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Irrigation rate and plant density effects on yield and water use efficiency of drip-irrigated corn

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ABSTRACT

The efficient use of water by modern irrigation systems is becoming increasingly important in arid and semi-arid regions with limited water resources. This study was conducted for 2 years (2005 and 2006) to establish optimal irrigation rates and plant population densities for corn (*Zea mays* L.) in sandy soils using drip irrigation system. The study aimed at achieving high yield and efficient irrigation water use (IWUE) simultaneously. A field experiment was conducted using a randomized complete block split plot design with three drip irrigation rates (I_1: 1.00, I_2: 0.80, and I_3: 0.60 of the estimated evapotranspiration), and three plant population densities (D_1: 48,000, D_2: 71,000 and D_3: 95,000 plants ha^{-1}) as the main plot and split plot, respectively. Irrigation water applied at I_1, I_2 and I_3 were 5955, 4762 and 3572 m^3 ha^{-1}, respectively. A 3-day irrigation interval and three-way cross 310 hybrid corn were used. Results indicated that corn yield, yield components, and IWUE increased with increasing irrigation rates and decreasing plant population densities. Significant interaction effects between irrigation rate and plant population density were detected in both seasons for yield, selected yield components, and IWUE. The highest grain yield, yield components, and IWUE were found for I_1D_1, I_1D_2, or I_2D_1, while the lowest were found for I_3D_2 or I_3D_3. Thus, a high irrigation rate with low or medium plant population densities or a medium irrigation rate with a low plant population density are recommended for drip-irrigated corn in sandy soil. Crop production functions with respect to irrigation rates, determined for grain yield and different yield components, enable the results from this study to be extrapolated to similar agro-climatic conditions.

1. Introduction

In recent years, drip irrigation has become increasingly popular to reduce the amount of water and fertilizer that are applied to the crop, and also to reduce the amount of labor (Tan, 1995; Hanson et al., 1997; Fekadu and Teshome, 1998). Because the drip irrigation is capable of applying small amounts of water where it is needed and to apply it with a high degree of uniformity and frequently, these features make it potentially much more efficient than other irrigation methods. However, the lateral line of drip system for most field row crops, such as corn, is laid out at intervals of about 0.7 m with an emitter spacing of 0.2 m (Mohamed, 1999). Using such design, the initial installation cost has not been considered a viable economic option for field row crops. Among the various components of a drip irrigation system, the

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cost of laterals is the major factor, which influences the total system cost. Most vegetable crops in Egypt such as muskmelons (*Cucumis melo*) and watermelon (*Citrulus lanatus*) are grown at lateral spacing of 1.4 m or more with an emitter spacing of 0.3–0.5 m. Using such design 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. Furthermore, such design may be considered for corn production through crop rotation with vegetable crops.

Under drip irrigation, the ponding zone that develops around the emitter is strongly related to both the water application rate and the soil properties (Assouline, 2002). Consequently, the water application rate is one key factor determining the soil water content around the emitter (Bresler, 1978) and the water uptake pattern (Phene et al., 1991; Coelho and Or, 1999). However, excessive or inadequate water application has a significant impact on either drip irrigation efficiency or final grain yield. For instance, very high rates of water application can eliminate crop water stress, but it will also lessen drip irrigation efficiency by increasing the amount of water and nutrients that leach below the root zone (Morton et al., 1988; Jordan et al., 2003). Very low rates of water application, by contrast, can cause water stress, especially in sandy soils, by failing to meet the water requirement of the plants. Therefore, a proper drip irrigation rate is one that both minimizes the amount of water leached from the root zone and maintains a high soil matrix potential in the rhizosphere to reduce plant water stress.

Corn is the major irrigated crop in Egypt. It is very responsive to the amount of irrigation water applied: positive when irrigation is sufficient and negative when not. Rhoades and Bennett (1990) and Lamm et al. (1995) both reported that it is difficult to plan for deficit irrigation for corn without simultaneously causing yield reduction. Corn plants are especially sensitive to water stress because their root system is relatively sparse. Laboski et al. (1998) found that corn root distribution assessed at tasseling showed an average of 94% of total root length within 60 cm of the soil surface and 85% within 30 cm. This sensitivity to water stress can lead to dramatic fluctuations in corn yield in light of frequent drought and poor irrigation management often found in Egypt. Therefore, precise drip irrigation management is essential to ensure optimal corn yield because water storage under drip irrigation conditions is generally less than that for surface and sprinkler irrigation techniques, and because most roots are concentrated in the damp soil near each emitter or along each lateral line. Accurate information on yield responses in light of the amount of water applied by drip irrigation is therefore essential to achieve the best drip irrigation management.

Increasing the plant population density usually increases corn grain yield until an optimum number of plants per unit area is reached (Lang et al., 1956; Holt and Timmons, 1968). Fulton (1970) also reported that higher plant densities of corn produce higher grain yields. Plant densities of 90,000 plants ha^{-1} for corn are common in many regions of the world (Modarres et al., 1998; Al-Kaisi and Yin, 2003). However, under surface irrigation conditions in Egypt, population densities from 50,000 to 56,000 plants ha^{-1} are considered optimal because greater plant densities result in reduced yields because of competition between plants (Mohamed, 1999; Griesh and Yakout, 2001). Population densities under drip irrigation could possibly be increased because of smaller plant statures accompanied by decreased leaf numbers and sizes. Little information is available about optimum plant population densities of corn when grown in drip systems of vegetable crops.

The design of drip irrigation system make it potentially enabling plant population densities of up to 90,000 plants ha^{-1}. However, optimum plant population densities are related to soil water availability (Holt and Timmons, 1968; Karlen and Camp, 1985), N fertility, and other environmental factors. For corn, yield increases with increasing available soil water content and nitrogen levels until plant densities reach about 50,000 plants ha^{-1} (Eckert and Martin, 1994). Al-Kaisi and Yin (2003) reported that the combination of 0.80–1.00 estimated evapotranspiration (ET) and 57,000–69,000 plants ha^{-1} population produced optimum corn yield, with irrigation treatments 0.80 ET at these densities being the best management system for optimum water use efficiency in loamy soil under a center-pivot sprinkler system.

The objectives of this study were to evaluate the impacts of various drip irrigation rates and plant population densities on corn production and irrigation water use efficiency (IWUE) when grown in drip systems of vegetable crops and to evaluate production functions in light of drip irrigation rates and yield and its components to enable extrapolation of the results to similar agro-climatic conditions.

2. Materials and methods

2.1. *Experimental site description*

This study was conducted on the Experimental Farm of the Faculty of Agriculture at Suez Canal University, Ismailia, Egypt (30°58′N, 32°23′E, and 13 m above mean sea level) during the 2005 and 2006 growing seasons. The soil of the experimental site is sandy throughout its profile (75.9% coarse sand, 19.7% fine sand, 2.7% silt and 1.7% clay). Selected chemical properties and soil water contents of the experimental soil are given in Table 1. Detailed climatic parameters for Ismailia are given in Table 2. Soil bulk density was determined with a classical method, using cylinders 100 mm wide and 60 mm in height according to Grossmann and Reinsch (2002). Soil field capacity and wilting point were determined in the laboratory using the method described by Cassel and Nielsen (1986).

2.2. *Agronomic practices*

Nitrogen fertilizer was applied at a rate of 288 kg ha^{-1} in the form of ammonium sulphate (20.5%) as fertigation. Nitrogen fertilizer was added 2 weeks after sowing in four equal doses with one dose every 10 days. 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. Weed, pests, and diseases control were done in a timely manner. Hand harvesting was performed about 120 days after sowing.

Table 1 – Chemical and physical properties of the experimental field soil (averaged over two seasons)

Soil depth (cm)	Soil bulk density ($g\ cm^{-3}$)	Field capacity % (P_w)	Wilting point % (P_w)	Available moisture % (P_w)	pH	Organic matter (%)	EC ($dS\ m^{-1}$)	Texture
0–30	1.66	6.97	1.45	5.52	8.00	0.48	0.53	Sandy
30–60	1.57	7.87	1.71	6.16	7.90	0.43	0.45	Sandy
60–90	1.68	6.15	1.50	4.65	7.65	0.35	0.40	Sandy

Table 2 – Monthly climatic data at Ismailia Governorate during the growing periods of corn in 2005 and 2006[a]

Months	Temperature (°C)						Average relative humidity (%)	
	Maximum		Minimum		Average		2005	2006
	2005	2006	2005	2006	2005	2006		
May	34.7	41.3	23.0	22.2	28.9	31.8	51.1	46.1
June	36.1	33.1	20.7	19.6	28.4	26.4	54.1	55.8
July	35.6	36.4	22.1	22.2	28.9	29.3	56.6	56.0
August	36.6	35.3	22.1	21.9	29.4	28.6	55.9	58.8
September	35.5	33.2	20.2	19.6	27.9	26.4	56.4	59.1

[a] Data collected from Agriculture Research Center Meteorological Station in Ismailia.

2.3. Experimental design and treatments

A randomized complete block split plot design with four replicates was used in each season. Irrigation treatments and plant population densities were randomly assigned to the main and split plots, respectively. A layout of the experimental plots is shown in Fig. 1.

The drip irrigation system, with a design typical for most vegetable crop production systems, was divided into three sectors, with the three irrigation treatments being randomly assigned to the three sectors and kept in the same place each year. Within each sector, there were four replicates of the same irrigation treatment. Each sector had one valve, one flow meter, and one pressure gauge to control the operating pressure and measure the irrigation quantity. The three irrigation treatments were I_1: 1.00, I_2: 0.80 and I_3: 0.60 of the estimated crop evapotranspiration (ET_c), which represented 5955, 4762 and 3572 $m^3\ ha^{-1}$ of water, respectively. The dates of each irrigation event and the quantities of water applied are given in Table 3. The amount of irrigation water needed in $mm\ ha^{-1}$ was calculated according to the crop coefficient (K_C) and the daily reference evapotranspiration (ET_O), the latter of which was computed using the Penman-Monteith equation (Allen et al., 1998) from 10 daily climatic data points obtained from the Central Laboratory of Agricultural Climate for Ismailia, 500 m away from the experimental field. 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 K_C was adjusted according to local climatic conditions, including minimum relative humidity, wind speed and maximum plant height. The adjusted K_C values in the months of the cropping season varied between 0.35 and 1.30. The drip irrigation efficiency was assumed to be 0.9, and the root extension coefficient according to Moon and Gulik (1996) was taken to be 0.8. To ensure full germination, 65 mm of irrigation was applied for all irrigation treatments at sowing with an additional irrigation of 89 mm were applied 20 days later for complete establishment of seedlings. Irrigation was carried out every 3 days throughout the growing season.

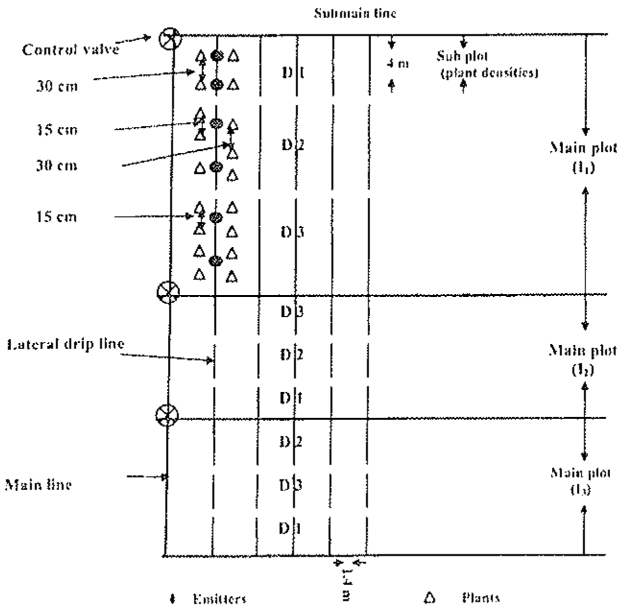

Fig. 1 – Layout of one replicate of an experimental plot, that includes three plant density treatments, showing locations of irrigation treatments, plant densities and plant distributions around the emitters. D_1, D_2 and D_3 indicate plant density treatments (48,000, 71,000 and 95,000 plant ha^{-1}, respectively). I_1, I_2 and I_3 indicate irrigation treatments (1.00, 0.80 and 0.60 of the estimated crop evapotranspiration, respectively).

Three plant population densities (D_1: 48,000, D_2: 71,000, and D_3: 95,000 plants ha^{-1}) were randomly nested within each main plot of irrigation treatment as a split plot. Each split plot

Table 3 – The dates of each irrigation event and the quantity of water applied for each of three irrigation treatments (data averaged over two seasons)

Days after sowing	Quantity of water applied each irrigation event (m^3 ha^{-1})		
	1.00 ET (I_1)	0.80 ET (I_2)	0.60 ET (I_3)
23	234.0	187.5	154.5
27	234.0	187.5	154.5
31	257.0	187.5	154.5
35	316.0	234.0	167.0
39	316.0	234.0	167.5
43	316.0	234.0	167.5
47	316.0	271.5	210.5
51	316.0	271.5	210.5
55	316.0	271.5	210.5
59	309.0	273.5	210.5
63	309.0	273.5	210.5
67	386.0	283.0	210.5
71	386.0	283.0	210.5
75	386.0	283.0	210.5
79	386.0	283.0	168.5
85	246.0	210.5	168.5
87	245.5	210.5	168.5
91	245.5	210.5	168.5
95	159.0	140.5	92.0
99	159.0	140.5	91.0
107	117.0	91.5	65.5
Total	5955.0	4762.0	3572.0

consisted of five polyethylene lateral drip lines (Twin-wall IV, 16 mm in diameter, and 0.3 m emitter spacing) with a length of 4 m. The lateral line was laid out along each corn row at 1.4 m. The split plot area was 28 m^2. The drippers had a discharge rate of 3.1 l h^{-1} at an operating pressure of 1.3 Pa. Two, three, and four seeds (cv. three-way-cross 310) around each dripper for D_1, D_2 and D_3, respectively, were sown on 28 May 2005 and 3 June 2006. The distribution of plants around the drippers in the different plant density treatments is shown in Fig. 1.

2.4. *Soil water content measurement*

Soil water content was monitored before and after each irrigation event starting 20 days after sowing at soil depth intervals of 0–30, 30–60, and 60–90 cm. Soil samples were taken at positions immediately under the drippers. Soil water content was determined by 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 by the following equation (Marshall et al., 1996):

$$De = \frac{\theta_v \times D}{100},$$

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

2.5. *Parameter assessments*

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

Irrigation water use efficiency (IWUE) in kg m^{-3} was calculated as IWUE = (GY/I) × 100, where GY is grain yield (kg ha^{-1}) from a given irrigation treatment and plant population density and I is the amount of applied irrigation water (m^3 ha^{-1}) for each irrigation treatment.

2.6. *Statistical analysis*

A factorial experimental design with three irrigation rates and three plant population densities was arranged in a completely randomized design with four replicates. Data were analyzed using an analysis of variance split plot design, with irrigation rate treatments assigned as the whole plot, plant population densities as split plots and replicates as blocks. Statistical analysis was done using CoStat Version 6.311 (CoHort software, Berkeley, CA 94701). Treatment means were compared using Duncan's multiple test (Steel and Torrie, 1980). Probability levels lower than 0.05 or 0.01 were held to be significant.

3. Results and discussion

3.1. *Yield components*

The yield components, namely weight of ears per plant, number of grains per ear, number of grains per row, and weight of grain per plant are presented in Tables 4 and 5. Both the irrigation rate and plant population density significantly affected all yield components. In 2005, the differences in number of grains per ear and number of grains per row between 1.00 and 0.80 ET were not significant, with 0.60 ET producing the lowest values for both variables. In 2006, 0.80 and 0.60 ET demonstrated lower values for yield components than 1.00 ET.

Yield components were also significantly affected by plant population density (Tables 4 and 5). As seen from the tables, the results indicate that values for yield components at 71,000 plants ha^{-1} were occasionally comparable to those at 48,000 plants ha^{-1}, but values at 95,000 plants ha^{-1} were not competitive with those at either 48,000 or 71,000 plants ha^{-1} The findings obtained in this study were in good agreement to those reported by Mohamed (1999) and Griesh and Yakout (2001), who found that most yield components under drip irrigation system were decreased by increasing plant densities (up to the maxima examined of 67,000 plants ha^{-1}). This result might be attributed to the competition between plants being more enhanced at high densities, which, in turn, led to a reduced quantity of dry matter and, consequently, a reduction of all yield components (Kamel et al., 1983; Soliman et al., 1995).

The combined effect of irrigation rate and plant population density had a significant effect on the weight of ears per plant, number of grains per ear and row, and weight of grain per plant with the highest values for these components being

Table 4 – Effects of irrigation rate and plant population density on selected yield components in 2005 and 2006

Plant population density (plant ha^{-1})	2005				2006			
	1.00 ET (I_1)	0.80 ET (I_2)	0.60 ET (I_3)	Mean	1.00 ET (I_1)	0.80 ET (I_2)	0.60 ET (I_3)	Mean
1. Weight of ears per plant (g)								
48,000 (D_1)	201.7 a	194.4 a	115.0 c	170.4 A	212.3 a	196.8 b	108.3 d	172.5 A
71,000 (D_2)	190.0 a	148.8 b	90.0 de	142.9 B	208.7 ab	128.8 c	83.3 ef	140.3 B
95,000 (D_3)	141.7 b	105.0 cd	83.9 e	110.2 C	135.7 c	95.7 e	73.9 f	101.7 C
Mean	177.8 A	149.4 B	96.3 C		185.6 A	140.4 B	88.5 C	
LSD (0.05)	ET 24.7	D 9.7	ET × D 16.5		ET 13.2	D 7.2	ET × D 12.5	
2. Number of grains per ear								
48,000 (D_1)	372.6 a	373.9 a	179.1 c	308.5 A	412.5 a	407.4 a	192.4 d	337.5 A
71,000 (D_2)	368.8 a	352.7 a	101.0 d	274.2 A	402.2 ab	352.7 b	107.4 e	287.4 B
95,000 (D_3)	276.9 b	182.6 c	60.1 d	173.2 B	291.9 c	169.2 d	56.8 e	172.6 C
Mean	339.4 A	303.0 A	113.4 B		368.9 A	309.8 B	118.9 C	
LSD (0.05)	ET 42.1	D 36.0	ET × D 62.4		ET 47.6	D 29.7	ET × D 51.9	
3. Number of grains per row								
48,000 (D_1)	26.7 a	26.1 a	16.7 c	23.2 A	29.7 a	27.4 a	17.0 b	24.7 A
71,000 (D_2)	25.7 a	26.1 a	11.9 d	21.2 B	26.5 a	26.1 a	10.4 c	21.0 B
95,000 (D_3)	25.7 a	22.5 b	7.9 e	18.7 C	28.9 a	16.3 b	7.4 c	17.5 C
Mean	26.0 A	24.9 A	12.2 B		28.3 A	23.3 B	11.6 C	
LSD (0.05)	ET 3.1	D 1.8	ET × D 3.1		ET 2.4	D 2.9	ET × D 5.0	

Means followed by the same letter are not significantly different from one another based on Duncan's multiple test at $P \leq 0.05$. Capital letters in rows and columns indicate significant differences among irrigation treatments and plant density treatments, respectively. Small letters indicate significant differences in the interaction between irrigation rate and plant density.

obtained for I_1D_1, I_1D_2 and I_2D_1 and the lowest for I_3D_2 and I_3D_3 (Tables 4 and 5). Karlen and Camp (1985) similarly reported that plant population significantly responded to water management for corn yield.

3.2. Grain yield

Grain yield was significantly affected by irrigation rate and plant population density (Table 5). In both seasons, 0.80 and 0.60 ET consistently resulted in lower yields than the 1.00 ET treatment. Average yield decreases for 0.80 and 0.60 ET relative to 1.00 ET were 32 and 63% in 2005 and 33 and 64% in 2006, respectively. Hergert et al. (1993) reported that corn yield under full irrigation was significantly greater than under limited irrigation. Darusman et al. (1997) reported that the highest yield of corn was achieved at an ET coefficient of 100%. Khalil et al. (2002) studied the effects of irrigation on grain yield of corn using the pan evaporation method and found that the highest yield was obtained at irrigations of 1.00 evaporation pan coefficients.

Grain yield was also influenced by plant population density. Densities of 48,000 or 71,000 plants ha^{-1} were optimum under the conditions of this study, with the values obtained at 71,000 plants ha^{-1} being competitive with those at 48,000 plants ha^{-1} (Table 5). Averaged over two seasons, grain yields at 71,000 plants ha^{-1} were only 18% less than those at 48,000 plants ha^{-1}, whereas yields at 95,000 plants ha^{-1} showed significant decreases averaging 51 and 40% of the values at 48,000 and 71,000 plants ha^{-1}, respectively (Table 5). Lower grain yield at the high plant density (95,000 plant ha^{-1}) may have resulted from fewer flower initials being formed, poor pollination resulting from asynchrony of tasseling and silking, or abortion of kernels after fertilization (Karlen and Camp, 1985; Hashemi-Dezfouli and Herbert, 1993). These results are confirmed by the correlation between grain yield and different yield components in the following section. Plant densities for Egyptian corn varieties possibly cannot be increased much beyond 71,000 plants ha^{-1} because of increased, and perhaps excessive, mutual shading. That being said, Modarres et al. (1998) showed that total grain yield was higher at 90,000 plants ha^{-1} than at 65,000 plants ha^{-1}, indicating that Egyptian corn genotypes could be bred to be more tolerant of higher plant densities.

The interaction between irrigation rate and plant population density had a significant effect on grain yield in both seasons (Table 5). The Duncan groupings in decreasing order of grain yield were I_1D_2; I_1D_1; I_2D_1 and I_1D_3; I_2D_2 and I_3D_1; I_2D_3 and I_3D_2; and finally I_3D_3, with quite similar results in both seasons. Therefore the combination of an irrigation rate of 1.00 ET with a density of 71,000 plants ha^{-1} is recommended as the treatment that maximizes grain yield of corn using the drip irrigation system.

3.3. Correlation between grain yield and yield components

Table 6 shows the correlations between selected yield components and grain yield. All yield components examined were positively and strongly correlated with grain yield (coefficient of determinations ranged from 0.72 to 0.90).

3.4. Production functions

Overall grain yield and its different components were mostly linearly and positively correlated with irrigation rates for the

Table 5 – Effects of irrigation rate and plant population density on weight of grains per plant, yield, and irrigation water use efficiency in 2005 and 2006

Plant population density (plant ha^{-1})	2005				2006			
	1.00 ET (I_1)	0.80 ET (I_2)	0.60 ET (I_3)	Mean	1.00 ET (I_1)	0.80 ET (I_2)	0.60 ET (I_3)	Mean
4. Weight of grains per plant (g)								
48,000 (D_1)	164.4 a	120.8 d	88.0 e	124.4 A	182.8 a	160.5 c	94.7 e	146.0 A
71,000 (D_2)	148.3 b	96.1 d	65.7 f	103.4 B	167.7 b	96.1 e	52.4 g	105.4 B
95,000 (D_3)	113.9 c	80.6 e	53.3 g	82.6 C	120.9 d	77.2 f	50.0 g	82.7 C
Mean	142.2 A	99.1 B	69.0 C		157.1 A	11.3 B	65.7 C	
LSD (0.05)	ET 13.2	D 7.2	ET × D 12.4		ET 7.4	D 4.7	ET × D 8.2	
5. Grain yield (kg ha^{-1})								
48,000 (D_1)	7909.0 b	7215.9 c	3716.4 e	6280.3 A	8433.3 b	7131.6 c	3827.3 e	6464.1 A
71,000 (D_2)	8891.9 a	4085.0 de	2577.8 f	5185.1 B	8892.0 a	4307.2 de	2466.9 g	5222.0 B
95,000 (D_3)	4489.4 cd	3104.2 f	1564.9 g	3052.8 C	4600.4 d	3215.4 f	1677.0 h	3164.0 C
Mean	7096.7 A	4801.9 B	2619.7 C		7308.6 A	4884.7 B	2656.8 C	
LSD (0.05)	ET 467.5	D 309.4	ET × D 535.9		ET 367.5	D 305.7	ET × D 529.6	
6. Irrigation water use efficiency (kg m^{-3})								
48,000 (D_1)	1.33 b	1.52 a	1.04 c	1.30 A	1.42 b	1.50 a	1.07 c	1.07 A
71,000 (D_2)	1.49 a	0.86 d	0.72 ef	1.02 B	1.50 a	0.91 d	0.69 ef	0.93 B
95,000 (D_3)	0.75 e	0.65 f	0.44 g	0.61 C	0.77 e	0.67 f	0.47 g	0.64 C
Mean	1.19 A	1.00 B	0.73 C		1.23 A	1.03 B	0.74 C	
LSD (0.05)	ET 0.06	D 0.04	ET × D 0.09		ET 0.06	D 0.05	ET × D 0.10	

Means followed by the same letter are not significantly different from one another based on Duncan's multiple test at $P \leq 0.05$. Capital letters in rows and columns indicate significant differences among irrigation treatments and plant density treatments, respectively. Small letters indicate significant differences in the interaction between irrigation rate and plant density.

development of production functions (Table 7). A good correlation was found between irrigation rate and weight of ears per plant ($R^2 = 0.58$ and 0.62), number of grains per ear ($R^2 = 0.59$ and 0.60), number of grains per row ($R^2 = 0.67$ and 0.69), weight of grain per plant ($R^2 = 0.76$ and 0.67), and grain yield per ha ($R^2 = 0.67$ and 0.67) in 2005 and 2006, respectively. Put into real numbers, a decrease in irrigation rate from 1.00 to 0.60 ET decreased the weight of ears per plant by 46 and 52% (in 2005 and 2006, respectively), the number of grains per ear by 67 and 68%, the number of grains per row by 53 and 59%, the weight of grain per plant by 52 and 58%, and the grain yield per ha by 63 and 64%.

These results indicate that weight of ears per plant, number of grains per ear, number of grains per row, weight of grain per plant, and grain yield per ha were affected most by changing irrigation rates and therefore are good candidates to predict the optimal irrigation rate for corn grown under similar agro-climatic conditions without conducting labor-intensive crop experiments. This fact might be attributed to that these variables being the most sensitive to environmental stress at several developmental stages of corn, with aborted grains being found under water deficit (Otegui and Andrade, 2000). Furthermore, Andrade et al. (2002) reported that number of grains is a function of the physiological condition of the crop under different environmental stress.

3.5. *Irrigation water use efficiency*

The combined effects of irrigation rate and plant population density on irrigation water use efficiency (IWUE) were significant in both seasons (Table 5). High irrigation rates and low population densities displayed the highest IWUE in both seasons. Averaged over all plant population densities and seasons, 1.00 ET had IWUE values that were 16 and 40% greater than those of 0.80 and 0.60 ET, respectively. Compared to

Table 6 – Regression equations and correlation coefficients between grain yield (Y) and selected yield components (X) in 2005 and 2006

Variables	Grain yield (kg ha^{-1}) 2005		2006	
	Regression equation	R^2	Regression equation	R^2
Weight of ears per plant (g)	Y = 15.02X − 313.0	0.77***	Y = 15.23X − 198.3	0.90***
Number of grains per ear	Y = 4.42X + 588.2	0.75***	Y = 4.83X + 522.3	0.84***
Number of grains per row	Y = 71.41X + 198.8	0.75***	Y = 71.58X + 296.9	0.72***
Weight of grains per plant (g)	Y = 20.04X − 238.3	0.84***	Y = 16.80X + 43.1	0.89***

*** Significant at the 0.001 level.

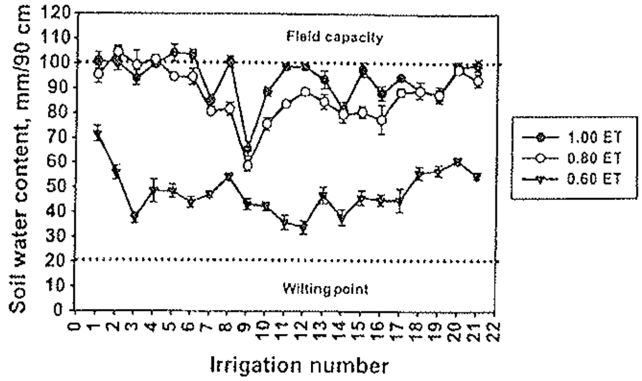

Fig. 2 – Soil water content measured after irrigation at rates of 1.00, 0.80 and 0.60 ET.

densities of 71,000 and 95,000 plants ha^{-1}, respectively, a density of 48,000 plants ha^{-1} had IWUE values averaged over all irrigation rates that were 8 and 53% greater in 2005 and 13 and 40% greater in 2006.

The interaction effect between irrigation rate and plant population density on IWUE was also significant in both seasons (Table 5). The highest IWUE was obtained either under an irrigation rate of 1.00 ET at 71,000 plants ha^{-1} or 0.80 ET at 48,000 plants ha^{-1}. By contrast, the lowest IWUE was recorded for an irrigation rate of 0.60 ET at 95,000 plants ha^{-1}. It is interesting to note that the 0.60 ET treatment at 71,000 plants ha^{-1} had IWUE values similar to those obtained for the 1.00 ET treatment at 95,000 plants ha^{-1}.

In addition to the effect of irrigation rate and plant population density, low IWUE can also occur when soil evaporation is high relative to crop evapotranspiration, early growth rates are low, water application does not correspond to crop demand, or shallow roots are unable to utilize any deep water in the soil profile. These problems are magnified when irrigating at lower rates for populations at higher densities, where small inputs of water irrigation and competition between plants are prevalent (Stark et al., 1983; Doerge and Roth, 1991; Ertek et al., 2006).

3.6. *Soil water content after and before the irrigation*

Soil water content measured after irrigation during the growing season and averaged over two seasons at soil depths of 0–90 cm are shown in Fig. 2. The 1.00 and 0.80 ET treatments were closer to field capacity after irrigation than was the 0.60 ET treatments because of the greater amount of water per irrigation event. For example, during the growing season, post-irrigation soil water content of the 90-cm profile for the 0.60 ET treatments was 49–45% lower than those for the 1.00 and 0.80 ET treatments.

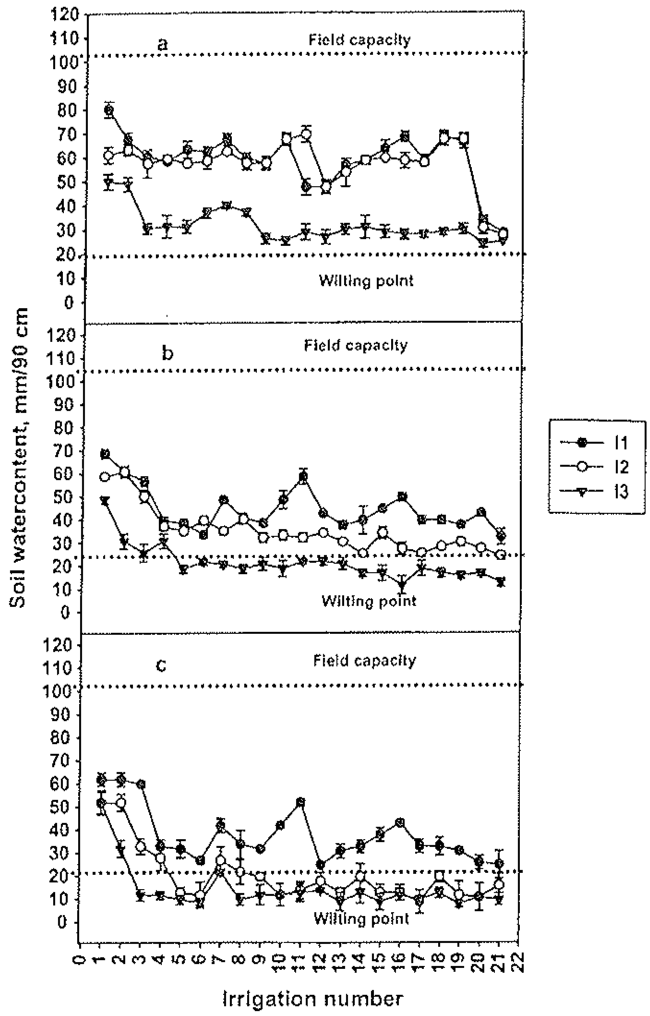

Fig. 3 – Soil water storage (0–90 cm) before irrigation averaged over two growing seasons in D_1 (a), D_2 (b) and D_3 (c) treatments.

Table 7 – Regression equations and correlation coefficients between grain yield and selected yield components (Y) and irrigation rates (X) in 2005 and 2006

Variables	Irrigation rates (m^3 ha^{-1})			
	2005		2006	
	Regression equation	R^2	Regression equation	R^2
Weight of ears per plant (g)	Y = 0.067X + 0.1	0.58***	Y = 0.084X − 35.9	0.62***
Number of grains per ear	Y = 0.226X + 200.1	0.59***	Y = 0.250X − 234.2	0.60***
Number of grains per row	Y = 0.014X − 6.6	0.67***	Y = 0.017X − 12.4	0.69***
Weight of grains per plant	Y = 0.060X − 23.0	0.76***	Y = 0.079X − 52.4	0.67***
Grain yield (kg ha^{-1})	Y = 1.228X − 754.0	0.67***	Y = 1.395X − 984.3	0.67***

*** Significant at the 0.001 level.

Analogous measurements of soil water content measured before irrigation showed that the influence of irrigation varied with plant population density (Fig. 3a–c). Averaged over 21 irrigations and compared to the 1.00 and 0.80 ET treatments, the 0.60 ET treatment displayed reductions in soil water content of 46 and 45% at D_1, 53 and 40% at D_2, and 62 and 30% at D_3, respectively. Similarly, soil water content for the 0.80 ET treatment was 3, 21 and 46% lower than those for 1.00 ET treatment at D_1, D_2 and D_3, respectively (Fig. 3a–c). This indicates that soil water content within the top 90 cm of soil was available for the growing corn plants in the I_1D_1, I_2D_1, I_1D_2, and I_2D_2 treatments. However, in the I_3D_2 treatment and almost all D_3 treatments, soil water contents were closer to the wilting point, leading to water stress during the sensitive growth stages. The greatest decrease in grain yield in corn is caused by water deficits during the flowering period (including tasseling and silking and pollination), owing mainly to a reduction in number of grains per ear. Severe water deficits during this period, particularly at silking or pollination, may result in little or no grain yield due to silk drying. Water deficits during the yield formation period may also lead to reduced yield due to a reduction in grain size (Musick and Dusek, 1980; Sinclair et al., 1990; Weerathaworn et al., 1992). Thus, the gradual increase in water stress at lower irrigation rates and higher population densities in this study, reduced grain yield and yield components significantly. By contrast, higher irrigation rates, especially at lower and medium population densities, created favourable soil water environments for corn growth under drip irrigation and resulted in higher yields.

4. Conclusion

In this study, we demonstrate that the drip systems being used for vegetable crops are also effective for successful corn production, with the combined and individual effects of drip irrigation rate and plant population density being significant determinants of overall yield, yield components and IWUE. The highest values of these components were obtained under the highest irrigation rate (1.00 ET) for medium to small densities (48,000 or 71,000 plants ha^{-1}), whereas the lowest values were obtained from the lowest irrigation rate (0.60 ET) for medium and high densities (71,000 and 95,000 plants ha^{-1}). Therefore, densities of 48,000 plants ha^{-1} was a viable alternative to 71,000 and 95,000 plants ha^{-1} under irrigation rates of 0.80 and 0.60 ET, and an increase in density to 71,000 plants ha^{-1} was possible under irrigation rates of 1.00 ET.

The soil water contents in the 1.00 and 0.80 ET treatments were closer to field capacity after irrigation than was that of the 0.60 ET treatment because of the greater amount of water per irrigation event. Soil water contents before irrigation were closer to the wilting point for high plant population densities under low irrigation rates.

In conclusion, we recommend the combination of an irrigation rate of 1.00 ET at a density of 71,000 plants ha^{-1} when irrigation water supplies are sufficient or a rate of 0.80 ET at 48,000 plants ha^{-1} when they are limited as the best management system for optimizing corn yield when grown in existing drip systems of vegetable crops.

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