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Drip Irrigation Frequency: The Effects and Their Interaction with Nitrogen Fertilization on Sandy Soil Water Distribution, Maize Yield and Water Use Efficiency Under Egyptian Conditions

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Abstract

Irrigation frequency is one of the most important factors in drip irrigation scheduling that affects the soil water regime, the water and fertilization use efficiency and the crop yield, although the same quantity of water is applied. Therefore, field experiments were conducted for 2 years in the summer season of 2005 and 2006 on sandy soils to investigate the effects of irrigation frequency and their interaction with nitrogen fertilization on water distribution, grain yield, yield components and water use efficiency (WUE) of two white grain maize hybrids (*Zea mays* L.). The experiment was conducted by using a randomized complete block split-split plot design, with four irrigation frequencies (once every 2, 3, 4 and 5 days), two nitrogen levels (190 and 380 kg N ha^{-1}), and two maize hybrids (three-way cross 310 and single cross 10) as the main-plot, split-plot, and split-split plot treatments respectively. The results indicate that drip irrigation frequency did affect soil water content and retained soil water, depending on soil depth. Grain yield with the application of 190 kg N ha^{-1} was not statistically different from that at 380 kg N ha^{-1} at the irrigation frequency once every 5 days. However, the application of 190 kg N ha^{-1} resulted in a significant yield reduction of 25 %, 18 % and 9 % in 2005 and 20 %, 13 % and 6 % in 2006 compared with 380 kg N ha^{-1} at the irrigation frequencies once every 2, 3 and 4 days respectively. The response function between yield components and irrigation frequency treatments was quadratic in both growing seasons except for 100-grain weight, where the function was linear. WUE increased with increasing irrigation frequency and nitrogen levels, and reached the maximum values at once every 2 and 3 days and at 380 kg N ha^{-1}. In order to improve the WUE and grain yield for drip-irrigated maize in sandy soils, it is recommended that irrigation frequency should be once every 2 or 3 days at the investigated nitrogen levels of 380 kg N ha^{-1} regardless of maize varieties. However, further optimization with a reduced nitrogen application rate should be aimed at and will have to be investigated.

Introduction

Maize has been reported in the literature as having high irrigation requirements (Rhoads and Bennett 1990; Stone et al. 2001). In arid and semi arid regions, the daily evapotranspiration rates of maize often exceed 10 mm day^{-1} for significant time periods (Howell et al. 1995). Furthermore, maize yields are most sensitive to water stress, especially at flowering and pollination stages. For instance, NeSmith and Ritchie (1992) reported that the reductions in maize yield exceeded 90 % due to water deficit during flowering and pollination stages. The high water requirement of maize with their sensitivity to water stress indicates that limited or deficit irrigation is difficult to implement successfully without causing yield reductions, particularly in light-textured soils. Therefore, a frequent and uniform supply of water is extremely important for maize yield to meet the water requirements of plants.

Water shortage is one of the main constraints for economic development in arid and semi-arid areas. However, it is very important for these areas to promote public awareness as regards water-saving measures so as to develop the social sustainability and extension of new cultivated areas. Agriculture is the major user of freshwater (with a world's average of 71 % of the water use), which, thus, is affected by decreased supply. Therefore, innovations are needed to increase the use efficiency of the water that is available. There are several possible approaches. Irrigation technologies and irrigation scheduling may be adapted for more effective and rational use of limited supplies of water. Drip and sprinkler irrigation methods are preferable to less efficient traditional surface methods.

All cultivated land in Egypt has an arid or semi-arid climate, and the water required for agricultural and horticultural crops is obtained mainly through irrigation systems which consume about 83 % of the country's available fresh water (Fahmy et al. 2002). On the other hand, field application efficiency in most traditional irrigation methods is still very low, typically less than 50 % and often as low as 30 % (Molden et al. 1998). Excessive application of water generally entails losses because of surface run-off from the field and because of deep percolation below the root zone within the field. Both run-off and deep percolation losses are difficult to control under furrow irrigation system, where a large volume of water is applied at a single instance. Alternative water application methods such as the drip irrigation method allow for much more uniform distribution as well as more precise control of the amount of water applied and also decrease nutrient leaching (Phene et al. 1994). Because the initial installation costs of drip irrigation are high, field crops together with vegetable in crop rotation, which needs more studies, would be one of the most significant factors in reducing the high overall investment costs of drip irrigation when it is used for field crop production.

Drip irrigation is an efficient method for minimizing the water used in agricultural and horticultural crops. However, the method can result in water saving if the correct management procedures are applied (Darusman et al. 1997). Frequency of water application is one of the most important factors in drip irrigation management because of its effects on soil water regime, root distribution around the emitter, the amount of water uptake by roots and the amount of water percolation under the root zone (Coelho and Or 1999, Assouline 2002, Wang et al. 2006). Due to these phenomena of irrigation frequency, water use efficiency (WUE) and crop yields may be different under different irrigation frequencies, although the same quantity of water is applied. Irrigation frequency that results in either excessive or inadequate water application applied in each irrigation can have a negative impact on either drip irrigation efficiency or final grain yield. For instance, very high irrigation frequency, once or more every day, might provide desirable conditions for water uptake by roots, but it will also lessen irrigation efficiency, increase energy and labour cost, and leach water and nutrients below the root zone (Jordan et al. 2003, Wan and Kang 2006). Very low irrigation frequency, on the other hand, may cause water stress between irrigations, especially in sandy soils because the duration of water application is much shorter than the time over which plants take up water. Low irrigation frequency on sandy soils also could result in substantial percolation below the root zone during irrigation because the amount of water applied at each irrigation may be higher than the soil-water storage capacity. Therefore, a proper irrigation frequency is one which minimizes the amount of water leached from the root zone, provides at least daily requirements of water to a portion of the root zone of each plant and maintains a high soil matric potential in the rhizosphere to reduce plant water stress between irrigations.

Although, several experiments have shown positive responses in some crops to high-frequency drip irrigation, this is not the general case for maize in different soils and regions. Furthermore, seeming inconsistencies as to the frequency which might be optimum can also be found in the literature when the same quantity of water is applied under different irrigation frequencies. Some authors found that the yield of maize grown on a clay loam soil or loamy sand soil with weekly irrigation did not differ significantly from maize yields obtained with daily irrigation (Camp et al. 1989, Caldwell et al.1994, Lamm et al.1995, Howell et al. 1997). However, higher irrigation WUE were obtained with weekly irrigation frequency because of reduction in deep percolation below the root zone. In contrast, other authors reported that daily irrigation led to the highest yield of sweet maize, both in terms of stem and ears, with the lowest performance being obtained from the weekly irrigation. (Assouline 2002; Oktem et al. 2003). The differences in theses results are probably due to the differences in climatic conditions and/or soil texture of the trials conducted by the above-mentioned authors. Therefore, it is important to determine a proper drip irrigation frequency that promotes maize yield for specific localities, thereby avoiding water stress or water leached from the root zone.

Several studies have also investigated the effect of irrigation and N interactions on maize production and WUE (Sexton et al. 1996, Al-Kaisi and Yin 2003). In general, increase in soil water enhances maize yield response to N fertilization, especially when high N rates are applied. Russelle et al. (1981) reported that the optimum N rate for maximum maize yield was the same under different irrigation treatments. However, N fertilization increases WUE on N-deficient soils where water is adequate (Al-Kaisi and Yin 2003). For these reasons the response of maize yield to N fertilization is probably related to drip irrigation frequency treatments.

The objective of this study was to evaluate the impact of drip irrigation frequency and its interaction with nitrogen fertilization on sandy soil water distribution, maize yield and WUE to develop a best management drip irrigation system for high maize yield and WUE simultaneously in a semi-arid region.

Materials and Methods

Experimental site and conditions

This study was conducted during the 2005 and 2006 summer seasons at the Experimental Farm of the Faculty of Agriculture at Suez Canal University, Ismailia, Egypt. The farm is located at an altitude of 13 m above mean sea level and is intersected by 30°58′N and 32°23′E. The weather is hot and dry from May to October where temperatures can reach up to 40 °C. On the other hand, the weather is usually warm during winter months and rainfall is rare. An average of 20 mm of rainfall occurs each year and the relative humidity averages about 55 %. The soil of the experimental site was sandy throughout the profile (79.9 % coarse sand, 15.7 % fine sand, 2.7 % silt and 1.7 % clay) with low moisture retentive capacity (17.0 %, volumetric water content, measured according to Klute 1986). The soil density was 1.59 g cm^{-3}. The organic matter content was 0.35 %. The soils have no salinity and drainage problem. Some soil characteristics relevant to irrigation frequency are provided in Table 1.

Experimental design and treatments

A randomized complete block split-split plot design with four replicates was used in each season. Irrigation treatments were randomly assigned to the main plots, nitrogen rates were assigned to the split plots, and maize varieties were assigned to the split-split plots.

Irrigation treatments were conducted using a drip irrigation system. The drip irrigation system was divided into four sectors, and each sector had one valve, one flow meter, and one pressure gauge to control the operating pressure and measure the irrigation quantity. The four irrigation frequencies, namely irrigation once every 2, 3, 4 and 5 days, were randomly assigned to the four sectors. Within each sector, there were four replicates of the same irrigation frequency.

The amount of irrigation water was applied according to the daily reference evapotranspiration (ET_o) computed from 10 daily climatic data, which were obtained from the Central Laboratory of Agricultural Climate CLAC (2004) for Ismailia location using the Penman-Monteith equation (Allen et al. 1998). Thereafter, the calculated ET_o values with the crop coefficient (K_c) that depended on plant growth stage were used to calculate the amount of water requirement for maize (mm ha^{-1}) with the following equation:

$$ET_c = ET_o \times K_c \qquad (1)$$

The crop coefficient, which depends on the growth stage of the plant, is the ratio of the crop evapotranspiration to the reference evapotranspiration and represents an integration of the effects of selected primary characteristics (albedo, canopy, resistance and crop height influences) that distinguish it from the reference crop grass (Achtnich 1980). As recommended by Allen et al. (1996) and Neale et al. (1996), the FAO KC was adjusted according to local climatic conditions, including minimum relative humidity, wind speed and maximum plant height. The adjusted KC values in the months of the cropping season varied between 0.35 and 1.30, and were calculated in those periods in which plants were not under water stress. The drip irrigation efficiency was assumed to be 0.9, and the root extension coefficient according to Moon and Gulik

Table 1 Soil characteristics of the experimental soil site (averaged over two seasons)

Soil depth (cm)	Soil bulk density (g cm^{-3})	Field capacity		Wilting point (air-dried soil)		Available moisture	
		% (P_w)	mm/25 cm	% (P_w)	mm/25 cm	% (P_w)	mm/25 cm
0–25	1.59	8.94	35.5	1.45	5.8	7.49	29.8
25.50	1.63	11.29	46.0	1.95	7.9	9.34	38.1
50–75	1.59	8.28	32.9	1.71	6.8	6.57	26.1
Total			114.5		20.5		93.9

(1996) was taken to be 0.8. The total amount of water applied for each irrigation treatment was 523.6 mm. The visual C^{++} program language was used for the calculation process. The same amount of water was divided into 28, 21, 17 and 14 doses for 2, 3, 4 and 5 interval days respectively. To ensure full germination, 65 mm of irrigation was applied for all irrigation treatments at sowing with an additional irrigation of 89 mm applied 20 days later for complete establishment of seedlings. Thereafter, each sector was irrigated according to the prescribed frequency treatments.

Two nitrogen fertilization levels (190 and 380 kg N ha^{-1}) as ammonium sulphate (20.6 %) were randomly nested within each main plot of the irrigation frequency treatments. The increased level of 380 kg N ha^{-1} represents a conventional application rate used in sandy soils with low organic matter contents. Nitrogen fertilizer as water solution was added after 2 weeks from sowing in five equal doses with one dose weekly. In addition, a starter of 30 kg N ha^{-1} plus equal P, K and micronutrients was applied to all treatments in each season. Phosphorus fertilizer was applied at a level of 350 kg ha^{-1} as calcium super phosphate (15.5 % P_2O_5). Whole of phosphorus was applied basally before sowing in all treatments. Potassium fertilizer was applied at a level of 100 kg ha^{-1} as potassium sulphate (48 % K_2O) in two equal doses every 2 weeks after sowing. Two white maize cultivars (three-way cross 310 and single cross 10) were randomly nested within each split plot of the N level.

A split-split plot consisted of five polyethylene lateral drip lines (Twin-wall IV, 16 mm in diameter, and 0.3 m emitter spacing; Chapin Watermatics, Watertown, NY, USA) with a length of 4 m. The lateral line was laid out along each maize row at 1.4 m. The drippers had a discharge rate of 3.1 l h^{-1} at an operation pressure of 0.13 MPa. Four seeds around each dripper were sown on 19 May 2005 and on 28 May 2006. Thinning to two plants per dripper was carried out after 14 days from sowing to obtain a final plant population of 47 600 plants ha^{-1}. Weed, pest and disease control were carried out in a timely manner.

Soil water content measurement

Soil water content was monitored before irrigation every 12 days from 35 to 107 days after sowing at the soil depth intervals of 0–25, 25–50 and 50–75 cm. Soil water content was determined using the gravimetric method (oven dry basis). The values were converted to a percentage volumetric basis by multiplying them by the bulk density of the soil of the respective layer. The equivalent depth of plant available water (mm) was estimated using the following equation (Marshall et al. 1996):

$$\mathrm{De} = \frac{\theta_v \times \mathrm{D}}{100} \tag{2}$$

where D_e is equivalent water depth (mm), θv is the volumetric water content (%) and D is the soil depth (mm).

Crop evapotranspiration estimation

Crop evapotranspiration was determined using Eqn (3) (James 1988).

$$\mathrm{ET_a} = \mathrm{I} + \mathrm{P} + \mathrm{Cr} - \mathrm{R} - \mathrm{D} \pm \Delta\mathrm{S} \tag{3}$$

where ET_a is evapotranspiration, I is applied irrigation amount, P is precipitation; Cr is capillary rise, R is surface run-off, D is downward flux below the crop root zone and ΔS is the change in soil water storage.

In this equation, the irrigation amount was calculated using Penman-Monteith equations. Precipitation and Cr were considered as zero because there was no precipitation during the growing seasons and no capillary rise from groundwater occurred. Surface run-off in this study was ignored due to the control of water application. If available water in the root zone (0–75 cm) and the total amount of applied water by irrigation were above the field capacity, it was assumed that the water amount above field capacity leaked into the deeper soil zones and was called deep percolation (Kanber et al. 1993).

To estimate ΔS, soil water contents in the soil profile at the respective soil layers from the soil surface down to 75 cm were determined just before planting and harvesting by gravimetric measurements. ΔS is the difference obtained by subtracting the soil water storage before harvesting with the soil water storage before planting.

Moreover, Eqn (4) was used to determine the contribution of different irrigation frequencies on plant water consumption (Ertek et al. 2004).

$$\mathrm{Irc} = \left(\frac{\mathrm{I}}{\mathrm{ET_a}}\right) \times 100 \tag{4}$$

where Irc is the irrigation water compensation for plant water consumption (ET_a, evapotranspiration) (%).

Water use efficiency

Water use efficiency and irrigation water use efficiency (IWUE) were calculated with Eqns (5) and (6) respectively (Kanber et al. 1993)

$$\mathrm{WUE} = \left(\frac{\mathrm{Y}}{\mathrm{ET_a}}\right) \times 100 \tag{5}$$

$$\mathrm{IWUE} = \left(\frac{\mathrm{Y}}{\mathrm{I}}\right) \times 100 \tag{6}$$

where WUE and IWUE are water use efficiency and irrigation water use efficiency (kg mm^{-1}), respectively, Y is the economic yield (kg ha^{-1}), ET_a is evapotranspiration (mm) and I is the amount of applied irrigation water (mm) calculated using Penman-Monteith equations.

Parameter assessments

After physiological maturity, 10 randomly selected plants were harvested from each sub-sub plot for measuring ear length, number and weight of ears per plant, number of grains per ear, weight of grains per plant and 100-grain weight. Grain yield was determined by hand harvesting an area of two rows 4.0 m in length, each on a split-split plot basis. Grain samples were collected from the yield samples for the determination of water content. Maize yield was adjusted to a water content of 15.5 %.

Statistical analysis

All measurements in this study were analysed using an analysis of variance appropriate for a randomized complete block split-split plot design with irrigation frequency as the main factor, N level as the split factor and variety as the split-split factor. Mean separation of treatment effects in this study was accomplished using Fisher's protected least significant difference (LSD) test. Probability levels lower than 0.05 were categorized as significant. All data analyses in this study were accomplished using the COSTAT system for windows, version 6.311 (CoHort software, Berkeley, CA, USA).

Results

Soil water distribution and changes

Figure 1 illustrates the changes in soil water content distribution prior to the next irrigation throughout crop growth from 35 to 107 days after sowing at depths of 25, 50 and 75 cm at positions immediately under the drippers for irrigation frequencies once every 2, 3 and 5 days (F2, F3 and F5) respectively. Soil water content distribution with depth for the irrigation frequency once every 4 days (F4) has not been presented here because the date of soil sampling for this treatment was not at the same time as mentioned for the other treatments. The results indicate that there were little differences in soil water content among different irrigation frequencies at the depth of 25 cm. The soil water contents at depths of 50 and 75 cm changed more drastically among the irrigation frequencies ($P > 0.001$). Moreover, the depth of retained available soil water content was higher at the high irrigation frequency (F2 and F3) than at the low irrigation frequency (F5). The sum depths of retained available soil moisture ranged from 17.8 to 25.5 mm for F2, from 17.5 to 23.4 mm for F3 and from 9.0 to 14.8 mm for F5 during the period from 35 to 107 days after sowing (Table 2). The main noticeable differences between the irrigation frequencies throughout the different soil layers

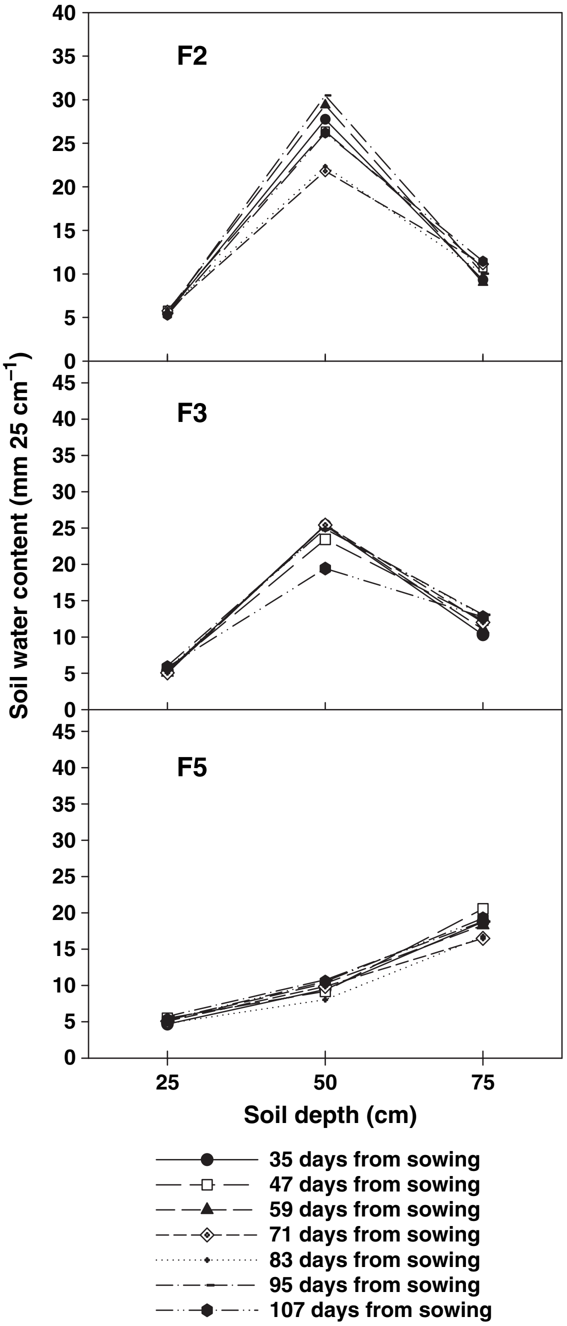

Fig. 1 Soil water storage before irrigation during the growing season averaged over two growing seasons at soil depths of 25, 50 and 75 cm for irrigation frequencies once every 2, 3 and 5 days (F2, F3 and F5) respectively.

Table 2 Average change in retained available soil water (mm) prior to the next irrigation affected by irrigation frequency at different soil depth layers. F2, F3 and F5 indicate irrigation frequencies once every 2, 3 and 5 days respectively

	Soil depth (cm)									Sum of retained available soil water (mm)		
	0–25			25–50			50–75					
Days after sowing	F2	F3	F5	F2	F3	F5	F2	F3	F5	F2	F3	F5
35	−0.3	−0.4	−1.1	19.8	17.4	1.5	2.5	3.5	12.0	22.0	20.5	12.4
47	0.1	−0.3	−0.3	18.5	15.5	1.2	3.9	5.5	13.7	22.4	20.7	14.7
59	−0.1	−0.7	−0.5	21.4	17.4	2.3	2.2	4.2	11.5	23.6	21.0	13.3
71	0.1	−0.7	−0.7	13.9	17.45	1.9	4.3	5.2	9.7	18.2	21.9	10.9
83	0.2	−0.2	−1.0	14.4	17.0	0.1	3.2	6.1	9.9	17.8	22.9	9.0
95	−0.3	0.3	−0.1	22.5	16.9	2.8	3.2	6.3	12.0	25.5	23.4	14.8
107	−0.5	0.1	−0.5	18.2	11.5	2.6	4.6	5.9	12.4	22.4	17.5	14.5
Total	−0.9	−1.9	−4.1	128.7	113.1	12.5	24.1	36.7	81.3	151.9	147.9	89.7
Average	−0.1	−0.3	−0.6	18.3	16.1	1.8	3.4	5.3	11.6	21.7	21.1	12.8

are that the depths of retained available soil water content at the soil layer 25 cm were significantly lower than the depth of available soil water from such layers. It was 18.3, 16.1 and 1.8 mm at the soil layer 50 cm and it was 3.4, 5.3 and 11.6 mm at the soil layer 75 cm averaged over the period from 35 to 107 days after sowing for F2, F3 and F5, respectively (Table 2), but the values were still also lower than the depth of available soil water from such layers, which were 38.1 and 26.1 mm respectively (Table 1).

Crop evapotranspiration (ET_a)

Table 3 presents data about crop evapotranspiration (ET_a) as estimated using Eqn (3) and irrigation water compensation values (Irc). In both seasons, ΔS values of all drip irrigation frequencies were negative, indicating that the soil became drier at the end of the growing season. However, ΔS value was generally higher in the F2 and F3 treatments than in the F4 and F5 treatments and vice versa for Irc values.

Table 3 Maize evapotranspiration calculated using the water balance equation. ET_c, P, D, ΔS, ET_a and Irc indicate amount of irrigation water applied (mm), precipitation (mm), deep percolation (mm), change in soil water storage (mm), evapotranspiration (mm) and irrigation water compensation (%) respectively

Year	Treatment	ET_C (mm)[1]	P (mm)	D (mm)	ΔS (mm)	ET_a (mm)	Irc (%)
2005	F2	523.6	0	0	−32.2	555.8	94.2
	F3	523.6	0	0	−31.8	555.4	94.3
	F4	523.6	0	0	−12.1	535.7	97.7
	F5	523.6	0	8.9	−1.6	516.3	101.4
2006	F2	523.6	0	0	−24.5	548.1	95.5
	F3	523.6	0	0	−30.3	553.9	94.5
	F4	523.6	0	0	−8.6	532.2	98.4
	F5	523.6	0	6.5	−5.5	522.6	100.5

[1] Applied irrigation amount calculated by using Penman-Monteith equations.

Grain yield

The results in the following section are based on the order of statistical significance, which ranges from the highest level interaction to the main effects of treatments. If there was a statistically significant interaction, then the main effect of the treatments and their interactions is presented. For example, the statistical analysis showed that irrigation frequency × nitrogen level interaction were the highest level interactions that were statistically significant in all measurements (Table 4); thus, the results are presented in a format corresponding to these significant interactions.

Analysis of variance showed that the effect of irrigation frequency on grain yield was highly significant ($P = 0.0001$ in 2005 and 2006). Grain yield was maximum (6570 and 6268 kg ha^{-1} in 2005, and 6832 and 6613 kg ha^{-1} in 2006) at an irrigation frequency given once every 2 and 3 days respectively. However, the F4 and F5 treatments resulted in a significant yield reduction of 19.6 % and 71.4 % in 2005 and 25.1 % and 72.8 % in 2006, respectively, compared with the F2 treatment (Table 5). Grain yield was also significantly affected by N level ($P = 0.0001$ in 2005 and 2006) and increased by increasing N from 190 to 380 kg N ha^{-1}. In 2005 and 2006, the application of 380 kg N ha^{-1} resulted in grain yields of 17.3 % and 13.3 % respectively. This was much higher than the previous application of 190 kg N ha^{-1}. Grain yield response to the N level was also affected by irrigation frequency. In both seasons, grain yield with the application of 190 kg N ha^{-1} was not statistically different from that of 380 kg N ha^{-1} at F5. However, the application of 190 kg N ha^{-1} resulted in a significant yield reduction of 25.0 %, 18.3 % and 9.0 % in 2005 and

Table 4 Mean squares and F-tests of main effects of irrigation frequencies, nitrogen levels and varieties and their possible interactions for grain yield, yield components, water use efficiency (WUE) and irrigation water use efficiency (IWUE) in 2005 and 2006

Source[1]	d.f.	Grain yield $\times 10^4$	Ear length	Ear number per plant	Ear weight per plant $\times 10^2$	Grain number per ear $\times 10^2$	Grain weight per plant $\times 10^2$	100-grain weight	WUE	IWUE
2005										
Irrigation frequency (F)	3	4387.3***	126.5***	0.72***	469.7***	2242.3***	257.7***	359.6***	138.0***	160.0***
Nitrogen levels (N)	1	1079.9***	102.4***	0.29***	259.9***	1531.5***	95.9***	1.7^{ns}	35.5***	39.4***
N × F	3	179.1***	11.0**	0.08**	44.3*	164.8**	29.1**	4.9^{ns}	5.7*	6.5*
Variety (V)	1	1.1^{ns}	1.2^{ns}	0.002^{ns}	6.6^{ns}	10.4^{ns}	0.1^{ns}	0.5^{ns}	0.1^{ns}	0.1^{ns}
V × F	3	70.1**	1.8^{ns}	0.002^{ns}	18.0*	9.0^{ns}	3.5*	0.8^{ns}	2.3^{ns}	2.7^{ns}
V × N	1	21.7^{ns}	1.3^{ns}	0.01^{ns}	4.7^{ns}	8.0^{ns}	1.2^{ns}	10.0^{ns}	0.8^{ns}	0.8^{ns}
V × N × F	3	9.1^{ns}	1.4^{ns}	0.002^{ns}	6.6^{ns}	2.5^{ns}	0.4^{ns}	2.7^{ns}	0.3^{ns}	0.3^{ns}
2006										
Irrigation frequency (F)	3	5095.1***	161.8***	0.50***	441.9***	2819.2***	238.2***	295.9***	161.5***	187.6***
Nitrogen levels (N)	1	634.9***	82.7***	0.23***	197.0***	610.7***	47.2**	0.7^{ns}	22.2***	24.5***
N × F	3	120.4***	12.9**	0.06***	18.5**	59.6**	5.8^{ns}	10.1^{ns}	4.0*	4.5**
Variety (V)	1	15.5^{ns}	2.9^{ns}	2.08^{ns}	1.8^{ns}	0.5^{ns}	2.4^{ns}	1.5^{ns}	0.3^{ns}	0.4^{ns}
V × F	3	22.7*	1.5^{ns}	0.008^{ns}	3.8*	1.8^{ns}	1.4^{ns}	0.8^{ns}	0.6^{ns}	0.7^{ns}
V × N	1	15.7^{ns}	4.4^{ns}	2.08^{ns}	0.7^{ns}	0.8^{ns}	2.8^{ns}	12.0^{ns}	0.3^{ns}	0.4^{ns}
V × N × F	3	15.5^{ns}	1.9^{ns}	0.005^{ns}	1.0^{ns}	6.0^{ns}	1.2^{ns}	8.7^{ns}	0.5^{ns}	0.6^{ns}

[1] The main effect of irrigation frequencies were tested using the first order interaction, replicate x irrigation frequency, as the error term. The main effect of nitrogen levels and the interaction between irrigation frequency and nitrogen level were tested using the second order interaction, replicate × irrigation frequency × nitrogen level, as the error term. The main effect of varieties and the possible interactions terms involving variety were tested using the highest order interaction, replicate × irrigation frequency × nitrogen level × variety, as the error term.

*, **, ***, ns: significant at $P \le 0.05$, 0.01, 0.001, or not significant, respectively, in the F-test.

Table 5 Effects of irrigation frequency and N level on grain yield in 2005 and 2006

Grain yield (kg ha^{-1})						
	2005			2006		
	N level (kg ha^{-1})			N level (kg ha^{-1})		
Irrigation frequency[1]	190	380	Mean	190	380	Mean
F2 (once in 2 days)	5631.7 Ab[2]	7508.7 Aa	6570.2 A	6072.4 Ab	7592.2 Aa	6832.3 A
F3 (once in 3 days)	5636.6 Ab	6899.0 Ba	6267.8 B	6141.9 Ab	7083.6 Ba	6612.8 A
F4 (once in 4 days)	5031.9 Bb	5531.7 Ca	5281.8 C	4954.2 Bb	5285.2 Ca	5119.7 B
F5 (once in 5 days)	1799.7 Ca	1955.2 Da	1877.4 D	1799.9 Cb	1916.9 Da	1858.4 C
Mean	4524.9 B	5473.7 A		4742.1 B	5469.5 A	

[1] Treatment means are averaged over varieties.

[2] Means in column within irrigation frequency in each year followed by the same upper-case letter are not significantly different at P = 0.05 according to Fisher's protected LSD test. Means in row within N level in each year followed by the same lower-case letter are not significantly different at P = 0.05 according to Fisher's protected LSD test.

20.0 %, 13.0 % and 6.3 % in 2006 compared with 380 kg N ha^{-1} at F2, F3 and F4 respectively (Table 5). Grain yield of the irrigation frequency treatments followed an F2 > F3 > F4 > F5 order at 380 kg N ha^{-1}; however, it followed an F2 ≈ F3 > F4 > F5 order at 190 kg N ha^{-1} (Table 5).

Yield components

The differences in yield components, namely ear length, number and weight of ears per plant, number of grains per ear, weight of grain per plant and 100-grain weight, in 2005 and 2006 under different treatments are listed in Table 6. The data revealed that different yield components were affected highly significantly by the irrigation frequency treatments. Fisher's protected LSD test showed that the F3 treatment was not statistically different from the F2 treatment, but the two treatments were significantly different from the F4 and F5 treatments (Table 6). Averaged over the two seasons, the F4 and F5 treatments decreased ear length by 15 % and 37 %, ear number per plant by 17 % and 38 %, ear weight per plant by 17 %

and 57 %, grain number per ear by 29 % and 77 %, grain weight per plant by 19 % and 62 %, and 100-grain weight by 27 % and 29 %, respectively, when compared with the reference treatment F2.

The response function between yield components and irrigation frequency treatments was quadratic in both growing seasons except for 100-grain weight, where the function was linear (Table 7). On the basis of the equation in Table 7, the proper irrigation frequency was once every 2.5 days for most yield components; yield components then began to decrease as irrigation frequency decreased.

The different yield components were also significantly affected by nitrogen levels and the interaction between nitrogen level and irrigation frequency (N × F) except 100-grain weight (Table 4). These trends were similar in both growing seasons. When the nitrogen level was reduced from 380 to 190 kg ha^{-1}, a reduction in all yield components except 100-grain weight was noticed (Table 6).

Water use efficiency

Water use efficiency and IWUE were significantly affected by irrigation frequency and nitrogen levels ($P > 0.001$) in the two growing seasons. WUE and IWUE increased with increasing irrigation frequency and nitrogen levels, and reached the maximum values when irrigation was given once every 2 and 3 days and nitrogen level was 380 kg N ha^{-1}, and then both began to decrease when irrigation frequency was given once every 4 and 5 days and nitrogen level was 190 kg N ha^{-1} (Table 8).

To ascertain the proper irrigation frequency for maximum WUE and IWUE, the variable WUE and IWUE (kg mm^{-1}) vs. irrigation frequency treatments (F) were fitted with second-degree polynomials and the equations obtained were:

$$\mathrm{WUE} = -1.206\mathrm{F}^2 + 6.07\mathrm{F} + 1.67 \quad (\mathrm{R}^2 = 0.79, \mathrm{n} = 48) \quad (2005) \qquad (7)$$

$$\mathrm{WUE} = -1.198\mathrm{F}^2 + 5.75\mathrm{F} + 2.87 \quad (\mathrm{R}^2 = 0.84, \mathrm{n} = 48) \quad (2006) \qquad (8)$$

$$\mathrm{IWUE} = -1.242\mathrm{F}^2 + 6.11\mathrm{F} + 2.32 \quad (\mathrm{R}^2 = 0.81, \mathrm{n} = 48 \quad (2005) \qquad (9)$$

$$\mathrm{IWUE} = -1.233\mathrm{F}^2 + 5.78\mathrm{F} + 3.58 \quad (\mathrm{R}^2 = 0.86, \mathrm{n} = 48) \quad (2006) \qquad (10)$$

On the basis of the above equations, the proper irrigation frequency for maximum WUE and IWUE

Table 6 Comparison of different yield components for various drip irrigation frequency and nitrogen levels in 2005 and 2006

	2005						2006					
Treatments	Ear length (cm)	Ear number per plant	Ear weight per plant	Grain number per ear	Grain weight per plant (g)	100-grain weight (g)	Ear length (cm)	Ear number per plant	Ear weight per plant	Grain number per ear	Grain weight per plant (g)	100-grain weight (g)
Irrigation frequency (F)												
F2 (once in 2 days)	19.3 a	1.2 a	227.5 a	379.4 a	153.5 a	34.1 a	21.8 a	1.2 a	224.7 a	412.0 a	156.1 a	32.0 a
F3 (once in 3 days)	19.6 a	1.2 a	234.9 a	373.9 a	157.7 a	33.6 a	20.3 a	1.1 a	223.6 a	421.0 a	154.4 a	31.4 a
F4 (once in 4 days)	17.6 b	1.0 b	189.4 b	257.7 b	126.9 b	25.1 b	17.4 b	1.0 b	185.3 b	302.7 b	123.6 b	23.3 b
F5 (once in 5 days)	12.6 c	0.7 c	98.7 c	87.7 c	57.5 c	23.8 b	13.4 c	0.8 c	95.5 c	91.5 c	60.8 c	22.9 b
LSD (0.05)	1.37	0.11	26.10	13.41	14.41	2.10	1.60	0.11	11.35	24.11	10.32	1.77
Nitrogen levels (N)												
190 kg N ha^{-1}	15.8 b	0.9 b	164.4 b	218.2 b	109.8 b	29.0 a	16.9 b	1.0 b	162.0 b	271.2 b	113.8 b	32.0 a
380 kg N ha^{-1}	18.7 a	1.1 a	210.9 a	331.2 a	138.0 a	29.3 a	19.5 a	1.1 a	202.6 a	342.5 a	133.6 a	31.4 a
LSD (0.05)	0.58	0.1	17.23	26.89	12.50	ns	0.85	0.05	8.84	15.58	10.51	ns

ns, not significant. Lower-case letters signify means in column within irrigation frequency or nitrogen level followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD test.

Table 7 Regression equations and correlation coefficients between selected yield components (Y) and irrigation frequency (F) in 2005 and 2006

	Irrigation frequency			
	2005		2006	
Variables	Regression equation	R^2	Regression equation	R^2
Ear length	$Y = -1.34F^2 + 7.20F + 10.2$	0.67***	$Y = -0.63F^2 + 1.62F + 21.1$	0.72***
Number of ears per plant	$Y = -0.09F^2 + 0.49F + 0.6$	0.76***	$Y = -0.06F^2 + 0.28F + 0.9$	0.69***
Weight of ears per plant	$Y = -24.54F^2 + 128.58F + 8.9$	0.68***	$Y = -22.16F^2 + 112.50F + 27.7$	0.81***
Number of grains per ear	$Y = -41.14F^2 + 188.86F + 169.1$	0.74***	$Y = -55.05F^2 + 277.36F + 79.2$	0.90***
Weight of grains per plant	$Y = -18.42F^2 + 97.04F - 7.1$	0.75***	$Y = -15.27F^2 + 75.22F + 26.6$	0.84***
100-grain weight	$Y = -3.95F + 42.9$	0.78***	$Y = -4.03F + 41.1$	0.64***

*** Significant at the 0.001 level.

Table 8 Effects of irrigation frequency and N level on water use efficiency (WUE) and irrigation water use efficiency (IWUE) in 2005 and 2006

	2005			2006		
	N level (kg mm^{-1})			N level (kg mm^{-1})		
Irrigation frequency[1]	190	380	Mean	190	380	Mean
WUE (kg mm^{-1})						
F2 (once in 2 days)	10.12 Ab[2]	13.48 Aa	11.80 A	11.08 Ab	13.85 Aa	12.47 A
F3 (once in 3 days)	10.15 Ab	12.42 Aa	11.28 A	11.10 Ab	12.80 Aa	11.95 A
F4 (once in 4 days)	9.40 Aa	10.33 Ba	9.87 B	9.32 Ba	9.93 Ba	9.63 B
F5 (once in 5 days)	3.48 Ba	3.82 Ca	3.65 C	3.47 Ca	3.68 Ca	3.58 C
Mean	8.29 B	10.01 A		8.74 B	10.07 A	
IWUE (kg mm^{-1})						
F2 (once in 2 days)	10.77 Ab	14.37 Aa	12.57 A	11.60 Ab	14.50 Aa	13.05 A
F3 (once in 3 days)	10.77 Ab	13.18 Aa	11.98 A	11.73 Ab	13.53 Aa	12.63 A
F4 (once in 4 days)	9.60 Aa	10.57 Ba	10.08 B	9.43 Ba	10.08 Ba	9.76 B
F5 (once in 5 days)	3.43 Ba	3.72 Ca	3.58 C	3.45 Ca	3.67 Ca	3.56 C
Mean	8.64 B	10.46 A		9.05 B	10.45 A	

[1] Treatment means are averaged over varieties.

[2] Means in column within irrigation frequency in each year followed by the same uppercase letter are not significantly different at P = 0.05 according to Fisher's protected LSD test. Means in row within N level in each year followed by the same lowercase letter are not significantly different at P = 0.05 according to Fisher's protected LSD test.

for drip-irrigated maize in sandy soil was about once every 2.5 days. This result was obtained by taking the first derivation of each equation and equalizing to zero.

There was a significant interaction between irrigation frequency and nitrogen level (Table 4). In both seasons, WUE and IWUE of the irrigation frequency treatments followed an $F2 \approx F3 > F4 > F5$ order at each N level, except in 2005 where the irrigation frequency treatments were in the order of $F2 \approx F3 \approx F4 > F5$ at 190 kg N ha^{-1} (Table 8). WUE and IWUE responses to N level were also influenced by irrigation frequency treatments. Both variables did not differ between the two N levels at F4 and F5. However, 380 kg N ha^{-1} had WUE and IWUE of 25.0 % and 18.3 % in 2005 and 20.0 % and 13.3 % in 2006 higher than 190 kg N ha^{-1} at F2 and F3 respectively (Table 8).

Discussion

The frequency of water application is one of the most important factors in drip irrigation management. Due to the differences in soil water potential and soil water distribution with depth, grain yield and WUE might differ when the same quantity of water is applied under different irrigation frequencies. Therefore, it is essential to develop the most suitable irrigation schedule for different ecological regions, especially as plant water consumption during plant growth depends mostly on soil and climatic conditions (Nath et al. 2001). As a result, in the present experiment, the main noticeable similarities/differences between the irrigation frequencies throughout the different soil layers were that (i) the different irrigation frequencies showed significant relative drying of the 25 cm soil layer (Fig. 1) and the soil water content was slightly lower than the level of the permanent wilting percentage (PWP) at this depth; (ii) the depth of available soil water at the soil layer 50 cm was higher in the F2 and F3 treatments than in the F5 treatment and vice versa at the soil layer 75 cm (Table 2); and (iii) the soil water content at both depths was found to be changed more dramatically among the irrigation frequencies (Fig. 1). The explanations for this phenomenon could be: (1) not only all available soil water at the depth of 25 cm was consumed, but also some of the soil water held with higher energy than that retained at the PWP was subjected to evapotranspiration from the soil surface; and (2) in a low irrigation frequency (F5), the quantity of water applied at each irrigation was more than could be retained by the sandy soil, thereby resulting in possible percolation losses beyond the root zone. However, in the higher frequency treatments (F2 and F3), the small quantity of water applied at each irrigation was sufficient to wet the root zone without resulting in water drainage. This might indicate that drip irrigation frequency has some beneficial effect on soil water storage and plant water consumption. These findings are evident from the values of soil water storage (ΔS) and irrigation water compensation for plant water consumption (Irc). The values of ΔS were generally higher in the F2 and F3 treatments than in the F4 and F5 treatments and vice versa for Irc values (Table 3). This is probably due to the low irrigation frequency having the highest probability of more deep percolation and the amount of water that percolated at lower depth was not depleted by roots. In case of maize, the plants extracted most of the soil water from the 0–35 cm soil depth (Panda et al. 2004). This may be due to approximately 85 % of the total maize root length being within the upper 30 cm of the soil with root length decreasing with depth (Laboski et al. 1998). Therefore, frequent irrigation prevents the large fluctuation in plant water stress caused by infrequent irrigations. This factor might explain the reduction in grain yield under less frequent irrigation treatments, as the ideal conditions for maize growth require high and nearly constant soil water potential, particularly during flowering and pollination stages (NeSmith and Ritchie 1992, Stone et al. 2001).

In the present study, averaged over the two seasons, the low irrigation frequencies (F4 and F5) resulted in a significant yield reduction of 22 % and 72 % compared with F2 and 20 % and 71 % compared with F3 respectively (Table 5). The highest reduction in grain yield with low irrigation frequencies, especially in F5, might be due to water deficit occurring at very critical growth stages of maize. Water deficit probably occurred at low irrigation frequency because the quantity of applied water at each irrigation was higher than the soil water storage capacity. This means that part of the water application may not be used by the plant and would most likely drain below the root zone (Coelho and Or 1999, Assouline 2002). This is in agreement with the results of the differences in soil water content distribution with depth among the irrigation frequency treatments before irrigation (Fig. 1). In the active root zone (at depth 25–50 cm), the soil water content of F5 was close to the wilting point before irrigation (Fig. 1). This means that a water deficit during sensitive growth stages probably occurred at low irrigation frequencies. These findings are also evident from the values of yield components, especially for components that developed at sensitive growth stages. In the present study, the low irrigation frequencies (F4 and F5) produced the lowest values for the ear number per plant, ear weight per plant, grain number per ear, grain weight per plant and 100-grain weight (Table 6). Claassen and Shaw (1970) reported that the yield component affected by water deficit at the flowering stage is the number of ears and grains per plant, whereas post-pollination water deficit chiefly decreases grain size. In general, with the onset of tasselling, the maize crop is in a critical growth and development stage for grain yield. The tasselling, silking and pollination stages of maize development are extremely critical because the yield components of ear and grain number can no longer be increased by the plant and the potential size of the grain is being determined (Weerathaworn et al. 1992).

In this study, WUE and IWUE values from the high irrigation frequency (F2 and F3) were generally higher when compared with those from the low irrigation frequency (F4 and F5) (Table 8). The findings obtained in this study are in contradiction with the observation of Camp et al. (1989), Howell et al. (1997), Oktem et al. (2003) and Wan and Kang (2006), who found that the low irrigation frequency resulted in higher values in WUE than the high irrigation frequency. The lower performance of the F4 and F5 treatments in the current study might be attributed to the relatively low water retention capacity of the sandy soil used in this experiment, compared with that of the clay loam soil in the experiments of the above-mentioned studies, and therefore more water might contribute to percolation losses beyond the active root zone because the amount of water applied at each irrigation in F4 and F5 treatments is higher than the soil water storage capacity. Therefore, these results suggest that it is important to determine the accurate irrigation frequency for specific locations under the drip irrigation system.

When the soil water content is very limited, as at low irrigation frequency, the development of the roots is restrained and root hairs are damaged. When the soil is wet, as at high irrigation frequency, the roots expand rapidly and the cells in the periderm expand correspondingly. Because of this phenomenon, frequently watered plants used more water because they found it much more easily without suffering from water deficit, and this caused increases in WUE and IWUE compared with infrequently watered plants.

In this study, there was a significant interaction between irrigation frequency and nitrogen levels for all measurements, with the exception of 100-grain weight (Tables 4, 5, 6 and 8). In most cases, measurements with the application of 190 kg N ha^{-1} were not statistically different from that at 380 kg N ha^{-1} at the low irrigation frequency, especially in F5. However, the application of 190 kg N ha^{-1} resulted in a significant reduction in these measurements compared with 380 kg N ha^{-1} at the high irrigation frequency. These results might be due to the higher irrigation frequency, such as F2 and F3, with the quantity of applied water at each irrigation being just sufficient to wet the root zone without causing water leaching, thereby preventing leaching losses of nitrogen as well. This increase in available soil water in the root zone, on the other hand, might have increased the mineralization of organic matter leading to increased availability of nitrogen and hence a better utilization of the applied nitrogen and subsequently help various physiological processes in plant growth and finally increase yield and yield components (Ramireddy et al. 1982). In contrast, at the low irrigation frequencies, the quantity of applied water at each irrigation was higher than the soil-water storage capacity, thereby increasing leaching losses of nitrogen. The low irrigation frequencies also lead to drying up of the active root zone over time between the irrigation cycles, which decreases the availability of nitrogen and hence decreases yield and yield components (Mbagwu and Osuigwe 1985). Therefore, the effect of the interaction between nitrogen level and irrigation frequency on yield and yield components was significant in this study.

The sandy soil used is characterized by a low organic matter content and this will result in a reduced amount of mineralizable organic nitrogen. Ammonium adsorption is further considered to be low in such soils with a significantly reduced cation exchange capacity. The investigated high nitrogen application rate of 360 kg N ha^{-1}, although representing local practice, however might be reduced by maintaining the yield and by further decreasing possible nitrogen losses by leaching. Use of high chemical N rate (267 kg N ha^{-1}) resulted in ear yields at least 20 % greater than sweet maize fertilized with reduced N rates of 200 kg N ha^{-1} or less in sandy soils (Cherr et al. 2007). Further studies will be required to recommend optimized nitrogen application rates in sandy soils.

Oner et al. (2002) reported that all factors that contribute to yield increase also increase WUE. Olsen et al. (1964) reported that N fertilization increases WUE on N-deficient soils where water is adequate.

In this study, no significant differences were observed between the single-cross 10 and the three-way cross 310 for all measurements. Additionally, the possible interaction terms involving the varieties were also not significant except for the variety × irrigation frequency interaction which had significant effects on grain yield and ear weight per plant (Table 4). This might be due to the two hybrids being produced from different varieties of the same species. Thus, the response of the two hybrids to irrigation frequency and nitrogen levels is similar.

Conclusions

The results of this study contribute to a better understanding of the behaviour of drip-irrigated maize in semi-arid conditions. Drip irrigation frequency affected soil water distribution patterns, depending on soil depth, maize yield and its components, WUE and IWUE. A somewhat higher yield and WUE was obtained for the high irrigation frequency (F2 and F3), although the total irrigation water applied was equal to that of the low irrigation frequency (F4 and F5).

The response of all measurements to N level was affected by the irrigation frequency. Grain yield, WUE and IWUE with the application of 190 kg N ha^{-1} were not statistically different from that of 380 kg N ha^{-1} at F4 and F5. However, the high irrigation frequency (F2 and F3) enhanced these measurements at 380 kg N ha^{-1}. In order to improve grain yield and WUE for drip-irrigated maize in sandy soils of Egypt, it is recommended that irrigation frequency should be once ever 2 days or 3 days at nitrogen levels of 380 kg N ha^{-1} regardless of maize varieties. However, further possible decreases in the increased nitrogen application rate of 380 kg N ha^{-1} should be investigated.

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