African Journal of Agricultural Research Vol. 7(11), pp. 1755-1760, 19 March, 2012
Available online at http://www.academicjournals.org/AJAR
DOI: 10.5897/AJAR11.2109
ISSN 1991-637X ©2012 Academic Journals

Full Length Research Paper

Yield and water productivity of maize and wheat under deficit and raised bed irrigation practices in Egypt

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Accepted 23 January, 2012

This work aims at evaluating the performance of deficit irrigation (DI) and raised bed techniques (RB) of maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) as compared to farmers' practice (FT) and full irrigation (FWR) in the Nile Delta of Egypt in 2005/2006 and 2006/2007 seasons. In maize, results showed that the application of FWR as compared to the FT reduced water application by 640 and 460 m^3/ha with yields decreases of 7 and 8% in the first and second seasons, respectively. DI and RB resulted in savings of 1600 m^3 water/ha in maize and 1500 m^3 water/ha in wheat. Water saving due to DI was accompanied by a yield reduction of 8.8% in maize, but with no effect on wheat. RB had no significant effect on yield in both crops. On average, WP values were 1.53, 1.66, 1.83, and 1.99 kg/m^3 in maize and 1.30, 1.38, 1.86 and 1.88 kg/m^3 in wheat for FT, FWR, DI and RB, respectively. From this study, we can conclude that substantial amounts of water can be saved by applying DI with no significant reduction in yields especially in wheat. However, RB remains more a promising technique for both crops.

Key words: Water saving, surface irrigation, on-farm trials, land productivity, tradeoff.

INTRODUCTION

Globally, agriculture is the main user of water. However, because of the increase in demand from other users and the occurrence of drought in many countries, the resource has become scarce and limited. In Egypt, where agriculture uses more than 80% of the available water and where crop production is based mainly on irrigation, high demand from the ever-increasing population and the expansion of irrigated areas put pressure on the resource. Despite this progressive water shortage, most farmers, especially small ones continue to use flood irrigation that results in high water loss by evaporation and drainage. Research shows that over 45% of water applied is lost to deep soil drainage and surface runoff. The use of large amounts of water can also promote nitrogen leaching and the contamination of ground water by nitrates. To increase the area of irrigated land and hence to increase overall crop production in Egypt using the same amount of available water, options that save water and improve yield (land productivity) and water productivity (WP) or crop water-use efficiency (grain yield/evapotranspiration) need to be developed. One of these potential options is deficit irrigation (DI) which is the application of a fraction of crop water requirements. Maize is one of the major irrigated crops grown at around 630,000 ha (1.5 million feddans) during the summer in Egypt (Khalifa et al., 2001). Maize has a high water and nutrient demand with the flowering stage being the most sensitive to water stress during which grain yield may be reduced by decreasing grain number and kernel weight (Pandey et al., 2000). Kirda (2002) reported that under scarce water-supply conditions, DI could lead to greater economic grain production than maximizing yields per unit of water applied for a given crop.

Maize is well suited to DI, applied either throughout the growing season or at pre-determined growth stages (Karam et al., 2003). However, DI use implies sacrificing some grain yield, and the level of loss depends the on the degree of water stress imposed. El-Sabbagh et al. (1997) found that applying irrigation when soil water content was at 80% of field capacity gave the highest yield as

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compared to applying water at 65 and 50% of field capacity. Moreover, Musick and Dusek (1980) showed that yields of summer annual crops such as maize were reduced in response to soil water deficit at any plant growth stage. Pandey et al. (2000) demonstrated that when deficit irrigation during the vegetative period was imposed, grain yield was reduced by 7 to 11%. When DI occurred during the vegetative stage and early reproductive stage, significant yield reductions of 23 to 26% were observed. However, many researchers have indicated that the flowering stage is the most sensitive to water stress (NeSmith and Ritchie, 1992; Ortegui et al., 1995). Yield decrease is mainly due to the effect of water deficit on grain number per m^2 rather than grain weight (Farré and Faci, 2009). Wheat is another important crop in Egypt. However, national production remains low and does not meet the needs of the growing population. For example, in 2003, total wheat production was 6.84 million tonnes and annual consumption was around 12 million tonnes. Hence, Egypt relies heavily on wheat imports to meet the needs of the rapidly-growing population. At the farm level, farmers try to increase production by applying irrigation; unfortunately, as in maize, they use a traditional technique (basin irrigation) that requires large amounts of water.

Deficit irrigation is also a possible alternative technique. DI can potentially save water especially in areas like the Menoufia region where salinity is low. Kang et al. (2002) showed a 20 to 45% increase in grain yield of spring wheat by reducing irrigation by 30 to 60 mm during the jointing stage. Zhang et al. (2006) demonstrated that grain yield, harvest index and water-use efficiency were greatly improved under regulated DI when compared to the non-stressed treatment. Metwally et al. (1984), Mohamed (1994), El-Bably (1998) and El-Sabbagh et al. (2002) showed that wheat plants irrigated to around 50 to 60% of soil moisture depletion gave significantly increased grain yields. Deficit irrigation can also improve water productivity and the saved water can be used to irrigate other areas or crops. A review of measured crop water productivity (Zwart and Bastiaanssen, 2004) concluded that this practice increased WP in many crops including maize and wheat. However, Farré and Faci (2006) found that in maize and sorghum WP decreased with decreasing irrigation. According to Oweis et al. (1998), the association of high WP values with high yields has important implications in crop management for achieving efficient use of water resources in water-scarce areas. Raised bed planting is another technique that allows water saving without reducing grain yields.

Hobbs et al. (2000) reported that raised-bed planting contributes significantly to the improvement of water distribution and efficiency, and increases fertilizer-use efficiency and reduces weed infestation, lodging and seed rate without sacrificing yield. Sayre and Hobbs (2004) using wheat data from different countries showed increases in grain yield and water productivity as compared to conventional planting and estimated water savings ranging from 20 to 46%. The reduced irrigation applications are probably largely due to reduced deep percolation losses (Humphreys et al., 2004), but also to evaporation. According to Farré and Faci (2006), the relationship between grain yield and irrigation water applied is economically more important than the relationship between grain yield and evapotranspiration. The objective of this study is to evaluate the impact of DI and the RB technique on yield and water productivity in field grown maize and wheat in Egypt.

MATERIALS AND METHODS

Trials were set up on farmers' fields with the full participation of farmers at the Al-Makataa site (Menoufia Governorate) in the old lands in the Middle Delta of Egypt (30° 36' N; 31° 01' E; alt. 17.9 m a.s.l.) during 2005/2006 (season 1) and 2006/2007 (season 2) growing seasons. The soil is deep and fine textured (clay 31 to 43%) and very low salt content (EC < 0.43 dS/m). Field capacity, wilting point and bulk density values in the soil profile (0 to 60 cm) were, in average, 40, 20 and 1.32 g/cm^3, respectively. The amounts of rainfall received were 45 and 22 mm during the 2005/2006 and 2006/2007 growing seasons, respectively. In 2005/2006, February and March were relatively wet with a monthly rainfall of 15 mm in the first month and 11.7 mm in the second. In 2006/2007, January received relatively more rain (14 mm). Hence, crops cannot be grown without irrigation. The experiments were conducted on four farmers' fields in the 2005/2006 and 2006/2007 cropping seasons for maize and wheat. Treatments included the farmers' normal surface irrigation practice (FT) where basin plots are filled with irrigation water (usually more than what the crop needs), the application of full irrigation to satisfy crop water requirements (FWR), deficit irrigation (DI) to satisfy 70% of crop water requirements at each irrigation and the raised bed (RB). In the FWR treatment, 20% of water was included as the leaching requirement. Surface irrigation was used with a calibrated cutthroat flume to measure water amounts. A standard rectangular cut-throat flume was installed at the inlet of the irrigation plots under free flow conditions. The depth of the water (Ha) was monitored and the discharge (Q) was determined using the equation Q = Cha 1.56 where C is a fixed coefficient of the flume. FT treatment followed the normal practice where the farmer fills the basins frequently without taking into account the crop's requirements. However, amounts and timing were recorded.

Irrigation scheduling for other treatments was based on crop evapotranspiration (ETc). ETc was calculated from the reference evapotranspiration ETo and the FAO crop coefficients (Kc) for maize and wheat (Allen et al., 1998). ETo was calculated using the Penman-Monteith equation. ETc was computed weekly and irrigation water was added accordingly to maintain the full water requirement for the FWR treatment. On average, the number of irrigations was five for wheat and eight for maize. The DI treatment received 70% of full supplemental irrigation requirements. In the RB treatment, the crop was planted in slightly raised beds, 1.2 m wide separated by furrows, 25 cm deep and 30 cm wide at the top where the irrigation water was applied. Maize was planted in early June and harvested in mid-September. Wheat was sown during the late November in 2005 and the early November in 2006. It was harvested in early May. Seeding rate was 144 kg/ha for wheat and 36 kg/ha for maize. For both crops, the experimental plots were ploughed twice by a chisel and this was followed by a scraper operation. The rotation was wheat-maize. Fertilizers used were based on the recommendations of the regional extension service. In

Table 1. Amounts of applied irrigation water, grain yield and water productivity of maize under different irrigation techniques in Egypt in 2005/2006.

Treatment	AW[(1)] (m^3)	GY (kg/ha)[(2)]	WPg[(3)] (kg/m^3)
FT	6330[a]	9610[a]	1.52[b]
FWR	5990[b]	8840[b]	1.56[b]
DI	4720[c]	8410[c]	1.79[a]
RB	4740[c]	9080[b]	1.92[a]

[(1)]AW = Applied irrigation water; [(2)]GY = grain yield; [(3)]WPg = grain water productivity. Letters a, b, c between parenthesis correspond to the descending ranking of means; means followed by the same letter are not significantly different at $P < 0.05$.

Table 2. Amounts of applied irrigation water, grain yield and water productivity of maize under different irrigation techniques in Egypt in 2006/2007.

Treatment	AW[(1)] (m^3)	GY[(2)] (kg/ha)	WPg[(3)] (kg/m^3)
FT	7950[a]	12228[b]	1.55[c]
FWR	7488[b]	13101[a]	1.76[b]
DI	6354[c]	11743[b]	1.86[b]
RB	6406[c]	13051[a]	2.06[a]

[(1)]AW = Applied irrigation water; [(2)]GY = grain yield; [(3)]WPg = grain water productivity. Letters a, b, c between parenthesis correspond to the descending ranking of means; means followed by the same letter are not significantly different at $P < 0.05$.

Table 3. Amounts of applied irrigation water, grain yield and water productivity of wheat under different irrigation techniques in Egypt in 2005/2006.

Treatment	AW[(1)] (m^3)	GY[(2)] (kg/ha)	WPg[(3)] (kg/m^3)
FT	5369[a]	8560[a]	1.60[c]
FWR	5341[a]	8330[a]	1.56[c]
DI	4205[b]	8440[a]	2.0[b]
RB	3841[c]	8990[a]	2.35[a]

[(1)]AW = Applied irrigation water; [(2)]GY = grain yield; [(3)]WPg = grain water productivity. Letters a, b, c between parenthesis correspond to the descending ranking of means; means followed by the same letter are not significantly different at $P < 0.05$.

maize, 240 kg N/ha, 36 kg P_2O_5/ha and 57 kg K_2O/ha; for wheat, 180 kg N/ha, 36 kg P_2O_5/ha and 57 kg K_2O/ha were applied. Phosphorus was applied as superphosphate (15% P_2O_5) and nitrogen as urea (46% N) and Potassium as potassium sulphate (48% K_2O).

Nitrogen was applied three times during the lifecycle of the crops at planting, tillering and boot stage for wheat and planting after thinning of the seedlings and before tasseling for maize. In each plot, the amounts of water applied and grain yields were measured. Grain water productivity (WPg) was calculated as a ratio of grain yield to the total quantity of irrigation water. Economic water productivity (WPe) was obtained by dividing the net return per ha by the total amount of irrigation water used. Net return was calculated as the difference between total revenue (price × yield) per hectare and total variable costs including land preparation, weeding, irrigation and harvesting and the cost of inputs such as seed, fertilizer, manure and pesticides. Fixed costs such as land rent were excluded. Statistical analyses were performed using SAS (1996) considering farmers as replications in each year as it was difficult to replicate the treatments at the farm level.

RESULTS AND DISCUSSION

Data on the amount of water applied, yield and water productivity are in Tables 1 and 2 for maize and Tables 3 and 4 for wheat. In general, the analyses of variance showed that the effects of water treatment were significant for all variables except for wheat yield in 2005/2006. During 2005/2006, the average amounts of irrigation water applied in maize were 6330, 5690, 4720 and 4740 m^3/ha for the FT, FWR, DI and RB techniques, respectively. In 2006/2007, these quantities were 7950, 7448, 6354 and 6406 m^3/ha, respectively. For wheat and

Table 4. Amounts of applied irrigation water, grain yield and water productivity (WPg) of wheat under different irrigation techniques in Egypt in 2006/2007.

Treatment	AW$^{(1)}$ (m^3)	GY$^{(2)}$ (kg/ha)	WPg$^{(3)}$ (kg/m^3)
FT	6193^a	5993^c	1.01^d
FWR	5538^b	6444^b	1.20^c
DI	4343^d	6005^c	1.72^a
RB	4698^c	6290^c	1.40^b

$^{(1)}$AW = Applied irrigation water; $^{(2)}$GY = grain yield; $^{(3)}$WPg = grain water productivity. Letters a, b, c, d between parenthesis correspond to the descending ranking of means; means followed by the same letter are not significantly different at $P < 0.05$.

for the same treatments, these amounts were 5369, 5341, 4205, and 3841 m^3/ha, respectively, for 2005/2006 and 6193, 5538, 4343 and 4698 m^3/ha for 2006/2007. The results showed that the water requirements of maize are higher than for wheat and that farmers apply more water to maize than to wheat. Maize is grown in summer and requires large amounts of water to produce high yields. Ainer (1983) showed that under the conditions of 20% depletion in available soil moisture, water use by maize was 5160 m^3/ha; this was slightly lower on average than for DI in our trials. In maize, the difference between FT and FWR was 640 and 460 m^3/ha, about a 5 and 6% of water saving, in the first and second season, respectively. Nevertheless, yield response to the FWR application compared to the farmers' usual practice tended to be different from one season to another (Tables 1 and 2). In fact, yield on the farm plot decreased from 9610 to 8840 kg/ha under the FWR treatment in the first season.

In 2006/2007, a slight increase in yield was observed. On average, the increase (2006/2007) and the decrease (2005/2006) in yield due to the application of FWR compared to the farmers' practice was 7 to 8%. In wheat, the data showed (Tables 3 and 4) that there was no difference in the amount of water saved between the farmers' practice and the full irrigation treatment in the first season. In the second season, the farmer used 730 m^3/ha more water than required by the crop. No significant negative effect on yield was observed by shifting from flood irrigation to the application of the crop water requirement even though in the second season a significant amount of water (11%) was saved with the FWR treatment. In general, the FWR treatment does not reduce yield in wheat and in certain circumstances, it can save water. In maize, the objective of water saving was reached with the FWR treatment; however, yield was reduced during one of the two seasons studied. It seems that the negative effect of FWR treatment on yield in 2005/2006 was due to water stress around flowering time. In the farmers' plot, the over-use of water may have resulted in water conservation in the soil and hence the crop made more water available at this critical stage. NeSmith and Ritchie (1992) and Ortegui et al. (1995) showed that the flowering stage is the most sensitive to water stress. In this case, yield decrease is due to flowers abortion and hence a decrease in the number of grains per m^2 (Farré and Faci, 2009). In both seasons, the amount of irrigation water saved by either the DI or RB treatment when compared to the farmers' technique was around 1600 m^3/ha in maize and 1500 m^3/ha in wheat.

So, if we apply only DI (5500 m^3/ha on average), the amount of water saved per hectare of the farmer's field is able to irrigate an extra 0.30 ha of the same crop. However, if we apply this technique, we should accept some yield reduction in maize in some years. In fact, in the first season of the trials, the yields obtained were 9610 kg/ha on the farmer's plot, 8410 kg/ha for the deficit irrigation treatment and 9080 kg/ha for the RB treatment. In the second season, the values were 12,228, 11,743 and 13,051 kg/ha, respectively for the same treatments (Tables 1 and 2). Consequently, the reduction in irrigation water in the DI treatment resulted in a significant reduction in maize yield (1200 kg/ha) only during the first season. Similarly, Ko and Piccinni (2009) demonstrated that irrigation management at 75% ETc was feasible with a 10% reduction in grain yield. From these findings, we postulate that for maize, a greater water deficit might have resulted in a higher reduction in land productivity. In fact, Ainer (1983) indicated that irrigating maize at 20% depletion of available soil moisture resulted in significantly higher yields as compared to irrigation at 40, 60 and 80% depletion. The same trend was observed by Zarkani (2000). To evaluate the trade-off between water saving and yield decline due to deficit irrigation, we calculated the yield loss per 1 m^3 of water saving. Averaging data across the years showed that this loss was 0.53 kg in maize, but only 0.07 kg in wheat, meaning that this technique has more potential for use in winter wheat crops than in summer maize crops. In wheat, DI saved water without any significant negative effect on yield. In fact, the advantage of DI by maintaining soil water at 70% crop requirement was demonstrated in spring wheat by Kang et al. (2002) who showed a 20 to 45% increase in grain yield by reducing irrigation by 30 to 60 mm during the stem elongation stage.

Similarly, Zhang et al. (2006) showed a positive effect of regulated DI on wheat yield. It is important to note that the water losses described here under the farmers'

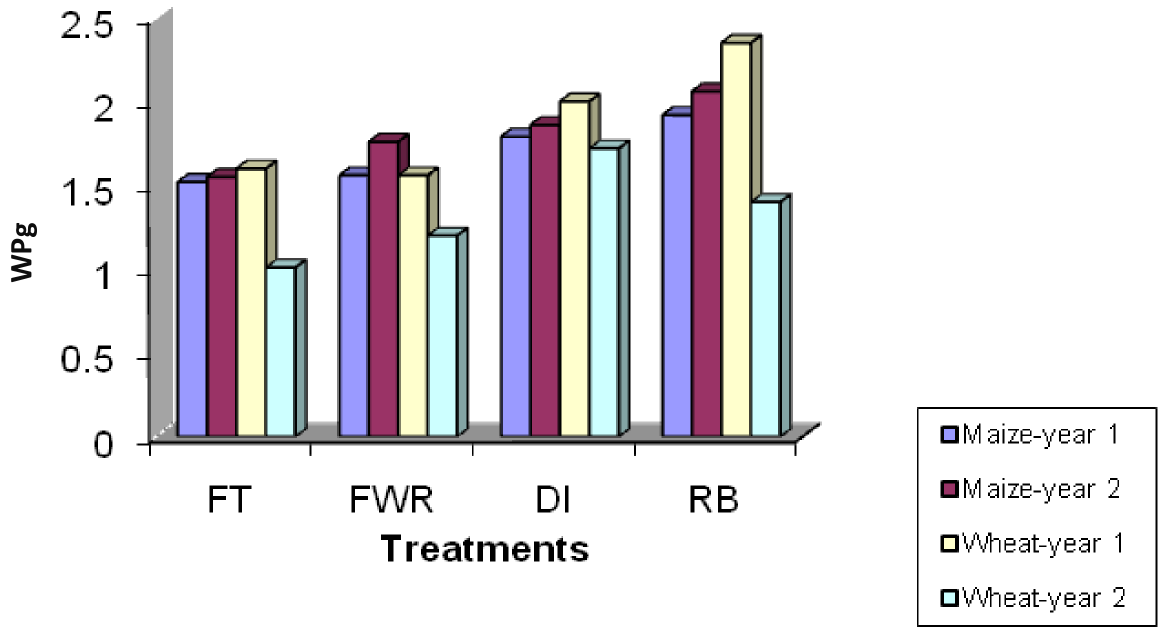

Figure 1. Grain yield water productivity of maize and wheat under FT, FWR, DI, and RB treatments in Egypt in 2005/2006 (year 1) and 2006/2007 (year 2).

treatment are at the field level. At a larger scale, water is not lost to the system since drainage water is re-used in irrigation. Using the RB, even though irrigation water supply was significantly less than the quantity applied by farmers, yield was not significantly affected. Grain yield increased by 7% in the second year in maize and by 5% for both growing seasons in wheat. Hamilton (2006) showed in Pakistan that the practice of irrigated maize-wheat cropping on permanent RB saved water and increased yield. The increased yield might be due to the fact that the beds were permanent and more efficient in reducing drainage in the furrow and in enhancing the lateral movement of water to the roots. The results of the effect of irrigation techniques on grain water productivity in maize are presented in Tables 1 and 2. WPg in the first season was 1.52, 1.56, 1.79, and 1.92 kg/m^3, for FT, FWR, DI and RB, respectively. In the second season, these values were 1.55, 1.76, 1.86 and 2.06 kg/m^3. Similar results for wheat are shown in Tables 3 and 4. WPg was 1.6, 1.56, 2.0 and 2.35 kg/m^3 in 2005/2006 and 1.01, 1.2, 1.72 and 1.4 kg/m^3 for 2006/2007, respectively, for the same treatments. The farmers' practice produced the same WPg as FWR in 2005/2006, but less well during the second season. Both DI and RB techniques gave higher WPg's than the other treatments; however, RB gave the highest value over the two seasons (Figure 1).

The use of the RB technique increased water productivity from around 1.5 kg/m^3 for the farmers' usual water management practice to 2.0 kg/m^3. In general, the relationship between water productivity and yield was significant with a coefficient of determination (R^2) of 0.47. Our data showed that, for similar amounts of applied water, RB gave in most cases higher WP than DI. Hobbs et al. (2000) demonstrated that RB planting contributed significantly to improved water distribution and efficiency, increased fertilizer use efficiency and reduced weed infestation, lodging and seed rate without sacrificing yield. Similar trends were observed when economic water productivity (net return per ha/irrigation water used) was calculated for both crops. However, the data showed that the values for wheat were generally higher than those for maize. These values varied from about 0.6 Egyptian Pounds/m^3 under high water application (FT and FWR treatments) to 0.8 Egyptian Pounds/m^3 for the water saving methods (DI and RB treatments) in maize and from 2.0 to 2.8 Egyptian Pounds/m^3 in wheat for the same treatments, respectively.

Conclusion

From this study, we can conclude that DI and the use of the RB technique reduce irrigation water application and improve water productivity. However, because maize is a water-stress sensitive crop, deficit irrigation may negatively affect grain yield. Consequently, if water saving is a major issue, then, some yield reduction must be accepted as shown by the trade-off in this study between water saving and yield loss. An alternative would be to introduce the wide-furrow RB technology because, according to our study and others, it did not involve any yield reduction.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to AFESD, IFAD and OFID for research funding. We also thank all ARC Egypt staff for data collection and management of the research work in Egypt.

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