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ORIGINAL PAPER

Bell pepper response to surface and subsurface drip irrigation under different fertigation levels

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Abstract A two-year field experiment was conducted in 2007 and 2008 to investigate different bell pepper responses to subsurface drip irrigation (SDI) and surface drip irrigation (DI) under four nitrogen levels: 0, 75, 150, and 300 kg/ha N (N_0, N_{75}, N_{150}, and N_{300}, respectively). Irrigation interval was set at 4 days. Bell pepper yield under SDI was significantly higher than that under DI by 4% in 2007 (13% in 2008). Water consumption under SDI was lower than that under DI by 6.7% in 2007 (7.3% in 2008). Meanwhile, root length density under SDI was obviously higher than that under DI by 11.8% in 2007 (12.5% in 2008). The percentage of root length below 10-cm soil depth under SDI was higher than that under DI by 7%, proving that SDI promotes crop root growth and enhances downward root development. Soil N residue under SDI was lesser than that under DI. Lastly, SDI with N application of 150 kg/ha is recommended as an optimal fertigation practice in improving bell pepper yield and water-use efficiency, as well as in NO_3^--N leaching.

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Introduction

Agricultural production is the largest water consumer, accounting for more than 60% of total water consumption in China (The Ministry of Water Resources of the People's Republic of China 2008). Hence, in resolving water shortage, more and more countries are paying greater attention to agricultural practices. The efficient utilization of available water resources is crucial because although China hosts 22% of the global population, it only has 7 and 6% of the world's farmlands and water resources, respectively (National Economic and Social Development 2008). Therefore, techniques to save irrigation water and increase crop water-use efficiency (WUE) are necessary.

Levels of nitrogen fertilizer application have increased sharply in north China in recent years (Zhu et al. 2005), resulting in nitrate leaching and groundwater contamination (Rossi et al. 1991; Cameron et al. 1997; Zhu et al. 2004). It was reported that overfertilization in north China is leading to high concentrations of nitrate in groundwater and drinking water (average of 68 mg/L) (Li et al. 2001; Zhu et al. 2004), whereas the percentage of applied N intake by crops is below 40% (Zhang et al. 1996).

Therefore, there is an urgent need to maximize the use of water and fertilizer to minimize nitrate leaching and groundwater contamination, and to achieve optimal agronomic, economic, and environmental benefits.

Surface drip irrigation (DI) introduces water and nutrients to soil surface near roots through emitters. Subsurface drip irrigation (SDI) laterals are buried underground, supplying water and nutrients directly to root zones (Phene and Beale 1979; Lamm 1995; Camp et al. 1997). DI and SDI are modern and enhanced water- and fertilizer-saving methods (Phene et al. 1991; Solomon and Jorgensen 1992; Lamm 1995, 2002; Camp 1998; Ayars et al. 1999).

There are limited comparative studies on SDI and DI under different fertigation conditions. Several studies have compared the effects of SDI and DI on crop yield, proving that SDI generally results in higher crop yield (Hanson et al. 1997; Hanson and May 2004; Gencoglan et al. 2006; Patel and Rajput 2009).

Under SDI or DI, irrigation volume and irrigation intervals have significant impacts on crop growth, development, and yield. Shorter irrigation intervals from 3–6 days could result in higher crop yield and water use (Sezen et al. 2005, 2006; Sensoy et al. 2007). However, different SDI frequencies (1 and 7 days) only have a slight effect on corn yields (Howell et al. 1997).

Irrigation methods affect root distribution and nitrogen utilization. Under DI, roots grow preferentially around the wetted emitter area and are concentrated within the top 40 cm of the soil profile (Oliveira et al. 1996; Machado et al. 2003). Larger concentrations of crop roots around the drip tube are found under SDI (Coelho and Dani 1999; Machado et al. 2003). The center of gravity of the root system in SDI and DI fertigation is near the emitter below the soil surface (Martinez Hernandez et al. 1991). Moreover, SDI treatment results in a wider distribution of roots across the bed compared with DI (Zotarelli et al. 2009). Hence, SDI can reduce percolation below the root zone (Hanson and May 2004) and decrease groundwater NO_3^--N pollution (Phene 1999). Meanwhile, too much N fertilizer application does not increase crop production (Camp et al. 1997; Thompson et al. 2002a, b; Sorensen et al. 2004; Mahajan and Singh 2006; Cabello et al. 2009). SDI has higher soil fertility after potato harvesting compared with DI, although this effect is not significant (Selim et al. 2009).

This study aims to investigate the root development, root distribution, nitrogen distribution, and crop yield of bell pepper under SDI and DI, considering different nitrogen fertilization levels, and to determine best management practices for bell pepper production.

Materials and methods

Site description

Field experiment was conducted at Yuhe Irrigation Experiment Station, Datong, Shanxi Province (40°06′N, 113°20′E, and elevation of 1,052 m above sea level). The soil is gravelly loam with 22.5% field capacity. Groundwater level was kept at about 19 m deep. The climate in Datong is semiarid, with an average annual precipitation of approximately 379 mm and an annual evaporation of about 1,152 mm. More than 60% of the annual precipitation occurs during the growing season, which extends from late May to mid-September. The frost-free period is about 110–130 days. Table 1 summarizes the monthly mean climatic data of 2007 and 2008 compared with the mean long-term data for the experimental district. The growing season temperatures in both years were typical of the long-term means at the site. Precipitations in 2007 growing season were all smaller than the long-term means. Total precipitation in 2008 was coincident with the long-term means. However, precipitations of June and September in 2008 were greater than the long-term means. Precipitation in July 2008 was 68 mm lower than the long-term means. The daily rainfall and temperature at the experimental site in 2007 and 2008 are shown in Fig. 1. The monthly average temperatures in 2008 were lower than those in 2007 except July, and a very low temperature (2.4°C) in May 30, 2008, inhibited seedling establishment.

Experimental treatments and field preparation

The field experiment was conducted using a randomized complete block design with eight treatments, including two irrigation techniques (SDI, DI) and four fertilization levels of 0, 75, 150, and 300 kg/ha N (N_0, N_{75}, N_{150}, and N_{300}, respectively) (Table 2). Each treatment was replicated

Table 1 Historical monthly and growing season climatic data of the experimental area

Months	Mean temperatures (°)									Relative humidity (%)			Precipitation (mm)		
	Minimum			Maximum			Average								
	2007	2008	Long term[a]	2007	2008	Long term	2007	2008	Long term	2007	2008	Long term	2007	2008	Long term
May	9.8	7.8	8.2	24.7	22.6	23.2	17.1	15.5	15.8	34.6	37.5	41.1	26.2	15.6	28.9
Jun	16.0	13.0	13.2	29.0	26.2	27.1	22.2	19.4	20.2	51.0	64.0	50.9	44.5	72	48.2
Jul	17.0	16.6	16.3	29.5	29.9	28.3	22.8	23.2	22.0	59.5	61.3	64.9	62.9	33.2	101.0
Aug	16.5	14.6	14.8	29.0	26.6	26.4	22.6	20.3	20.3	57.4	71.4	68.3	75.5	86.6	86.1
Sep	10.1	10.0	8.5	25.8	23.1	21.7	8.9	16.2	14.7	59.4	72.3	61.4	38.0	90.6	51.1
Sum													247.1	298	315.3

[a] 1956–2006

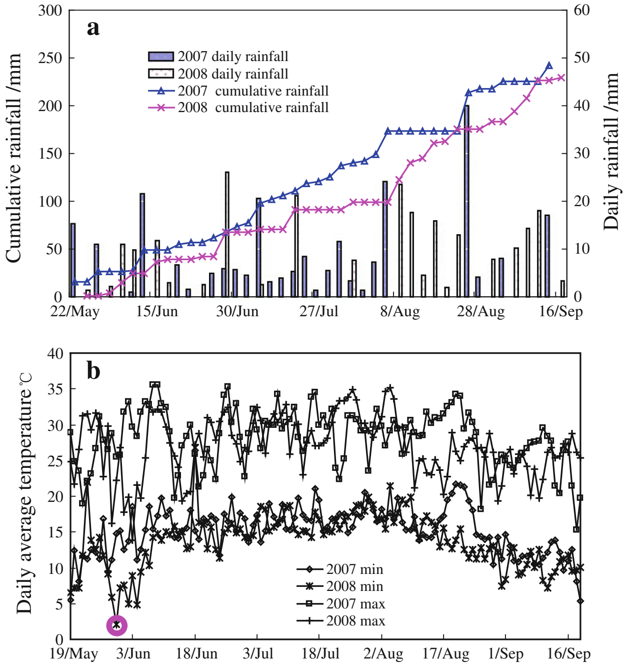

Fig. 1 Meteorological data during the crop growth season. **a** Cumulative and daily average rainfall during the crop season and **b** daily average temperature

thrice. There were 24 plot measuring 7 m × 3 m (6 rows per plot) (Fig. 2).

The test crop was Tongfeng 16,a local variety of bell paper. Two-month-old pepper plants were transplanted in the field 40 cm in rows and 50 cm between plants on May 20, 2007, and May 21, 2008. The plants were irrigated with either SDI or DI systems installed prior to planting. The laterals were installed between every other crop row at a space of 1 m, whereas the SDI laterals were buried at a depth of 20 cm between crop rows. Water was supplied every 4 days using laterals (Netafim super Taphoon 125) with 1.1 L/h of drippers discharge at a spacing of 40 cm.

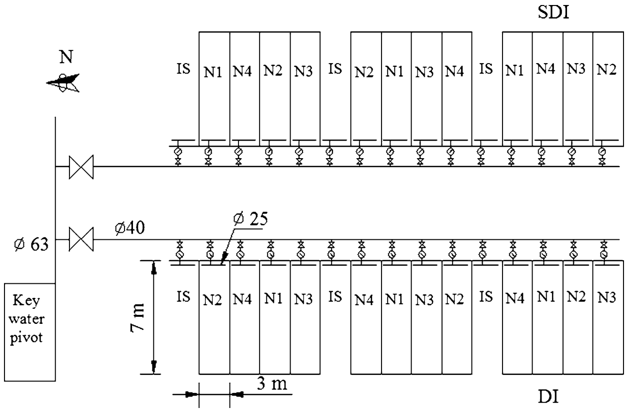

Fig. 2 Experimental plot arrangement. *IS* stands for isolation strip; N_1, N_2, N_3, and N_4 stand for nitrogen levels of 0, 75, 150, and 300 kg/ha, respectively

Soil water content was measured by a portable time domain reflectometry (TDR). Three access tubes were placed at a distance of 0, 25, and 50 cm from lateral pipes for each plot at a depth of 1 m. A total of 24 PVC access tubes were installed (Fig. 3). Volumetric water content for all treatments at 0–20, 20–40, 40–60, 60–80, and 80–100-cm layers was measured before and after each irrigation and after each rainfall.

To measure leaching, a lysimeter (Fig. 4) was installed for each treatment. The lysimeter is a rectangular plastic box measuring 70 × 50 × 90 cm. The top of the lysimeters was buried at 10 cm below the soil surface. The soil was back-filled in layers to maintain its original structure.

Table 2 Experimental treatments

Irrigation method	Treatment	Nitrogen application rate (kg N ha^{-1})		
		Blossom and fruit-set period	Full bearing period	Late stages of development
SDI	SDI N_0	0	0	0
	SDI N_{75}	30	30 (2007)	15 (2007)
			0 (2008)	45 (2008)
	SDI N_{150}	60	60 (2007)	30 (2007)
			0 (2008)	90 (2008)
	SDI N_{300}	120	120 (2007)	60 (2007)
			0 (2008)	180 (2008)
DI	DI N_0	0	0	0
	DI N_{75}	30	30 (2007)	15 (2007)
			0 (2008)	45 (2008)
	DI N_{150}	60	60 (2007)	30 (2007)
			0 (2008)	90 (2008)
	DI N_{300}	120	120 (2007)	60 (2007)
			0 (2008)	180 (2008)

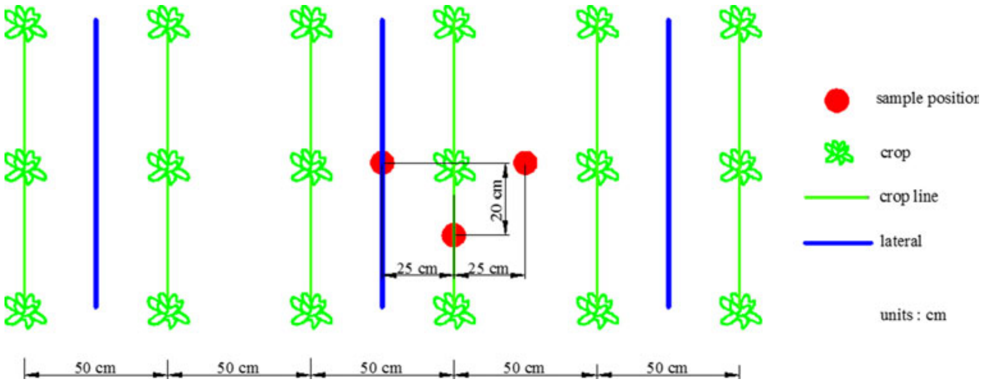

Fig. 3 Layout of trime PVC tubes

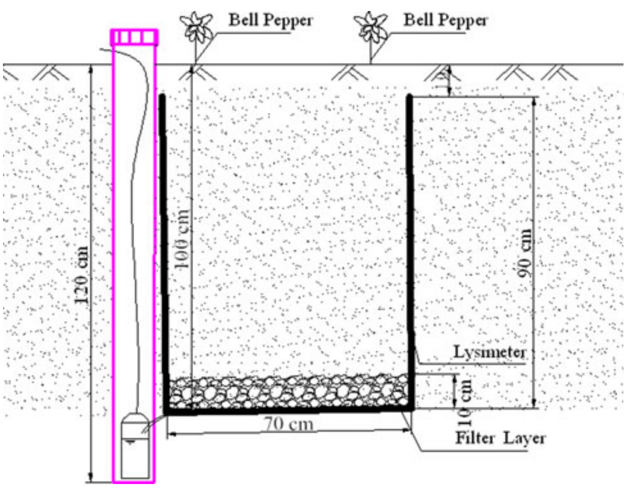

Fig. 4 Structure of a simple lysimeter

Table 3 Average soil physical parameters at the experimental site

Soil layers (cm)	Texture	Bulk density (g cm^{-3})	Field capacity (V/V, %)	Wilting point (V/V, %)
0–20	Silt loam	1.29	27.7	11.3
20–60	Silt loam	1.46	33.3	12.7

Drainage water was collected from the outlet at the bottom of lysimeters using a bottle placed in a separate tube next to the lysimeters and measured once every 2 days. Two crops were transplanted in each lysimeter.

Before the plants were transplanted, three sampling points were randomly selected from the entire experimental field to determine basic soil parameters, including soil texture, bulk density, field capacity, and permanent wilting point (Table 3).

Irrigation application

Irrigation volume was determined every 4 days based on the difference between estimated ET_p and measured effective rainfall. Penman–Monteith's formula, multiplying crop coefficients from FAO-56 (Allen et al. 1998), was used to estimate ET_p. Weather data were collected from an automatic weather station, 20 m away from the field site.

Evapotranspiration estimation

Actual crop evapotranspiration was estimated using the following water balance equation:

$$ET_c = \Delta W + I + P - R - D \quad (1)$$

where ΔW is the change of soil water storage (mm), I is irrigation amount (mm), P is precipitation (mm), R is surface runoff (mm), and D is the deep percolation (mm). The calculation soil layer was set at 0–100 cm.

The ΔW was estimated using the change in soil water content in the soil profile. Surface runoff was ignored, and D was considered as the volume of water drained from the lysimeters.

Nutrient management

Organic fertilizer (chicken manure: 11.1 m^3/ha) was uniformly applied in all plots as basal fertilizer before land leveling. During the growth season, urea dissolved in irrigation water in a fertilizer tank was applied according to nitrogen fertilization application levels of the different treatments. In 2007, nitrogen application was applied at July 23, August 16, and September 9 for three different growth stages. But in 2008, nitrogen was applied only two times at July 31 and September 3.

Before and after fertilization, soil samples were collected from 0–20, 20–40, 40–60, 60–80, and 80–100-cm soil layers and at 0, 25, and 50 cm distance from the lateral pipes. Soil samples were then pulverized and sifted out using a 2-mm sieve, soil (10 g) was weighed with an electronic balance, and 50 mL KCl solution (1 mol/L) was added to the soil through a pipette. The samples were then shook for 1 h on a shaker and filtrated through a 0.45-μm membrane after clarification. NO_3^--N content in the soil leach liquor was calculated, assuming that all NO_3^--N were dissolved in water. After leaching, dissolved NH_4^+-N and NO_3^--N were determined directly by flow injection analysis (Skalar San^{++}).

Yield

Bell pepper was manually picked eight times in 2 years (August 4, August 23, September 12, and September 14, 2007; and July 29, August 24, September 8, and September 12, 2008). Bell pepper yield was determined by harvesting bell pepper from two adjacent center rows in each plot. ANOVA was performed using the SPSS software package (SPSS V17.0). Significant differences between means for different treatments were compared using Duncan's test at $P < 0.05$.

Root sampling and analysis

Soil samples containing crop roots were taken from center rows 1 days after harvest. The soil surface sampling area was 40 cm × 50 cm, with a plant at the middle. Samples were taken at three different depths (0–10, 10–20, and 20–30 cm) in 2007 and four different depths (0–10, 10–20, 20–30, and 30–40 cm) in 2008. After washing away soils using a 0.5-mm sieve, crop roots and organic debris were stored in plastic bags at 4°C until further cleaning and then placed in a glass bowl. Crop roots were handpicked and placed in glass dishes. Root length and other root characteristic parameters were determined with using the Winrhizo (Re′gent Instrument Inc., Quebec City, Canada) software and hardware. ANOVA was performed using the SPSS software package.

Results and discussion

Water application

Rainfall during the crop growing season and the volume of irrigation water are shown in Table 4. The crops were irrigated 14 times, and the total irrigation volume was 257 mm in 2007. However, irrigation frequency was reduced to 10 times in 2008 (164 mm).

Table 4 Irrigation application and rainfall (mm)

2007	Rainfall	Irrigation	2008	Rainfall	Irrigation
22 May	15		26 May	2	
30 May	11		1 Jun	2	
5 Jun		30	3 Jun	11	
13 Jun	22		10 Jun	10	
18 Jun	7		15 Jun	12	
26 Jun		10	17 Jun	3	
28 Jun	5		27 Jun	2	
29 Jun	6		29 Jun	26	
30 Jun	6		4 Jul	3	10
3 Jul	5		8 Jul		10
4 Jul	21		14 Jul	21	
9 Jul	4		16 Jul		19
14 Jul	5		20 Jul		18
15 Jul		31	24 Jul		21
19 Jul		20	28 Jul		23
22 Jul	8		31 Jul	7	
23 Jul		10	1 Aug		6
27 Jul		16	5 Aug		22
29 Jul	5		8 Aug	24	
30 Jul	12		9 Aug	18	
31 Jul	3		10 Aug	5	
2 Aug	7		13 Aug	16	
4 Aug		13	18 Aug	2	
7 Aug	24		21 Aug	13	
12 Aug		23	25 Aug		16
16 Aug		25	29 Aug	8	17
20 Aug		21	3 Sep	10	
24 Aug		24	7 Sep	14	
26 Aug	40		9 Sep	18	
28 Aug	4		16 Sep	3	
1 Sep		8	Total	230	162
2 Sep	8				
5 Sep		8			
9 Sep		18			
13 Sep	17				
Total	234	257			

Seasonal patterns of soil moisture

Average soil moisture of different points (0, 25, and 50 cm from the lateral pipes) in different profiles (0–20, 20–40, 40–60 cm) for 2 years (2007 and 2008) under the 150 kg/ha nitrogen treatment is presented in Fig. 5a as an example for the same nitrogen application. Soil water content in the 0–20-cm layer fluctuating violently, and the moisture there under DI N_{150} was slightly higher than under SDI N_{150}. Soil water content under SDI N_{150} was higher than under DI N_{150} in the 20–40-cm layer, and there were also significant fluctuations of the moisture. However, soil moisture remained almost the same level, and fluctuations were not obvious in 40–60-cm layer under SDI and DI.

Figure 5b showed the average soil moisture of three points (0, 25, and 50 cm from the lateral pipes) and two profiles (0–20, 20–40 cm) for 2 years (2007 and 2008) under different nitrogen application amounts. All average soil moistures from 0 to 40 cm depth in whole growth period were maintained at above 50% available soil

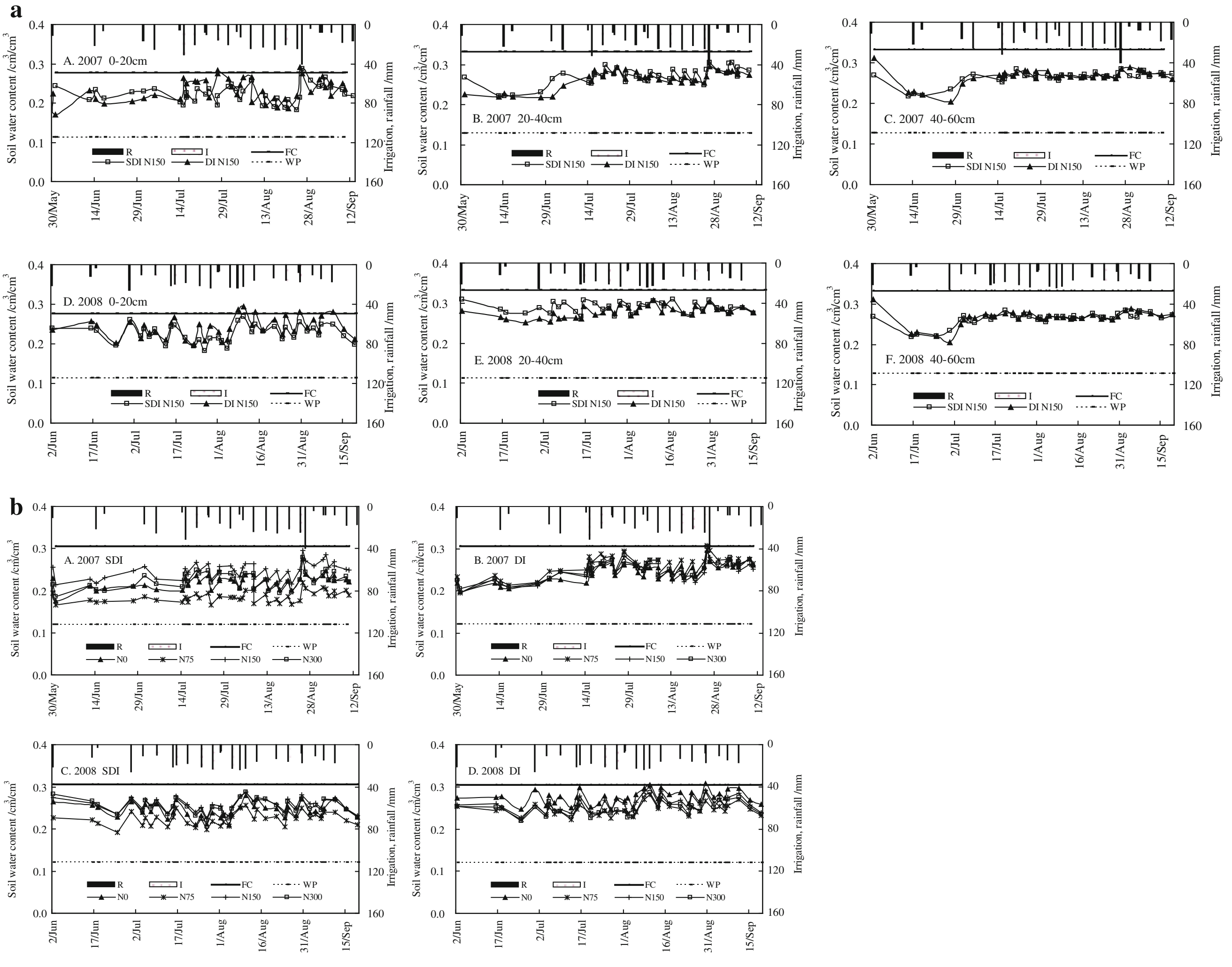

Fig. 5 Soil moisture at different layers. **a** Soil water content in 0–20, 20–40, 40–60 cm depth under N_{150}. **b** Average soil moisture of 0–40 cm depth under different nitrogen treatments

moisture except SDI N_{75} under SDI and DI irrigation method.

Root distribution

Table 5 shows a significant difference in RLD between SDI and DI and among the different nitrogen levels. RLD obviously increased with increasing nitrogen levels until the nitrogen level reached 150 kg/ha in both years, and then it sharply decreased. The effect of irrigation methods on RLD was apparent; the RLD of SDI was obviously higher than that of DI.

At the same fertilization level, the root length and percentage of root length in each layer to total root length decreased with soil depths (Table 6). The percentages of

Table 5 Root length density (RLD) of bell pepper as influenced by irrigation method and N application levels

Treatment	RLD (cm/cm^3)	
	2007	2008
*Nitrogen**		
N_0	0.42 c	0.18 d
N_{75}	0.51 b	0.30 b
N_{150}	0.61 a	0.33 a
N_{300}	0.39 c	0.22 c
*Irrigation***		
SDI	0.51 a	0.27 a
DI	0.45 b	0.24 b

* Average of two irrigation methods

** Average of four different nitrogen levels

Table 6 Bell pepper root length at different soil depths

	Depth (cm)	0–10	10–20	20–30	30–40	0–40
DI N_0	Root length (cm)	7,431	3,772	719	431	12,354
	Proportion (%)	53.47	27.14	5.18	3.10	100
SDI N_0	Root length (cm)	6,038	4,976	1,370	750	13,135
	Proportion (%)	45.97	37.88	10.43	5.71	100
DI N_{75}	Root length (cm)	8,263	6,917	1,922	937	18,038
	Proportion (%)	45.81	38.34	10.65	5.19	100
SDI N_{75}	Root length (cm)	6,923	8,017	3,035	1,255	19,231
	Proportion (%)	36.00	41.69	15.78	6.53	100
DI N_{150}	Root length (cm)	11,582	4,588	1,089	219	17,479
	Proportion (%)	66.26	26.25	6.23	1.25	100
SDI N_{150}	Root length(cm)	15,235	7,353	2,319	719	25,625
	Proportion (%)	59.45	28.69	9.05	2.81	100
DI N_{300}	Root length (cm)	8,555	4,076	919	827	14,377
	Proportion (%)	59.51	28.35	6.39	5.75	100
SDI N_{300}	Root length (cm)	7,199	6,419	951	820	15,390
	Proportion (%)	46.78	41.71	6.18	5.33	100

root length at 30–40-cm soil depth to total root length under DI and SDI were 1.25% (DI N_{150}) and 2.81% (SDI N_{150}), respectively, indicating that there were almost no bell pepper roots below 40-cm soil depth. Root lengths under SDI N_0, SDI N_{75}, SDI N_{150}, and SDI N_{300} were 1.06, 1.06, 1.46, and 1.07 times longer than those under DI N_0, DI N_{75}, DI N_{150}, and DI N_{300}, respectively. The percentage of root length below 10-cm soil depth under SDI N_{150} was higher than that under DI N_{150} by 7%. Hence, SDI does not only promote root growth but also results in deeper root development.

Under the same irrigation methods, the impact of different nitrogen levels on RLD at harvest is shown in Fig. 6. At 0–10-cm soil depth, RLD gradually increased with increasing nitrogen levels. However, at 10–20-cm soil depth, RLD declined sharply when the nitrogen level exceeded 150 kg/ha. These findings imply that too much nitrogen application inhibits root growth in deeper soil layers.

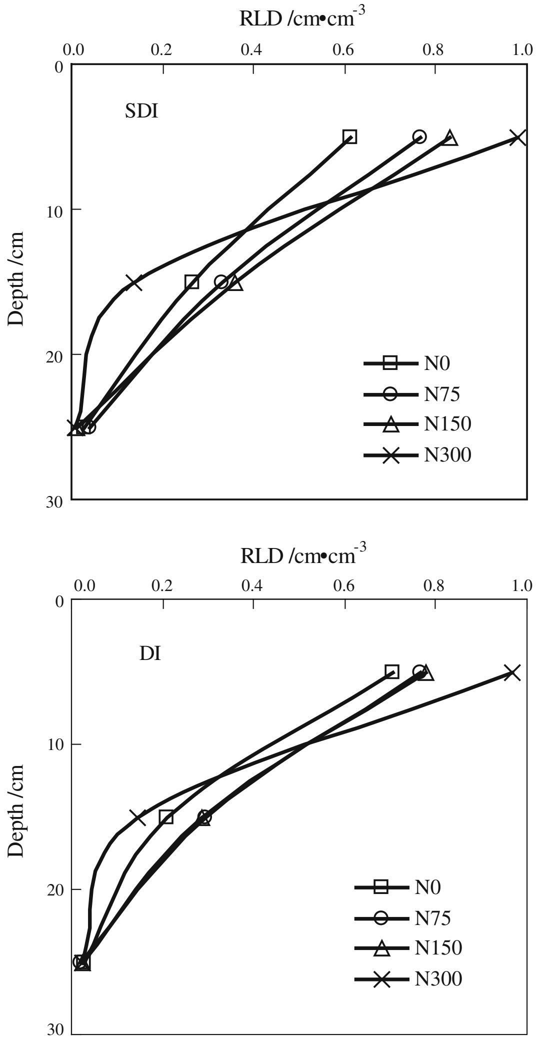

Fig. 6 RLD distribution during the 2007 growing season in all treatments

NO_3^--N distribution in soils

Figure 7 shows NO_3^--N concentrations in soil 2 days before fertilization (August 14), 2 days after fertilization (August 18), and 22 days after fertilization (September 7).

Before fertilization, there was no significant difference in NO_3^--N distribution between SDI and DI. However, 2 days after fertilization, NO_3^--N concentrations under SDI treatment were distributed with a parabolic curve; the maximum value (14.2 mg/kg) was found at 20–40-cm soil depth. In contrast, NO_3^--N concentrations under DI treatment declined with increasing soil depth, and a maximum concentration (15.7 mg/kg) was obtained at the top soil (0–20 cm). Furthermore, 22 days after the fertilization, NO_3^--N gradually moved downward due to water movement, crop growth, and root activities. The maximum NO_3^--N concentration 22 days after fertilization under SDI and DI occurred at 40–60 cm and 60–80 cm, respectively.

As mentioned earlier, bell pepper roots were concentrated at 0–40-cm soil depth. Nitrogen leaching below 40 cm, which was hardly useful to the plants, was of residual value. The maximum residual NO_3^--N concentration at 40–60 cm under SDI (8.4 mg/kg) was far lower than that under DI treatment (13.8 mg/kg at 60–80 cm).

Residual NO_3^--N concentrations in soil profiles increased with increasing levels of nitrogen fertilizers (Fig. 8), but the residual of N_{150} was only slightly higher than N_{75}. The NO_3^--N residual concentration for N_{300} treatment was sharply higher than that for N_{150} treatment

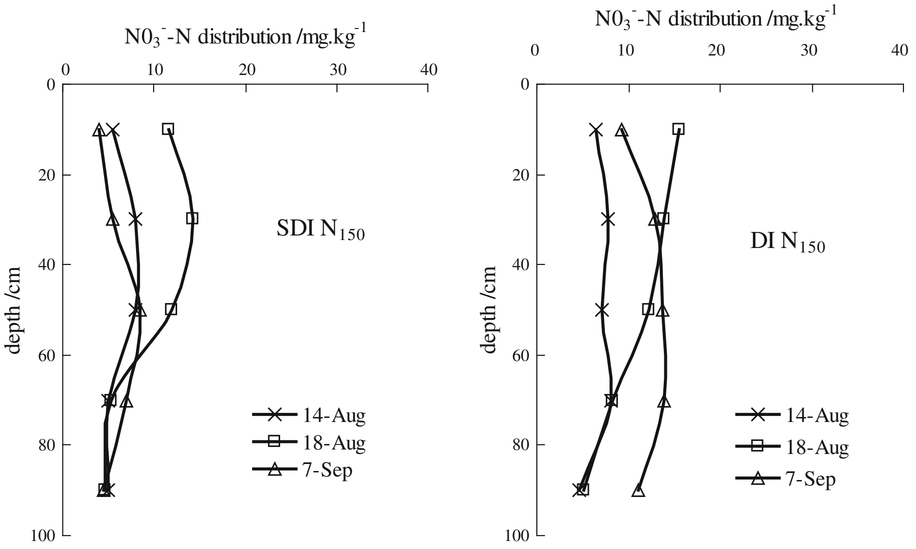

Fig. 7 Vertical distribution of NO$_3^-$-N concentration in soil profiles

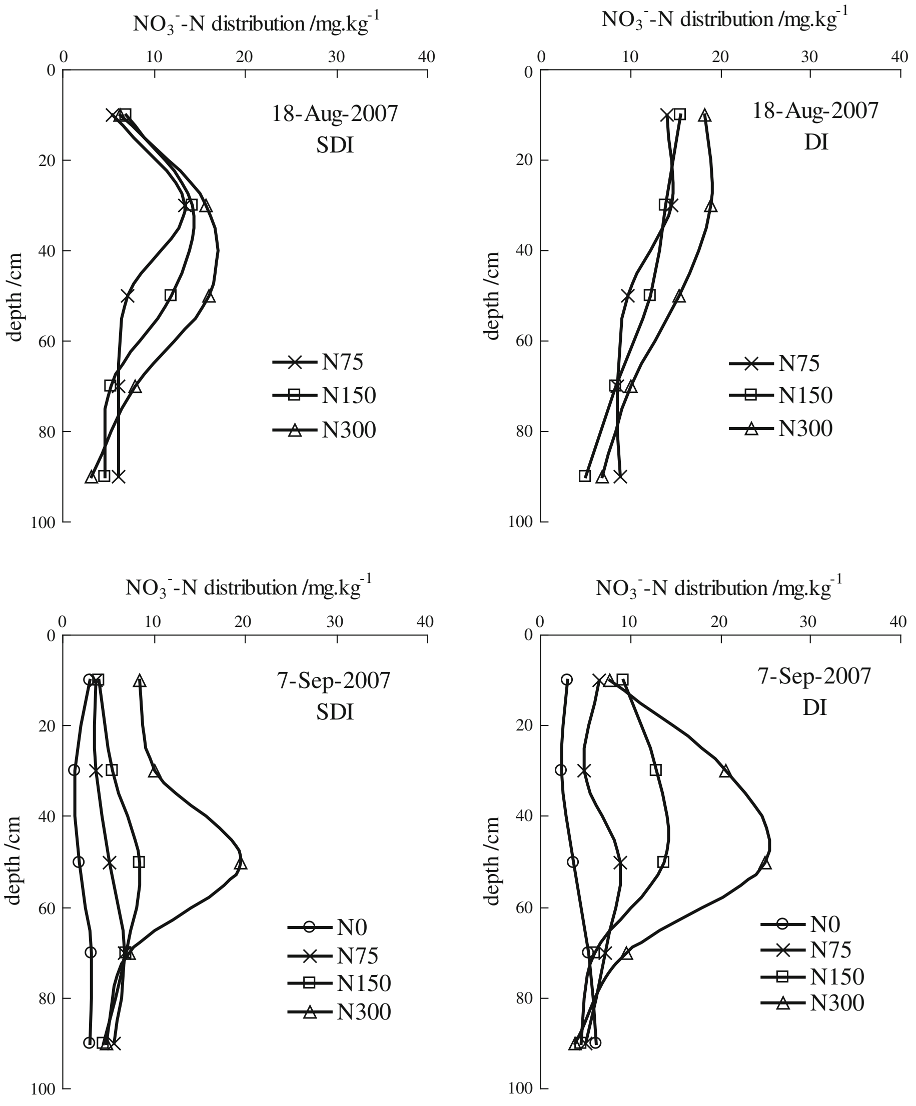

Fig. 8 Vertical distribution of NO$_3^-$-N as influenced by different nitrogen levels

Table 7 Drainage water amounts (mm)

	SDI N_0	SDI N_{75}	SDI N_{150}	SDI N_{300}	DI N_0	DI N_{75}	DI N_{150}	DI N_{300}
a. 2007								
16 Jul	5.2	2.4						
20 Jul	5.6		4.9					
24 Jul	6.0	2.9						
27 Jul	8.5	6.9						
5 Aug	5.7							
7 Aug				3.9				
13 Aug	4.9	5.3						
16 Aug	5.0							
17 Aug	13.9	5.9						
21 Aug	11.4	5.7				5.5		
25 Aug	11.8	5.6				3.5		
26 Aug	8.2	6.5	14.7	7.8	22.7	10.7		10.8
2 Sep	2.1							
5 Sep	3.4							
9 Sep	1.8							
10 Sep	11.5	6.3				8.3		
Total	105	47.5	19.6	11.7	22.7	28	0	10.8
b. 2008								
9 Jul			3.6					
16 Jul	9.8	5.3	5.4	7.5				
20 Jul	16.7	15.3	12.2	18.2	3.1			
24 Jul	19.2	12.3	10.6	16.6	2.2	2.4		
25 Jul					2.3	2.1	2.6	1.2
29 Jul	2.9	5.3	2.7	5.4	4.6	5.4		5.4
5 Aug	10	8.4	3.5	7.2	9	7.0		
10 Aug	3.5		7.5		3.8	8.5		2.7
Total	62.1	33.2	31.8	42.7	25	25.4	2.6	9.3

22 days after fertilization. This tend was found in all nitrogen treatments.

The data above show that SDI promoted the development of bell pepper roots and favored the establishment of intensive root layers, which can prevent nitrate leaching. At nitrogen level lower than 150 kg/ha, fertigation produced lesser residues.

ET_c

Bell pepper plants were transplanted at May 20 in 2007 and May 21 in 2008. The growth seasons last 118 days and 115 days separately in 2007 and 2008.

Bell pepper ET_c was calculated by formula (1). D in formula (1), the amounts of drainage water collected from the lysimeter are shown in Table 7.

Table 8 shows the cumulative water consumption of bell pepper and ET_0 calculated by Penman–Monteith's formula during the two growing seasons. The ET_c and ET_0 of all treatments in 2008 were lower than those in 2007 due to the lower monthly average temperature in 2008 as compared with 2007. A very low temperature (2.4°C) in May 30, 2008, inhibited seedling establishment.

Table 8 Cumulative water consumption under different irrigation and fertilization practices

ET_0 (mm)			ET_c (mm)			
			N_0	N_{75}	N_{150}	N_{300}
2007	508	DI	407	426	451	404
		SDI	301	405	438	432
2008	406	DI	362	387	382	382
		SDI	334	357	377	359

The maximum and minimum water consumption were recorded for DI N_{150} treatment (451 mm) and SDI N_0 treatment (301 mm), respectively, in 2007. In 2008, the

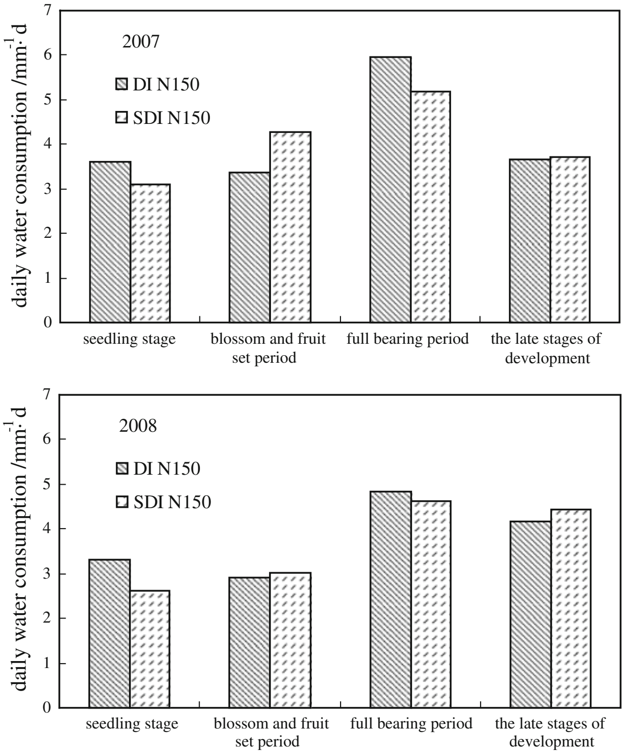

Fig. 9 Daily averaged water consumption at different growth stages

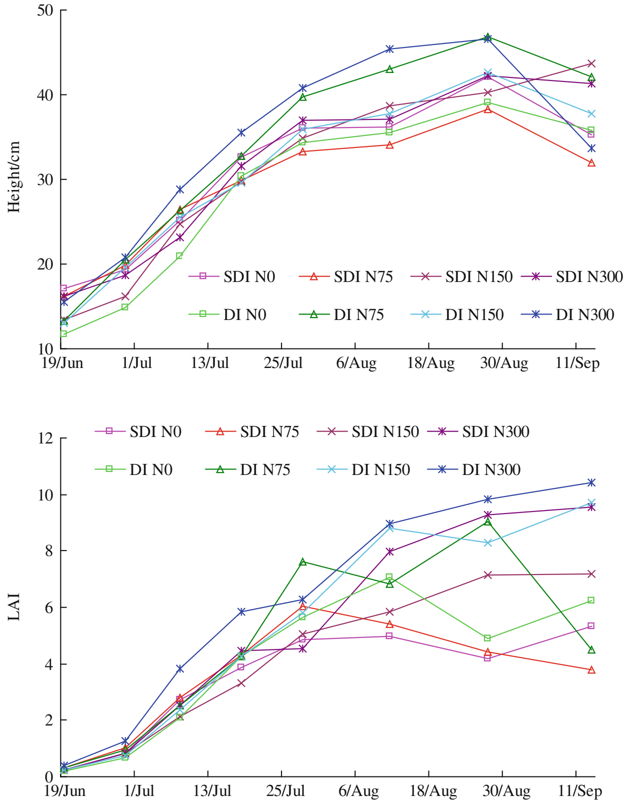

Fig. 10 Plant height and LAI for different treatments (2007)

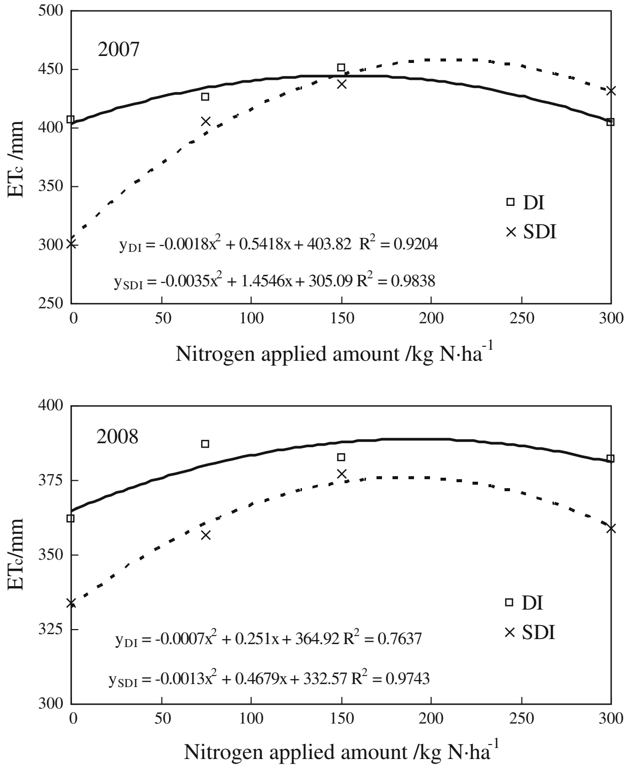

Fig. 11 Relationship between ET_c and nitrogen levels

maximum water consumption was recorded for DI N_{75} (387 mm), followed by DI N_{150} and DI N_{300} (382 mm). The minimum value was at 334 mm for SDI N_0. Except for N_{300} treatment in 2007, all cumulative water consumptions under SDI were lower than under DI.

Daily average water consumptions at different growth stages under different irrigation techniques (N_{150} treatment) are shown in Fig. 9. During the seedling establishment period, the DI method resulted in higher daily averaged water consumption compared with SDI because of higher evaporation under DI. After entering the blossom and fruit-set period, the daily average water consumption under SDI became higher than that under DI. This result may be attributed to faster root growth under SDI than under DI. At full bearing period, the plants grew vigorously, leading water consumption to reach its maximum. Water consumption under SDI was lower than that under DI, contributing to low plant height and leaf area (Fig. 10). However, daily average water consumption under DI was slightly lower than that under SDI at the late crop growth stages.

There was a polynomial correlation between crop water consumption and nitrogen levels (Fig. 11). ET_c increased with increasing nitrogen levels, reaching a maximum value at 150 kg/ha nitrogen level. Thereafter, ET_c again declined. Nitrogen became excessive after 150 kg/ha, and too much nitrogen restricts bell pepper growth leading to lower ET_c.

Table 9 Calculated k_c at each growth stage

	ET_0	ET_c	Calculated k_c	k_c recommended by FAO-56
a. SDI N_{150}, 2007				
Seedling establishment period	167	115	0.69	0.6
Blossom and fruit-set period	120	101	0.84	1.05
Full bearing period	160	191	1.19	1.05
Late crop growth stages	60	44	0.74	0.9
Whole growing season	508	451	0.89	
b. SDI N_{150}, 2008				
Seedling establishment period	115	76	0.66	0.6
Blossom and fruit-set period	107	87	0.82	1.05
Full bearing period	115	149	1.30	1.05
Late crop growth stages	69	65	0.93	0.9
Whole growing season	406	377	0.93	

Table 10 Bell pepper yield and WUE for different treatments

Year	Treatment	SDI		DI	
		Yield (t ha^{-1})	WUE (kg m^{-3})	Yield (t ha^{-1})	WUE (kg m^{-3})
2007	N_0	39.46 c	13.11*	36.07 b	8.87
	N_{75}	43.43 b	10.71	42.70 a	10.01
	N_{150}	46.54*a	10.64	44.72*a	9.92
	N_{300}	46.29 a	10.72	43.29 a	10.71*
2008	N_0	29.72 c	8.90	28.11 b	7.76
	N_{75}	35.89 b	10.06	30.44 ab	7.86
	N_{150}	42.83*a	11.35*	34.50*a	9.02*
	N_{300}	35.44 b	9.87	30.17 ab	7.90

a, b, and c are significantly different between values at $P < 0.05$ using Duncan's test

* Highest yield and highest WUE

Crop coefficient k_c for bell pepper at different growth stages for the experimental site under SDI N_{150} is shown in Table 9. At the seedling establishment and full bearing periods, k_c values were higher than the values recommended by FAO-56. On the contrary, k_c at the blossom and fruit-set period was higher than that recommended by FAO-56. Meanwhile, k_c at the late crop growth stages was not stable.

Yield and water-use efficiency

Bell pepper yields were measured for each treatment in 2007 and 2008. Results are shown in Table 10.

Yield under SDI was significantly higher than that under DI in both years. It was higher by 4 and 13% in 2007 and 2008, respectively. The maximum yield was obtained under SDI at 150 kg/ha (SDI N_{150}). SDI had a higher WUE than DI by 13 and 21% in 2007 and 2008, respectively. Maximum WUEs were obtained under SDI without nitrogen supply (SDI N_0) in 2007 and under SDI with 150 kg/ha (SDI N_{150}) in 2008.

Standard ANOVA was carried out with Duncan's test at the 0.05 level of significance. The level of fertilizer application showed a significant effect on bell pepper yield. The relationship between yield and the level of fertilization

Table 11 Variance analysis of the yield of bell pepper

Source	Type III sum of squares	df	Mean square	F	P
Corrected model	2,040.178[a]	15	136.012	12.330	0.000
Intercept	79,518.497	1	79,518.497	7,208.462	0.000
Year	214.006	1	214.006	19.400**	0.000
Irrigation	950.859	1	950.859	86.197**	0.000
Nitrogen	287.295	3	95.765	8.681**	0.000
Year * irrigation	533.524	1	533.524	48.365**	0.000
Year * nitrogen	45.978	3	15.326	1.389	0.264
Irrigation * nitrogen	3.475	3	1.158	0.105	0.957
Year * irrigation * nitrogen	5.041	3	1.680	0.152	0.927
Error	353.001	32	11.031		
Total	81,911.676	48			
Corrected total	2,393.178	47			

df Degrees of freedom

** $P < 0.05$

[a] $R^2 = 0.852$ (Adjusted $R^2 = 0.783$)

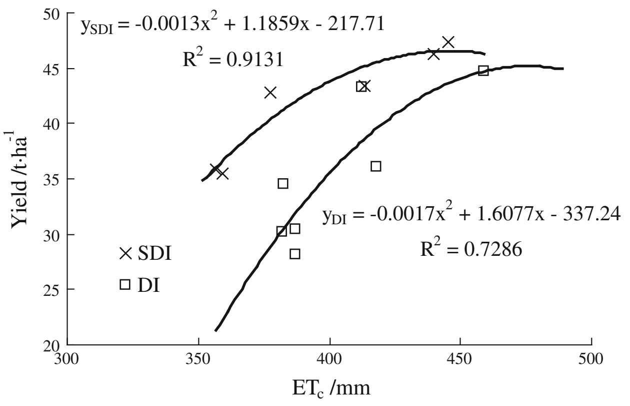

Fig. 12 Relationship between yield and ET_c

nitrogen was conical, the yield increased with urea fertilization up to a point (150–200 kg/ha N) when fertilization became excessive.

The variance analysis indicated that experimental years (*Y*), irrigation methods (*I*), and nitrogen application amounts (*N*) significantly influenced pepper yields (Table 11). There was no significant interaction effect among *Y*, *I*, and *N*, except between *Y* × *I*.

There was a significantly polynomial correlation between bell pepper yield and cumulative water consumption (Fig. 12). Bell pepper yield was improved when water consumption increased at a certain range.

Conclusions

Bell pepper yield under SDI was significantly higher than that under DI in both years. The highest yield (46.54 t/ha) was recorded in the case of SDI at 150 kg/ha (SDI N_{150}). The lowest yield (28.11 t/ha) was recorded in the case of DI with no after-manuring (SDI N_0).

Compared with DI, all treatments of SDI had lower water consumption. The total root length densities from 0–40-cm soil depth and the percentage of root length below 10 cm under SDI are higher than under DI. SDI does not only promote crop root growth; it also enhances the downward development of roots. There are lesser soil N residues under SDI than under DI. Consequently, the experiment obtained a preliminary conclusion that SDI was more beneficial to the growth of bell pepper than DI.

From the perspective of increasing bell pepper yield and WUE, as well as reducing NO_3^--N leaching, SDI with N application of 150 kg/ha is the optimal fertigation practice.

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