MAIZE YIELDS UNDER SUPPLEMENTARY IRRIGATION IN THE OLIFANTS RIVER BASIN, SOUTH AFRICA.

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Abstract

A daily field water balance experiment was conducted for three consecutive years to study the effects of supplementary irrigation on grain yield and water productivity of maize (*Zea mays L.*) crop in semi-arid Olifants river basin, South Africa. Maize average yield under rainfed and supplementary irrigation conditions were 0.78 t/ha (standard deviation of 0.43 t/ha) and 1.90 t/ha (standard deviation of 0.39 t/ha), respectively. Supplementary irrigation with added fertilisation of 14 kg-N/ha during dry spells increased average yields by 185 %. Maize yield was affected by seasonal rainfall and its poor distribution. The average evapotranspiration under rainfed and supplementary irrigation for the three seasons was 574 mm and 640 mm respectively. Nevertheless water use efficiency was significantly greater for supplementary irrigation plots (3.0 kg mm^{-1} ha^{-1}) than for rainfed plots (1.3 kg mm^{-1} ha^{-1}). Furthermore, with mean incremental water use efficiency of supplemental irrigation of 13.7 kg mm^{-1} ha^{-1}, implies that 1 m^3 of irrigation water applied timely can produce ZAR 27.4 (US$ 3.4) worth of maize. The values demonstrate the monetary gains from timely and adequate supplementary irrigation to bridge dry spells. The results show significant yield increases irrespective of the season under supplementary irrigation. Based on these results, the potential of supplementary irrigation exist to improve and stabilise smallholder farmer maize yields, thereby enhancing livelihoods.

Keywords: dry spells; moisture stress; rainfed agriculture; supplementary irrigation

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With supplementary irrigation, opportunity to triple current rainfed yields is real. One cubic meter of irrigation can produce up to US$ 3 worth of maize, thereby reducing poverty.

1. Introduction

Increasing the productivity of rainfed agriculture which caters for 60 % of the world's food, would make strides towards global food security. However, the potential to improve yields for the growing populations in semi-arid regions, home to 2 billion people of which half are poor (DFID, 2003) depends on appropriate adaptation to rainfall patterns. Even though total rainfall might be adequate for maize cultivation, poor distribution during the growing season results in total crop failure disrupting livelihoods. Researches from semi-arid tropical regions show that the occurrences of 2 to 4-weeks dry spells is more frequent than droughts (Botha et al. 2003). Magombeyi and Taigbenu (forthcoming) reported that 14-day dry spells in the Olifants river basin of South Africa occurred with a probability of 0.52, with associated shortfall in the average family food requirement of 500 kg/ha/year occurring once every two years. Similar results from Kenya and Tanzania were obtained by Barron et al. (1999) of 20% - 30% chance of dry spells exceeding 10 days. Supplementary irrigation is vital to improving water productivity (produce more crop per unit of water) and stabilising rainfed agriculture in resource constrained semi-arid tropics (Rockström 2002; Rockström et al. 2002; DFID 2003; Mupangwa et al. 2006).

Over the years the yields of maize (a staple food) have plummeted in Ga-Sekororo, Olifants river basin. The farmers are vulnerable to recurrent droughts and dry spells which significantly reduce yields and consequently their income, thereby making them fall back on social grants from the central government (Magombeyi and Taigbenu, forthcoming). Furthermore, the high cost of irrigation infrastructure is beyond the reach of resource-constrained subsistence farmers. Full irrigation is not feasible as Olifants river basin a closed basin with 70 % of catchment water consumed by agriculture. This paper reports on the use of field experimentation to quantify the impacts of ex-field supplementary irrigation on rainfed fields to assist farmers in upgrading maize crop yield under climate and weather variability.

Study area

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

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and recurrent droughts. Rainfall average is 630 mm, with potential evapotranspiration rates of over 1500 mm (actual evapotranspiration is around 840 mm) results in low runoff.
According to rating guidelines by Marx et al. (1999) the macronutrients (nitrogen, phosphorus, potassium) and cation exchange ratio in the study sites are low (Rasiuba 2007). Maize is grown by more than 70 % (Magombeyi and Taigbenu forthcoming) of the farmers as a stable food for the community even in zones where success is not guaranteed, yet it is still the preferred choice for cultivation.

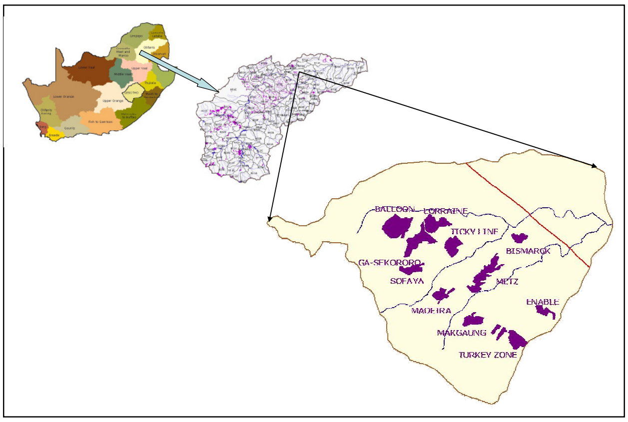

Fig. 1. Location of the study area in northern South Africa, and in the Olifants river basin.

2. Materials and methods

2.1 Field experiment

Controlled plot experiments were conducted in collaboration with three smallholder farmers with two replicates per farm to determine various parameters for the water balance model. The field layout for the experiment consisted of one hectare plots, with two equal smaller runoff plots of dimensions 4 m × 2 m. The farmers were initially taught on daily field data capturing. The seasons studied were 2005/2006, 2006/2007 and 2007/2008. In the irrigated plots, water was supplied by gravity-fed furrow irrigation system from a weir build across a seasonal stream. Irrigation scheduling was left at discretion of the farmers but measured by a 90^0 V-notch weir. All plots were planted on the same day and farmers agreed on the same farm management strategies. Fertilisation treatment of 14 kg-N/ha per season was applied in all plots except for the 2006/2007 rainfed plot because of little rainfall. Soil moisture levels at 200 mm depth were measured on a daily basis at 12 positions diagonally across the field using a hydrosense neutron probe (Campbell Scientific, Inc. 2001). Daily rainfall and runoff was also recorded from each field. The plots were harvested by hand and the grain recorded.

2.2 Water balance model

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

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

where E_C is the evapotranspiration (mm/d), P is the daily precipitation (mm), R is the runoff from the field (mm/d), D is the deep drainage beyond the root zone (mm/d), ΔS is the change in soil-water content in the root zone (mm/d) and I is the irrigated water to the plot (mm/d). E_c was calculated from the A-pan evaporation and maize crop factors (Sinclair and Seligman 1996; Walker and Ogindo 2003) as in Equation. (2) below.

$$E_c = E_p K_p K_c \tag{2}$$

where E_p is the A-pan evaporation (mm/d), K_p is the pan coefficient and K_c is the maize crop coefficient for the three growth stages. Deep drainage was calculated from the balance between soil moisture change and E_c in Equation (1) (Grove, 2006). The drainage was considered to be negligible below the maximum crop root length of 1 m depth used as lower boundary for the soil water balance (Ali et al. 2007; Tingem et al. 2008).

Water use efficiency or productivity (W_P) was calculated from the ratio of yield (kg/ha) to seasonal water evapotranspired (mm) (van Der Zel et al. 1993; Rockström et al. 1998; DFID 2003; Grove 2006 Zhang et al. 2006). Irrigation water productivity (I_{WP}) was calculated from the ration yield (kg/ha) to supplementary irrigation water (mm). Marginal supplementary irrigation water productivity (M_{SIWP}) was calculated from the ratio of change in yield to change in irrigation water applied, with other inputs held constant (Ali et al. 2007).

3 Results and discussions

3.1 Evapotranspiration and yield

The seasonal rainfall during the three seasons for maize varied from 388 to 1422 mm (Table 1). The 2006/2007 and 2007/2008 seasons were very dry below the long-term average, while 2005/2006 season received above normal rainfall. The average evapotranspiration (E_C) under rainfed and supplementary irrigation for the three seasons was 574 mm and 640 mm respectively. The observed E_C values are closer to the general maximum (500 - 800 mm) required by a medium maturity maize crop for maximum yields (FAO, 2002). The variation of yield with evapotranspiration (Fig. 2) shows good correlation but more data is required to make it conclusive. As E_C increases the proportion that satisfies transpiration is increased resulting in higher crop yields.

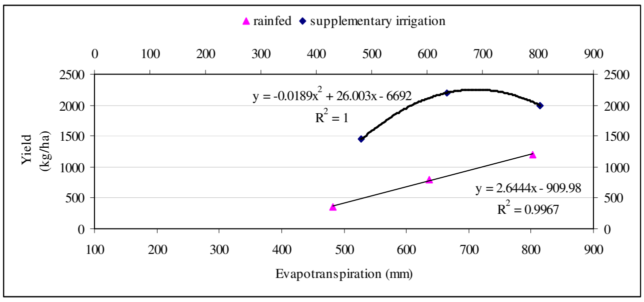

Fig. 2. Variation of yield with evapotranspiration in the study plots.

Maximum grain yields in fields with supplementary irrigation ranged from 1.45 to 2.2 t/ha, while yields in exclusive rainfed fields ranged from 0.35 to 1.2 t/ha (Table 1). Similar results were reported by earlier researchers working on maize in South, East and West Africa (Rockström et al. 1998; Oweis and Hachum. 2003). Maize yield was affected by seasonal rainfall (Fig. 3) and its erratic distribution throughout the growing season depicted by soil moisture changes in rainfed plots (Fig. 4a - 4c). A good correlation of yield reduction with rainfall (Fig. 3) strongly suggests that lack of water during critical growing periods was the main cause for yield reduction rather than nutrients.

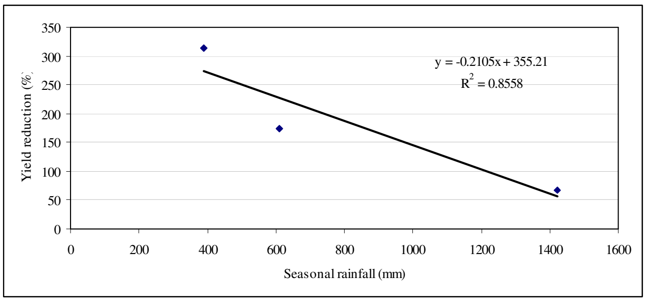

Fig. 3. Correlation of yield reduction under rainfed compared to supplementary irrigation with rainfall during the growing seasons from 2005 to 2008.

Supplementary irrigation with added fertilisation of 14 kg-N/ha during dry spells increased yields on average by 185 % (Fig. 3 and Table 1). Fox and Rockström (1999) reported similar result of 180 % yield increase in semi-arid Burkina Faso. During the dry seasons 2006/7 and 2007/8 the grain yield reduction without supplementary irrigation ranged from 175 % to 314 %, while for the wettest year the yield reduction was 67 % indicating significant yield improvement with supplementary irrigation are realized during drier years. Rain yields, rainfall and supplementary irrigation water use efficiencies (kg dry matter grain per mm rainfall) for the studied area are shown in Table 1.

Table 1. Water productivity, irrigation water productivity, marginal irrigation water productivity and yield reduction.

site	P (mm)	I (mm)	ΔS (mm)	R (mm)	D (mm)	E_C (mm)	Crop yield (kg/ha)	W_P (kg mm^{-1} ha^{-1})	I_{WP} (kg mm^{-1} ha^{-1})	M_{SIWP} (kg mm^{-1} ha^{-1})
Rainfed with supplementary irrigation										
2005/2006	1422	48	-40	527	100	803	2000	2.49	41.7	16.7
2006/2007	388	112	18	36	0	482	1450	3.01	13.0	9.8
2007/2008	611	96	65	136	0	636	2200	3.46	23.0	14.6
Control – exclusive rainfed										
2005/2006	1422	0	-40	503	100	779	1200	1.54	0	0
2006/2007	388	0	34	36	0	386	350	0.91	0	0
2007/2008	611	0	81	136	0	556	556	1.44	0	0

The field results indicate there is a significant scope for improving water productivity in rainfed farming through supplemental irrigation, especially when combined with soil fertility management as reported in other parts of Africa (Rockström et al. 1999; Fox and Rockström 2000).

3.2 Soil moisture variation and yield effects

Figs 4a - 4c show the variation of soil moisture in the experimental sites for the three seasons from sowing to harvest. In some days soil moisture content fell below the permanent wilting point of the sandy loam soil of 9.5 % volumetric water content (field capacity is 20.7 %) (Mzirai et al. 2001). In addition, the sub-soil acidity (pH < 5) in the study area could have further restricted water uptake by the crop roots (Robertson et al. 2003). Despite high annual rainfall of 1422 mm in 2005/2006 season, the crop suffered from periods of water shortage, during the vegetative stage early in 2005/2006 (Fig. 4a) (18 - 32 days after sowing) and flowering (50 - 70 days after sowing). In 2006/2007 season (Fig. 4b) water stress occurred in the vegetative and grain filling stages, while in 2007/2008 (Fig. 4c) water stress was experienced from flowering through to grain filling (80 - 100 days after sowing) (Rockström et al. 1998; FAO 2002).

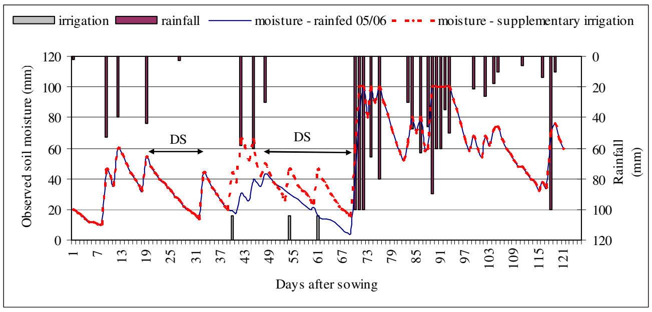

Fig. 4a. Rainfall, irrigation and soil moisture changes monitored under rainfed and supplementary irrigation agriculture 2005/2006 season (DS = long dry spells).

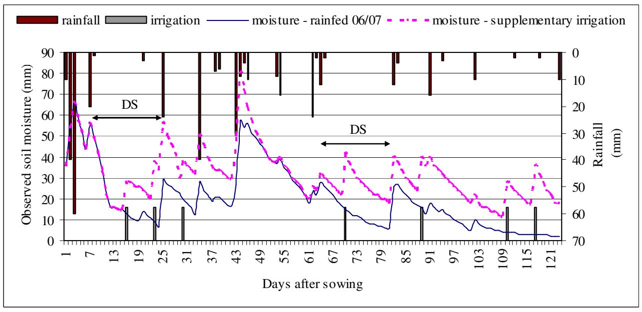

Fig. 4b. Rainfall, irrigation and soil moisture changes monitored under rainfed and supplementary irrigation agriculture 2006/2007 season (DS = long dry spells).

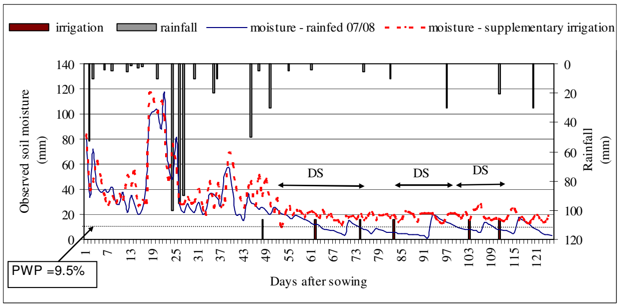

Fig. 4c. Rainfall, irrigation and soil moisture changes monitored under rainfed and supplementary irrigation agriculture for 2007/2008 season (DS = dry spells; PWP = permanent wilting point).

Dry spells greater 10 days resulted in soil moisture levels falling below 5 % and below the soil permanent wilting point of 9.5 %. Soil moisture deficits adversely affected plant growth and yield attributes under rainfed plots due to increased total resistance in the soil-plant system resulting in reduced photosynthesis and growth. In 2006/2007 the maize grain yield was drastically reduced to about 350 kg/ha because the soil moisture stress experienced in the early growth stages (12 - 25 days after sowing) reduced the crop leaf area index and radiation use efficiency which have direct bearing on dry matter accumulation in plants (Rockström et al. 2002; Ali et al. 2007). The moisture levels can be used to determine the onset of crop stress for the efficient utilisation of irrigation and precipitation (Abraha and Savage 2008). With improved timely and adequate supplementary irrigation coupled with good soil management, farmers will ensure minimum water stress to crops thereby enhancing food security for their families.

3.3 Marginal irrigation water productivity (M_{SIWP})

The M_{SIWP} is a good indicator for assessing the performance of supplementary irrigation management method (Rockström et al. 2002) if higher yields upset cost of supplying additional water. The M_{SIWP} ranged from 9.8 to 16.7 kg mm^{-1} ha^{-1} (average of 13.7 kg mm^{-1} ha^{-1}) for 2005/2006, 2006/2007 and 2007/2008 seasons respectively (Table 1). The results are higher than 2.5 - 7.6 kg mm^{-1} ha^{-1} reported in Burkina Faso (Rockström et al. 2002) but on the lower side in comparison with 15 to 62 kg mm^{-1} ha^{-1} of supplemental irrigation (Li et al. 2000). With the current (2008) price of maize grain at ZAR 2.0 per kilogram, on average 1 m^3 of irrigation water applied timely can produce ZAR 27.4 (US$ 3.4) worth of maize. The return per m^3 of supplementary irrigation is very high compared to the cost of 1 m^3 water under full irrigation of ZAR 0.5/m^3. The values demonstrate the gains to be actualized with timely and adequate supplementary irrigation to bridge dry spells.

3.4 Water productivity (W_P)

Shifting from exclusive rainfed agriculture to supplementary irrigation agriculture in the study area resulted in increased average W_P from 1.3 to 3 kg mm^{-1} ha^{-1} (or 131 % increase) (Table 1). The corresponding average yield increase was from 780 kg/ha to 1900 kg/ha. The results are comparable to increased average grain yield of 1.5 kg mm^{-1} ha^{-1} with rainfed to 3.5 - 10 kg mm^{-1} ha^{-1} with supplementary irrigation (Rockström et al. 2002). The yield improvement can be attributed to timely water application to crops to avoid water stress and availability of more soil water for the plant. Similar results from Burkina Faso reported tripling yields of 460 kg/ha to 1400 kg/ha by combining supplemental irrigation and fertiliser application (Rockström et al. 2002). On the other hand, for seasons with severe dry spells, e.g., 2006/2007 in Ga-Sekororo, complete crop failure resulted for all treatments lacking dry spell mitigation such as supplementary irrigation. The results indicate that water harvesting for dry spell mitigation can play a critical role in reducing the risk of crop failure during cropping seasons with severe dry spells.

4 Conclusions and recommendations

A water balance for rainfed and supplementary rainfed maize was developed. The maize grain yields difference of 1.12 t/ha between supplementary irrigation fields and rainfed fields coupled with incremental water use efficiency of supplemental irrigation of 13.7 kg mm^{-1} ha^{-1}, imply 1 m^3 of irrigation water applied timely can produce ZAR 27.4 (US$ 3.4) worth of maize. The results demonstrate the great opportunities that exist for upgrading rainfed agriculture and ensuring food security in rural communities through timely and adequate supplementary irrigation to bridge dry spells. Harvesting rain water in storage facility offers one way of realizing supplementary irrigation. Furthermore, low soil nutrients that characterise the study area can be overcome through better soil fertility management with the overall result of higher water productivity.

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