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Effect of drip irrigation with saline water on tomato (*Lycopersicon esculentum* Mill) yield and water use in semi-humid area

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ABSTRACT

Due to the decreasing availability of fresh water to agriculture in many regions, saline water utilization in irrigation gets more and more attention. In order to facilitate the safe use of saline water for irrigation, the effects of salinity on crops should be understood, and optimal management strategies should be developed. A 3-year field experiment was carried out to investigate the effect of saline water on tomato yield and water use under mulched drip irrigation in North China Plain in 2003, 2004 and 2005. Five treatments of irrigation water with average salinity levels of 1.1, 2.2, 2.9, 3.5 and 4.2 dS/m in 2003 and 2004, and 1.1, 2.2, 3.5, 4.2 and 4.9 dS/m in 2005 were designed. Throughout tomato growing season, the soil matric potentials at 0.2 m depth immediately under drip emitters of all treatments were kept higher than −20 kPa and saline water was applied about 30 days after transplant. Results showed that irrigation water salinity ranging 1.1–4.9 dS/m had few effects on tomato yield, but had some effects on tomato seasonal accumulative water use, water use efficiency (WUE) and irrigation water use efficiency (IWUE). With the increase of irrigation water salinity, tomato seasonal accumulative water use decreased, WUE and IWUE increased. After 3-year irrigating with saline water, soil salinity in the 0–90 cm soil depths did not increase. So in North China Plain, or similar semi-humid area, when there were not enough fresh water for irrigation, saline water with salinity from 2.2 to 4.9 dS/m can be applied to irrigate field culture tomatoes after appropriate management strategies were adopted.

1. Introduction

One of the major problems confronting irrigated agriculture nowadays throughout the world is the decreasing availability of fresh water. In many countries and regions, fresh water is relatively scarce, but there are considerable resources of saline water, which could be utilized for irrigation if proper crops, soil and water management practices were established (Mantell et al., 1985; Rhoades et al., 1992). In China, especially in North China Plain, less and less fresh water is available for agriculture with increasing population and rapid economic growth, and saline water has been included as an important substitutable resource for fresh water in agricultural irrigation.

The safe and efficient use of saline water for irrigation is to undertake appropriate practices to prevent the development of excessive soil salination for crop production. Many factors should be considered in making management strategies, such as crops, crop cultivars, local climate, soil, type of salt, salinity

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levels, irrigation method and water management practices (Ferreyra et al., 1997; Shannon and Grieve, 1999; Bustan et al., 2004). Shalhevet (1994) and Minhas (1996) indicated that applying non-saline water in sensitive stage and saline water in relatively tolerant stage could minimize the reduction in yield by salinity. So, the growth stage at which salinization is initiated must also be taken into account.

Tomato (*Lycopersicon esculentum* Mill) is one of the important and widespread crops in the world, and is considered moderately sensitive to salt stress, since it can tolerate an EC_e (EC of the saturated soil extract) of about 2.5 dS/m and fruit yield decrease by 10% with each unit of EC_e increasing above the threshold value (Maas, 1986). Large amount of laboratory research and on-farm applied and adaptive research activities on tomatoes have been executed by numbers of researchers in many different countries.

Mizrahi et al. (1988) directly sowed tomato (cv. FC111) seeds on sand dunes in glasshouse, and drip irrigated tomatoes with tap water (1.5 dS/m) or diluted seawater (3 and 6 dS/m) at appearance of the first true leaf (early) or the onset of ripening of the first fruits (late). They found out that the overall yield of plants irrigated with 3 dS/m applied at the late stage of development was not significantly different from that of control plants, while fruit quality was significantly improved. Katerji et al. (1998) transplanted tomato (cv. ELKO 190) seedlings (at three-leaf stage) in tanks filled with loam and clay, and irrigated them with water of three different levels of salinity (0.9, 2.3 and 6 dS/m). They pointed out that evapotranspiration of tomato decreased moderately with the increase of salinity, whereas the fruit yield decreased strongly. Del Amor et al. (2001) conducted a green house study where tomatoes (cv. Daniela) were drip irrigated with nutrient solutions of four salinity levels (2, 4, 6 and 8 dS/m) at three different plant growth stages. The results indicated salt tolerance of tomato plants increased when the application of salinity was delayed, and fruit quality could be improved while yield was not significantly reduced when 4 dS/m saline water was applied 16 days after transplanting. Tomatoes responses to salinity in laboratory or greenhouse have been well summarized by Cuartero and Fernández-Muñoz (1999).

In many places, tomatoes are often planted in open fields in early spring or later summer. In an open field experiment conducted by Mitchell et al. (1991) in California, tomatoes (cv. UC82B) were seeded on a Panoche clay loam soil, and irrigated weekly with saline drainage water (8.1 dS/m) after first flower stage by furrow irrigation. The results demonstrated that irrigation with saline drainage water had no effect on total fresh fruit yield, but slightly reduced fruit water content. Several brackish water irrigation researches were carried out in open fields of Ramat Negev experimental station on loamy soil to sand dunes. The results evidently revealed that if suitable management practices were adapted, it was feasible to irrigate tomato using relatively high saline water under arid conditions of Israel. These management practices included using drip irrigation, applying nitrogen daily by fertigation from the first day of irrigation, starting saline water irrigation after the appearance of the 11th leaf, or irrigating tomato five times per day, and so on (Pasternak et al., 1986a,b; Pasternak and De Malach, 1995).

Most of the above-mentioned studies were conducted in relatively controlled growing conditions, e.g. in greenhouse or in hydroponics cultures. The open field experiments were made mainly under Mediterranean climate or desert conditions. While under a semi-humid condition (i.e., in North China Plain), open culture tomatoes' responses to saline water irrigation are still in need of further investigation.

The objectives of this study were: (1) to measure the effect of different salinity levels of irrigation water on tomato yield and water use under drip irrigation system in North China Plain; (2) to describe a management strategy by establishing safe salinity levels of irrigation water to maintain crop productivity under drip irrigation system in North China Plain.

2. Materials and methods

2.1. *Experimental site*

Field experiments were conducted at Tongzhou Experimental Station for Water Cycle and Modern Water-saving Irrigation Research, Institute of Geographic Science and Natural Resource Research during 2003, 2004 and 2005. The station (latitude: 39°36′N; longitude: 116°48′E; 20 m a.s.l.) is located in the southeast region of Beijing, and about 60 km away from Beijing. It is a temperate semi-humid monsoon climate, with mean annual temperature 11.3 °C and mean annual global radiation 5.24 GJ/m^2. The mean annual precipitation is 620 mm, mainly concentrated from July to September. The dominant soil is a silt loam. In the 0–30 cm plow layer, the average bulk density is 1.35 g/cm^3, the soil organic matter is about 1.3%, and the average soil salinity and pH of 1:5 soil:water extracts is 0.090% and 7.8, respectively.

2.2. *Experimental design*

The experiment consisted of a control treatment and four salinity levels of irrigation water treatments. The control treatment was local groundwater (fresh water) with an electrical conductivity (EC) of 1.1 dS/m. Artificial saline water was produced by adding industrial-grade $NaHCO_3$, Na_2SO_4, $MgSO_4$, $MgCl_2$ and $CaCl_2$ to local groundwater in molar proportion of 0.5:0.05:0.24:0.09:0.1, similar to the ionic compositions of the aquifer in Cangzhou area, one of the large areas with rich saline water (2–5 dS/m) resource in North China Plain. The average EC for the four saline water treatments (EC_{iw}) were 2.2, 2.9, 3.5 and 4.2 dS/m in 2003 and 2004, and were 2.2, 3.5, 4.2 and 4.9 dS/m in 2005. Ionic composition for local groundwater and saline water in this trial is given in Table 1. All of the treatments were replicated three times followed a complete randomized block design. In order to study the accumulative salinity hazard on crop and soil, the experimental site was kept unchanged in the 3 years.

2.3. *Agronomic practices*

In 2003, about 37.5 m^3/ha well-rotted cow manure was uniformly applied to all plots before field was ploughed. About 3–4 days later, 300 kg/ha compound fertilizers (mono-ammonium phosphate: 18% N, 46% P_2O_5, 1.5% SO_4^{2-}) were uniformly applied to the plots when the soil was bedded.

Table 1 – Ionic composition of local groundwater and saline water in 2003, 2004 and 2005

$\overline{EC_i}$ (dS/m)	Ionic concentration (mmol/L)								SAR[a]
	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	K^+	Na^+	
1.1 (local groundwater)	0.4	6	2.7	1.7	0.6	4	0.7	2.7	1.3
2.2	0.4	10.8	6	5	1	5	2.6	10.5	4.3
2.9	0.4	13.8	9.2	5.8	2.2	7.2	3.4	13.5	4.4
3.5	0.4	17.7	13	6.4	1.2	8.3	4.3	17.3	5.7
4.2	0.4	19.4	13.8	8.5	2	8.1	5.4	21.5	6.8
4.9	0.4	23.1	17.1	9.8	2.3	9.8	6.4	25.7	7.4

[a] SAR means sodium adsorption ratio.

While in 2004 and 2005, just about 600 kg/ha monoammonium phosphate was applied.

Every plot consisted of three raised beds, with 1.4 m between bed centers. The beds were 0.6 m wide, 4.4 m long and 0.15 m high. The area of each plot was 4.2 m × 4.4 m. Every treatment plot was a single unit of gravity drip irrigation system. In the front of each plot, a tank, with volume about 120 l, was installed at 1 m high and used to contain irrigation water. Drip tubes with emitters spacing 0.2 m were placed on the center of each raised beds.

Six-leaf tomato (*L. esculentum* Mill cv. L-402) seedlings (about 35,720 plants/ha) were transplanted on 6 May, 16 April and 19 April in 2003, 2004 and 2005, respectively. Double row plantings (in a zigzag) spaced 0.3 m apart per bed and the interplant spacing was 0.4 m. After all transplanted tomato seedlings established, black polyethylene mulches were applied over the beds on 18 May (12 days after transplanting: DAT), on 24 April (8 DAT) and on 6 May (17 DAT) in 2003, 2004 and 2005, respectively. Because large amounts of rainfall will leach salts concentrated in the soil profile, the polyethylene mulches were taken off after growing season.

In order to guarantee tomato fruit quality, plants were trained with a single stem, all side shoots were removed and only four branches were kept. Pruning of axillaries buds and fruit thinning were performed weekly, and were the same as local farmers.

2.4. *Irrigation*

During tomato growing periods in the 3 years, irrigation was applied only when the soil matric potential at 0.2 m depth immediately under drip emitters (measured with a vacuum tensiometer) was close to −20 kPa, except in seedling establishment stage. In order to ensure tomato seedling surviving, four tanks of fresh water (about 25.4 mm) were applied immediately after tomato seedlings were transplanted, and only fresh water was applied during seedling establishment period.

The treatments were initiated on 31 May (25 DAT), 22 May (36 DAT), and 26 May (37 DAT) in 2003, 2004 and 2005, respectively. When saline water was applied, surplus water was added to provide a leaching fraction. According to *NRCS National Engineering Handbook* (*section* 15) (USDA-NRCS, 1987), the leaching requirement ratio (LR_t) for high-frequency, daily or alternate-day irrigation were computed by the following equations:

$$LR_t = \frac{EC_i}{2(\max EC_e)} \quad (1)$$

$$F_g = \frac{F_n}{1.0 - LR_t} \quad (2)$$

where LR_t is the leaching requirement ratio, EC_i the electrical conductivity of the irrigation water (dS/m), EC_e the electrical conductivity of the saturated soil extract (dS/m), $\max EC_e$ the theoretical level of salinity that would reduce yield to zero (dS/m), the $\max EC_e$ value for tomato is 12.5 dS/m, F_n the net water requirement per irrigation (mm) and F_g is the gross water application per irrigation (mm).

The applied water per irrigation for the control treatment (1.1 dS/m) was designed as 5.1 mm, that is, the F_n was 5.1 mm. Because the tanks were made in advance, there was a deviation between actual volume (actual F_g) and desired volume (desired F_g) for each treatment. The calculated LR_t, desired F_g and actual F_g for each treatments were listed in Table 2.

2.5. *Fertilizer*

After the treatments started, 30% (weight concentration) urea solution was put into tanks at each irrigation event until the last irrigation. During the whole growing period of tomato, a top dressing of urea (N: 46%) about 286, 345 and 260 kg/ha was applied with irrigation in 2003, 2004 and 2005, respectively.

2.6. *Observation and equipments*

2.6.1. *Soil matric potential*

One set of mercurial tensiometers with 30 sensors was installed in each treatment to observe soil matric potential

Table 2 – The calculated LR_t, desired F_g and actual F_g for each treatment

$\overline{EC_i}$ (dS/m)	Calculated LR_t	Desired F_g (mm)	Actual F_g (mm)
1.1	0.00	5.1	5.1
2.2	0.09	5.6	5.4
2.9	0.12	5.8	5.7
3.5	0.14	5.9	6.0
4.2	0.17	6.1	6.3
4.9	0.20	6.3	6.3

LR_t: the leaching requirement ratio; F_g: gross water application per irrigation.

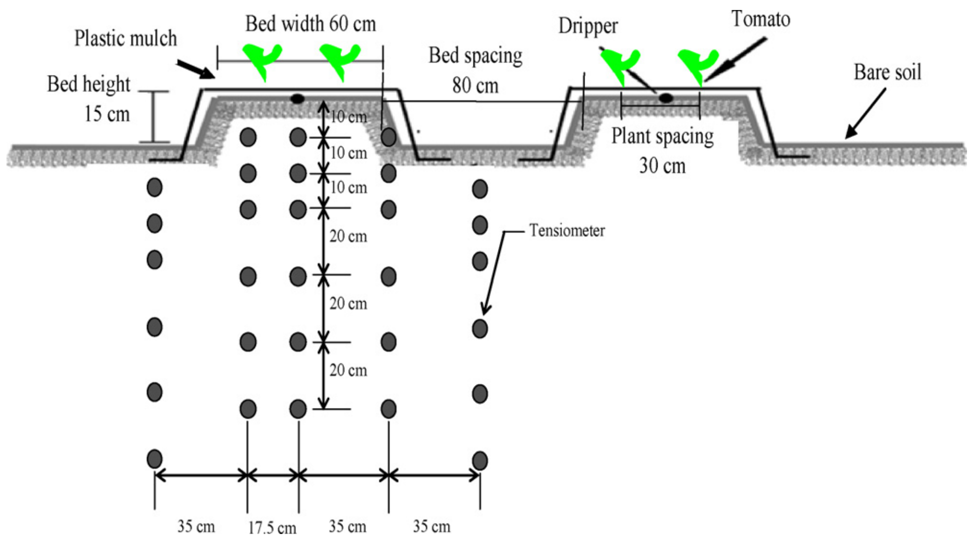

Fig. 1 – Placement of beds, tomatoes and tensiometers.

distribution in the 3 years. The sensors placement was the same for all treatments. There were five series of sensors in the vertical transect perpendicular to the drip tapes at five horizontal distances (0, 17.5, 35, 52.5 and 70 cm) and six vertical soil depths (10, 20, 30, 50, 70 and 90 cm) (Fig. 1). Observations were made daily at 8:00 h.

In order to schedule irrigation properly and timely, one tensiometer with a vacuum gauge was installed at 0.2 m depth immediately under emitters for each treatment in the 3 years. These tensiometers were observed four times daily at 8:00, 11:00, 14:00 and 17:00 h.

2.6.2. *Tomato water use*

One weighing lysimeter was installed in the center of each treatment to measure tomato water use (Fig. 2). Each lysimeter consisted of an inner tank for crop cultivation and an outer tank for protection and drainage reservoir. The volume of the inner tank was 0.36 m^3 (0.5 m × 0.8 m × 0.9 m), and a layer of coarse sand and gravel, 0.2 m thick, was overlain by a repacked soil profile of 0.7 m. The topsoil of the inner tank was shaped to the same forms as field beds, and at the bottom of the inner tank, a pipe serving as a drainage outlet connected the inner tank to the outer tank. Three tomatoes were cultivated in each tank. The drip tapes (including three emitters) were located along the center line of the lysimeter for irrigation. The five weighing lysimeters were also mulched with black polyethylene, when mulches were applied in the field. The five lysimeters were weighed at 8:00 h every day in 2003 and 2005, and every 2 days in 2004.

Considering the different plant density in lysimeter and field, the water use (for field) was calculated by the following formulas:

$$\text{the water use (lysimeter : mm)} = \text{precipitation (mm)} + \text{irrigation (mm)} - \text{drainage (mm)} - \text{storage change (mm)};$$

$$\text{the water use (field : mm)} = \text{the water use (lysimeter)}/2.1$$

2.6.3. *Twenty centimeter diameter pan evaporation over canopy (EW_{20})*

A standard diameter of 20 cm pan was installed over the canopy of tomatoes in the middle of the experiment field when tomato seedlings were transplanted. The starting height of the evaporation pan was 35 cm above the ground and adjusted according to the growth of tomato. The pan reached the highest height of 110 cm above the ground on 22 June (47 DAT),

Fig. 2 – A set of weighing lysimeter showing the rail-guided and hoist.

18 June (63 DAT) and 17 June (59 DAT) in 2003, 2004 and 2005. The pan was kept at this height till the harvest of tomato. Pan evaporation was observed at 8:00 h daily.

2.6.4. EC_e

Soil samples were obtained on soil cores extracted between rows with an auger (2.5 cm in diameter and 10 cm high) on 27 May (21 DAT) and on 31 August (6 days after the end of experiment) in 2003. The distances to drip tapes for sampling were 0, 17.5, 35, 52.5 and 70 cm, and sample depths were 0–2, 2–10, 10–20, 20–40, 40–60 and 60–90 cm depth. Soil sample was gotten on 10 April (9 days before seedling transplanting) and on 13 August (18 days after the end of experiment) in 2005. In order to determine the salinity distribution, the sampling locations were located 0, 7, 14, 21, 28, 35, 42, 49, 56, 63 and 70 cm from the center of the beds, and sample depths were the same as before.

All soil samples were air-dried and sieved through a 2 mm sieve. The EC were based on soil: water 1:5 extracts (on a volume basis), and were determined using a conductivity meter. The relationships between EC_e and $EC_{1:5}$ were determined after experiments and were used to convert $EC_{1:5}$ to EC_e for all samples. For different soil textures, the relationships were different for different depths:

$$\text{At } 0\text{–}60\,\text{cm depths}: EC_e = 14.77 EC_{1:5} \quad (R^2 = 0.90) \tag{3}$$

$$\text{At } 60\text{–}90\,\text{cm depths}: EC_e = 9.55 EC_{1:5} \quad (R^2 = 0.92) \tag{4}$$

Table 3 – Weather data during tomatoes growing periods in 2003, 2004 and 2005

Week	Temperature (°C)						Relative humidity (%)			Pan evaporation (mm/day)			Cumulative rainfall (mm/week)		
	Mean			Minimum			2003	2004	2005	2003	2004	2005	2003	2004	2005
	2003	2004	2005	2003	2004	2005									
1	17.1	17.2	17	11.2	10	5.4	73.7	48.2	32.2	5.1	7.3	7.7	6.8	0.0	0.0
2	19.5	13.8	19.9	12.7	9	12.7	73	48.0	44.4	6.1	4.2	10.3	0.0	28.9	0.0
3	22	17.2	14.8	16.1	10.8	8.5	74.5		57.0	5.4	7.6	6.2	6.4	1.4	14.6
4	22.6	18.5	17.6	15.3	12.8	12.2	69.1		56.7	7.4	6.2	5.6	0.2	25.0	37.3
5	21	18.7	20.6	15.5	11.7	13.1	71.5		52.0	5.6	7.2	7.8	17.2	14.4	0.0
6	23.1	21.4	22	16.1	15.6	15	64.1	61.4	61.7	6.2	5.6	6.1	3.4	19.3	3.7
7	25.3	22.5	21.8	20	15	16	68.8	50.5	81.2	6.5	7.6	6.8	72.2	0.0	17.5
8	23.9	25	23.9	18.5	17.5	16.7	71.2	56.6	64.6	5.1	7.8	4.9	24.2	0.0	25.3
9	25.1	22.5	26.5	20.1	17.3	19.4	70.4	72.9	56.4	5.2	7.1	7.3	2.6	48.9	0.4
10	25.1	23.7	25.2	19.1	18.4	20.3	72.6		71.1	5.3	5.7	4.6	0.0	72.3	90.2
11	24.8	23.6	27.7	21	19.6	20.3	70.3		61.0	4.0	4.9	8.2	43.0	17.0	0.0
12	27.3	25	24.9	24.2	19.5	20.1	76.7		85.0	3.6	6.0	7.1	4.6	2.5	58.6
13	26.8	25	27.2	22	21	23	59.7		83.7	4.9	4.7	3.4	40.5	9.0	11.1
14	25.5	26.8	26.4	19.4	23.5	21.9	54.9		82.2	6.1	3.9	4.0	3.5	34.6	14.4
15	24.1	27.2		19.1	23.3		74.9			4.4	3.5		0.0	0.0	
16	25.9			21			78.8			4.0			0.2		

Table 4 – The irrigation and seasonal average salinity of applied water for each treatment during tomato growing-period in 2003, 2004 and 2005

Years	Treatments (dS/m)	Seasonal water depths (mm)	Fresh water for seedlings (mm)	During treatment		Seasonal water depths vs. control (%)
				Irrigation times	Water depths (mm)	
2003	1.1	252.2	44.4	41	207.8	100
	2.2	184.3	44.4	26	139.9	73
	2.9	187.0	44.4	25	142.6	74
	3.5	182.9	44.4	23	138.5	73
	4.2	171.1	44.4	20	126.7	68
2004	1.1	154.6	38.0	23	116.6	100
	2.2	108.0	38.0	13	70.0	70
	2.9	112.2	38.0	13	74.1	73
	3.5	104.3	38.0	11	66.3	67
	4.2	95.0	38.0	9	57.0	61
2005	1.1	145.8	69.7	15	76.1	100
	2.3	139.7	69.7	13	70.0	96
	3.5	172.4	69.7	18	102.7	118
	4.2	142.0	69.7	12	72.3	97
	4.9	120.4	69.7	8	50.7	83

2.6.5. *Yield*

Harvest was started on 3 July (58 DAT), 20 June (65 DAT), and 27 June (69 DAT), finished on 25 August (111 DAT), 25 July (100 DAT) and 26 July (98 DAT), and the total harvest period lasted 53, 35 and 29 days in 2003, 2004 and 2005, respectively. Fruits were picked by hand at 2–4 days interval. The fruit number and the total weight per plot were checked on each harvest time.

2.7. *Statistical analysis*

The treatments were run as a single-factor analysis of variance (ANOVA). The ANOVA was performed at $\alpha = 0.05$ level of significance to determine if significant differences existed among treatment means.

3. Results and discussion

3.1. *Weather*

Weather data during tomato growing periods in the 3 years were given in Table 3. Weekly mean temperatures during the whole tomato-growing periods were very close, which was about 23.7, 21.9 and 22.5 °C, respectively in 2003, 2004 and 2005. But average minimum temperature higher than 15 °C appeared 2 weeks after transplant in 2003, whereas 5 weeks after transplant in 2004 and 2005.

Total evaporation was 585.9, 607.0, and 626.8 mm, and average daily pan evaporation was 5.3, 6.0 and 6.4 mm in 2003, 2004 and 2005, respectively. Due to heavy wind, average daily pan evaporation values in the first week in 2004 and in the first

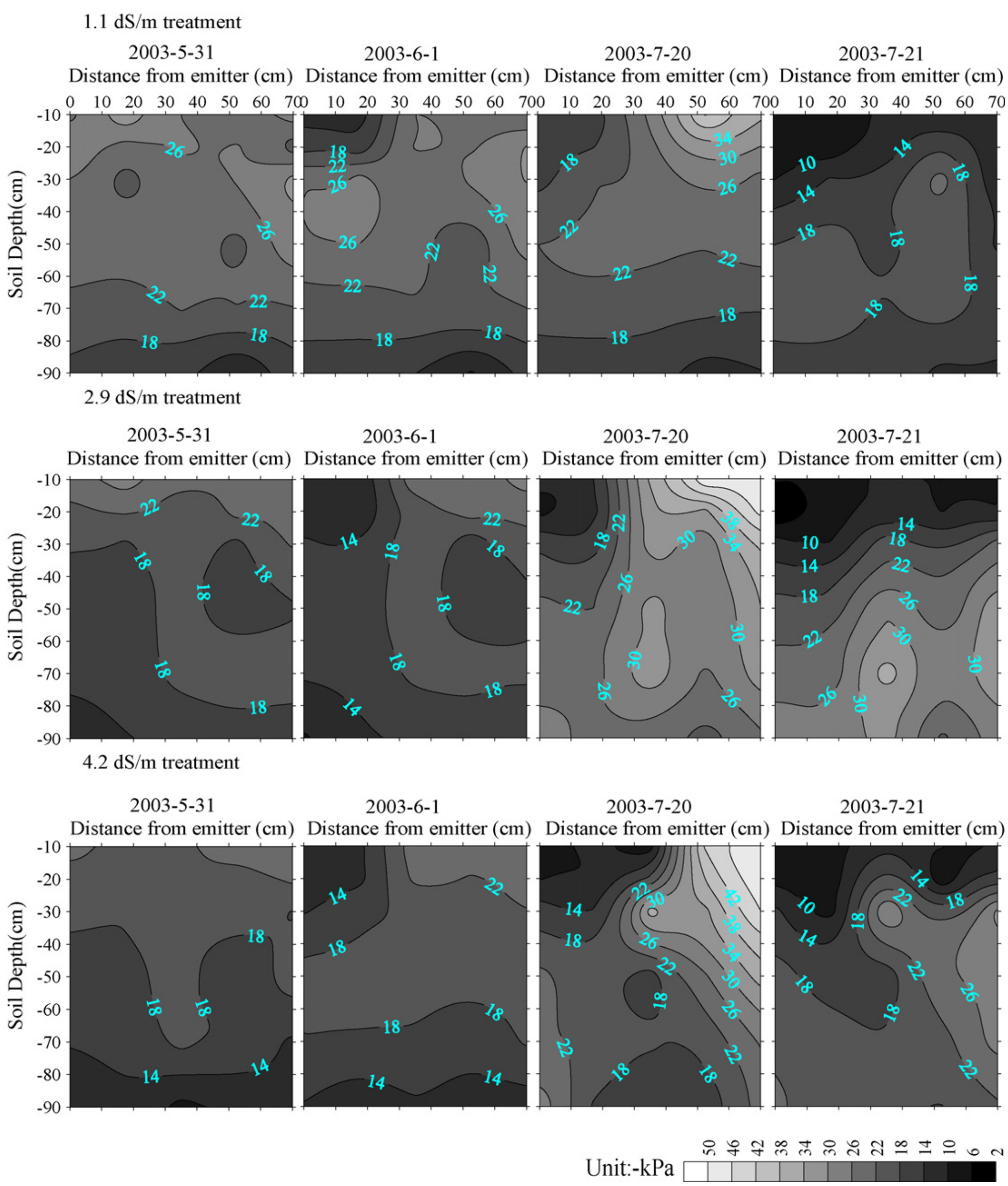

Fig. 3 – The spatial distributions of soil matric potentials in the vertical transect perpendicular to the drip tapes for different treatments on middle and later growing stages in 2003.

2 weeks in 2005 were obviously higher than those in the corresponding periods in 2003.

Total rainfall during the experiment period was 224.8, 273.3 and 273.0 mm, the events of effective rainfall (>5 mm) were 7, 16 and 14, and the quantity totaled 190.9, 247.5 and 269.0 mm in 2003, 2004 and 2005, respectively. The rainfall distribution was 6, 20, and 19% in tomato seedling establishment stage, 52, 12 and 17% in the flowering and fruiting stage and 42, 67 and 64% in the harvest stage in 2003, 2004 and 2005, respectively. The ratio of seasonal evaporation to rainfall was 2.6, 2.2 and 2.3 in 2003, 2004 and 2005. The weather in 2004 and 2005 was relatively more humid than that in 2003.

The average relative humidity values of the first 2 weeks in 2004 and 2005 were lower than that in 2003. Though most of the relative humidity data in 2004 were lost, it can be inferred that the average values in the last 3 weeks were higher than 80%, for the weather in later growth period in 2004 was similar to that in 2005.

Therefore, the relatively low minimum temperature together with low relative humidity and the windy weather prolonged the seedling establishment stages for about a week in 2004 and 2005, while frequent rainfall and high relative humidity in later tomato growing period shortened the harvest period in 2004 and 2005, compared with that in 2003.

3.2. *Irrigation*

Prior to treatments initiation, only fresh water was applied and the irrigation depth was 44.4, 38.0 and 69.7 mm in 2003, 2004 and 2005, respectively. Because of the windy weather in the first 2 weeks in 2005, much more fresh water was applied to enable seedlings to survive bad weather successfully.

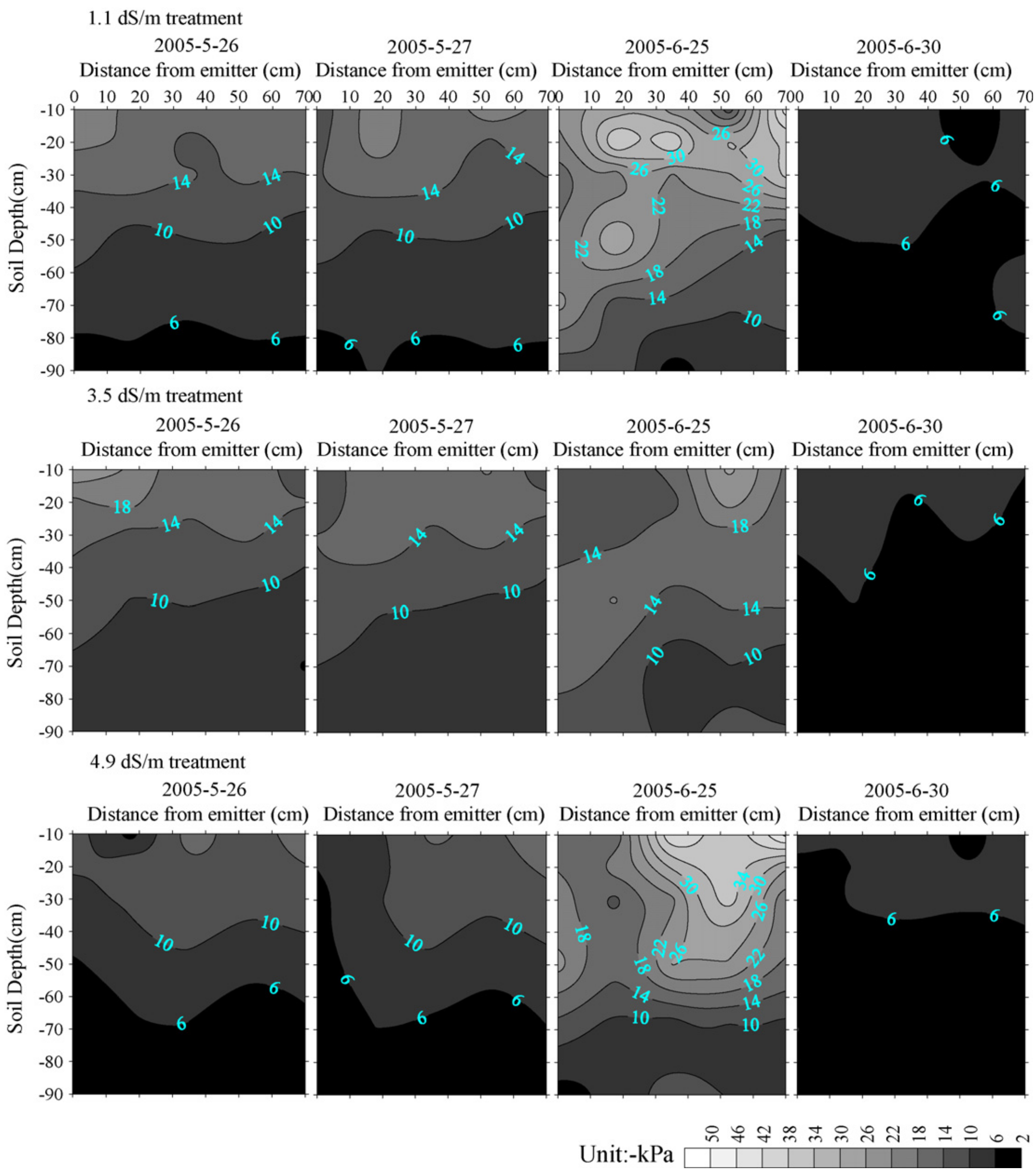

Fig. 4 – The spatial distributions of soil matric potentials in the vertical transect perpendicular to the drip tapes for different treatments on middle and later growing stages in 2005.

It is clear that the total irrigation times and depths decreased when saline water was applied, and the higher the salinity level of irrigation water was, the less irrigation times and depths were needed (Table 4), except in 2005. In 2005, the total irrigation amount for 3.5 dS/m treatment was 26.6 mm more than that for 1.1 dS/m treatment. It was perhaps because the soil texture of the tensiometer placement location was special compared with that of other treatments.

In conclusion, applying saline water in tomato planting not only can save valuable fresh water, but also can decrease irrigation times and depths.

3.3. *Soil matric potential*

The spatial distributions of soil matric potential along the vertical transect perpendicular to the drip tapes for different treatments on middle and later growing stages in 2003 and 2005 were showed in Figs. 3 and 4, respectively.

On 31 May 2003, when the soil matric potential at 0.2 m depth immediately under drip emitters was controlled close to −20 kPa for each treatment, the average soil matric potential values in the root zone were around −22 kPa. For different treatments, there was a similar tendency for soil matric potentials values to increase gradually from about −22 to −14 kPa as soil depths increased. On 1 June, 1 day after a uniform irrigation of 5.1, 5.7 and 6.3 mm for 1.1, 2.9 and 4.2 dS/m treatments, a wetting pattern can be observed obviously around the emitters, and the average soil matric potential values in the wetted zone increased to −14 kPa or higher, those outside the wetted area were almost unchanged. The area wetted along a horizontal plane was about 30 cm for different treatments, and below the soil surface depended on irrigation quantity. The depth of wetting was within 30 cm when irrigation quantity was 5.1 mm, and can reach 80 cm if 6.3 mm water was applied per time.

On 20 July, similar wetting patterns occurred for different treatments. The average soil matric potentials values in the wetted zone were high, around −20 kPa, whereas those near to the furrow surface were low, about −38 kPa or lower. In the morning, a tank of water was applied for different treatments, and in the afternoon, 17.4 mm of rain fell. On 21 July, because of irrigation and rainfall, the average soil matric potential values in the whole soil for different treatments increased, especially those at depths of 0–40 cm.

It is evident that the soil water condition in 2005 was wetter than that in 2003. On 26 May, 2005, for different treatments, the average soil matric potentials values increased gradually from −18 to −6 kPa or higher as soil depth increased from 0 to 90 cm. This day, tomatoes were uniformly fertigated with 100 ml urea solution prepared in a tank of water. One day after irrigation, the soil matric potentials values near the emitters increased to about −14 kPa or higher.

On 25 June, the soil matric potentials below 60 cm depth were higher than about −18 kPa because of frequent rainfall. Up to 60 cm depth, the soil matric potentials near emitters were around −20 kPa, whereas those near the furrow surface

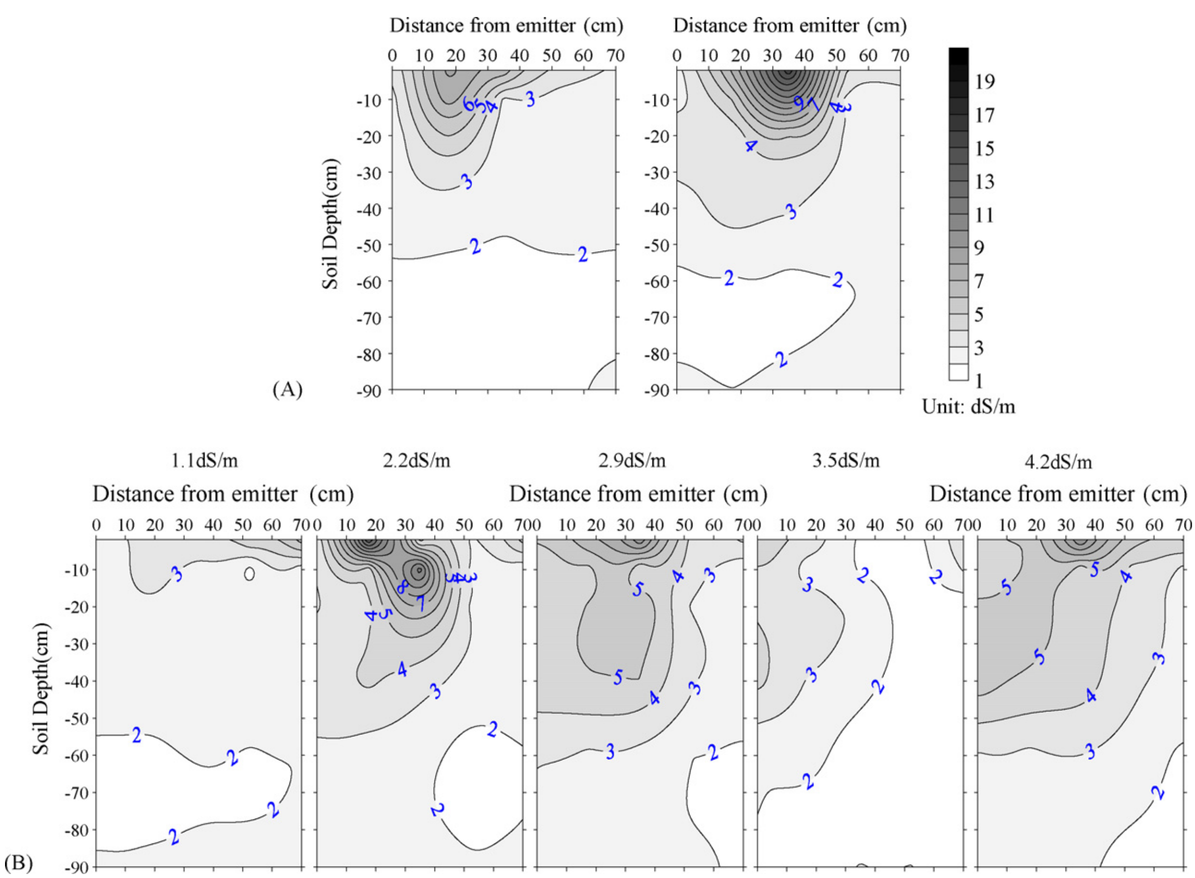

Fig. 5 – The spatial distributions of EC_e in the vertical transect perpendicular to the drip tapes for each treatment in the beginning and the end of the experiment in 2003.

were relatively low, except that for 3.5 dS/m treatment. For relative frequent irrigation, the average soil matric potential in the whole soil for 3.5 dS/m treatment was around −14 kPa. After a 90.2 mm rainfall event, the soil matric potential in the whole soil increased dramatically to −6 kPa or higher (30 June), and the soil was nearly saturated.

The soil matric potential changing trends for other treatments were similar to those mentioned above. The soil water content in 2004 was relatively high because more rain occurred in 2004 than in the other 2 years.

3.4. EC_e

Fig. 5(A) and (B) and 6(A) and (B) demonstrates the spatial distributions of EC_e in the vertical transect perpendicular to the drip tapes for each treatment in the beginning (27 May) and the end (31 August) of the experiment in 2003, and the beginning (10 April) and the end (13 August) of the experiment in 2005, respectively.

Before saline water and plastic mulches were applied, the EC_e values on the edge of beds were relatively high: averaged 9 dS/m at 0–10 cm depths, whereas the average EC_e value close to drip tapes was about 3 dS/m for periodic leaching of salts. The EC_e values below 40 cm depth were about 3 dS/m, and decreased as soil depths increased (Fig. 5A).

At the end of the experiment in 2003, except some salts accumulated in the furrow surface layer (0–10 cm), the EC_e value for 1.1 dS/m treatment averaged about 2.4 dS/m through the whole soil profile. It is obvious that after applying saline water with drip irrigation, some salts in irrigation water accumulated in the wetted zone, especially at the periphery of the wetted bulb, while only slight salt increased in the soil below 60 cm depths (Fig. 5B). The EC_e values below 60 cm depths for all treatments were lower than 2.5 dS/m.

Before the experiment initiation in 2005, excess salt built up in 0–10 cm depths, especially in 0–2 cm soil layer. However, the EC_e values below 40 cm depths were no higher than 2.5 dS/m for all treatments except 2.9 dS/m treatments, which may be caused by spatial variability (Fig. 6A).

At the end of experiments, the EC_e values in 0–10 cm depths decreased dramatically due to frequent rainfall. Whereas the EC_e values below 40 cm depths decreased little, and were no higher than 2.3 dS/m (Fig. 6B).

High spatial variability was observed in salinity along soil profiles when applying saline water with drip irrigation. Though salts always accumulated in the wetted zone and in

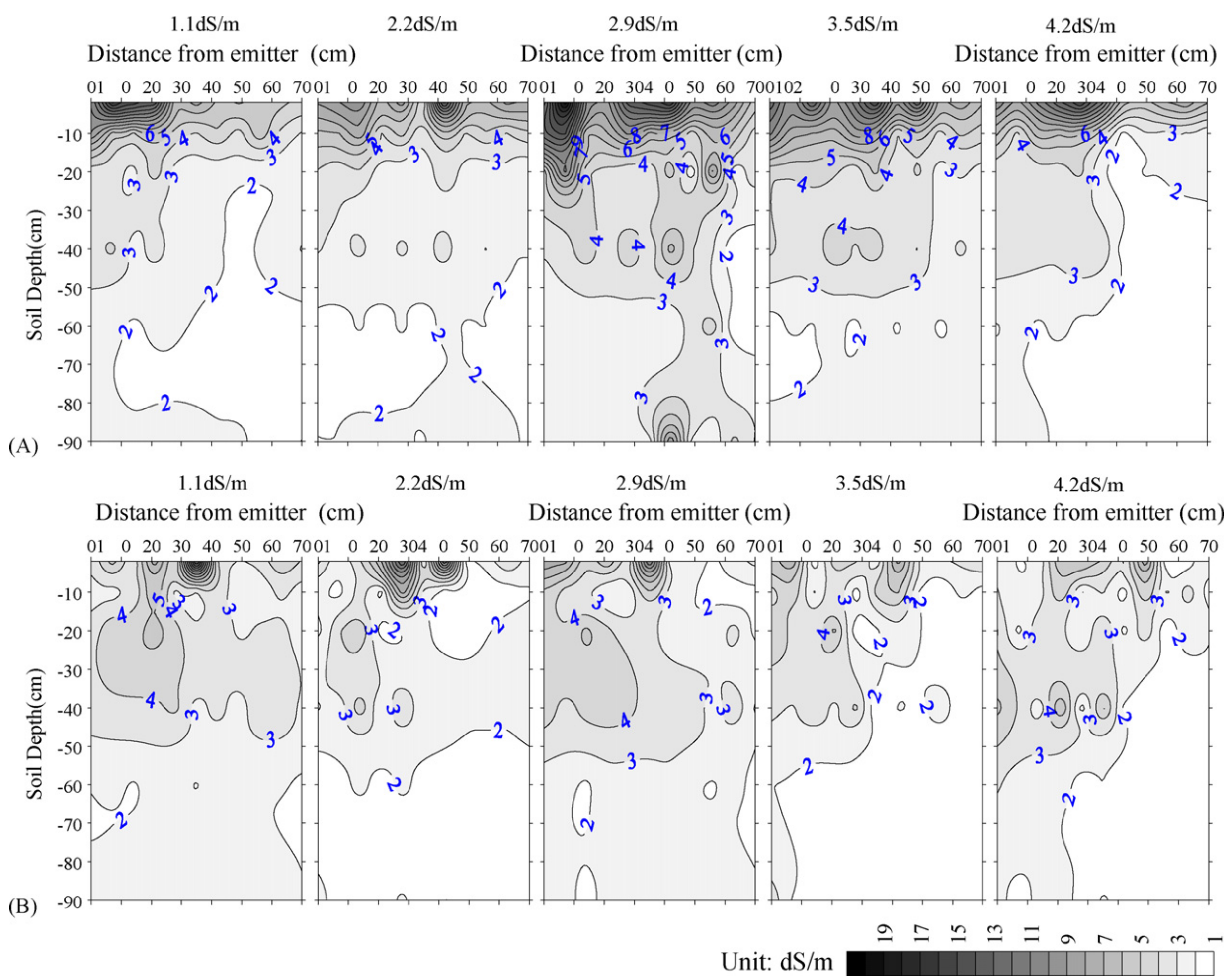

Fig. 6 – The spatial distributions of EC_e in the vertical transect perpendicular to the drip tapes for each treatment in the beginning and the end of the experiment in 2005.

the upper 0–10 cm soil layer, the EC_e values below 60 cm depths were no higher than 2.5 dS/m. Furthermore, after 3 years of saline water irrigation, salts did not accumulate in the soil profile of 0–90 cm. So in North China Plain, a semi-humid area, applying saline water (2.2–4.9 dS/m) in tomato planting under mulched drip irrigation seemed not to result in soil salinization.

3.5. *Tomato yield*

The total yield for 1.1, 2.2, 2.9, 3.5 and 4.2 dS/m treatments was 72.4, 76.2, 75.3, 74.3 and 75.9 Mg/ha in 2003, and 52.6, 53.4, 52.2, 50.1 and 54.3 Mg/ha in 2004, respectively. The total yield for 1.1, 2.2, 3.5, 4.2 and 4.9 dS/m treatments was 46.1, 44.9, 45.7, 47.1 and 42.1 Mg/ha in 2005, respectively. Statistical analysis showed that different salinity levels of irrigation water had no obvious effect on tomato yield in the 3 years.

The responses of tomato to salinity in the experiment can probably contribute to the climate and the growth stages at which saline water was applied. In the experiment, saline water was applied about 30 days after transplanting. A possible reason was that tomato plants were exposed to salinity at a stage of plant development when the potential fruit productions were formed. Besides, frequent and heavy rain falls at tomato fruit set stage in North China Plain. Tomato plants were kept away from high salinity stress during fruit development season. In addition, spatial variability of soil salinity under drip irrigation was high, and the EC_e values below 60 cm depths were no higher than 2.5 dS/m during most of tomato growing period.

Though different salinity levels of irrigation water had little effect on tomato yield, the average total yield of the five treatments in the 3 years was quite different. The average total yield in 2003, 2004 and 2005 was 74.8, 52.1 and 43.3 Mg/ha, which was 1.7, 1.2 and 1.0 times as many as the average yield of the cultivar "L-402" (43.7 Mg/ha). The reduction in yield in 2004 and 2005 was probably caused by the prolonged seedling establishment stages and the shortened harvest periods.

3.6. *Tomato water use*

3.6.1. *Ten-day water use*

Fig. 7 illustrates variations of tomato 10-day water use and corresponding 10-day 20 cm pan evaporation (EW_{20}) in 2003, 2004 and 2005. In the 3 years, the temporal patterns of the 10-day water use variations for different treatments were similar.

At the first and second 10-day, tomato water use values for all of the treatments were low, and obviously lower than the corresponding EW_{20} values, especially after the black plastic mulches were applied. The maximum 10-day water use of the five treatments in the 3 years was no more than 20 mm, which meant the water use of tomato during seedling establishment stage was no more than 2 mm per day. Tomato water use for all treatments increased gradually from the third 10-day and reached its maximum values at the fourth 10-day in 2003, the sixth 10-day in 2004, and the eighth 10-day in 2005. At the same time, the corresponding EW_{20} values got to or were close to the highest values. The maximal value for treatments with EC_{iw} from low to high was 45.7, 41.2, 39.4, 33.9 and 35.9 mm in 2003, and 52.8, 36.6, 49.6, 39.9 and 31.3 mm in 2004, and 43.8, 44.2, 51.1, 40.9 and 39.0 mm in 2005, respectively. It can be concluded the maximum daily water use of tomato was no more than 6 mm under mulched drip irrigation. Tomato water use decreased gradually at the harvest stage. At the last few days of the experiment, the average 10-day water use for the five treatments reduced to 13.5, 10.2 and 13.0 mm in 2003, 2004 and 2005, respectively.

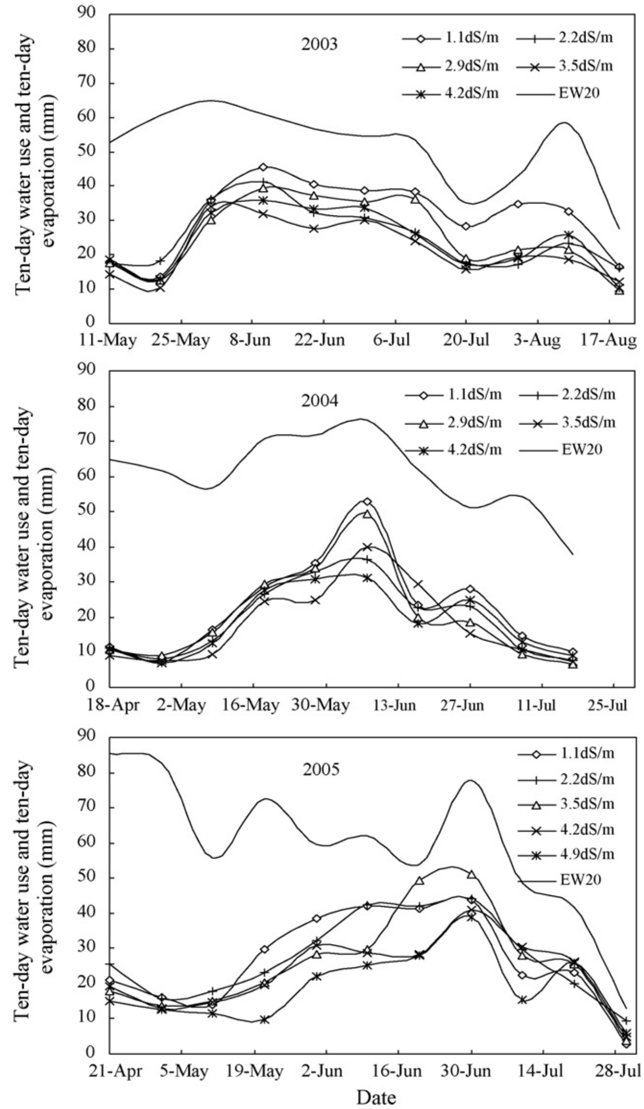

Fig. 7 – Ten-day water use curves for different treatments and the corresponding 10-day evaporation curve during the whole tomato-growing period in 2003, 2004 and 2005.

Furthermore, it can be seen that in middle and later growing periods the temporal patterns of tomato 10-day water use for each treatment were related to those of EW_{20}. This is in agreement with the results obtained by Yuan et al. (2001) and Kang and Wan (2005).

3.6.2. *Seasonal water use*

At the end of the experiment, the seasonal accumulative tomato water use value for treatments with EC_{iw} from low to high was 342.7, 276.9, 279.8, 238.4 and 265.6 mm in 2003, and

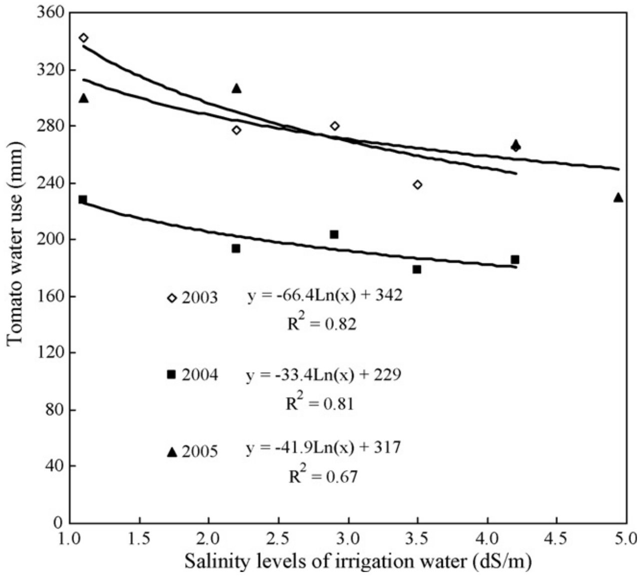

Fig. 8 – Relationship between tomato seasonal accumulative water use and different salinity levels of irrigation water in 2003, 2004 and 2005.

228.3, 193.2, 203.3, 178.4 and 185.4 mm in 2004, and 299.3, 306.9, 292.3, 267.2 and 230.0 mm in 2005, respectively.

The general relationships between the seasonal accumulative water use and irrigation water salinity in the 3 years are shown in Fig. 8. According to the irrigation records in the 3 years, the irrigation amount for 3.5 dS/m treatment in 2005 was apparently abnormal, so the water use for the treatment in 2005 was excluded in Fig. 8. It is clear that the general relationships in the 3 years were very similar. Tomato accumulative water use decreased logarithmically as irrigation water salinity increased.

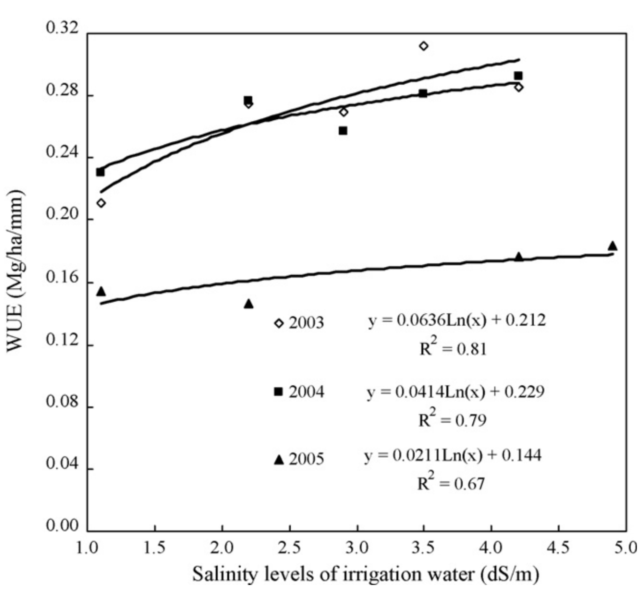

Fig. 9 – Relationship between tomato WUE and different salinity levels of irrigation water in 2003, 2004 and 2005.

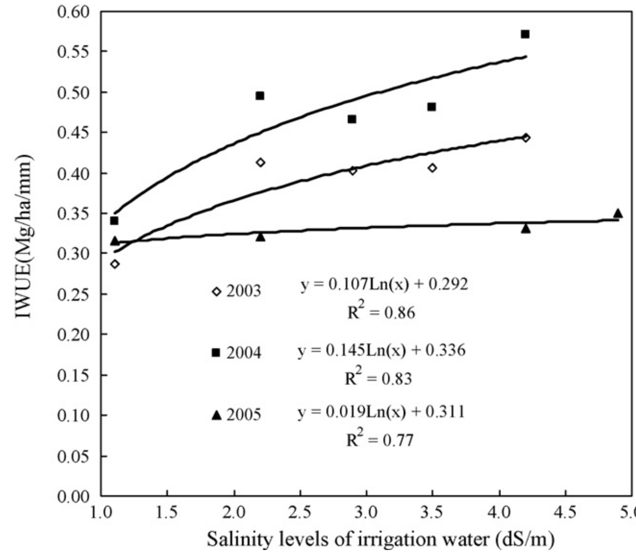

Fig. 10 – Relationship between tomato IWUE and different salinity levels of irrigation water in 2003, 2004 and 2005.

3.7. *Water use efficiency (WUE) and irrigation water use efficiency (IWUE)*

Water use efficiency is defined as the ratio of tomato yield to its seasonal accumulative water use. The relationships between tomato WUE and irrigation water salinity in 2003, 2004 and 2005 are illustrated in Fig. 9. Though there existed a discrepancy about 83 mm on average between the seasonal accumulative water use in 2003 and 2004, the average tomato WUE values in 2003 and 2004 were similar. In 2005, the average tomato WUE values of different treatments were obviously less than those in 2003 and 2004, which was possible because much fresh water was applied at tomato seedling establishment stage in 2005. In spite of this, the general tendency of the curves was similar in the 3 years, i.e., tomato WUE increased logarithmically as salinity of irrigation water increased.

Irrigation water use efficiency is computed based on tomato yield dividing by the total irrigation water. Tomato IWUE also increased logarithmically with the increase of EC_{iw} in the 3 years, though the increasing tendency in 2005 was not very obvious (Fig. 10).

4. Summary and conclusions

From the experiment conducted in North China Plain, it can be concluded that irrigation water salinity ranging 1.1–4.9 dS/m had little effect on tomato yield, but had some effect on tomato water use, WUE and IWUE. Tomato seasonal accumulative water use decreased as the irrigation water salinity increased, WUE and IWUE increased as the irrigation water salinity increased. Moreover, applying saline water in tomato planting not only can save valuable fresh water, but also irrigation times and depths. After 3 years of saline irrigation, the soil salinity in the soil profile from 0 to 90 cm depths did not increase.

Based on the results of the experiment, several proper management strategies are useful for tomatoes irrigating with saline water in North China Plain. The strategies includes using drip irrigation method, mulching tomato seedlings with black polyethylene, applying saline water about 30 days after tomato seedlings transplanting, controlling the soil matric potential at 0.2 m depth immediately under drip emitters above −20 kPa and so on.

It is safely to infer that if above-mentioned management strategies are taken, saline water ranging 2.2–4.9 dS/m can be applied to irrigate tomato without yield loss and salts accumulation in 0–90 cm soil profile in North China Plain or in similar climate areas.

The conclusions in this study were based on only 3-year data. To assess the sustainability of saline water irrigation in North China Plain, many further researches should be made.

Acknowledgements

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REFERENCES

Bustan, A., Sagi, M., De Malach, Y., Pasternak, D., 2004. Effects of saline irrigation water and heat waves on potato production in an arid environment. Field Crops Res. 90, 275–285.

Cuartero, J., Fernández-Muñoz, R., 1999. Tomato and salinity. Sci. Hort. 78, 83–125.

Del Amor, F.M., Martinez, V., Cerdá, A., 2001. Salt tolerance of tomato plants as affected by stage of plant development. Hortscience 36, 1260–1263.

Ferreyra, R.E., Aljaro, A.U., Ruiz, R.S., Rojas, L.P., Oster, J.D., 1997. Behavior of 42 crop species grown in saline soils with high boron concentrations. Agric. Water Manage. 34, 111–124.

Kang, Y., Wan, S., 2005. Effect of soil water potential on radish (*Raphanus sativus* L.) growth and water use under drip irrigation. Sci. Hort. 106, 275–292.

Katerji, N., van Hoorn, J.W., Hamdy, A., Mastrorilli, M., 1998. Response of tomatoes, a crop of indeterminate growth, to soil salinity. Agric. Water Manage. 38, 59–68.

Maas, E.V., 1986. Salt tolerance of plants. Appl. Agric. Res. 1, 12–26.

Mantell, A., Frenkel, H., Meiri, A., 1985. Drip irrigation of cotton with saline-sodic water. Irrig. Sci. 6, 95–106.

Minhas, P.S., 1996. Saline water management for irrigation in India. Agric. Water Manage. 35, 1–24.

Mitchell, J.P., Shennan, C., Grattan, S.R., May, D.M., 1991. Tomato fruit yields and quality under water deficit and salinity. J. Am. Soc. Hort. Sci. 116, 215–221.

Mizrahi, Y., Taleisnik, E., Kagan-Zur, V., Zohar, Y., Offenbach, R., Matan, E., Golan, R., 1988. A saline irrigation regime for improving tomato fruit quality without reducing yield. J. Am. Soc. Hort. Sci. 113, 202–205.

Pasternak, D., Zohar, Y., De Malach, Y., Borovic, I., Twersky, M., 1986a. Irrigation with brackish water under desert conditions V. Nitrogen requirement of tomatoes (*Lycopersicon esculentum* Mill.) during germination under drip irrigation. Agric. Water Manage. 11, 313–318.

Pasternak, D., De Malach, Y., Borovic, I., 1986b. Irrigation with brackish water under desert conditions.VII. Effect of time of application of brackish water on production of processing tomatoes (*Lycopersion esculentum* Mill.). Agric. Water Manage. 12, 149–158.

Pasternak, D., De Malach, Y., 1995. Irrigation with brackish water under desert conditions. X. Irrigation management of tomatoes (*Lycopersicon esculentum* Mills) on desert sand dunes. Agric. Water Manage. 28, 121–132.

Rhoades, J.D., Kandiah, A., Mashali, A.M., 1992. The Use of Saline Waters for Crop Production. FAO Irrigation and Drainage paper. FAO, United Nations, Rome, p. 48.

Shalhevet, J., 1994. Using water of marginal quality for crop production: major issues. Agric. Water Manage. 25, 233–269.

Shannon, M.C., Grieve, C.M., 1999. Tolerance of vegetable crops to salinity. Sci. Hort. 78, 5–38.

USDA-NRCS, 1987. National Engineering Handbook, Irrigation Section 15, Chapter 7. Trickle Irrigation. US Department of Agriculture, Natural Resource and Conservation Service, Washington, DC.

Yuan, B.Z., Kang, Y., Nishiyama, S., 2001. Drip irrigation scheduling for tomatoes in unheated greenhouses. Irrig. Sci. 20, 149–154.