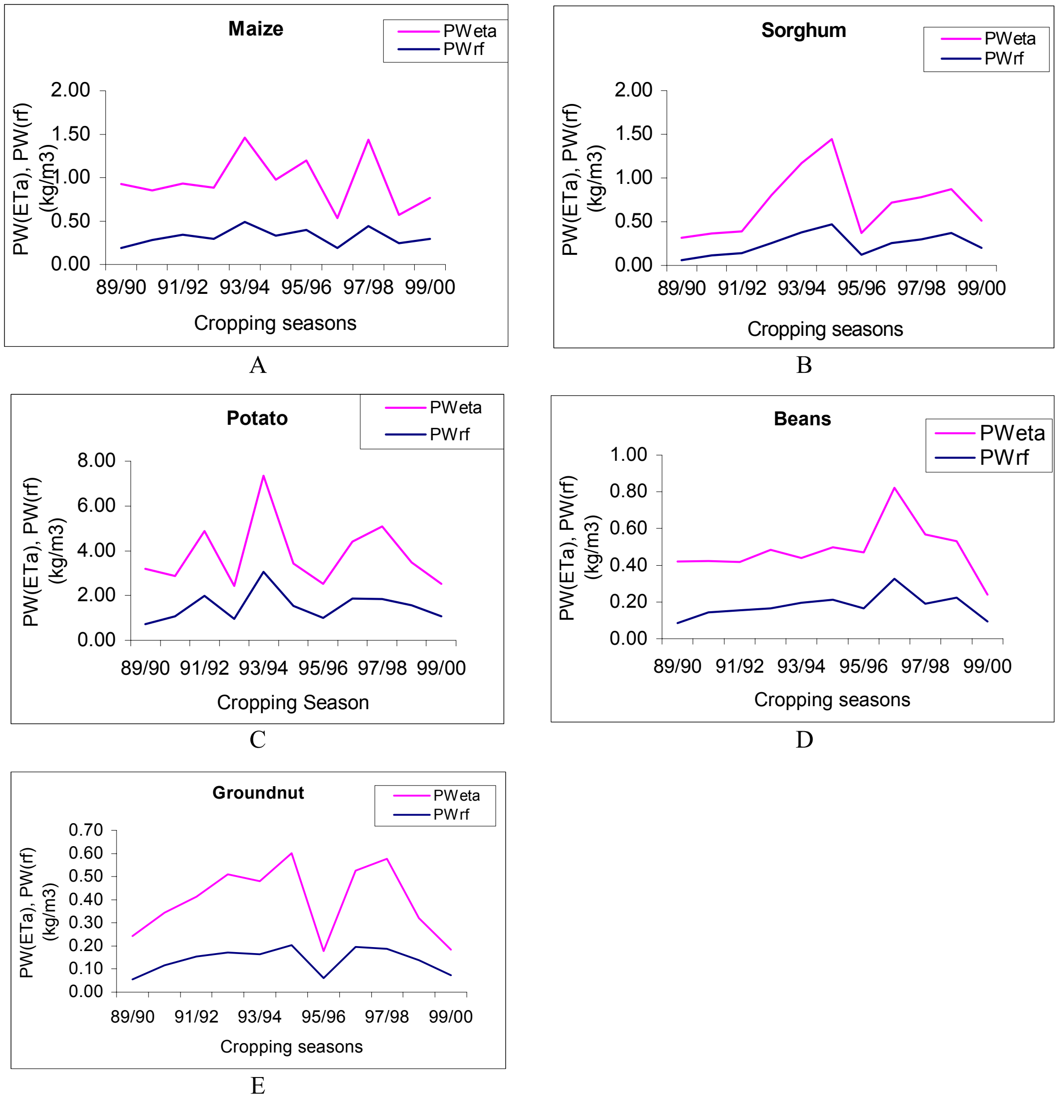

Figure 1(a-e). Trends of productivity of water of rainfall PW(rf) and evapotranspiration PW(ETa) for Maize, sorghum, potato, beans and groundnut

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