



Chinese rose (*Rosa chinensis*) growth and ion accumulation under irrigation with waters of different salt contents



Xiaobin Li^{a,b}, Shuqin Wan^{a,*}, Yaohu Kang^a, Xiulong Chen^{a,b}, Linlin Chu^a

^a Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^b University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:

Received 1 December 2014

Received in revised form 7 September 2015

Accepted 21 September 2015

Keywords:

Saline silt-soil

Drip-irrigation

Chinese rose

Saline water

Growth

Ions

ABSTRACT

Soil salinity and saline groundwater are major constraints to the cultivation of landscape plants in coastal regions. Soil tillage, drip-irrigation and a gravel–sand layer were used for reclamation of high saline silt-soils in a coastal region of China. Chinese roses (*Rosa chinensis*), a salt-sensitive species, were planted in the reclaimed soil under field conditions to determine the effects of salinity on rose growth and ion uptake, using five salinity levels of 0.8, 3.1, 4.7, 6.3 and 7.8 dS/m of drip irrigation. Tensiometers were buried at a depth of 20 cm to control the soil matric potential (SMP), keeping the SMP over -5 kPa the first year, and over -10 kPa the second year. Chinese rose relative leaf water deficit, dry matter production, number of flowers, root development and distribution and other plant growth parameters were assessed. Sodium (Na), chloride (Cl), potassium (K), magnesium (Mg) and calcium (Ca) concentrations in roots, stems and leaves were determined. The increasing salinity of irrigation water had adverse effects on rose growth and ion balance, and salt stress had the greatest impact on relative leaf water deficit value. When irrigated with saline water, most roots penetrated beyond 16–19 cm depth into the high-salinity subsoil, which was disadvantageous to the absorption of water and nutrients. The SMP should be controlled at -5 to -10 kPa in the second year for irrigation with saline water of >3 dS/m, to promote a greater concentration of roots in the lower-salt top soil. Rose plants stored most absorbed Na and Cl ions in roots and stems, and Ca, Mg and K in leaves; however, leaf damage still occurred due to greater reductions in Ca/Na, Mg/Na and especially K/Na ratios. Increasing Na concentration and decreasing K/Na ratio had an adverse impact on dry matter production. Therefore, soluble potash should be applied for saline water irrigation to increase the selective absorption ratio of K, to better counteract the effect of the high Na concentrations in this soil.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Soil salinity is a major environmental factor limiting the productivity of crops and appearance of landscape plants in many coastal regions of the world, where there are large areas of saline land. In China, saline land is common along the 6000 km of coastline bor-

Abbreviations: SMP, soil matric potential; EC_{iw} , electrical conductivity of irrigation water; EC_e , electrical conductivity of saturated paste extracts; SAR, sodium adsorption ratio; GR, growth ratio; RLD, root length density; β , root distribution coefficient; SWSR, shoot water storage ratio; SD, stem diameter; PH, plant height; V, soil volume; FW, fresh weight; DW, dry weight; TW, turgid weight; RWC, relative leaf water content; RWD, relative leaf water deficit value; RR, reference ratio.

* Corresponding author at: Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11 A Datun Road, Anwai, Beijing 100101, China. Fax: +86 10 64856516.

E-mail address: wansq@igsnrr.ac.cn (S. Wan).

<http://dx.doi.org/10.1016/j.agwat.2015.09.020>

0378-3774/© 2015 Elsevier B.V. All rights reserved.

dering the Pacific Ocean from Jiangsu Province to Liaoning Province (Yu and Chen, 1999). These coastal soils are usually quite saline (Chen et al., 2015), with pH of 7.5–8.5 (Wang et al., 1993). The average sodium adsorption ratio (SAR) is >30 (mmol/L)^{0.5}, especially in silt-soil, which has marked detrimental effects on soil structure and consequently on root growth (Rengasamy et al., 2003). Saline groundwater is another factor restricting growth of crops and landscape plants in coastal regions. In coastal areas the groundwater table is persistently high, at only 0.5–3 m depth, and has an electrical conductivity (EC) within 2.5–20.5 dS/m (Chen et al., 2015). However, saline water can be successfully used for irrigation (Malash et al., 2008; Meiri et al., 1992), especially in areas with shortages of fresh water. Many crops, such as cotton (Wang et al., 2012), cowpea (Neves et al., 2009), Bermuda grass and Duncan paspalum (Robinson et al., 2004), corn (Yazar et al., 2003), barley (Khoshgofarmanesh et al., 2003), and beet (Ammari et al., 2013) have been irrigated with the saline water.

With the rapid industrialization and urbanization in coastal saline regions, there is an urgent need to improve the landscape to meet the demand for living environments in cities and surrounding districts (Li et al., 2015). Roses are some of the most popular flowering plants in the world. However, they are generally sensitive to salinity of >3.0 dS/m. Although, some rose cultivars can tolerate an EC of 3.5 dS/m without reduction in yield and quality (Cabrera and Perdomo, 2003), the excessive concentration of some ions in saline soil, due to the irrigation with saline water, is toxic to rose vegetative growth, root development and flowering (Cai et al., 2014).

Many studies were reported in literature on rose growth under saline conditions. These studies were based either on soilless saline solution culture or soil culture using added sodium chloride (NaCl) in greenhouse conditions and, sometimes with NaCl added at various ratios to irrigation water to create various salinity levels (Cabrera and Perdomo, 2003; Cai et al., 2014; Feigin et al., 1989; Hughes and Hanan, 1978b; Ishida et al., 1979; Massa et al., 2009; Muhammad Jafar et al., 1991; Niu et al., 2008, 2013). There is little information about the effect of saline water irrigation on roses in field condition. Under field conditions, salinity is a dynamic property in the root zone resulting from evaporation of the soil solution, water extraction, selective plant uptake from plant roots and replenishment by irrigation or rainfall (Tanji, 2002). Meanwhile, environmental conditions such as temperature, light intensity, humidity and wind speed can considerably affect plant response to salinity (Niu and Cabrera, 2010; Zollinger et al., 2007). Moreover, the negative relationships between soil salt or salinity and plant growth, dry matter production and ion balance have been confirmed in crops and plants (Chauhan et al., 2008; Jaskani et al., 1991; Karlberg et al., 2007; Malash et al., 2008; Mantell et al., 1985; Muhammad Jafar et al., 1991; Sonneveld et al., 1999; Valdez-Aguilar et al., 2011); however, it is not clear which indicator is the most sensitive to salt stress based on these parameters. Determination of the most salt-sensitive indicator would help in early diagnosis of plant status to salt stress, and to make further adjustment to avoid yield loss.

In the present study, Chinese rose (*Rosa chinensis*), a sensitive landscape flower plant to soil salinity, was planted in coastal regions with very heavy saline silt-soil to: (1) investigate the effects on plant dry matter production, number of flowers and root development and distribution, of irrigating with waters of five different salt loads; (2) study the effect of salinity on the uptake of major ions and the effect of ion levels on dry matter production.

2. Materials and methods

2.1. Experimental site

During 2012–2013, a field experiment was conducted in the International Eco-City of Caofeidian District ($39^{\circ}20'N$, $118^{\circ}54'E$)

in the south of Tangshan city, east China, and north of Bohai Gulf bordering the Pacific Ocean. The study area is characterized by a temperate semi-humid monsoon climate with annual precipitation of approximately 550 mm, with most rainfall during June–September.

According to Wang et al. (1993), the saline soil of the experimental site is a typical coastal saline soil developed from beach mud, with the main ions being chloride (Cl) and sodium (Na). Before water irrigation treatment, the soil texture and soil bulk density were determined (Table 1). The soil in the experimental field was silt-soil, with clay (<0.002 mm) content of 0.7%, silt (0.002–0.05 mm) of 80.7% and sand (0.05–2 mm) of 18.6%, and had a characteristic silty texture and poor ventilation and permeability. The bulk density of saline soil was in the range of 1.4–1.65 g/cm³ in the 0–30 cm soil profile, and 1.6–1.8 g/cm³ in 30–120 cm.

2.2. Soil reclamation and freshwater irrigation

The roses used in this study were established in a gravel–sand layer soil as described in Li et al. (2015). This experiment included five treatments of saline irrigation with waters of different salt contents. Each treatment was replicated three times in a total of 15 plots and laid out permanently in a completely randomized block design. There were 30 roses planted at a spacing of 0.5 m \times 0.6 m in each 3.0 m \times 3.0 m experimental plot. Each treatment had a separate gravity drip-irrigation system consisting of a tank (200 L) and 15 drip tubes (five tubes per plot). The tank was installed at 0.8 m above the ground to contain irrigation water. Drip tubes with 0.3-m emitter intervals were placed 5 cm apart from rose plants.

For each treatment, one vacuum gauge tensiometer was installed 0.2 m directly underneath one emitter located in the center of the middle plot. The tensiometers were observed twice daily (at 8:00 and 18:00 h). The primary irrigation strategies were controlling the SMP throughout the growing season. According to the previous research results of our group on different saline soils, a SMP threshold of -5 kPa in the first year could achieve the best salt leaching, and the value should be slightly lower than -5 kPa from the second year based on the decreased soil salinity and the purpose of water saving (Kang et al., 2012; Liu et al., 2011; Sun et al., 2012, 2013; Zhang et al., 2013). In this study, irrigation was applied when the tensiometer reading dropped below -5 kPa during the first year, and -10 kPa during the second year according to the experimental results of Sun et al. (2012, 2013) on coastal saline soil. The experiment was divided into two parts. The first part was soil reclamation and freshwater irrigation, by means of excavating down to 120 cm, refilling of the bottom 20 cm with a gravel–sand layer, and then upwards with the original soil, and breaking up large soil clods using a rotary tiller to increase soil infiltration, next planting with rose seedlings, and finally irrigating with freshwater. Immediately after transplanting rose seedlings on 1 June 2012, ~ 90 mm of freshwater was applied over a period of 5 days to reduce the levels of soil salinity within the 0–10-cm soil layer. After the ini-

Table 1
Soil characteristics after soil reclamation and freshwater irrigation.

Soil depth (cm)	Soil texture in % (USDA)			Soil texture	Bulk density (g/cm ³)	At the beginning of the experiment (June 2012)			After soil reclamation and freshwater irrigation (July 2012)		
	<0.002 mm	0.002–0.05 mm	0.05–2 mm			EC _e (dS/m)	pHs	SAR (mmol/L) ^{0.5}	EC _e (dS/m)	pHs	SAR (mmol/L) ^{0.5}
0–10	0.7	80.2	19.1	Silt	1.39	32.34	7.97	58.86	9.12	7.89	29.74
10–20	0.7	80.3	19.0	Silt	1.56	30.05	7.94	57.43	10.67	7.94	32.77
20–30	0.8	79.6	19.6	Silt loam	1.64	25.03	8.13	56.57	14.82	7.87	39.77
30–40	0.7	81.4	17.9	Silt	1.72	24.80	8.19	56.05	18.62	7.77	46.97
40–60	0.6	81.2	18.2	Silt	1.63	26.78	8.04	59.29	22.00	7.67	51.34
60–80	0.8	80.5	18.7	Silt	1.78	29.34	7.97	55.53	23.00	7.64	51.55
80–100	0.6	82.1	17.3	Silt	1.65	26.77	8.02	58.08	22.83	7.62	51.94
100–120	0.9	80.1	19.0	Silt	1.64	29.56	7.91	58.20	22.87	7.64	51.88

Note: EC_e is electrical conductivity of saturated paste extracts; pHs is pH of saturated paste; and SAR is sodium adsorption rate of saturated paste extracts.

Table 2
Water characteristics in each salinity treatment.

Treatments	EC _{iw} (dS/m)	Ionic concentration (mmol/L)						pH	SAR (mmol/L) ^{0.5}
		Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	SO ₄ ²⁻	Cl ⁻		
S1	0.8	6.38	0.16	1.45	0.45	0.29	4.65	8.55	4.63
S2	3.1	24.40	0.51	2.94	2.32	1.58	22.75	8.52	10.64
S3	4.7	36.46	0.74	3.66	3.79	2.46	36.78	8.40	13.35
S4	6.3	47.82	0.95	4.04	5.27	3.37	50.01	8.37	15.68
S5	7.8	62.84	1.24	4.55	7.15	4.34	66.41	8.05	18.37

Note: EC_{iw} is irrigation water electrical conductivity; SAR is sodium adsorption ratio.

tial 5 days, all treatments were uniformly irrigated to maintain the SMP at -5 kPa if the SMP fell below -5 kPa, until all plants were successfully established in the experimental soil. About ~ 36 mm of freshwater was applied over a period of 25 days to provide favorable soil moisture for seedling survival.

2.3. Saline water irrigation

The second part of this experiment was saline irrigation with water of different salt contents. To determine the effective use of irrigation with saline water on Chinese rose, during 2012–2013, five treatments with EC of irrigation water (EC_{iw}) of 0.8, 3.1, 4.7, 6.3 and 7.8 dS/m were designed (coded S1–S5). Ionic composition of irrigation water is shown in Table 2.

Water treatments based on different EC_{iw} were initiated on 1 July 2012, and when the SMP reached the threshold value, 6 mm of irrigation was applied to all treatments. The 6 mm irrigation depth was determined according to the ability to retain moisture in the soil (soil water reserves) and the maximum daily evapotranspiration of plants in this local area. Each treatment was connected to an individual gravity drip-irrigation system, which irrigated the plants from a 200-L tank. Other management issues of this experiment were as described in Li et al. (2015).

2.4. Observations and measurements

Soil cores were obtained from each plot using an auger (2.0 cm diameter, 15 cm high) on 1 June, 13 July and 28 October 2012; and on 18 March and 11 November 2013. The samples were obtained at 0, 10, 20 and 30 cm from the emitters and all sample depths were the same: 0–10, 10–20, 20–30, 30–40, 40–60, 60–80, 80–100 and 100–120 cm. The three replicate soil samples were mixed into one sample per treatment.

All soil samples were air-dried and passed through a 1-mm sieve. Soluble salt estimates were based on extracts of saturated soil. EC was determined using a conductivity meter (DDS-11A, REX, Shanghai, China).

In this experiment, average EC_e values within the whole soil profile (depth of 0–120 cm) and the root zone (identified as about 40 cm horizontal to the center of two rows at a depth of 0–40 cm) were integrated to account for both spatial and temporal variations. The average EC_e values in the soil profile were calculated:

$$EC_e(t) = \frac{\sum_{j,k}^{n,m} EC_e(t, j, k) \times S(j, k)}{\sum_{j,k}^{n,m} S(j, k)} \quad (1)$$

where t represents the time when soil samples were obtained, j the four (n) distances from the emitter where soil samples were obtained, k the seven (m) depths of soil samples and $S(j, k)$ the depth interval of the soil sample.

In addition, average EC_e value for 2 years was calculated:

$$EC_e(TY) = \frac{\{EC_e(J)+EC_e(O)\}/2 \times 110 + \{EC_e(O)+EC_e(M)\}/2 \times 142 + \{EC_e(M)+EC_e(N)\}/2 \times 240}{492} \quad (2)$$

where EC_e(J), EC_e(O), EC_e(M) and EC_e(N) refer to the spatial weighted mean value of the soil profile on 13 July and 28 October 2012, and 18 March and 11 November 2013, respectively. 110, 142 and 240 are the intervals between two sampling times, and they are the days between 13 July and 28 October 2012, 28 October 2012 and 18 March 2013, 18 March and 11 November 2013, respectively. 492 is the sum of the days.

The number of surviving rose plants was counted to calculate the survival rate, and the height and stem diameter were measured and flower number was recorded in 2012–2013. The branches were counted in 2013. At the end of 2013, plants (one plant per replicate) were destructively harvested and divided into leaves, stems and roots. Fresh weight was measured, and after drying in a ventilated oven at 70 °C for 48 h, dry weight of each organ was determined. A representative sub-sample of each plant organ was grounded in a mill (Retsch MM200, Retsch, Germany) to pass a 0.2-mm mesh. A standard plant was chosen in each replicate, and root distribution was observed by taking soil samples to a depth of 50 cm in 10-cm increments in a square of 30 cm \times 30 cm using the plant as center. Roots were divided into coarse and fine (diameter <2 mm) roots when root length was counted.

Effects of saline treatment on growth of rose shoots and distribution of roots were analyzed. Growth ratio (GR), root length density (RLD, cm/cm³), root distribution coefficient (β , dimensionless) and shoot water storage ratio (SWSR, %) were obtained using the following equations:

$$GR = \frac{SD \times 10}{PH} \quad (3)$$

$$RLD = \frac{RL}{V} \quad (4)$$

$$Y = 1 - \beta^d \quad (5)$$

$$SWSR = \frac{(FW_s - DW_s)}{FW_s} \times 100 \quad (6)$$

where SD is stem diameter (mm), PH is plant height (cm) and RL is root length (cm) for the excavated soil volume (V , cm³). Y is the cumulative root fraction (%) from the soil surface to depth d (cm) and was fitted to the data for each excavation. FW_s and DW_s are the fresh and dry weights of shoots, respectively (g/plant).

Twelve fully opened leaves were collected in 2012 and 2013. Relative leaf water content (RWC, %) and relative leaf water deficit values (RWD, %) were determined by these equations:

$$RWC = \frac{(FW_1 - DW_1)}{(TW_1 - DW_1)} \times 100 \quad (7)$$

$$RWD = \left[1 - \frac{(FW_1 - DW_1)}{(TW_1 - DW_1)} \times \frac{TW_1}{FW_1} \right] \times 100 \quad (8)$$

FW₁, DW₁ and TW₁ are the fresh, dry and turgid weights of leaves, respectively (g/plant). Twelve leaf disks were collected into

Table 3

The change of EC_e (electrical conductivity of saturated paste extracts) in the different soil sample time for each treatment in 0–40 cm and 0–120 cm soil profile in 2012 and 2013.

Treatments	EC_e in 0–40 cm soil profile (dS/m)					EC_e in 0–120 cm soil profile (dS/m)				
	2012.6	2012.7	2012.11	2013.3	2013.11	2012.6	2012.7	2012.11	2013.3	2013.11
S1	28.06	13.25	5.56	2.34	3.62	28.09	20.02	15.17	10.74	8.10
S2	28.06	13.13	6.27	2.78	2.40	28.09	19.53	15.62	7.61	4.31
S3	28.06	13.47	5.56	3.11	2.79	28.09	19.42	15.17	8.73	5.23
S4	28.06	13.04	5.32	3.45	3.00	28.09	19.19	14.60	7.63	3.74
S5	28.06	13.66	5.17	3.52	3.88	28.09	19.61	14.74	7.12	5.33

Table 4

Chinese rose growth characteristics for different irrigation water quality (EC_{iw}) in 2012 and 2013.

Years	Treatments	Survival rate (%)	Plant height (cm)	Stem diameter (mm)	Growth ratio	Total length of branches(cm)	Length of branch(cm)
2012	S1	100.00a	77.41ab	8.43a	1.09a		
	S2	98.89a	80.22a	8.15ab	1.02a		
	S3	96.67a	72.60ab	7.88ab	1.09a		
	S4	98.89a	71.82ab	7.79ab	1.08a		
	S5	98.89a	68.19b	7.63b	1.13a		
2013	S1	96.67a	106.60ab	12.57ab	1.19a	563.81ab	40.73b
	S2	68.89b	117.03a	13.43a	1.17a	602.11a	50.47a
	S3	40.00c	101.05ab	12.23ab	1.21a	468.09b	37.09bc
	S4	10.00d	96.40ab	11.83b	1.23a	441.65b	34.35c
	S5	8.89d	92.90b	11.46b	1.23a	436.00b	34.25c

Note: Values followed by different letters within the same year in column differ significantly at $P < 0.05$.

weighed sealed vials and weighed for FW_1 , then floated on double deionized water for 12 h under light near the compensation point to attain maximum turgidity. These disks were blotted dry then weighed for TW_1 and oven-dried for DW_1 .

The oven-dried samples of leaves, stems and roots were digested in concentrated nitric acid at 130 °C for elemental analysis using inductively coupled plasma spectrometry (Optima 5300DV, USA) and a UV–vis spectrophotometer (HACH DR5000, USA).

2.5. Statistical analyses

Analyses of variance (ANOVAs) were carried out using SPSS 16.0 statistical software (SPSS Inc., Chicago, IL, USA). The significance of the effect of all variables was examined by one-way ANOVA. Figures were created using Origin 8.0 (Origin Lab Inc., MA, USA). The relationship equations that related the leaf, shoot and root parameters to the salinity level of water and soil were calculated.

3. Results

3.1. Soil salinity (EC_e)

Before transplanting of roses, EC_e values in the 0–40 and 0–120 cm soil profiles were relatively uniform, with average values up to 28.06 and 28.09 dS/m, respectively (Table 1). After the soil reclamation and freshwater irrigation stage, average EC_e was 13–14 dS/m for S1–S5 in the 0–40 cm soil profile, which was 51.3–53.5% lower than soil EC_e values before transplanting of roses. The corresponding values were 19–20 dS/m in the 0–120 cm soil profile, reduced by 28.7–31.7%.

In November 2013 (salt water irrigation stage), the heavy saline soils became mildly saline soil (2–4 dS/m). The average EC_e values were 2.4–3.9 dS/m in the 0–40 cm soil profile for S1–S5 (Table 3), which were reduced by 71.6–81.7% compared with EC_e in the soil reclamation and freshwater irrigation stage. The corresponding values were 3.7–8.1 dS/m in 0–120 cm soil profile (Table 3), reduced by 60.0–80.5%. Regardless of the salinity level of irrigation water, soil salinity decreased significantly with time under drip-irrigation.

3.2. Rose growth

The data of plant growth characteristics of Chinese rose for different treatments during the experiment and the ANOVA results are shown in Table 4. The average survival rate was 98.67% in 2012, with no difference in the five treatments, but it was significantly reduced in 2013 with increasing salinity of irrigation water. In 2013, S1 had the highest survival rate (96.67%) and S5 the lowest (8.89%) (Table 4).

Plant height and stem diameter increased significantly from 2012 to 2013, and showed a trend of reduction with increasing salinity of irrigation water. In the 2 years, the S1 and S2 treatments formed one group, with plant height and stem diameter values higher than these for the other treatments. Similar trends were observed for total length of branches and length of branches in 2013. GR increased with increasing salinity of irrigation water

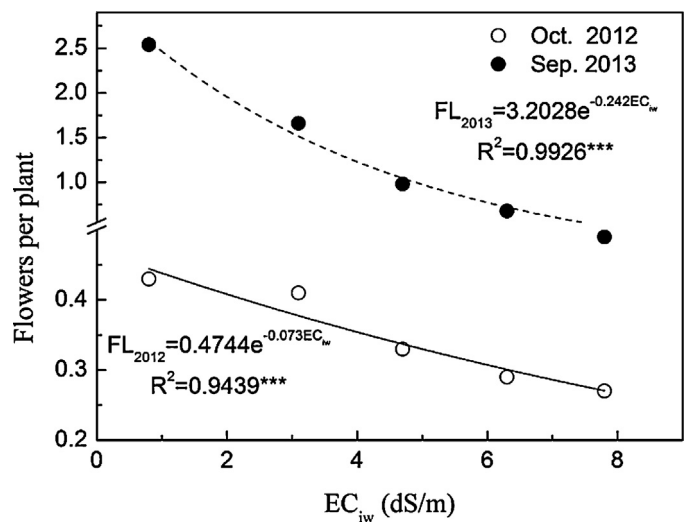


Fig. 1. Flowers per plant (FL) for the two years in relation to irrigation water salinity (EC_{iw}) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

Table 5
Chinese rose flower and leaf characteristics for different irrigation water quality (EC_{iw}) in 2012 and 2013.

Treatments	Flowers per plant		Relative leaf water content (%)		Relative leaf water deficit value (%)	
	October 2012	June 2013	November 2012	September 2013	November 2012	September 2013
S1	0.43a	2.54a	97.74a	97.11a	0.76b	1.00c
S2	0.41a	1.66ab	97.92a	96.17ab	0.69b	1.30bc
S3	0.33ab	0.98b	97.52a	93.89b	0.82b	2.11b
S4	0.29ab	0.68b	96.76ab	93.08bc	1.04ab	2.41ab
S5	0.27b	0.49b	94.79b	91.25c	1.67a	3.14a

Note: Values followed by different letters for the same month in column differ significantly at $P < 0.05$.

Table 6
Chinese rose root and shoot characteristics for different irrigation water quality (EC_{iw}).

Periods	Treatments	Total root length (cm)	Fine root length (cm) (<2 mm)	Coarse root length (cm) (>2 mm)	Shoot fresh weight (g)	Shoot dry weight (g)	Shoot water storage ratio (%)	Root dry weight (g)	Root shoot ratio
2013	S1	3102.67a	2568.67a	534.00a	542.19a	305.10a	43.73b	53.96a	0.1764a
	S2	2689.50ab	2401.50ab	288.00b	401.74b	206.03b	48.72a	37.92b	0.1837a
	S3	2396.16ab	2224.83ab	171.33b	244.72c	126.90c	48.14a	24.50bc	0.1931a
	S4	2153.00b	1957.00b	196.00b	243.50c	117.65c	51.68a	24.02bc	0.2039a
	S5	2220.19b	1888.69b	331.50ab	205.71c	100.10c	51.34a	21.12c	0.2110a

Note: Values followed by different letters in column differ significantly at $P < 0.05$.

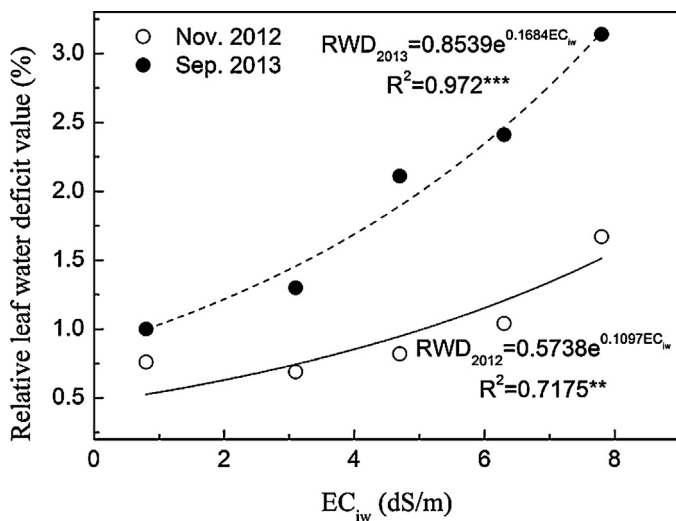


Fig. 2. Relative leaf water deficit value (RWD) for the two years in relation to irrigation water salinity (EC_{iw}) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

(Table 4), indicating that salt stress had a greater negative effect on rose height than stem diameter.

3.3. Leaf water status and flower numbers

Irrigation with saline water had a significantly negative effect on numbers of flowers (Table 5). The flower numbers were 0.43 and 2.54 at EC_{iw} of 0.8 dS/m in October 2012 and June 2013, respectively, and correspondingly 0.27 and 0.49 at 7.8 dS/m. The relationship between flowers per plant and EC_{iw} was described by a highly significant power function, with a better fit in 2013 ($R^2 = 0.9926$) than in 2012 ($R^2 = 0.9439$) (Fig. 1).

High salinity reduced RWC, especially in 2013, which resulted in poor leaf water status, and increased the RWD value (Table 5). There was a highly significant power relationship between RWD and EC_{iw} , especially in 2013 (Fig. 2, $R^2 = 0.9720$).

3.4. Root and shoot

At the end of 2013, plants were collected and divided into roots and shoots to determine the dry mass, and analysis

of root distribution (Table 6). Both total root and fine root lengths significantly decreased with increasing salinity of irrigation water—notably, fine root length significantly decreased in a linear fashion ($R^2 = 0.9734$). Total root lengths decreased from 3102.7 cm for 0.8 dS/m to 2220.2 cm for 7.8 dS/m. Fine root lengths correspondingly decreased from 2568.7 cm to 1888.7 cm. However, after an initial decrease, coarse root length tended to increase with increasing salinity of irrigation water (Table 6).

RLD and percentage of root dry mass in 10-cm increments of soil layers were significantly affected by salinity (Fig. 3a and b). Increasing salinity of irrigation water reduced RLD for each layer in the 0–20-cm soil profile but increased RLD in the 30–50-cm profile, except for the S5 treatment in which RLD decreased throughout the soil profile (Fig. 3a). Interestingly, the fitted curve between percentage of root dry mass in each soil layer and soil depth for the S1 treatment nearly intersected at a point in a range of 16–19 cm of soil depth with other fitted curves of the S2–S5 treatments (Fig. 3b), indicating that more roots penetrated beyond 16–19 cm into the subsoil when irrigated with saline water of >3 dS/m. Increased salinity of irrigation water significantly reduced RLD for all 0–50-cm soil profiles ($R^2 = 0.9473$; Fig. 4). The relationship between RLD for all soil profiles and EC_{iw} was represented by a highly significant logarithmic function ($R^2 = 0.9473$). In the 0–50-cm soil profile, β showed a reducing trend after an initial increase with increasing salinity of irrigation water ($R^2 = 0.7396$; Fig. 4).

FW_s , DW_s and root dry weight decreased as the salinity in irrigation water increased, but there were no significant differences among the S3–S5 treatments (Table 6). SWSR increased, but there were no differences among the S2–S5 treatments (Table 6). Root:shoot ratio increased as salinity of irrigation water increased, but there were no significant differences.

3.5. Ion concentrations in plants

Calcium (Ca), magnesium (Mg) and Na concentrations (unit: mmol/kg) in all plant organs increased significantly with increasing salinity of irrigation water (Fig. 5a, c and d). Notably, when irrigated with water of 7.8 dS/m, the Na concentrations in leaves, stems and roots were $(231.1 \pm 47.7)\%$, $(111.7 \pm 32.4)\%$ and $(51.4 \pm 21.8)\%$ higher than those of 0.8 dS/m, respectively. Both Ca and Mg concentrations were lower in roots than in leaves (Fig. 5a and c), but Na concentration was higher in roots than in aerial organs (Fig. 5d). Cl concentration also increased as salinity of irriga-

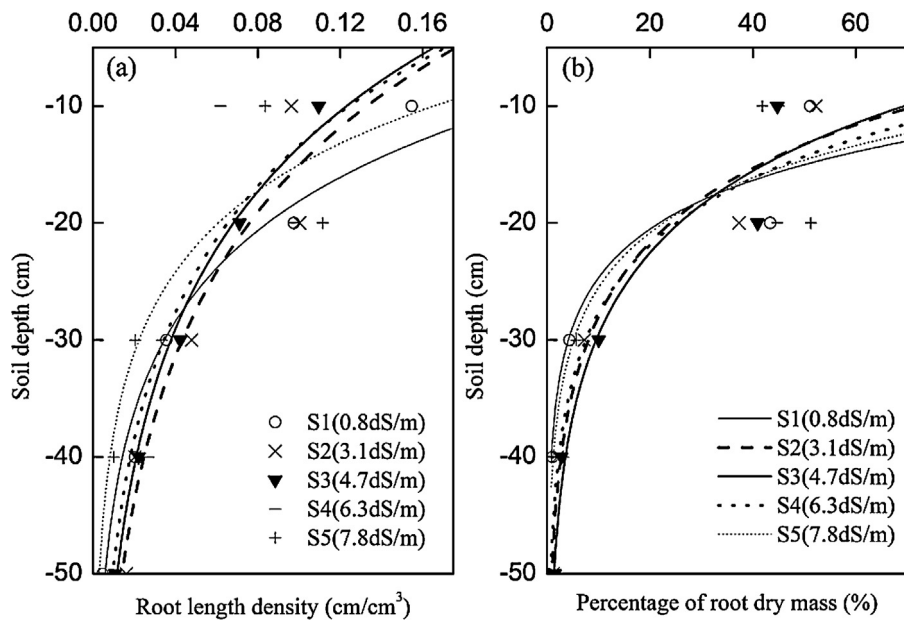


Fig. 3. Root length density and percentage of root dry mass for each soil layer in relation to soil depth.

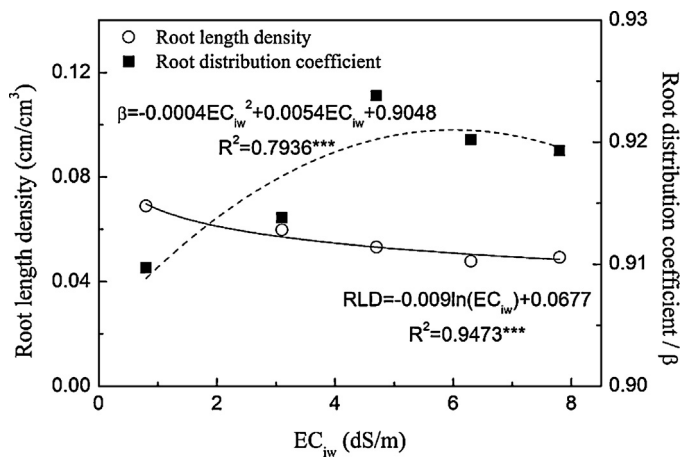


Fig. 4. Root length density (RLD) and root distribution coefficient (β) for all soil profiles in relation to irrigation water salinity (EC_{iw}) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

tion water increased (Fig. 5e), but potassium (K) concentration decreased (Fig. 5b) and there were no differences for Cl and K concentrations among the treatments. K concentration was higher in leaves than in other organs, but Cl concentration was higher in roots than in aerial organs.

Total plant Ca, Mg, Na, K and Cl contents (unit: mg) – as well as that of roots, stems and leaves (except for Na in leaves) – were significantly depressed by increasing salinity of irrigation water (Table 7). Regardless of the salt level, most of total plant Na and Cl contents were present in stems, followed by roots, while only 8–21% was in leaves (Table 7). However, most of total plant Ca, K and Mg contents were present in stems, followed by leaves, while only 6–11% was in roots (Table 7).

The Ca/Na, Mg/Na and K/Na ratios decreased in all plant organs with increasing salinity of irrigation water, especially in leaves (Fig. 6). The Ca/Na, Mg/Na and K/Na ratios of leaves were depressed from 7.85, 4.10 and 10.22, respectively, to 3.14, 1.51 and 3.11 by increasing salinity of irrigation water from 0.8 to 7.8 dS/m.

4. Discussion

4.1. Rose growth and plant water status

The vegetative and reproductive growths of rose plants were significantly reduced by increasing salinity of irrigation water. The data suggested that rose was sensitive to soil salinity. However, average EC_e values during the 2 years were 4.5–5.2 dS/m (Table 3), which were higher than the threshold value for roses reported as 1–2.4 dS/m in soilless cultures and 1–3.5 dS/m in soil as calculated using flower characteristics (Cabrera and Perdomo, 2003; De Kreij and Berg, 1990; Feigin et al., 1989; Hughes and Hanan, 1978b; Ishida et al., 1979; Sonneveld et al., 1999; Yaron et al., 1969; Zeroni and Gale, 1989). The reason can be attributed to the different irrigation managements, growing medium properties and environmental factors. It is likely that environmental conditions such as temperature, light intensity, humidity, rainfall and wind speed considerably affect plant response to salinity (Niu et al., 2007; Zollinger et al., 2007). Thus salt tolerance threshold of plants differs in different cultural environments, and salt tolerance can be improved by creating a suitable environment.

There were significant differences in survival rates between both experimental years (Table 4). The average EC_e values were 5–7 dS/m for S1–S5 in 0–40 cm soil profile in November 2012 (Table 3), and the corresponding values decreased to 2–4 dS/m in March 2013 (Table 3). Although soil salinity decreased for all treatments from the first year to the second, markedly decrease in survival rates with increasing salinity of irrigation water occurred in the spring of 2013. This suggested that rose was more sensitive to salt at emergence stages of growth. Similar results were obtained by Rhoades and Mashali (1992), who reported that plants were more sensitive during emergence and early stages of seedling growth.

In the current study, GR calculated from plant height and stem diameter increased with increasing salinity, indicating that salt stress had a greater negative effect on plant height than on stem diameter. This suggested that the saline water irrigation could also affect the plant shape, which plays an important role in landscape spatial structure.

Flower per plant was significantly reduced by salinity. Similar results were also found in other studies (Cai et al., 2014; Muhammad Jafar et al., 1991; Niu et al., 2013). The influence of

Table 7
Ion contents in plant organs.

Treatments	Ca (mg)			K (mg)			Mg (mg)			Na (mg)			Cl (mg)		
	Leaves	Stems	Roots	Leaves	Stems	Roots	Leaves	Stems	Roots	Leaves	Stems	Roots	Leaves	Stems	Roots
S1	586.80	1342.38	140.72	745.22	2640.35	303.46	183.90	546.78	84.57	43.00	274.51	173.49	29.49	155.11	69.33
S2	685.52	933.17	101.53	708.36	1323.93	246.23	196.64	356.57	62.87	40.66	184.29	157.17	35.79	180.29	55.06
S3	370.88	613.52	75.11	398.70	729.61	135.56	106.24	253.25	44.56	36.55	189.51	111.14	22.09	98.54	40.73
S4	674.03	511.04	74.35	706.43	514.16	130.28	204.90	194.73	48.32	80.89	175.10	117.04	42.54	105.42	35.02
S5	356.68	544.77	74.55	344.98	482.53	108.28	103.22	219.14	42.48	65.37	177.77	103.03	19.14	59.31	33.45

salinity on flowers was higher than that on vegetative growth, indicating that reduced reproductive growth may have important implications for the persistence of vegetative growth under continued saline irrigation (Rogers et al., 1994). Therefore, control of vegetative growth by pruning may be an effective measure to ensure relatively high production of rose flowers under saline irrigation.

Under our experimental conditions, irrigation with saline water had a negative effect on leaf water status: RWC decreased with increasingly saline water and RWD increased (Table 5). Although the average EC_e values (2–4 dS/m) for S1–S5 in 0–40 cm soil profile in 2013 were lower than those (>7 dS/m) in 2012 (Table 3), both flowers per plant and leaf water status (RWC and RWD) were more closely related with EC_{iw} in 2013 (Table 5 and Figs. 1 and 2) than in 2012. The better relation between them was mainly related with the less rainfall and a lower SMP in 2013. Similar results were also found in wheat (Grewal, 2010). This suggested that water stress had a depressing effect on growth when subjected to different subsoil salinities.

4.2. Root characters and dry matter production

Salinity had severe detrimental effects on root growth and consequently affected water uptake, and finally the grain yield and water use efficiency (Grewal, 2010; Musacchi et al., 2006; Rogers et al., 1994). In the current study, the total root and fine root lengths decreased as salinity of irrigation water increased

(Table 6), while coarse root length increased after an initial decrease (Table 6)—indicating that fine roots were more susceptible to salt injury than coarse roots. Similar results were reported by Musacchi et al. (2006) in pear and quince. In the present study, as the salinity level increased, RLD was reduced in the 0–20-cm soil layer and increased in the 30–50-cm except for the S5 treatment (Fig. 3a), while RLD for the whole soil profile was reduced when irrigated with saline water (Fig. 4). Chinese rose presented a different response against salinity than clover according to the comparison between our results and Roger's (1994), in which white clover showed no difference in the pattern of root distribution between salinity levels or between cultivars at soil depths >15 cm.

Interestingly, most roots penetrated beyond 16–19 cm depth into the subsoil when irrigated with saline water of >3 dS/m (Fig. 3b), where the tensiometers were buried at a depth of 20 cm to control the SMP. This implied that it was effective to change the root dry matter distribution in soil layer by regulating the SMP through tensiometers when irrigating with saline water. Thus, in order to promote a concentration of roots in the top 0–20 cm of soil, a higher SMP should be applied, i.e., controlling the SMP at –5 to –10 kPa in the second year may be more profitable for irrigation with saline water of >3 dS/m in our experiment.

In this study although roots penetrated beyond the surface soil into the highly saline subsoil, there were no reductions in root growth—i.e., RLD in the 30–50-cm soil layer and percentage of root dry mass in the 20–50-cm (Fig. 3a and b)—instead, root growth in subsoil was promoted for S2–S4 treatments. Thus, the reductions

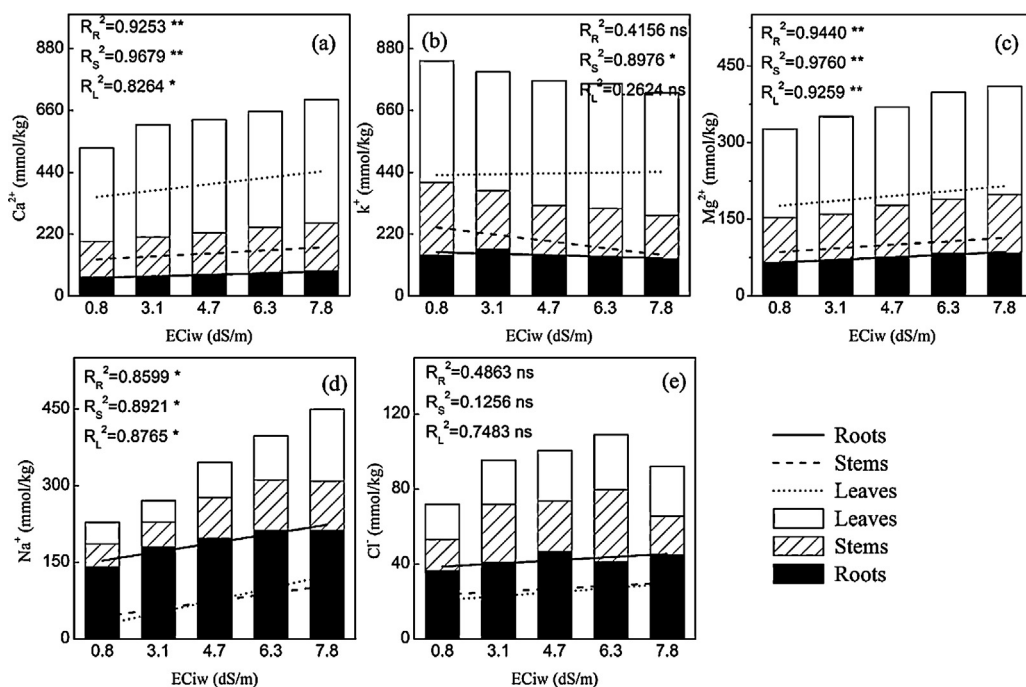


Fig. 5. Ions concentration in roots, stems and leaves at the end of 2013 in relation to irrigation water salinity (EC_{iw}) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

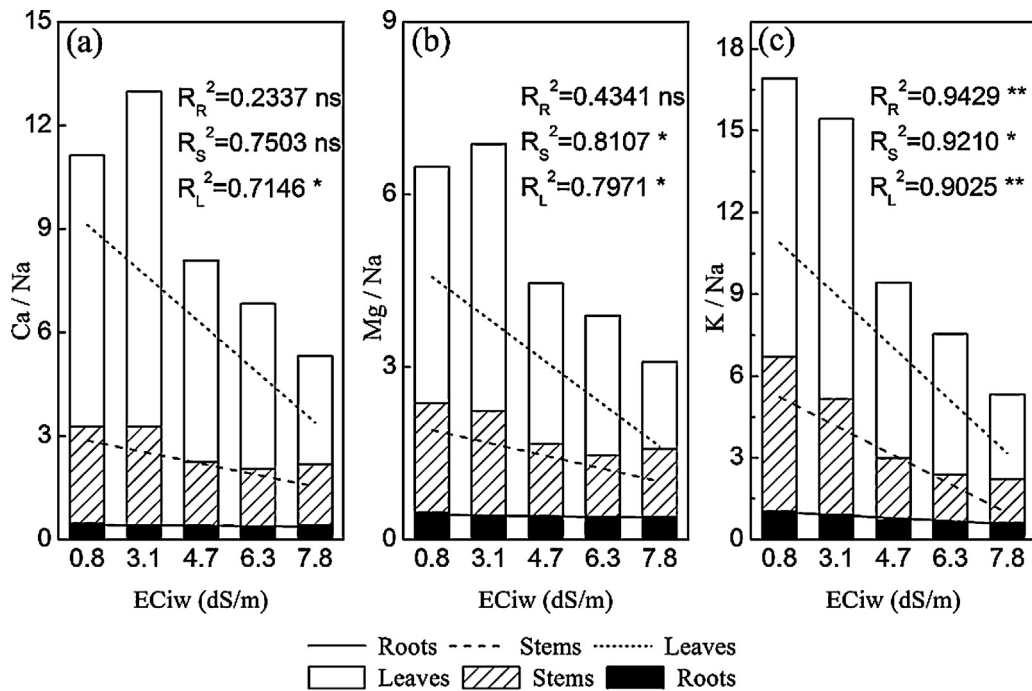


Fig. 6. Ca/Na, Mg/Na and K/Na ratios in roots, stems and leaves at the end of 2013 in relation to irrigation water salinity (EC_{iw}) (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

in plant growth may be due to the absorption of excess ions from the high saline subsoil in the 30–50-cm soil layer where more root growth was observed when irrigated with saline water of < 6.3 dS/m. For the S5 treatment, the decreased rose growth may be attributed to the reduction in root growth in the entire soil profile and the excessive absorption of ions.

With increased salinity levels, β increased, further suggesting that rose plants were intolerant species and proportionately more deeply rooted when subjected to salinity (Gale and Grigal, 1987). However, β was reduced when irrigated with saline water of ≥ 6.75 dS/m (Fig. 4). This could be attributed to a significant reduction in root growth under higher salinity conditions, and was also consistent with the observed decrease in RLD in all soil layers when irrigated with saline water of 7.8 dS/m. Irrigation with increasing salinity caused plants to devote less dry matter to shoots and more to roots, resulting in an increasing root:shoot ratio with increasing salinity levels; however, there were no significant differences among the five treatments (Table 6).

4.3. Salt-sensitive indicators

Although there was a tendency for all organs to be affected by salinity, the various indicators responded differently when subjected to salinity. In the present study, reference ratio (RR: the reference value of plant indicators when irrigated with fresh water or low salinity water to the actual value of plant indicators at the given salinity level) was used to evaluate the effect of salinity on rose indicators. RWD was the most sensitive indicator, followed by flowers per plant, shoot dry weight and shoot fresh weight (data not shown). There was a highly significant exponential relationship between EC_{iw} and RWD or flowers per plant (data not shown). Using our previous finding that irrigation water salinity should not exceed 4.01 dS/m (Li et al., 2015), the RRs of RWD and flowers per plant should not exceed 1.68 and 0.48, respectively.

The advantages of using RWD and flowers per plant as indicators are non-destructive and non-invasive measurements easily to be determined using a light portable piece of equipment.

4.4. Ion concentrations, contents and selective ratios

Concentrations of Ca, Mg, Na and Cl were elevated in all organs of rose, while their contents in roots, stems and leaves (except for Na content of leaves) and total contents in the whole plant were significantly depressed by increasing salinity of irrigation water (data not shown). This implied that the detrimental effects on rose plant growth were mainly due to ion concentrations rather than contents. Munns et al. (1995) also reported that the plant growth reductions were mainly due to salt concentrations rising to toxic levels.

Most of the total Na and Cl amounts were present in roots and especially in stems, while only 8–21% was in leaves (Table 7). There were also higher Na and Cl concentrations in stems and especially in roots. The data suggested that the major strategy used to cope with salinity was to store most absorbed Na and Cl in the roots, followed by stems, thus avoiding excessive Na and Cl reaching the leaves—the organs most sensitive to salinity.

Leaf Cl and especially Na concentrations increased as salinity levels increased. Necrotic leaf tips and margins were observed at high salinity levels under our experimental conditions, probably due to accumulation of Cl and especially Na ions reaching toxic levels in leaf tissue (Grewal, 2010), although the concentrations in leaves were lower than those in stems and roots. This information is inconsistent with the finding by Cai et al. (2014) that leaf Cl and Na concentrations increased in six garden roses as salinity levels increased, but the concentration of Cl was much higher in leaves than that of Na. Our results also differed from those of other studies that found the scorching and salt burn damage in older foliage of roses receiving the highest salinity applications were due to Cl and not Na accumulation (Bernstei et al., 1972; Cabrera and Perdomo, 2003; Hughes and Hanan, 1978a; Yaron et al., 1969). In the present study, saline soil and saline water under field conditions were rich in other ions and these ions may regulate the uptake of Cl, further resulting in lower Cl concentrations in all plant organs; however, in other studies, roses were grown in solutions receiving NaCl as the sole salt and had lower levels of other nutrients. Thus adding nutrient elements could regulate the ion absorption of plant and reduce some ions below toxic levels.

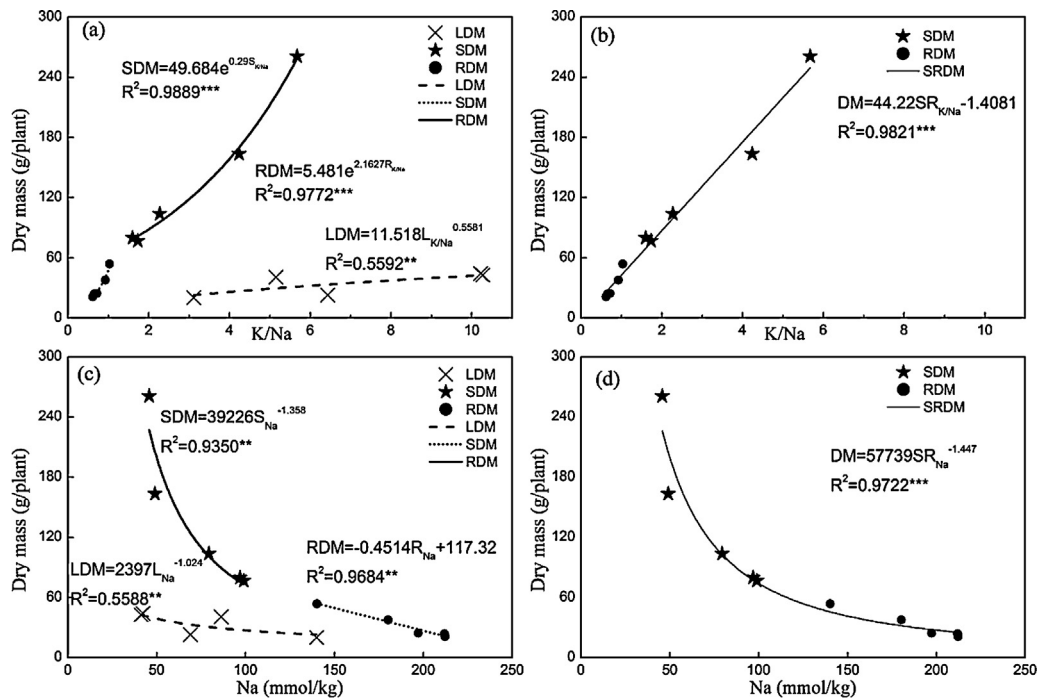


Fig. 7. Leaf dry mass (LDM), stem dry mass (SDM), root dry mass (RDM) and combined stem and root dry mass (SRDM) at the end of 2013 in relation to Na concentration and K/Na ratio in corresponding organs. (* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; ns: not significant).

K concentrations in roots decreased with increasing salinity levels, and especially in stems, but there were no adverse effects in leaf tissue, possibly because sampling occurred at the end of the growth season. The leaves with reduced K concentrations following salt stress had likely fallen off, and so there was no difference in K concentrations in those leaves remaining on plants. High K concentrations in tissues are associated with salt tolerance in many plant species (Grewal, 2010; Khatun and Flowers, 1995; Storey et al., 1993).

Increasing salinity of irrigation water was significantly related to linear declines in K/Na ratio, followed by Mg/Na and Ca/Na, especially in leaves. The low Ca/Na ratio plays a significant role in growth inhibition, in addition to causing significant changes in morphology and anatomy of plants (Ashraf, 2004). High K^+/Na^+ selectivity in plants under saline conditions has been suggested as an important selection criterion for salt tolerance (Ashraf, 2004), and has also been proposed as a physiological marker for the ion component of salt stress response (Muhling and Lauchli, 2002). Our experimentation with roses indicated that salt sensitivity was associated with a decline in the K^+/Na^+ discrimination trait.

4.5. Correlation between dry matter production and ions

A significant accumulation of Na and reduction of K/Na ratio occurred in target organs such as leaves as salinity levels increased, which was considered a major sign of detrimental effects of salinity on roses. Rogers et al. (1994) reported that concentrations of Na and Cl in the shoots of white clover linearly increased with increasing soil EC_e levels above 1 dS/m, and values were negatively related to shoot dry matter production. In the present study, K/Na ratio in stems had a slightly greater positive correlation with stem dry mass than the corresponding correlation in roots (Fig. 7a), and Na concentration in roots had a slightly greater negative correlation with root dry mass than the corresponding correlation in stems (Fig. 7c), while there was a low (although significant) correlation between leaf dry mass and Na concentration and/or K/Na ratio (Fig. 7a and c). This may be partially related to the loss of leaves observed in the

experimental period due to injury from salt stress. Analyses on the combined root and stem datasets gave the best fit for linear relationships for root and stem dry mass with K/Na ratio in these organs ($R^2 = 0.9821$; Fig. 7b), while a power relationship gave the best fit for Na concentration ($R^2 = 0.9722$; Fig. 7d). These results suggested that effects determined by high Na concentration and low K/Na ratio were the major cause of declines in dry matter production. Unfortunately, the K/Na ratio in irrigation water or soil decreased with increasing salinity of irrigation water (data not shown), implying soluble potash is necessary for plants to improve the selective absorption ratio of K, to further enhance plants salt tolerance when irrigated with saline water.

5. Conclusions

An increase of irrigation water salinity resulted in adverse effects on rose growth, dry matter production, root distribution, plant water status, flower numbers and ion balance. Most roots penetrated beyond 16–19 cm depth and β increased with salinity levels, suggesting that as a saline-intolerant species Chinese rose plants were proportionally more deeply rooted when subject to salinity. Controlling the SMP could be effective in promoting a concentration of roots in the top 0–20 cm depth (i.e., a low-salt environment) to adapt to salt stress. RWD was the most salt-sensitive indicator because it showed large differences among the different salinity treatments of irrigation water.

Chinese rose plants stored most absorbed Na and Cl in the roots, followed by stems, thus avoiding excessive amounts of Na and Cl reaching the leaves, which suggested a mechanism that prevented xylem loading and transporting to leaves. Ca, Mg and K concentrations were higher in leaves, followed by stems, and also suggested a mechanism to regulate ion balance in leaves and reduce damage from excess Na ions. However, leaf damage still occurred with higher salinity treatments due to large reductions in Ca/Na, Mg/Na and especially K/Na ratios in leaves. Na ions accumulated more in plant organs than Cl ions, indicating that other ions rich in saline soil and saline water under field conditions may regulate Cl uptake.

The increasing Na concentration and declining K/Na ratio had an adverse impact on dry matter production, implying soluble potash is necessary to enhance plants' salt tolerance when irrigated with saline water.

The results of this study have important implications for planting Chinese rose in coastal regions soils of high EC_e and SAR. Growth, flower numbers and dry matter production will be reduced on these soils with increased salinity in soil and irrigation water, unless more salt-tolerant cultivars with improved ion-regulation ability are developed. Alternative suitable micro root-zone environments should also be explored through agronomic measures and fertigation in these problematic soils, as plant growth can be improved by nutrient application when subject to salinity.

Acknowledgements

This study was supported by the National High Technology R&D Program of China (Grant No. 2013BAC02B02 and 2013BAC02B01), and the Action Plan for the Development of Western China of the Chinese Academy of Sciences (Grant No. KZCX2-XB3-16).

References

- Ammari, T.G., Al-Hiary, S., Al-Dabbas, M., 2013. Reclamation of saline calcareous soils using vegetative bioremediation as a potential approach. *Arch. Agron. Soil Sci.* 59, 367–375.
- Ashraf, M., 2004. Some important physiological selection criteria for salt tolerance in plants. *Flora* 199, 361–376.
- Bernstei, L., Clark, R.A., Francois, L.E., 1972. Salt tolerance of ornamental shrubs and ground covers. *J. Am. Soc. Hortic. Sci.* 97, 550.
- De Kreijl, C., Berg, T.H.J.M.V.D., 1990. Nutrient uptake: production and quality of *Rosa hybrida* in rockwool as affected by electrical conductivity of the nutrient solution. *Plant Nutr.—Physiol. Appl.* 41, 519–523.
- Cabrera, R.I., Perdomo, P., 2003. Reassessing the salinity tolerance of greenhouse roses under soilless production conditions. *Hortscience* 38, 533–536.
- Cai, X.Y., Niu, G.H., Starman, T., Hall, C., 2014. Response of six garden roses (*Rosa Chi hybrida* L.) to salt stress. *Sci. Hortic.* 168, 27–32.
- Chauhan, C.P.S., Singh, R.B., Gupta, S.K., 2008. Supplemental irrigation of wheat with saline water. *Agric. Water Manage.* 95, 253–258.
- Chen, X., Kang, Y., Wan, S., Chu, L., Li, X., 2015. Chinese rose (*Rosa chinensis*) cultivation in Bohai Bay, China, using an improved drip irrigation method to reclaim heavy coastal saline soils. *Agric. Water Manage.* 158, 99–111.
- Feigin, A., Ganmore-Neumann, R., Gilead, S., 1989. Response of rose plants to Cl and NO₃ salinity under different CO₂ atmospheres. *Proc. 7th Int. Congr. Soilless Culture* 7, 135–143.
- Gale, M.R., Grigal, D.F., 1987. Vertical root distributions of northern tree species in relation to successional status. *Can. J. For. Res. Rev. Can. Res. For.* 17, 829–834.
- Grewal, H.S., 2010. Response of wheat to subsoil salinity and temporary water stress at different stages of the reproductive phase. *Plant Soil* 330, 103–113.
- Hughes, H.E., Hanan, J.J., 1978a. Effect of salinity in water-supplies on greenhouse rose production. *J. Am. Soc. Hortic. Sci.* 103, 694–699.
- Hughes, H.E., Hanan, J.J., 1978b. Effect of salinity in water supplies on green-house rose production. *J. Am. Soc. Hortic. Sci.* 103, 694–699.
- Ishida, A., Masui, M., Nukaya, A., Ogura, T., 1979. Salt tolerance of roses in sand and soil cultures. *J. Jpn. Soc. Hortic. Sci.* 47, 517–523.
- Rhoades, J.D., Mashali, A.K.A.M., 1992. The use of saline waters for crop production food and agriculture organization of the united nations. 1–132.
- Jaskani, M.J., Qasim, M., Qureshi, R.H., 1991. Salt tolerance studies in roses. *Pak. J. Agric. Sci.* 28, 59–62.
- Kang, Y., Wang, R., Wan, S., Hu, W., Jiang, S., Liu, S., 2012. Effects of different water levels on cotton growth and water use through drip irrigation in an arid region with saline ground water of Northwest China. *Agric. Water Manage.* 109, 117–126.
- Karlberg, L., Rockstrom, J., Annandale, J.G., Steyn, J.M., 2007. Low-cost drip irrigation—a suitable technology for southern Africa? An example with tomatoes using saline irrigation water. *Agric. Water Manage.* 89, 59–70.
- Khatun, S., Flowers, T.J., 1995. Effects of salinity on seed set in rice. *Plant Cell Environ.* 18, 61–67.
- Khoshtofarmanesh, A.H., Shariatmadari, H., Vakili, R., 2003. Reclamation of saline soils by leaching and barley production. *Commun. Soil Sci. Plant Anal.* 34, 2875–2883.
- Li, X., Kang, Y., Wan, S., Chen, X., Chu, L., 2015. Reclamation of very heavy coastal saline soil using drip—irrigation with saline water on salt sensitive plants. *Soil Tillage Res.* 146, 159–173.
- Liu, S., Kang, Y., Wang, R., Wan, S., Wang, Z., Liang, Z., Sun, X., 2011. Water and salt regulation and its effects on *Leymus chinensis* growth under drip irrigation in saline-sodic soils of the Songnen Plain. *Agric. Water Manage.* 98, 1469–1476.
- Malash, N.M., Ali, F.A., Fatahalla, M.A., Khatib, E.A., Hatem, M.K., Tawfic, S., 2008. Response of tomato to irrigation with saline water applied by different irrigation methods and water management strategies. *Int. J. Plant Prod.* 2, 101–116.
- Mantell, A., Frenkel, H., Meiri, A., 1985. Drip irrigation of cotton with saline-sodic water. *Irrig. Sci.* 6, 95–106.
- Massa, D., Mattson, N.S., Lieth, H.J., 2009. Effects of saline root environment (NaCl) on nitrate and potassium uptake kinetics for rose plants: a Michaelis-Menten modelling approach. *Plant Soil* 318, 101–115.
- Meiri, A., Frenkel, H., Mantell, A., 1992. Cotton response to water and salinity under sprinkler and drip irrigation. *Agron. J.* 84, 44–50.
- Muhammad Jafar, Jaskani, Muhammad, Qasim, Qureshi, R.H., 1991. Salt tolerance studies in roses. *Pak. J. Agric. Sci.* 28, 59–62.
- Muhling, K.H., Lauchli, A., 2002. Effect of salt stress on growth and cation compartmentation in leaves of two plant species differing in salt tolerance. *J. Plant Physiol.* 159, 137–146.
- Munns, R., Schachtman, D.P., Condon, A.G., 1995. The significance of a two-phase growth response to salinity in wheat and barley. *Aust. J. Plant Physiol.* 22, 561–569.
- Musacchi, S., Quartieri, M., Tagliavini, M., 2006. Pear (*Pyrus communis*) and quince (*Cydonia oblonga*) roots exhibit different ability to prevent sodium and chloride uptake when irrigated with saline water. *Eur. J. Agron.* 24, 268–275.
- Neves, A.L.R., De Lacerda, C.F., Guimaraes, F.V.A., Hernandez, F.F.F., Da Silva, F.B., Prisco, J.T., Gheyi, H.R., 2009. Biomass accumulation and nutrient extraction by cowpea plants irrigated with saline water at different growth stage. *Cienc. Rural* 39, 758–765.
- Niu, G., Rodrigues, D.S., Aquiniga, L., 2007. Growth and landscape performance of ten herbaceous species in response to saline water irrigation. *J. Environ. Hortic.* 25, 204–210.
- Niu, G.H., Cabrera, R.I., 2010. Growth and physiological responses of landscape plants to saline water irrigation: a review. *Hortscience* 45, 1605–1609.
- Niu, G.H., Rodriguez, D.S., Aguiniga, L., 2008. Effect of saline water irrigation on growth and physiological responses of three rose rootstocks. *Hortscience* 43, 1479–1484.
- Niu, G.H., Starman, T., Byrne, D., 2013. Responses of growth and mineral nutrition of garden roses to saline water irrigation. *Hortscience* 48, 756–761.
- Rengasamy, P., Chittleborough, D., Helyar, K., 2003. Root-zone constraints and plant-based solutions for dryland salinity. *Plant Soil* 257, 249–260.
- Robinson, P.H., Grattan, S.R., Getachew, G., Grieve, C.M., Poss, J.A., Suarez, D.L., Benes, S.E., 2004. Biomass accumulation and potential nutritive value of some forages irrigated with saline-sodic drainage water. *Anim. Feed Sci. Technol.* 111, 175–189.
- Rogers, M.E., Noble, C.L., Nicolas, M.E., Halloran, G.M., 1994. Leaf, stolon and root-growth of white clover (*trifolium-repens*) in responses to irrigation with saline water. *Irrig. Sci.* 15, 183–194.
- Sonneveld, C., Baas, R., Nijssen, H.M.C., de Hoog, J., 1999. Salt tolerance of flower crops grown in soilless culture. *J. Plant Nutr.* 22, 1033–1048.
- Storey, R., Gorham, J., Pitman, M.G., Hanson, A.D., Gage, D., 1993. Response of melanthra-biflora to salinity and water-stress. *J. Exp. Bot.* 44, 1551–1560.
- Sun, J., Kang, Y., Wan, S., Hu, W., Jiang, S., Zhang, T., 2012. Soil salinity management with drip irrigation and its effects on soil hydraulic properties in north China coastal saline soils. *Agric. Water Manage.* 115, 10–19.
- Sun, J.X., Kang, Y.H., Wan, S.Q., 2013. Effects of an embedded gravel-sand layer on reclamation of coastal saline soils under drip irrigation and on plant growth. *Agric. Water Manage.* 123, 12–19.
- Tanji, K.K., 2002. Salinity in the soil environment. In: Lauchli, A., Lutge, U. (Eds.), *Salinity: Environment-Plants-Molecules*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 21–51.
- Valdez-Aguilar, L.A., Grieve, C.M., Razak-Mahar, A., McGiffen, M.E., Merhaut, D.J., 2011. Growth and ion distribution is affected by irrigation with saline water in selected landscape species grown in two consecutive growing seasons: spring-summer and fall-winter. *Hortscience* 46, 632–642.
- Wang, X.B., Zhao, Q.S., Hu, Y.J., Zheng, Y., Wu, X.P., Wu, H.J., Zhang, G.X., Cai, D.X., Manzur, C.L., 2012. An alternative water source and combined agronomic practices for cotton irrigation in coastal saline soils. *Irrig. Sci.* 30, 221–232.
- Wang, Z.Q., Zhu, S.Q., Yu, R.P., Li, L.Q., Shan, G.Z., You, W.R., Zeng, X.X., Zhang, C.W.Z., Song, L.J., 1993. *China Saline and Sodic Soils*. Soils Science Press, Beijing, pp. 145.
- Yaron, B., Zieslin, N., Halevy, A.H., 1969. Response of Baccara roses to saline irrigation. *J. Am. Soc. Hort. Sci.* 94, 481–484.
- Yazar, A., Gencel, B., Sezen, M.S., 2003. Corm yield response to saline irrigation water applied with a trickle system. *J. Food Agric. Environ.* 1, 198–202.
- Yu, R., Chen, D., 1999. The development and utilization of saline soil resources in China. *Chin. J. Soil Sci.*, 158–159.
- Zeroni, M., Gale, J., 1989. Response of Sonia roses to salinity at three levels of ambient CO₂. *J. Hortic. Sci.* 64, 503–511.
- Zhang, T., Kang, Y., Wan, S., 2013. Shallow sand-filled niches beneath drip emitters made reclamation of an impermeable saline-sodic soil possible while cropping with *Lycium barbarum* L. *Agric. Water Manage.* 119, 54–64.
- Zollinger, N., Koenig, R., Cerny-Koenig, T., Kjelgren, R., 2007. Relative salinity tolerance of intermountain western United States native herbaceous perennials. *Hortscience* 42, 529–534.