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A comprehensive method of evaluating the impact of drought and salt stress on tomato growth and fruit quality based on EPIC growth model

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ABSTRACT

Owing to the severe shortages of fresh water in arid and semi-arid areas, growers are forced to apply deficit irrigation with fresh or saline water. To quantify the impacts of water deficit and salt stress individually and the interaction on tomato yield and quality, three pot experiments were conducted from spring 2016 to autumn 2017. The EPIC growth model was also used to simulate fruit growth process. Three irrigation treatments used were full irrigation, 2/3 and 1/2 of the full irrigation. Salt stress varied with the season: 0, 3‰, 6‰, 9‰ for 2016 season, 0, 3‰ for 2016–2017 season and 0, 2‰, 3‰, 4‰ for 2017 season. Decreases in single fruit weights were associated with increasing soil salt content. However, fruit quality parameters including CI (color index), TSS (total soluble solids) and TSSC (total soluble sugar content) improved significantly with increasing salt content of soil. In the absence of salt stress, the application of 2/3 of full irrigation showed a 18.9% and 1.0% increase of yield per plant, respectively in 2016 and 2017 seasons with comparison to full irrigation, mainly owing to the increase of fruits number per plant. Fruit quality also improved with increasing Fn (fruit firmness), CI, TSS and TSSC by 7.9%, 43.8%, 9.8% and 3.8% in 2016 season, and by 4.7%, 0.7%, 20.9% and 34.2% in 2017 season, respectively. Fruit quality parameters were more affected by salt stress than drought, the interactive impact of water and salt on fruit quality parameters was not significant. At mild water stress (2/3 of full irrigation) with moderate salt stress (salt content of 3‰), although yield showed a decline of 20.3%–32.0%, fruit quality parameters of Fn, CI, TSS and TSSC increased by 4.9%–43.4% through 2016 and 2017 seasons. Two of van Genuchten and Hoffman models (i.e. non-linear and exponential reduction model) were used to evaluate the relations of relative yield and soil salt content with acceptable accuracy, R^2 of 0.989 and 0.971, respectively. Soil salt content at which yield decreased by 50% is 4.0‰ and 4.7‰, respectively in the non-linear reduction model and the exponential reduction model. The EPIC growth model simulated fruit growth process with acceptable accuracy for no stress, water stress and salt stress, with R^2 of 0.863, 0.839 and 0.895, respectively. The two yield reduction models and the relationship between fruit quality parameters and soil salt content showed that there are tradeoffs between tomato yield and fruit quality in saline soils.

1. Introduction

Abiotic stresses, such as drought and salinity, severely restrict crop productivity and quality worldwide, and the areas affected by these two stresses continue to expand (Wang et al., 2003). Owing to the shortages of fresh water in arid and semi-arid areas, farmers are forced to decide among the following strategies, applying deficit irrigation using fresh water, irrigation with available saline water or combination of insufficient fresh water and saline water, even applying alternant fresh water and saline water in some large irrigation districts. Thus, crops are subjected to water stress, salt stress or both (Ors and Suarez, 2017). The cultivable land in China is affected by varying degrees of salinity, of which about 60% is in the arid areas of northwest China, where light and heat resources are rich enough to support corn and fruit production. Over the past decade, drip irrigation under mulch was generalized across these regions, coupled with the high evaporation and low precipitation, spatial extent of saline area is increasing over time. Only in Xinjiang Province of Northwest China, about 32% of the cultivated land is salt affected. The effective approaches to counter drought and salinity stress include application of optimal field irrigation management and development of tolerant cultivars. It is thus necessary to assess the impacts of drought and salt stress on crop production and quality.

Tomato is a water demanding crop (Peet, 2005) and is moderately tolerant to salinity (Maggio et al., 2004). The individual effects of water

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and salt stress on tomato yield and fruit quality are well documented. In general, the deficit irrigation can adversely affect tomato plant growth, physiological characteristics, and yield (Yang et al., 2017). In contrast, the fruit quality could improve due to suitable deficit irrigation (Chen et al., 2013, 2014). Tomato fruits were found to be sweeter and less acidic under deficit irrigation (Ripoll et al., 2016). Applications of 1/3 to 2/3 of full irrigation at flowering, fruit development and maturation stages significantly increased the total soluble solids, reduced sugars, vitamin C contents and fruit firmness, sugar to acid ratio and fruit color index (Chen et al., 2013). Salt stress reduced tomato yield but improved total soluble solids and sugar content in the fruits (Cantore et al., 2012; De Pascale et al., 2015; Van de Wal et al., 2017), fruit shelf life and firmness were unchanged or slightly lowered (Cuartero and Fernandez-Munoz, 1999). The high salinity inhibited crop leaf area index and root density, seed germination and stomatal conductance, radiation use efficiency and above-ground dry weight (Maggio et al., 2004; Koushafar et al., 2011; Shahbaz and Ashraf, 2013; Galli et al., 2016; Albaladejo et al., 2017;). Nutrient imbalance and increases in leaf Na^+ and Cl^- concentrations resulted in plant being stunted or dead (De Pascale et al., 2007; Cuartero and Fernandez-Munoz, 1999). Although drought and salinity affect the plant in a similar way to some extent, it is still unclear whether the plants' responses of yield and quality to an increase of 1 cm of osmotic potential are the same as their responses to a decrease 1 cm of matric potential. (Katerji et al., 2004). Several researches investigated the interactive effect of water and salt stress as related to crop yield and physiological responses on spinach, barley, cotton, maize (Ors and Suarez, 2017; Ahmed et al., 2013; Zhang et al., 2017; Wang et al., 2016). Unfortunately, only few studies were conducted to investigate the interactive effects of these two abiotic stresses on tomato growth, yield and quality (Gawad et al., 2005; Mitchell et al., 1991b).

Most of the reported experiments were conducted under simulated conditions of using either salinity water by mixing natural river water with fresh water (Bahazadeh et al., 2016; Aguilar et al., 2017), or fresh water by adding different amounts of NaCl (Cuarter et al., 1999; Koushafar et al., 2011; Galli et al., 2016; Ahmed et al., 2013) or NaCl and $CaCl_2$ (Katerji et al., 2009, 2011). Plants in many of these experiments were grown in hydroponic culture with different levels of Hoagland nutritive solution (Hoagland and Arnon, 1950) to simulate different salinity gradients (De Pascale et al., 2007; Albaladejo et al., 2017). Unfortunately, none of these experiments were conducted in the saline soils. Because the uptake and transport rates of saline ions from root to the shoot in nutritive solution were faster and higher than in soil cultivation conditions, the leaf symptoms caused by salinity were much earlier under this growth condition (Albaladejo et al., 2017). Moreover, salinity-induced changes in nutrient availability, uptake and transport may lead to nutritional imbalances (Hussain et al., 2016). Increase in ions of Na^+ and Cl^- in rhizosphere induced intense competition with other crucial minerals, e.g. K^+, Ca^{2+}, NO_3^-, and inhibited their uptake (Hu and Schmidhalter, 2005). Toxic ions in saline soils are usually Na^+, Cl^-, and SO_4^{2-} (Munns and Tester, 2008), therefore, only multiple salts-affected soil can reflect the actual plant response under saline soil condition.

Total radiation and the plant efficiency to utilize it for dry biomass production were estimated to describe the physiological crop growth (Monteith, 1977). This theory was used in crop growth module of EPIC to simulate crop dry biomass accumulation (Williams et al., 1989; Steduto et al., 1995). Potential plant growth in EPIC model was restrained by stress factors including water, temperature, aeration, nitrogen and phosphorus. (Williams et al., 1989). Thus, various studies have been conducted to analyze crop response under different climatic conditions and water regimes (Steduto et al., 1995; Han et al., 2015; Bao et al., 2017; Wang et al., 2017a,b; Wang et al., 2015a,b; Candido et al., 2015; Lovelli et al., 2017). Although the original EPIC growth model has many components of an agronomic system, it did not consider the soil salt stress component (Tayfur et al., 1995), to the best of our knowledge, water and salt stresses inhibit the root water uptake in a similar way due to osmotic regulation (Munns, 2002; Farooq et al., 2015). Thus we extended EPIC to model crop growth in saline soil. Although crop morphological indexes such as plant height, leaf area and biomass, were rigorously described using EPIC growth model under different water treatments, the simulation of tomato fruit growth process and how the fruit growth is influenced by water and salt stress are still unsearchable. The fruit growth modeling involved two parts. The first part was to model crop leaf area due to water and salt stress. The second part was to simulate fruit weight as a dependent variable, which can be calculated using heat unit accumulation, maximum value of single fruit weight and crop stress as independent variables.

The aims of this research were to: (i) investigate the impacts of simultaneous water and salt stresses on tomato yield and fruit quality parameters; (ii) establish quantitative relationship between fruit quality and soil salt content for the whole growth season as well as for different irrigation treatments; (iii) evaluate EPIC growth model prediction for tomato fruit growth under various stress scenarios.

2. Materials and methods

2.1. Experimental site

Three pot experiments were done at the Shiyanghe Experimental Station, Gansu Province, Northwest China from May to August 2016 (2016 season) and from April to August 2017 (2017 season), and the crop growth chamber located in College of Water Resources and Civil Engineering of China Agricultural University, Beijing from December 2016 to April 2017 (2016–2017 season). The annual mean temperature of the Shiyanghe Experimental Station site (37°52′N, 102°50′E, 1,581 m a.s.l.) is about 8.8℃, with precipitation of 164.4 mm, pan evaporation of 2000 mm, and sunshine duration of 3000 h. The local crops are irrigated with groundwater and the electrical conductivity of water is $0.62\ dS\ m^{-1}$. The environmental conditions in growth chamber (40°00′N, 116°21′E, 52 m a.s.l.) were controlled with relative humidity of 45 ± 5%, day/night temperatures of 25/25 ± 5℃, CO_2 concentration of 400 ± 100 ppm and 10 h period at a photosynthetic photon flux density of $350\ \mu mol\ m^{-2} s^{-1}$ (LI-250 A Light Meter, LI-CORInc., USA). The soil used in the pots during three seasons was collected from the top 30 cm around the Shiyanghe Experimental Station, it was air dried, gently crushed and sieved through a 5 mm sieve. The soil texture is sandy loam, with a mean dry bulk density of $1.45\ g\ cm^{-3}$, mean field capacity of $0.272\ cm^3\ cm^{-3}$, mean soil conductivity of $0.281\ dS\ m^{-1}$, and soil pH of 7.91. Tomato plants (*Lycopersicon esculentum Mill,* cultivar Neisen, Fenoubao, Jinpeng-11) all belong to the pink tomato series, were respectively applied during three growth seasons (Table 1). Tomato seedlings were transplanted at 3–4 leaf stage to each pot and irrigated with same volume of water (Table 1). Fertilizers and other management practices were kept

Table 1
Tomato cultivars, transplanting date, water use at transplanting, and fertilizer in three growing seasons.

Cropping season	2016	2016/17	2017
Tomato cultivars	Neisen	Fenoubao	Jinpeng-11
Transplanting date	May 9, 2016	Dec 6, 2016	Apr 24, 2017
Transplanting water use (mm)	9.04	9.55	9.91
Basal fertilizer	90 kg/hm^2 of urea (N 46%) 75 kg/hm^2 of monopotassium phosphate (N + P2O5 + K2O ≥ 20%) 525 kg/hm^2 of triple superphosphate (P2O5 ≥ 16%) fertilizer was uniformly broadcasted in the soil before transplanting		
Topdressing fertilizer	135 kg/hm^2 of urea (N 46%) fertilizer was applied with irrigation events during the fruit enlargement stage		

consistent during three seasons (Table 1).

2.2. Experimental method

2.2.1. Experiment 1

The pot experiment was conducted in a field in Shiyanghe Experimental Station from May 9 to Aug 15 in the 2016 season. Tomato plants (cultivar Neisen) were transplanted in the pots of height of 25 cm, top diameter of 35 cm and bottom diameter of 30 cm (volume of 0.021 m^3). Each pot was packed with 16 kg soil with bulk density of 1.3 ± 0.5 g cm^{-3}. Four levels of salt treatments were salt content of 0.6‰ (original soil; S0/control), 3‰ (moderate level; S3), 6‰ (medium level, S6) and 9‰ (high level, S9) of soil mass in the pot (Table 3). At the beginning of the growing season, three salts (mass ratio of NaCl, $MgSO_4$ and $CaSO_4$: 2:2:1) were weighed corresponding to the salt gradients for each pot and were homogeneously mixed into the soil before packing into pots. In addition, two water treatments including full irrigation (W1) and deficit irrigation (W2/3, 2/3 of full irrigation) were carried out. The full irrigation treatments were irrigated to field water capacity (θ_f) every two days, deficit irrigation treatments received 2/3 of water amount over the growth stage. A completely randomized design was used with 12 replications, hence different salt and water treatments were denoted as W2/3S0, W2/3S3, W2/3S6, W2/3S9, W1S0, W1S3, W1S6 and W1S9, respectively (Table 3). The whole growth season was divided into vegetative stage (Stage I, transplant to the first blossom), flowering stage (Stage II, first blossom to first fruit set) and fruit development and ripening stage (Stage III, first fruit set to harvesting) (Table 2). After 7 d transplanting, white polyethylene film covered the soil to prevent evaporation as well as the infiltration of precipitation water. Each pot has four holes at the bottom to improve breathing of tomato root, therefore, the irrigation intervals were relatively short (2–3 d) to make sure that no leaching occurred. The irrigation amounts and times for different treatments through growth season are in Table 3.

2.2.2. Experiment 2

Tomato plants (cultivar Fenoubao) were transplanted on Dec 6, 2016 and harvested on Apr 7, 2017 in pots with the height of 25 cm, top diameter of 25 cm and bottom diameter of 20 cm (volume of 0.01 m^3) during 2016–2017 season. The pots were placed in three growth chambers. Each pot was packed with 10 kg soil with bulk density of 1.2 ± 0.5 g cm^{-3}. There were two water treatments including full irrigation (W1) and deficit irrigation (W1/2, 1/2 of full irrigation). Two levels of salt content were control (original soil; S0) and 3‰ (moderate level; S3). The mass ratio of NaCl, MgSO4 and CaSO4 mixed in the soil was 2:2:1. The treatments of this study were denoted as W1S0, W1/2S0 and W1S3 with 12 replications. The irrigation intervals were 3–4 d and no leaching occurred. The irrigation amounts and times for three treatments during growth season are in Table 3.

Table 2
The average daily mean solar radiation (Rs), air temperature (T), relative humidity (RH), precipitation (P) and vapor pressure deficit (VPD) for various growth stages in two growing seasons.

Cropping season	Growth stage	Rs (W/m^2)	T (°C)	RH (%)	P	VPD (kPa)
2016	Stage I(May 9-June 5)	226.4	16.7	44.3	15.4	1.10
	Stage II(June 6-June 26)	271.3	21.2	47.8	12.2	1.23
	Stage III(June 27-Augest 15)	246.3	23.1	59.2	38.4	1.12
2017	Stage I(April 24-May 24)	215.2	15.6	40.1	0	1.07
	Stage II(May 25-June 13)	170.8	23.3	42.3	0	1.78
	Stage III(June 14-Augest 9)	172.8	24.0	52.7	0	1.49

2.2.3. Experiment 3

Experiment 3 was carried out from Apr 24 to Aug 9, 2017 in the greenhouse about 200 m away from Experiment 1. Tomato plant (cultivar Jinpeng-11) were transplanted to pots packed with 16 kg soil with bulk density of 1.3 ± 0.5 g cm^{-3}. The pots used were same to those used for experiment 1. Four salt content levels – i.e. control (S0), 2‰ (S2), 3‰ (S3) and 4‰ (S4) were treated. The mass ratio of salts was similar to Site 1 experiment. Three water levels – i.e. full irrigation treatment (W1), 2/3 deficit irrigation treatment (W2/3) and 1/2 deficit irrigation treatment (W1/2) – were used. The irrigation intervals of full irrigation were 2–3 d, deficit irrigation treatments W2/3 and W1/2 received 2/3, 1/2 of full irrigation amount, respectively. All of the treatments with 20 replications, were denoted as W1/2S0, W2/3S0, W2/3S2, W2/3S3, W2/3S4, W1S0, W1S2, W1S3 and W1S4, respectively (Table 3).

2.3. Measurements

2.3.1. Meteorology

During experiment 1 period, solar radiation (Rs), air temperature (Ta), relative humidity (RH), and precipitation (P) were measured every 30 min using HOBO weather station (HOBO, Onset Computer Corp., USA) nearby the experiment field. The weather parameters during the experiment 3 period were collected with a same weather station to experiment 1 which was located in the middle of the greenhouse. The Rs, T, RH and P at each growing stage are shown in Table 2. The environmental condition in growth chamber during experiment 2 period was almost constant as controlled.

2.3.2. Leaf area index

Three random plants were selected in each treatment to measure the maximum width and length of lateral branch every eight to ten days. At the harvesting day, actual leaf area per branch was scanned using AM300 leaf area meter (ADC BioScientific Ltd., UK). The linear relationship between branch area (branch length × maximum width) and actual leaf area per branch was obtained. The leaf area during the growth season was calculated by adding branch area of per plant multiplied by a factor. The factor was obtained from the linear regression of the calculated and measured value. Leaf area index (LAI) is calculated by total leaf area dividing average ground area each plant.

2.3.3. Yield and water use efficiency (WUE)

Five plants of each treatment were selected to measure yield and single fruit weight at each harvest. Three clusters of fruits were remained per plant during three seasons. Water use efficiency (WUE, kg m^{-3}) was described as below:

$$WUE = \frac{Y}{I} \tag{1}$$

where Y was fruit yield per plant (g), I was total irrigation amount per plant through the growing season (L).

2.3.4. Fruit growth

During 2016–2017 and 2017 seasons, five plants from each treatment were randomly selected to measure the longitudinal diameter and transverse diameter of the fruits every 7–10 days from 10 d after anthesis. At the end of Stage II and III, three plants were harvested to measure fruit diameters and individual fruit weight. The relationship between single fruit weight (FW) and the average of the longitudinal and transverse diameters (FD) is shown in Fig. 1. The individual fruit weight had a significant exponential correlation with the average of longitudinal and transverse diameters ($P < 0.01$) in both seasons. Hence, the consecutive increasing process of fruit weight was obtained

Table 3
Irrigation amount, yield per plant and water use efficiency (WUE) for different water and salt treatments in three growing seasons.

Cropping season	Treatment	Irrigation amount (mm)			Whole season (mm)	Yield (g per plant)	WUE (kg/m^3)
		Stage I	Stage II	Stage III			
2016	W2/3S0	32.3(8)	27.8(11)	68.5(22)	128.6(41)	1125.7a	28.36a
	W2/3S3	32.3(8)	27.8(11)	68.5(22)	128.6(41)	755.0c	19.02b
	W2/3S6	32.3(8)	27.8(11)	68.5(22)	128.6(41)	304.9e	7.68e
	W2/3S9	32.3(8)	27.8(11)	68.5(22)	128.6(41)	122.2 g	3.08 g
	W1S0	32.3(8)	37.7(11)	98.0(22)	168.0(41)	947.1b	17.97c
	W1S3	32.3(8)	37.7(11)	98.0(22)	168.0(41)	751.0c	14.25d
	W1S6	32.3(8)	37.7(11)	98.0(22)	168.0(41)	364.0d	6.91f
	W1S9	32.3(8)	37.7(11)	98.0(22)	168.0(41)	167.1f	3.17 g
2016/2017	W1S0	19.1(7)	30.6(13)	92.4(33)	147.5(53)	972.9a	21.01a
	W1S3	19.1(7)	30.6(13)	92.4(33)	147.5(53)	714.4b	15.43b
	W1/2S0	13.5(7)	20.1(13)	46.2(33)	79.8(53)	402.6c	16.04b
2017	W1/2S0	20.2(7)	24.0(10)	74.6(36)	118.8(53)	401.2 g	11.24e
	W2/3S0	22.8(7)	33.0(10)	100.1(36)	155.9(53)	1057.7a	22.22a
	W2/3S2	22.8(7)	33.0(10)	100.1(36)	155.9(53)	807.7b	16.97b
	W2/3S3	22.8(7)	33.0(10)	100.1(36)	155.9(53)	711.9d	14.96c
	W2/3S4	22.8(7)	33.0(10)	100.1(36)	155.9(53)	518.9f	10.90e
	W1S0	27.4(7)	53.8(10)	152.9(36)	234.1(53)	1047.4a	16.78b
	W1S2	27.4(7)	53.8(10)	152.9(36)	234.1(53)	767.7c	12.30d
	W1S3	27.4(7)	53.8(10)	152.9(36)	234.1(53)	676.4e	10.84e
	W1S4	27.4(7)	53.8(10)	152.9(36)	234.1(53)	533.5f	8.55f

Numbers in the brackets indicate irrigation times for the respective growth stage. W_1, $W_{2/3}$, $W_{1/2}$ represent full irrigation, 2/3 and 1/2 of full irrigation amount, respectively. S_0 is no salt stress, S_2, S_3, S_4, S_6, S_9 represent 0.3%, 0.6%, 0.9% of salt content, respectively. Letters following the values of the indexes (yield and WUE) of each season are the significant differences according to the Duncan's multiple range tests at 0.05 P level, the same letter represents no significant difference of indexes between two treatments.

by the non-destructive method.

2.3.5. Fruit quality

Four tomato fruits with similar maturity in each treatment were picked for the fruit quality measurement in 2016 and 2017 seasons. First, the appearance and storage qualities were measured, and then fruits were squeezed with a blender to measure taste quality.

2.3.5.1. Appearance quality. The diameters in transverse and longitudinal directions were obtained using a vernier caliper, respectively. The SI (fruit shape index) was expressed as (Wang et al., 2015a,b):

$$\mathrm{SI} = \frac{y}{x} \tag{2}$$

where x is the transverse diameter; y is the longitudinal diameter.

The fruit color was obtained using a spectrophotometer (SP60, X-rite, Incorporated, MI, USA). The values of color space coordinates L, a, b were determined from 4 equatorial direction of each fruit, and then the averages were used to calculate CI (fruit color index) as below (Chen et al., 2014):

$$CI = 2000 \times \frac{a}{L\sqrt{a^2 + b^2}} \tag{3}$$

where a and b were values ranging from -100 to +100; and L is the lightness, the value ranged from 0 to 100.

2.3.5.2. Taste quality. TSS (total soluble solids) were measured with a handheld saccharometer (ATAGO, Japan). TSSC (total soluble sugar concentration) was measured using the method of anthrone colorimetric (Li, 2000).

2.3.5.3. Storage quality. The Fn (fruit firmness) was obtained using a firmness tester (FHR-5, Japan). Then the other half of fruit was dried in the oven to measure FWC (fruit water content).

2.4. Yield reduction functions

In this study, two models were applied to assess the impact of salinity on relative yield (Y/Ymax). One was non-linear yield reduction model (van Genuchten and Hoffman, 1984; Babazadeh et al., 2016; Qiu et al., 2017):

$$Y_r = \frac{1}{1 + \left[\frac{SSC}{SSC_{50}}\right]^p} \tag{4}$$

where SSC was soil salt content, SSC_{50} (‰) was the soil salt content at which Y_r (%) was decreased by 50%, and p was a constant.

The other model used was proposed by van Genuchten and Hoffman (1984) as follows:

$$Y_r = e^{(\alpha SSC - \beta SSC^2)} \tag{5}$$

where α and β were empirical constants.

2.5. EPIC crop model description

EPIC simulates plant growth on a daily time scale. The potential dry biomass growth is derived as a function of the climatic variables and LAI of the previous day. A stress factor ranging from 0 to 1, which is calibrated using the experimental data in this study, is assigned to each potentially stress factor to restrained the potential growth on that day to the actual growth. The crop phenological process is based on the daily heat unit accumulation, which was calculated as below (Williams et al., 1989; Steduto et al., 1995; Neitsch et al., 2005):

$$\mathrm{HU}_j = \left(\frac{T_{max,j} + T_{min,j}}{2}\right) - T_{b,i} \tag{6}$$

where HU_j was the heat unit in the day j; $T_{max,j}$ was the highest temperature (°C) in the day j, and $T_{min,j}$ was the lowest temperature (°C) in the day j. $T_{b,i}$ was the lowest temperature which sustained crop growth.

The HUI (heat unit index) ranging from 0 at transplanting to 1 at physiological maturity was calculated as (Williams et al., 1989; Steduto et al., 1995; Neitsch et al., 2005):

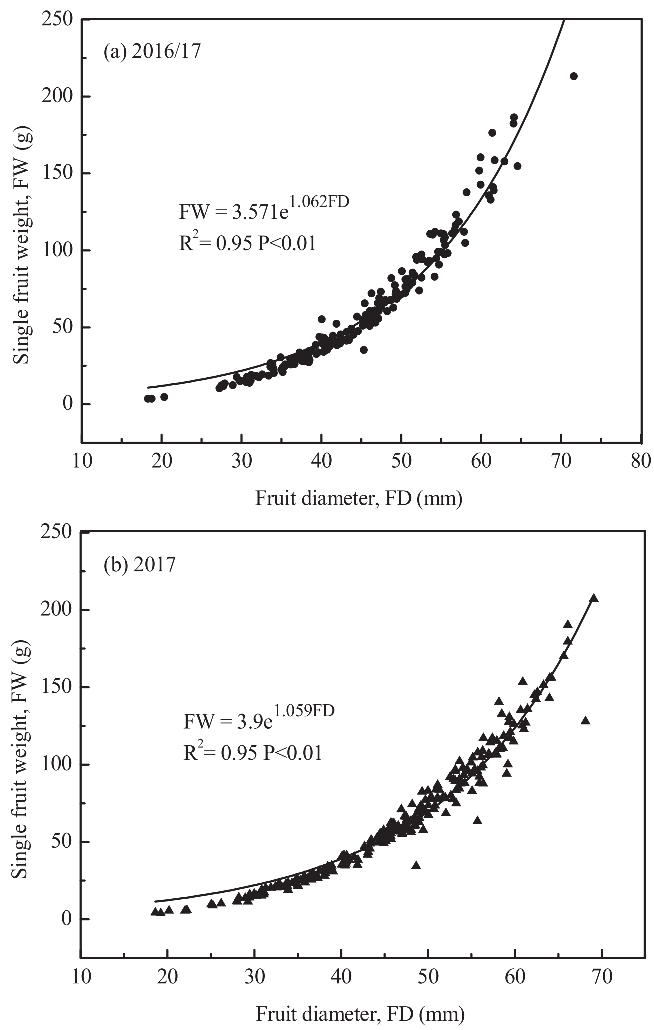

Fig. 1. The relationship between single fruit weight (FW) and the mean value of the longitudinal and transverse diameter (FD) of tomato.

$$HUI_i = \frac{\sum_{k=1}^{i} HU_k}{PHU} \tag{7}$$

where HUI_i was the heat unit index on day i and PHU was the maximum accumulation of heat units when crop harvested; and PHU was calculated as (Steduto et al., 1995):

$$\text{PHU} = \sum_{n=planting}^{maturity} HU_k \tag{8}$$

The LAI can be calculated using heat units, crop stress factor and leaf development stages. Only the first development stage, considering the cultivars' characteristics of indeterminate growth, was simulated in this study. From transplanting to the cease of leaf increasing, LAI was calculated as (Williams et al., 1989; Wang et al., 2017a,b):

$$LAI_i = LAI_{i-1} + \Delta LAI \tag{9}$$

$$\Delta\text{LAI} = (\Delta\text{HUF})(LAI_{max})(1 - exp(5.0(LAI_{i-1} - LAI_{max})))\sqrt{REG_i} \tag{10}$$

where HUF was the heat unit factor, Δ was the change variable of every day. Sub max was the possible maximum value. REG is the minimum crop stress factor, i.e. water stress and salt stress in this study. The HUF (heat unit factor) was calculated with the equation (Williams et al., 1989; Wang et al., 2017a,b):

$$HUF_i = \frac{HUI_i}{HUI_i + exp(ab_1 - (ab_2)(HUI_i))} \tag{11}$$

where ab_1 and ab_2 were two crop parameters.

The theory of heat unit accumulation has proven to be a credible predictor of the plant physiological growth. In this study, the fruit growth process was estimated with the equation:

$$FW_i = FW_{max}\sqrt{(HUF_i)(REG_i)} \tag{12}$$

where FW_i was the fruit weight for day i after anthesis, FW_{max} was the maximum value of fruit weight.

2.6. Model calibration and validation

The meteorological data and LAI data collected from experiment 3 (2017 season), when there was no stress (i.e. W1S0 treatment), water stress only (i.e. W1/2S0 treatment), and salt stress only (i.e. W1S3 treatment), were chosen to calibrate the EPIC crop model. The leaf area index measured from the experiment 2 (2016–2017 season) were used to verify the results simulated by the model under no stress, water stress only and salt stress only conditions. The growth process of fruit weight collected from both experiments 2 and 3 (i.e. W1S0 treatment, W1/2S0 treatment and W1S3 treatment) were collected for the validation.

The output of EPIC against observed measurements were assessed using the determination (R^2), the root mean square error (RMSE), the normalized root mean square error (NRMSE), the coefficient of regression (b_0) and the Willmott index of agreement (d) (Ran et al., 2017), which were calculated as:

$$R^2 = \left[\frac{\sum_{j=1}^{n}(M_j - \bar{M})(S_j - \bar{S})}{\sum_{j=1}^{n}(M_j - \bar{M})\sum_{j=1}^{n}(S_j - \bar{S})}\right]^2 \tag{13}$$

$$\text{RMSE} = \left[\frac{\sum_{j=1}^{n}(M_j - S_j)^2}{n}\right]^{0.5} \tag{14}$$

$$\text{NRMSE} = \frac{100}{\bar{M}}\left[\frac{\sum_{j=1}^{n}(M_j - S_j)^2}{n}\right]^{0.5} \tag{15}$$

$$b_0 = \frac{\sum_{j=1}^{n} M_j S_j}{\sum_{j=1}^{n} M_j^2} \tag{16}$$

$$d = 1 - \frac{\sum_{j=1}^{n}(S_j - M_j)^2}{\sum_{j=1}^{n}(|S_j - \bar{S}| + |M_j - \bar{M}|)^2} \tag{17}$$

where M_j was measured values, S_j was simulated values, $\bar{S}$ was average of the simulated values and $\bar{M}$ was average of the measured values. b_0, d and R^2 close to 1 indicated good fitness between simulated and measured ones. The agreement between the simulated and measured ones is considered acceptable if the value of $R^2 > 0.5$ (Santhi et al., 2001; Van Liew et al., 2003). RMSE and NRMSE are used measure of the differences between the observed values and simulated ones, RMSE close to 0 shows a perfect agreement between the simulated and measured ones. The simulation is labeled excellent; good; fair and poor when the value of NRMSE is smaller than 10%, 10%–20%, 20%–30% and > 30%, respectively (Bannayan and Hoogenboom, 2009).

2.7. Data analysis

To investigate the impacts of water and salt treatment on total yield and fruit quality parameters, two-way analysis of variance (ANOVA) were analyzed in each growth season using SPSS software. Differences between mean values were assessed for significance using the Duncan's multiple range test at P = 0.05. Relative values adopted in the regression analysis were calculated as the values for each treatment dividing that of maximum treatment.

3. Results

3.1. Effect of drought and salt stress on tomato yield and WUE

Tomato yield decreased with increasing salt stress (Table 3). Compared to S0, yield declined by 32.9%, 72.9% and 89.1% for S3, S6 and S9, respectively, under W2/3 treatments in the 2016 season; and by 20.7%, 61.6% and 82.4%, respectively, under well-watered W1 treatments. The yield decline was significant at soil salt content (SSC) of 3‰, but it became sharp at SSC of 6‰ and 9‰, suggesting that tomato was moderately sensitive to salt stress. Thus, we adjusted salt gradients during the following growth seasons. In the absence of water stress, yield loss in S3 during 2016–2017 season was 26.6% compared to S0 (Table 3). During 2017 season, yield decreased by 23.6%, 32.7% and 50.9% for S2, S3 and S4, respectively, under W2/3 treatments; and by 26.7%, 35.4% and 49.1%, respectively, under W1 treatments.

Moreover, yield reduction caused by water and salinity stresses were different. Compared to W1 treatments, yield increased 18.9% and 1.0% for W2/3 treatments in the 2016 and 2017 seasons, respectively in the absence of salt stress. But at moderate salt stress (S3), yields under two water treatments had no significant difference for 2016 season. Yield for W1/2S0 decreased by 22.7% in comparison to W2/3S4 during 2017 season, which showed that tomato yield decline was more under the application of 1/2 of full irrigation than under soil salt content of 4‰.

To compare the two-yield reduction models (Eq. (4) and Eq. (5)), their parameters were first determined by minimizing the sum of the squared deviations between measured yield and predicted yield by the two models, respectively. The results indicated that both models performed well in simulating yield response to SSC, with R^2 of 0.989 and 0.971, respectively (Fig. 2; Table 6). Moreover, the non-linear reduction model (Eq. (4)), with RMSE of 30.6 g and NRMSE of 5.18%, conformed better to the measured data than the exponential model (Eq. (5)), with RMSE of 53.8 g and NRMSE of 9.10%, respectively. In van Genuchten and Hoffman (1984) (Eq. (4)) and (Eq. (5)), the SSC at which yield decreased by 50% is 4.0‰ and 4.7‰, respectively.

WUE decreased significantly with the increasing salt stress under both W2/3 and W1 treatments during 2016 and 2017 seasons. WUE for W2/3S3 was higher by 5.84% compared to W1S0 treatment in 2016 season, while WUE for W2/3S2 improved by 1.13%, compared to W1S0 in 2017 season (Table 3). In 2016 and 2017 season, WUE for W1/2S0 was slightly higher than W1S3, but the yield decreased significantly.

3.2. Effect of drought and salt stress on tomato fruit quality

Table 4 shows the fruit quality parameters of tomato under different water and salt stress treatments during 2016 and 2017 growth seasons. Fn firstly increased at moderate salinity levels (S3) and then began to decrease under W2/3 and W1 treatments during both seasons (except W2/3 in 2017 season). FWC was significantly low for W2/3S9 in 2016 season and W1/2S0 in 2017 season, respectively. Compared to W1S0, FW for W2/3S0 was not significantly lower, but decreased by 32.6%, 52.8% and 64.2%, respectively in 2016 season. The FW decrease became significant at SSC of 4‰ under both W2/3 and W1 treatments in 2017 season. SI varied from 0.714 to 0.838 in 2016 season. For fruits of W2/3S2, W2/3S3 and W1S4 in 2017 season, SI values were 1.054, 1.006 and 1.004, respectively. CI increased with the salt and water stresses, the highest CI of 46.59 was obtained for W1/2S0, and the lowest were in both W1S0 treatments during 2016 and 2017 seasons. TSS and TSSC significantly increased with the salt stress in both seasons. TSS and TSSC for W2/3S9 increased by 48.7% and 31.1% of W2/3S0, respectively, during the 2016 season; and those for W1S9 increased by 54.0% and 34.3% of W1S0, respectively. In 2017 season, the decline of TSS and TSSC for W2/3S0 reached at 8.08% and 32.7%, respectively, when compared to W2/3S9, and those for W1S0 reached at 29.5% and 46.1%, respectively, as compared to W1S4.

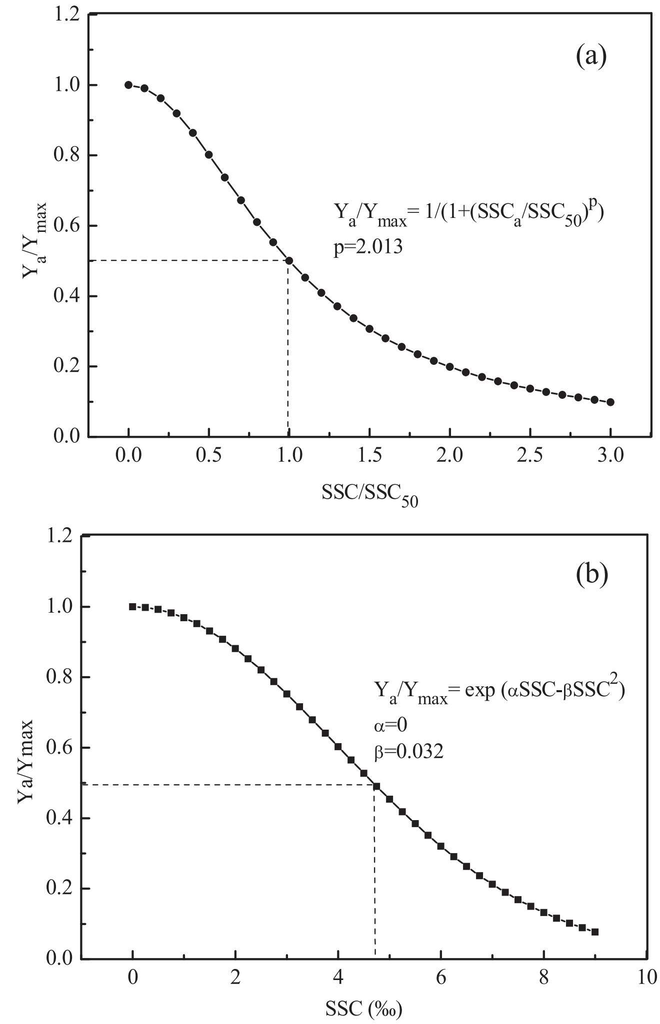

Fig. 2. Relative tomato yield as a function of SSC/SSC_{50} and SSC based on Eq. (4) and (5), respectively.

The two-way ANOVA results showed that water had significant or extreme significant influence on FWC, FW and TSSC during both seasons, while salt had extreme significant influence on all the quality parameters except SI and CI. The interactive effect of water and salt was not significant (Table 5).

3.3. Quantitative relationship between relative fruit quality and salt gradient

The relationship between relative values of fruit quality parameters (CI_a/CI_{max}, SI_a/SI_{max}, FWC_a/FWC_{max}, TSS_a/TSS_{max}, FW_a/FW_{max}, $TSSC_a/TSSC_{max}$) and relative soil salt content (SSC_a/SSC_{max}) are presented in Fig. 3a-n, for the pooled data of 2016 and 2017 seasons. FWC_a/FWC_{max} showed a significant negative linear correlation with SSC_a/SSC_{max} ($P < 0.01$) (Fig. 3 e). Negative correlation was also found between FW_a/FW_{max} and SSC_a/SSC_{max} ($P < 0.05$) (Fig. 3 m). CI_a/CI_{max} and $TSSC_a/TSSC_{max}$ had a significant positive linear correlation with SSC_a/SSC_{max} ($P < 0.05$) (Fig. 3 a, k). SI_a/SI_{max} was significantly positive correlated with SSC_a/SSC_{max} ($P < 0.01$) (Fig. 3 c). TSS_a/TSS_{max} increased with the increasing SSC_a/SSC_{max}, but no significant correlation was found ($P > 0.05$) (Fig. 3 i). The relations of all the quality parameters with SSC_a/SSC_{max} under W1 and W2/3 treatments were evaluated using linear regression, respectively. The results showed that SI_a/SI_{max} were not significantly related with SSC_a/SSC_{max} under both W1 and W2/3 treatments (Fig.3 d). Slope values implied that FWC was

Table 4
Effects of different water and salt management on tomato quality parameters in the two growth seasons.

cropping season	Treatment	Fn (kg/cm^2)	FWC (%)	FW (g)	fruit shape index	CI	TSS (%)	TSSC (mg/100 g)
2016	W2/3S0	2.73bc	0.906a	106.22a	0.714b	29.89a	6.37cd	7.17cd
	W2/3S3	3.33a	0.829a	50.84c	0.779ab	30.75a	6.77bcd	8.01b
	W2/3S6	2.80abc	0.809a	39.34c	0.759ab	31.81a	8.37abc	8.98a
	W2/3S9	2.46bc	0.587b	36.07c	0.838a	34.53a	9.47a	9.40a
	W1S0	2.53bc	0.941a	111.50a	0.788ab	20.79a	5.80d	6.91d
	W1S3	3.33a	0.872a	75.11b	0.746ab	25.14a	7.47abcd	7.53c
	W1S6	2.98ab	0.834a	52.66c	0.802ab	29.21a	7.73abcd	8.36b
	W1S9	2.33c	0.796a	39.90c	0.770ab	32.62a	8.93ab	9.28a
2017	W1/2S0	1.17ab	0.892c	80.53bc	1.118a	46.59a	6.53a	9.14a
	W2/3S0	0.89c	0.946a	94.76abc	0.978ab	39.79b	6.37ab	6.24d
	W2/3S2	1.15ab	0.928abc	109.69ab	1.054ab	40.57b	6.60a	7.14c
	W2/3S3	1.10ab	0.910abc	70.67bc	1.006ab	41.52ab	6.50a	8.21b
	W2/3S4	1.04ab	0.909abc	49.69c	0.985ab	44.44ab	6.93a	9.27a
	W1S0	0.85c	0.946a	137.89a	0.945b	39.50b	5.27b	4.65d
	W1S2	1.05ab	0.941ab	137.17a	0.917b	39.57b	6.40ab	5.85d
	W1S3	1.34a	0.912abc	107.97ab	0.925b	40.19b	7.40a	6.97c
	W1S4	1.27ab	0.904bc	81.30bc	1.004ab	42.18ab	7.47a	8.63b

Fn = fruit firmness, FWC = fruit water content, FW = single fruit weight, CI = fruit color index, TSS = total soluble solids, TSSC = total soluble sugar concentration; Letters following the values of the fruit quality parameters of each season are the significant differences according to the Duncan's multiple range tests at 0.05 P level, the same letter represents no significant difference of indexes between two treatments.

more sensitive to SSC under W2/3 than that under W1 (Fig. 3 f), TSSC and FW were more sensitive to SSC under W1 than that under W2/3 (Fig. 3 l, n). TSS showed a significant positive correlation with SSC_a/SSC_{max} for W2/3, but not for W1 (Fig. 3 j).

3.4. Performance of the EPIC crop model in simulating fruit growth process

The default and calibrated parameters of EPIC crop model are presented in Table 8. The parameters that were calibrated in this study also were selected for calibration in previous studies, such as Han et al. (2015) and Wang et al. (2015a,b), except crop stress factor (REG). The LAI was calibrated and validated first of all owing to the fruit growth depending on the LAI curve. Stress factor, REG, was calibrated under conditions of no stress, water stress and salt stress (Table 8). The LAI curves under three conditions didn't show tendency for over or under estimations, and Table 7 shows the goodness of fit indicators for the comparisons. After the calibration of LAI, the data collected in 2016–2017 season were used to validate LAI curves. The R^2, RMSE, NRMSE, b_0 and d were 0.997, 0.036 m^2/m^2, 4.88%, 0.998 and 0.999 under no stress, 0.995, 0.018 m^2/m^2, 5.65%, 1.009 and 0.999 under water stress, and 0.958, 0.091 m^2/m^2, 17.76%, 0.986 and 0.988 under salt stress, respectively (Table 7). These results showed a close agreement between measured and simulated LAI.

Data simulated by the EPIC crop model and measured data generally matched, although there were differences during 20–30 days after anthesis under water stress condition (Table 9; Fig.4 c). With respect to no stress, water stress and salt stress over the two-year periods, the model performance index showed good agreement between measured and simulated data with high R^2 (0.863, 0.839 and 0.895) and d (0.967, 0.933 and 0.966), respectively. In 2016 season, the R^2, RMSE, NRMSE, b_0 and d for water stress were 0.799, 8.8 g, 35.8%, 0.878 and 0.925, respectively. The NRMSE value of 35.8% was higher than 30%. The results showed that EPIC crop model performed well to simulate fruit weight under no stress and salt stress conditions. In 2017 season, values of R^2, RMSE, NRMSE, b_0 and d under no stress condition were 0.891, 18.0 g, 30.2%, 1.041 and 0.971, respectively. The NRMSE value of 30.2% was slightly > 30%. With regard to salt stress condition, the values of R^2, RMSE, NRMSE, b_0 and d were 0.907, 11.6 g, 32.4%, 1.100 and 0.970, respectively. The NRMSE value of 32.4% was slightly > 30%. Accuracy of simulation by EPIC crop model during both years were acceptable.

4. Discussion

Salinity inhibited the root water uptake of plants, and quickly caused decrease in plant growth rate. Salinity-induced metabolic changes were similar to water stress (Munns, 2002; Katerji et al., 2004). The initial reduction in plant growth was likely induced by hormonal signals due to osmatic stress, but later the salt-specific effect, ion toxicity and the associated growth reduction occurred (Munns, 2002; Farooq et al., 2015). Thus, plant response to drought and salt stress was similar but salinity induces plant nutrient imbalance that is distinct from water stress (Munns, 2002; Farooq et al., 2015; De Pascale et al., 2007; Cuartero and Fernandez-Munoz, 1999). Most studies concentrated on the effect of single factor (drought or salt). In general, the enhancement of tomato fruit quality by water stress is accompanied with yield reductions (Chen et al., 2013, 2014; Yang et al., 2017; Ripoll et al., 2014, 2016; Ozbahce and Tari, 2010; Lovelli et al., 2017; Candido et al., 2015). In contrast, this research shows that compared to well-watered treatments (W1), mild water stress (W2/3) showed a 18.9%

Table 5
The results of two-way ANOVA on tomato quality parameters in the two growth seasons.

cropping season	F value	Fn (kg/cm^2)	FWC (%)	FW (g)	fruit shape index	CI	TSS (%)	TSSC (mg/100 g)
2016	Fw	0.071 NS	5.939 S	6.159 S	0.026 NS	2.593 NS	0.239 NS	13.04 ES
	Fs	9.793 ES	9.101 ES	45.39 ES	0.846 NS	1.392 NS	6.326 ES	97.61 ES
	Fc	0.432 NS	1.864 NS	0.993 NS	1.721 NS	0.303 NS	0.367 NS	1.154 NS
2017	Fw	2.129 NS	7.231 ES	7.673 ES	4.976 S	6.374 ES	1.206 NS	199.2 ES
	Fs	2.630 NS	5.335 ES	6.575 ES	0.220 NS	1.949 NS	5.157 ES	150.4 ES
	Fc	0.870 NS	0.227 NS	0.108 NS	0.965 NS	0.120 NS	2.73 NS	2.578 NS

Fw means the value of two-way ANOVA of water effect, Fs means the value of two-way ANOVA of salt effect, Fc means the value of two-way ANOVA of water and salt cross effect; ES: extreme significant, S: significant, NS: non-significant.

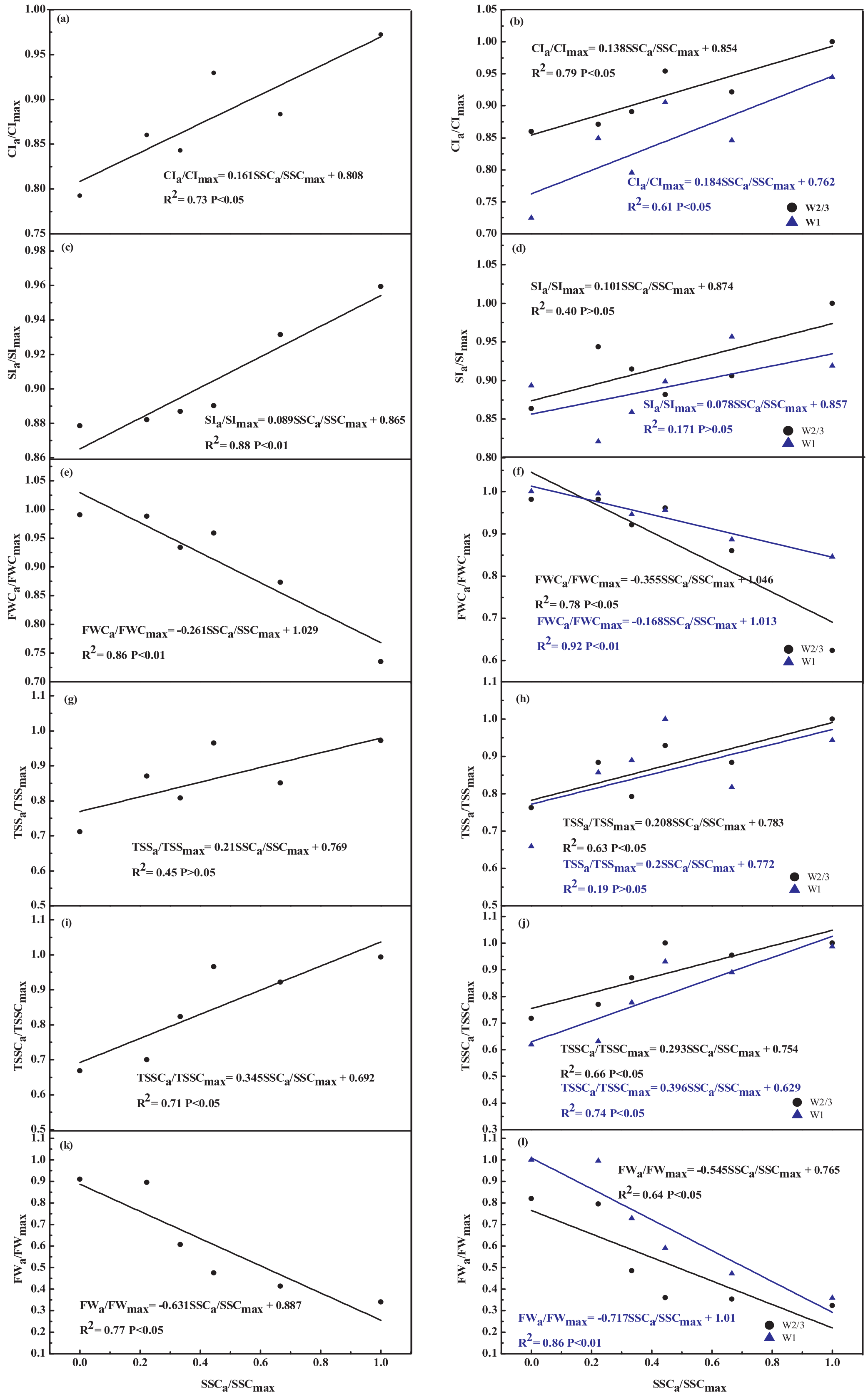

Fig. 3. The relationships between relative values of fruit quality parameters (CI_a/CI_{max}, SI_a/SI_{max}, FWC_a/FWC_{max}, TSS_a/TSS_{max}, FW_a/FW_{max}, $TSSC_a/TSSC_{max}$) and relative soil salt content (SSC_a/SSC_{max}), and the relationships between relative values of fruit quality parameters and relative soil salt content at deficit irrigation (W2/3) and full irrigation (W1), respectively.

Table 6
Statistical analysis of measured and simulated yield with two formulations on tomato affected by salt stress.

	Yield per plant (g)				
	R^2	RMSE (g)	NRMSE (%)	b_0	d
Eq. (4)	0.989	30.6	5.18	0.998	0.997
Eq. (5)	0.971	53.8	9.10	0.993	0.992

Table 7
The coefficient of determination (R^2), the root mean square error (RMSE), the normalized root mean square error (NRMSE), regression coefficient through the origin (b_0) and Willmott's index of agreement (d) for leaf area index during calibration (during 2017 growing season) and validation (2016/2017 growing season).

		Leaf area index (m^2/m^2)				
		R^2	RMSE (m^2/m^2)	NRMSE (%)	b_0	d
without stress	Calibration	0.999	0.023	2.25	1.000	1.000
	Validation	0.997	0.036	4.88	0.998	0.999
water stress	Calibration	0.985	0.034	8.09	0.996	0.996
	Validation	0.995	0.018	5.65	1.009	0.999
salinity stress	Calibration	0.949	0.108	15.40	0.982	0.985
	Validation	0.958	0.091	17.76	0.986	0.988

Table 9
The coefficient of determination (R^2), the root mean square error (RMSE), the normalized root mean square error (NRMSE), regression coefficient through the origin (b_0) and Willmott's index of agreement (d) with EPIC model for tomato single fruit weight under no stress, water stress and salt stress conditions from 2016 to 2017.

	Fruit weight (g)					
	n	R^2	RMSE (g)	NRMSE (%)	b_0	d
2016/17						
No stress	35	0.846	16.8	16.3	0.960	0.958
Water stress	23	0.799	8.8	35.8	0.878	0.925
Salt stress	18	0.901	10.5	26.8	1.068	0.962
2017						
No stress	35	0.891	18.0	30.2	1.041	0.971
Water stress	26	0.783	9.9	23.7	0.889	0.932
Salt stress	33	0.907	11.6	32.4	1.100	0.970
Overall						
No stress	70	0.863	17.4	16.9	0.995	0.967
Water stress	49	0.839	8.5	25.1	0.885	0.933
Salt stress	51	0.895	11.2	28.8	1.090	0.966

and 1.0% increase of yield per plant, respectively in 2016 and 2017 seasons, at S0 level (Table 3). However, single fruit weight showed an opposite trend (Table 4), which indicated that the increase of yield was mainly attributed to the increase of fruit number under mild water stress. It was reported that TSS, TSSC, VC and reducing-sugar contents in tomato fruits were higher in the deficit treatments than control (Wang et al., 2015a,b). Mild drought (W2/3) improved fruit quality parameters of Fn, CI, TSS and TSSC in some extent (Table 4). Similarly, yield reduction was associated with increasing soil salinity levels (Katerji et al., 2009, 2011; Schiattone et al., 2017), but the fruit quality was enhanced (Cantore et al., 2012; Van de Wal et al., 2017; De Pascale et al., 2015; Mitchell et al., 1991a). In our research, the more stressful of soil salt content the higher yield decline was identified, yield per plant was reduced by 49.1% when soil salt content reached at 4‰ in 2017 season (Table 3). Fruit quality parameters of CI, TSS and TSSC improvements were associated with increasing soil salt levels under both W2/3 and W1 treatments during both 2016 and 2017 seasons, while FWC showed a decrease trend (Table 4). FW decreased with increasing salt stress, which indicated that salinity-induced yield decline was mainly attributed to the decrease of single fruit weight (Table 3 and 4).

Few researches focused on the interactive impact of soil water and salt content on tomato yield and fruit quality, it has not been fully understood that whether the same yield reduction and quality variation are caused by the same change in plant water status owing to either drought or salinity. De Pascale et al. (2007) conducted a comparative stress experiment on cherry tomato and illustrated that growth inhibition in water-stressed (soil matric potential = -72 kPa) plants was greater than salinity stressed plants (12 Mm NaCl). The contents of TSS and dry matter of tomato fruits increased with increasing salinity but not by decreasing irrigation amounts (Cantore et al., 2012). Simultaneous water and salt stress aggravated yield reduction but enhanced fruit parameters of CI, TSS and TSSC (Table 3 and 4), yield per plant was more affected by severe drought (1/2 of full irrigation) than moderate salt stress (SSC 4‰). The two-way ANOVA showed that the interactive impact of water and salt on fruit quality parameters was not significant, and the fruit quality was more affected by salt stress than drought (Table 5). Fruit quality parameter of TSSC approached to the higher values in mild drought with severe salt stress (Table 4). The results demonstrated that tomato quality is more sensitive to salt than water.

Two of van Genuchten and Hoffman models (1984) (Eq. (4)) and (Eq. (5)) conformed well to simulate the relations of relative yield and soil salt content, R^2 of 0.989 and 0.971, respectively (Fig. 2 and Table 6). By contrasting the goodness of fitting indicators of the two models (Table 6), the non-linear reduction model (Eq. (4)) conformed better to the measured data than the exponential one (Eq. (5)). Babazadeh et al. (2016) also illustrated that the reduction function (Eq. (4)) performed better than the (Eq. (5)) for estimating yield responses of basil to irrigation, and salinity at which yield decreased by 50% is 6 $dS\,m^{-1}$ in the non-linear reduction model (Eq. (4)). Positive linear relations between tomato quality parameters e.g. CI, TSSC, SI and TSS and soil salt content were also found (Fig. 3a-d, g–j), indicating that tomato fruit quality was improved by increasing soil salt content, however, negative linear relationships were found between FWC, FW and soil salt content (Fig. 3e, f, k, l). These quantitative relationships of

Table 8
Default and calibrated parameters of tomato for leaf area growth and single fruit weight growth assigned in EPIC growth model.

Parameter	Units	Description	Value Adopted		
$T_{b,\,i}$	°C	Minimum temperature for plant growth (Eq. (6))	5		
			Default	Calibrated	
PHU	—	Potential heat units required for maturity (Eq. (8))	1926	1926	
LAI_{max}	m^2/m^2	Maximum leaf area index (Eq. (10))	2.0	1.67	
ab1	—	First leaf development parameter of the crop (Eq. (11))	0.5	0.30	
ab2	—	Second leaf development parameter of the crop (Eq. (11))	0.5	8.73	
FW_{max}	g	Maximum fruit weight (Eq. (12))	200	150	
				Water stress	Salt stress
REG	—	Minimum crop stress factor (Eq. (10))	1.0	0.15	0.43

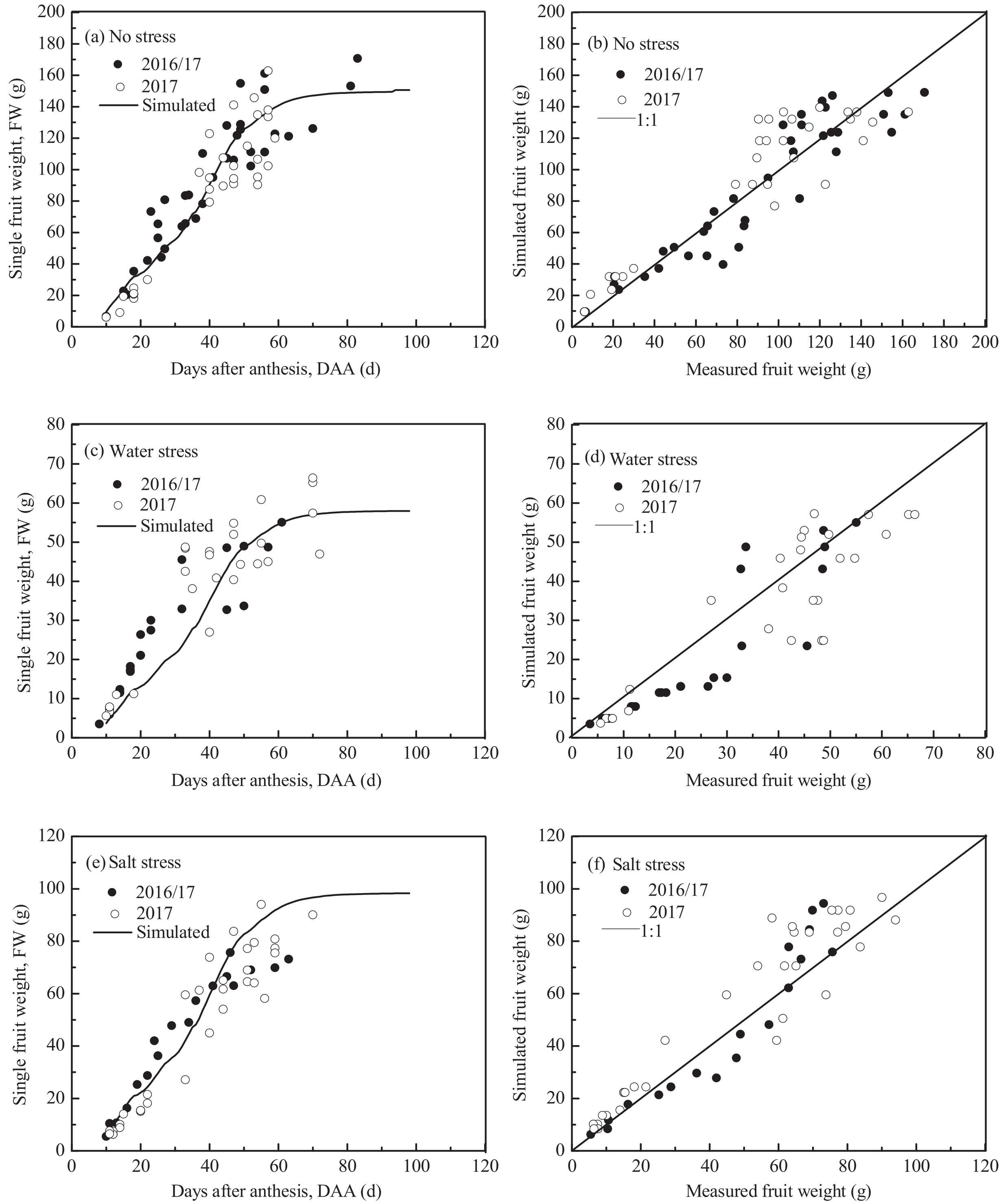

Fig. 4. Comparisons of single measured versus simulated fruit weight by EPIC model under no stress, water stress and salt stress conditions from 2016 to 2017.

fruit quality with soil salt content are identical to those with soil water content (Chen et al., 2013, 2014; Yang et al., 2017; Ozbahce and Tari, 2010). This was mainly the consequence of a reduced fruits water uptake and a low dilution owing to the osmatic stress, not an increased fruit compounds accumulation such as sugar in the fruits (Mitchell et al., 1991a), but the salt-specific effects on fruit nutrient compounds are still needed to be investigated.

As the literatures have been reported, unlike evaluating the plant yield and biomass by EPIC growth model, there were no attempts to be made to simulate the tomato fruit growth process using the growth module of EPIC. We use the types of basic equations of EPIC for reference, and made attempts to simulate tomato fruit growth process. The model was calibrated and validated against pot experiments data of 2016 and 2017 years. EPIC growth model simulated fruit growth process with acceptable accuracy under three conditions (i.e. no stress, water stress and salt stress) (Table 9 and Fig. 4). Wang et al. (2017a,b) coupled the growth module of EPIC with HYDRUS-1D to assess salinity stress on wheat evapotranspiration, yield and WUE and long-term use of saline water on grain yield and salt accumulation. In our study, the growth module of EPIC was used to evaluate salt stress on tomato leaf and fruit growth within an acceptable accuracy. However, the salt-fruit quality relationships and the EPIC growth model evaluating fruit growth are all empirical and mathematical models, further physiological responses of tomato fruit growth and quality to soil water content and salt content should be considered in the future study. In addition, our study only tested the approach in experimental pots, but it still has difficulty extending to field scale due to its destructive effect on original soil and imprecise control of salt content in plant root zone.

5. Conclusion

The responses of tomato yield per plant and fruit quality parameters to soil water and salt content were different. In the absence of salt stress, yield increased at mild water stress (W2/3) and the increase of yield was mainly attributed to the increase of fruit number, while fruit quality was enhanced by increasing Fn, CI, TSS and TSSC. Under both irrigation treatments (W2/3 and W1), yield decreased with increasing soil salt level mainly owing to the decline of single fruit weight, but fruit quality parameters of CI, TSS and TSSC improved. Moreover, yield under water stress treatments performed more sensitivity to salt stress than that under non-drought treatments. fruit quality parameters were more affected by salt stress than drought, the interactive impact of water and salt on fruit quality parameters was not significant. Positive linear relations were found between soil salt content and tomato quality parameters i.e. CI, TSSC, SI and TSS, while FWC and FW had negative linear relationships with soil salt content. Two of van Genuchten and Hoffman models (1984) conformed well to simulate the relationships of soil salt content and relative yield, the soil salt content at which yield decreased by 50% is 4.0‰ and 4.7‰, respectively in the non-linear reduction model and the exponential reduction model. The EPIC crop model simulated fruit growth process with acceptable accuracy in situations of no stress, water stress and salt stress, with acceptable accuracy.

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