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Modeling relations of tomato yield and fruit quality with water deficit at different growth stages under greenhouse condition

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ABSTRACT

Nowadays more and more attentions are paid to fruit quality in the production of tomato. In order to better understand the effects of deficit irrigation on tomato yield and fruit quality, four years of deficit irrigation experiments were investigated to simulate water-yield and water-fruit quality relationships of tomato in greenhouses. The yield and fruit quality parameters like total soluble solids (*TSS*), reducing sugars (*RS*), organic acids (*OA*), sugar/acid content ratio (*SAR*), vitamin C (*VC*), firmness (*Fn*), color index (*CI*) were correlated with seasonal evapotranspiration (*ET*) and *ET* deficit at flowering and fruit development stage (*Stage II*) and fruit ripening stage (*Stage III*) using linear regression. Three water-yield models (Jensen, Stewart, Minhas) and three water-fruit quality models (multiplicative, additive, exponential) were applied to simulate the relationships of tomato yield and fruit quality parameters with water deficit at various growth stages. The water deficit sensitivity indexes ($\lambda/Ky/\delta$ or $\gamma/Kq/\psi$) of the models were calculated with the method of multiply linear regression. The performance and sensitivity analysis of the models were evaluated. Results showed that the relative yield decreased linearly with the drop of relative seasonal *ET*, mainly due to the yield depression by *ET* deficit at *Stage II* and *Stage III*; the relative values of fruit quality parameters increased with the drop of relative seasonal *ET*, mostly because of the enhancement by *ET* deficit at *Stage III*. The calculated water deficit sensitivity indexes indicated that both the yield and fruit quality were hardly sensitive to water deficit at *Stage I*, but sensitive to water deficit at *Stage II* and that at *Stage III*; *TSS*, *RS*, *SAR* and *VC* were much more sensitive to water deficit at *Stage III* than that at *Stage II*; *RS*, *SAR* and *VC* were more sensitive to water deficit than *TSS*, *OA*, *Fn* and *CI*. The Minhas model with its water deficit sensitivity indexes was recommended to simulate water-yield relations of greenhouse tomato in the study area; multiplicative model and additive model were, respectively, recommended to simulate the relationships of fruit quality parameters like *TSS*, *RS*, *SAR*, *Fn* and fruit quality parameters like *OA*, *VC*, *CI* with water deficit at various growth stages. The water-yield and water-fruit quality models would be helpful to optimally allocate irrigation water during the growth season, thus achieving efficient production of tomato in greenhouses in consideration of the compromise between tomato yield and fruit quality.

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1. Introduction

In recent years, fruit quality has become a major concern for fruit production in response to the increasing consumers' demand (Guichard et al., 2001), for its importance to human health and pleasure (Dumas et al., 2006). Tomato is favored by people as an important source of lycopene, phenolic, and vitamin C in human diets (Toor et al., 2006). The consumption of tomato is also associated with a lower risk of developing some cancers (Giovannucci et al., 1995; Franceschi et al., 1994). Since the fruit with high quality is more popular among consumers, the price of tomato fruit would increase with the improvement of fruit quality. It has been predicted that the tomato consumption and profitability for producers would increase due to consumers' satisfaction with the quality of tomato fruit (Kader, 2008). Hence, improving tomato fruit quality is beneficial for consumers as well as growers.

A ripe tomato is principally composed of water and 5–8% dry matter, half of which is mainly glucose and fructose (Davies and Hobson, 1981). The quantity of water present in the fruit is responsible for its quality since it determines the concentration of different elements such as sugars and acids. Therefore the factors which influence the water uptake of the fruit play a significant role in

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determining the fruit size and the dry matter concentration, that is, its final quality (Guichard et al., 2001). Irrigation is considered as one of the most influential factors which affect the fruit water status. Many studies have shown that tomato fruit quality is enhanced by deficit irrigation (Mitchell et al., 1991; Pulupol et al., 1996; Zushi and Matsuzoe, 1998; Veit-Köhler et al., 1999; Johnstone et al., 2005; Favati et al., 2009; Patanè and Cosentino, 2010; Wang et al., 2011; Patanè et al., 2011). However the improvement of tomato fruit quality by deficit irrigation is often paralleled with an undesirable reduction in yield, mainly due to a smaller fruit size (Nuruddin et al., 2003; Kirda et al., 2004; Machado and Oliveira, 2005; Zegbe et al., 2006; Topcu et al., 2007; Marouelli and Silva, 2007; Zheng et al., 2013; Kuscu et al., 2014).

The effects of deficit irrigation on tomato fruit yield and quality are poorly defined because of its complexity, despite much research (Renquist and Reid, 2001; Marouelli and Silva, 2007; Favati et al., 2009; Patanè and Cosentino, 2010). The incompatible relationship between tomato yield and fruit quality should be taken into consideration when regulating tomato fruit quality through irrigation management. A good tradeoff between tomato yield and fruit quality could be achieved when irrigation amount was reduced to 70–85% of crop evapotranspiration (*ET*) during fruit enlargement and ripening either by irrigation cutting-off 2 weeks earlier than conventional cut-off dates or by applying deficit irrigation (Cahn et al., 2001). In a typical Mediterranean environment, an optimal irrigation strategy which balanced the relationship between yield and fruit quality of processing tomato was that irrigation was carried out to supplement crop evapotranspiration once the cumulative crop evapotranspiration minus effective rain reached 40 or 60 mm and with a reduction of 50% irrigation volume during fruit ripening (Favati et al., 2009).

In order to achieve more precise management of regulated deficit irrigation in tomato production, a better understanding of quantitative relationships between tomato yield, fruit quality and water use would be expected. Relative tomato yield reduction $(1 - Y_a/Y_m)$ was described as a function of relative crop seasonal *ET* deficit $(1 - ET_a/ET_m)$ with the equation: $1 - Y_a/Y_m = Ky(1 - ET_a/ET_m)$, developed by Stewart et al., 1977 (Kirda et al., 2004; Patanè et al., 2011; Kuscu et al., 2014). The positive relationships between tomato yield and seasonal *ET* were fitted by linear models (Zheng et al., 2013; Kuscu et al., 2014) as well as by curvilinear models (Renquist and Reid, 2001; Patanè et al., 2011). It was also reported that tomato yield was linearly or nonlinearly correlated with soil water deficit (Patanè and Cosentino, 2010), soil water tension thresholds (Marouelli and Silva, 2007), and seasonal irrigation volume (Cahn et al., 2002; Machado and Oliveira, 2005; Favati et al., 2009; Zheng et al., 2013; Kuscu et al., 2014). Accompanying with the positive relations between tomato yield and seasonal irrigation volume, negative linear or curvilinear relationships were found between total soluble solids content (*TSS*) of tomato fruit and seasonal irrigation amount (Cahn et al., 2002; Machado and Oliveira, 2005; Favati et al., 2009; Ozbahce and Tari, 2010; Kuscu et al., 2014). Some positive relationships of *TSS*, reducing sugars content (*RS*), organic acids content (*OA*), firmness (*Fn*), color of tomato fruit with soil water deficit during fruit enlargement and ripening were also evaluated by Patanè and Cosentino (2010). Moreover, some negative linear relationships were established between fruit quality parameters (such as *TSS*, *RS*, *OA*, vitamin C (*VC*), *Fn*, color index (*CI*), sugar/acid content ratio (*SAR*)) and seasonal *ET* as well as *ET* at tomato fruit development and ripening stages (Chen et al., 2013).

Many studies showed that the response of tomato yield and fruit quality to deficit irrigation at various growth stages was different, depending on the period and the degree of water deficit (Nuruddin et al., 2003; Zegbe et al., 2006; Marouelli and Silva, 2007; Chen et al., 2013; Kuscu et al., 2014). It was reported that there were no adverse effects on tomato yield and fruit quality by imposing a certain degree of water stress during vegetative stage (Zegbe et al., 2006; Marouelli and Silva, 2007; Chen et al., 2013; Kuscu et al., 2014). Moreover, the study of Ngouajio et al. (2007) showed that withholding irrigation between transplanting and flowering may save the amount of irrigation water by 20% while increase tomato yield by 8–15%. Chen et al. (2013) stated that tomato yield was sensitive to water deficit during fruit development and ripening, while fruit quality was mainly affected by water deficit during fruit ripening. Lots of studies also reported that tomato fruit quality was enhanced by water deficit at fruit growth and ripening stages, but with a yield depression (Renquist and Reid, 2001; Nuruddin et al., 2003; Favati et al., 2009; Patanè and Cosentino, 2010; Kuscu et al., 2014). Consequently, before using deficit irrigation strategies to regulate tomato yield and fruit quality, it is important to obtain adequate information about the relationships between tomato yield, fruit quality and water deficit with its timings and magnitudes.

The dated crop water production functions (*DCWPF*) describe the functional relationships of crop yield with *ET* or *ET* deficit at some specific growth stages, which include the effects of both timings and magnitudes of water deficit (Rao et al., 1988). The *DCWPF* are formulated in additive or multiplicative forms by postulating that water deficit in each growth stage has independent effects on crop yield, and the combined effects of water deficit at different growth stages are additive or multiplicative (Rao et al., 1988). Typical examples of multiplicative-type *DCWPF* are the models by Jensen (1968), Minhas et al. (1974) and Hanks (1974); and the additive-type *DCWPF* include those by Blank (1975), Stewart et al. (1976) and Sudar et al. (1981). The *DCWPF* are useful in predicting the crop yield and optimizing irrigation water allocation during the whole growing season when the available water is not sufficient to cover the crop water requirement. The *DCWPF* like Jensen, Stewart and Minhas models are widely used to simulate the relationship between some cereal crops' production and water deficit at various growth stages, e.g. rice, wheat, and maize (Mao et al., 1994; Zhang and Oweis, 1999; Zhang et al., 1999; Igbadun et al., 2007; Li et al., 2011; Paredes et al., 2014). However, few studies (Xu et al., 2001) were reported about the application of *DCWPF* in water-yield relations of tomato. And unfortunately, so far as the literatures reported, no modeling equations have been established to evaluate the effects of different degrees of water deficit at various growth stages on tomato fruit quality.

In order to improve tomato fruit quality and simultaneously compromise its incompatible relationships with tomato yield by precise deficit irrigation, modeling equations should be established to simulate the relationships of tomato yield and fruit quality with deficit irrigation. In the present study, four years of deficit irrigation experiments on greenhouse tomato in Northwest China were investigated. The aims of this study were to model water-yield and water-fruit quality relationships of greenhouse tomato considering the combined effects of timings and magnitudes of water deficit. The specific objectives, using the data acquired from the field experiments, include: (1) investigating the relationships of tomato yield and fruit quality parameters with crop seasonal *ET* as well as *ET* deficit at flowering and fruit development and fruit ripening stages; (2) Using Jensen, Stewart and Minhas models to simulate the response of tomato yield to water deficit at various growth stages; (3) Developing an additive model, a multiplicative model and an exponential model to simulate the relationships between fruit quality parameters and water deficit at various growth stages; (4) Evaluating the performance of the models in predicting tomato yield and fruit quality parameters under deficit irrigation. The output of this study is expected to improve our knowledge of deficit irrigation and predict its influence on tomato yield and fruit quality, and will have potential applications in precise irrigation management for high quality tomato production.

2. Materials and methods

2.1. Field experimentation

2.1.1. Experimental site

Field experiments were carried out for four crop growing seasons (2008/09, 2009/10, 2010 and 2012/13 season) in the solar greenhouses at Shiyanghe Experimental Station of China Agricultural University. The experimental station is located in Wuwei city, Gansu province of northwest China, lying at latitude 37°52′N, longitude 102°51′E, at an altitude of 1581 m above sea level. The annual precipitation of the study area is about 164.4 mm with pan evaporation of 2000 mm, mean temperature of 8.8 °C, mean sunshine duration of 3000 h and frost-free period of more than 150 d. The local crops are irrigated by well water with the electrical conductivity of 0.52 dS m^{-1} and the groundwater table is below 25 m. The greenhouses used for the experiments are 76 m in east–west orientation and 8 m in south–north orientation with the planting area of 405 m^2. The greenhouses have no heating system. The inner temperature during night in cold seasons is maintained by the straw mats which are spread on the surface of the thermal polyethylene sheet, while the temperature during the daytime is controlled by a narrow ventilation system on the roof. More details of the construction of the solar greenhouses were described by Qiu et al. (2011). The greenhouses have a desert sandy loam. The mean dry bulk density and field water capacity at the 0–50 cm soil layer for 4 crop growing seasons were shown in Table 1. The field water capacity was measured with the method developed by Wilcox (1965).

2.1.2. Experimental design and agronomy

The present study was part of an extended investigation, which was conducted over consecutive years in order to determine the effects of deficit irrigation on the yield and fruit quality of greenhouse tomato. The findings and details of field experiments in 2008/09 and 2009/10 seasons have been reported by Chen et al. (2013). In the present study, field data obtained from these two field experiments were used. There were three replications per treatment resulting in a total of 21, 15, 18 and 27 plots for 2008/09, 2009/10, 2011 and 2012/13 seasons, respectively, arranged in a completely random design. Each plot consisted of 4 rows of crop plants with an area of 12.88 m^2 (5.6 m long by 2.3 m wide). In order to prevent water exchange among plots, a plastic sheet was embedded to a depth of 1 m to separate the neighboring plots. Soil moisture content measurements in every plot were made at 0.1 m intervals with maximal soil depth of 1.0 m every 3–5 days or before and after irrigation using portable soil moisture monitoring system (Diviner 2000, Sentek Pty. Ltd., Australia). Details of the arrangement of PVC access tubes used for the measurements of soil moisture content were specifically described by Chen et al. (2013). Calibration was conducted before using the data obtained from Diviner 2000. Soil samples near every tube were acquired at 0.1 m intervals with maximal soil depth of 1.0 m, and the moisture content of the samples was determined using the gravimetric method (oven dry basis). The ratios of the soil moisture content values measured by the gravimetric method to those by Diviner 2000 were used to calibrate the measurements by Diviner 2000.

Four local leading varieties, all of which belong to pink tomato series, were used in the experiments (Table 1). Tomato seedlings at 3–4 true leaves stage were transplanted along the furrow side with row spacing of 0.35 m and interplant spacing of 0.35 m. For a better establishment, the seedlings in all plots were irrigated immediately after transplanting with the same amount of water (Table 1). At 3–10 days after transplanting, the entire soil surface was covered with 0.005 mm thick polyethylene film to reduce soil evaporation and increase the soil temperature. At 30–40 days after transplanting, the stems of the plants were hanged with plastic stings and the flowers were manually pollinated. Standard cultivation practices of local farmers were adopted during the crop growing seasons. Except for irrigation, other management practices such as pollination, pruning branch stem, fertilization (Table 1) and pest control were the same within all the treatments in the experiments.

2.1.3. Irrigation treatments

The furrow irrigation method was applied to irrigate the crops. Since 10 days after transplanting, tomato crops were irrigated to 90% of field water capacity (*FC*) for the full irrigation treatment (*CK*) when its average soil volumetric moisture content at the 0–50 cm soil layer decreased to 75 ± 2% of *FC*. Deficit irrigation treatments received various levels of irrigation amount reduction over different growth periods for four growing seasons. A list of description of deficit irrigation treatments and their irrigation scheduling are given in Tables 2 and 3. The whole growth season, considering the cultivars' characteristics of overlaps of flowering, fruit enlargement and fruit ripening, was divided into the three stages (Table 2): vegetative stage (*Stage I*, transplant to first fruit set), flowering and fruit development stage (*Stage II*, first fruit set to first fruit maturity), fruit ripening stage (*Stage III*, first fruit maturity to uprooting crops after all fruits are harvested). Considering that no evident effects of deficit irrigation at *Stage I* ($V_{1/3}$ and $V_{2/3}$) were found on tomato yield and fruit quality in the 2008–2009 season, no water treatments were set up at *Stage I* in the 3 following seasons. All the experimental treatments were irrigated at the same time as *CK* in 4 growing seasons. Water was applied by pipes to the dead end furrow without tail flow, and the amount was recorded by water meters (Accuracy of 0.1 L) at the end of the pipes for each plot in each irrigation event.

2.1.4. Actual crop evapotranspiration estimation

The actual crop evapotranspiration was estimated with the soil water balance method. The soil moisture changes in 0–100 cm soil layer over a period time were used to estimate actual crop evapotranspiration with the following equation (Allen et al., 2011):

$$ET_a = P + I + \Delta W - R - D \tag{1}$$

where ET_a is actual crop evapotranspiration (mm); P is precipitation (mm); I is irrigation water amount (mm), ΔW is the change in soil water storage (mm); R is the surface runoff (mm) and D is deep drainage (mm). In the study area, the contribution from groundwater was negligible because groundwater table is deeper than 25 m. There was no rain in the greenhouses, so $P = 0$. No tail flow occurred in the irrigation events, so $R = 0$. Lysimeters (1 mm thick steel) of 1.0 m long and 1.2 m wide with leakage collection vessel were installed 0.6 m beneath the bottom of the furrows in *CK* treatments to collect drainage water. No drainage was observed from the lysimeters, so $D = 0$. Thus Eq. (1) can be simplified as follows:

$$ET_a = I + \Delta W \tag{2}$$

where I was measured using water meters; ΔW was obtained from soil moisture observations in the 0–100 cm soil layer at the beginning and end of the period.

2.1.5. Weather data

The automatic weather stations (Hobo, Onset Computer Corp., USA) were installed in the center of the greenhouses to monitor the environmental conditions. Measurements of solar radiation (*Rs*), air temperature (*Ta*), relative humidity (*RH*), vapor pressure deficit (*VPD*) were obtained every 5 s. The averages of these measurements in 15 min were calculated and stored in a data logger. The reference evapotranspiration (ET_0) was estimated using the FAO Penman–Monteith equation with a fixed aerodynamic resistance of 295 S m^{-1} which is described by Fernández et al. (2010, 2011)

Table 1
The mean dry bulk density, field water capacity at 0–50 cm soil layer and tomato cultivars, date and water use at transplanting and fertilizer in four growing seasons.

Cropping season	2008/09	2009/10	2011	2012/13
Dry bulk density (g cm^{-3})	1.45	1.46	1.50	1.49
Field water capacity (cm^3 cm^{-3})	0.340	0.364	0.321	0.351
Tomato cultivars	*Jinzuan*-3	*Taikong*-1	*Zhongyan*-999	*Ruifeng*
Transplanting date	Oct 5, 2008	Sept 22, 2009	Jan 19, 2011	Nov 2, 2012
Transplanting water use (mm)	25.5	18.5	26.8	28.0
Basal fertilizer[a]	110 t ha^{-1} of decomposed organic manure (pig and sheep manure)			
	1200 kg ha^{-1} of diammonium phosphate (N 18%, P_2O_5 46%)			
	350 kg ha^{-1} of compound fertilizer (N 18%, P_2O_5 15%, K_2O 12%)			
Topdressing fertilizer[b]	300 kg ha^{-1} of urea (N 46.7%)			
	150 kg ha^{-1} of potassium sulfate (K_2O 52%)			
	450 kg ha^{-1} of compound fertilizer (N 18%, P_2O_5 15%, K_2O 12%)			

[a] Fertilizer was uniformly broadcasted in the soil before transplanting.
[b] Fertilizer was applied with irrigation events after transplanting.

Table 2
Descriptions of greenhouse tomato growth stages and irrigation treatments in 4 growing seasons.

	Description
Stage I	Vegetative stage, transplant to first fruit set
Stage II	Flowering and fruit development stage, first fruit set to first fruit maturity
Stage III	Fruit ripening stage, first fruit maturity to uprooting crops after all fruits are harvested
CK	Full irrigation
$V_{1/3}$, $V_{2/3}$	1/3, 2/3 full irrigation at *Stage I*
$F_{1/3}$, $F_{2/3}$	1/3, 2/3 full irrigation at *Stage II*
$R_{1/3}$, $R_{2/3}$	1/3, 2/3 full irrigation at *Stage III*
$F_{2/3}R_{2/3}$	2/3 full irrigation at *Stage II* and 2/3 full irrigation at *Stage III*
$F_{2/3}R_{1/3}$	2/3 full irrigation at *Stage II* and 1/3 full irrigation at *Stage III*
$F_{1/3}R_{2/3}$	1/3 full irrigation at *Stage II* and 2/3 full irrigation at *Stage III*
$F_{1/3}R_{1/3}$	1/3 full irrigation at *Stage II* and 1/3 full irrigation at *Stage III*
$F_{8/9}R_{8/9}$–$F_{4/9}R_{4/9}$	8/9–4/9 full irrigation at both *Stage II* and *Stage III*

Table 3
Irrigation amount (mm) and times for different irrigation treatments in four growing seasons.

Cropping season	Treatment	*Stage I*	*Stage II*	*Stage III*	Whole season[b]
2008/09	$V_{1/3}$	8.5(1)[a]	76.5(3)	153.0(6)	263.5(11)
	$V_{2/3}$	17.0(1)	76.5(3)	153.0(6)	272.0(11)
	$F_{1/3}$	25.5(1)	25.5(3)	153.0(6)	229.5(11)
	$F_{2/3}$	25.5(1)	51.0(3)	153.0(6)	255.0(11)
	$R_{1/3}$	25.5(1)	76.5(3)	51.0(6)	178.5(11)
	$R_{2/3}$	25.5(1)	76.5(3)	102.0(6)	229.5(11)
	CK	25.5(1)	76.5(3)	153.0(6)	280.5(11)
2009/10	$F_{1/3}$	18.5(1)	28.0(3)	139.8(5)	204.8(10)
	$F_{2/3}$	18.5(1)	56.0(3)	139.8(5)	232.8(10)
	$R_{1/3}$	18.5(1)	84.0(3)	46.6(5)	167.6(10)
	$R_{2/3}$	18.5(1)	84.0(3)	93.2(5)	214.2(10)
	CK	18.5(1)	84.0(3)	139.8(5)	260.8(10)
2011	$F_{8/9}R_{8/9}$	26.8(1)	71.4(3)	166.7(7)	291.7(12)
	$F_{7/9}R_{7/9}$	26.8(1)	62.5(3)	145.8(7)	261.9(12)
	$F_{6/9}R_{6/9}$	26.8(1)	53.6(3)	125.0(7)	232.2(12)
	$F_{5/9}R_{5/9}$	26.8(1)	44.6(3)	104.2(7)	202.4(12)
	$F_{4/9}R_{4/9}$	26.8(1)	35.7(3)	83.3(7)	172.6(12)
	CK	26.8(1)	80.4(3)	187.5(7)	321.5(12)
2012/13	$F_{1/3}$	28.0(1)	28.0(3)	139.8(5)	223.8(10)
	$F_{2/3}$	28.0(1)	56.0(3)	139.8(5)	251.8(10)
	$R_{1/3}$	28.0(1)	84.0(3)	46.6(5)	186.6(10)
	$R_{2/3}$	28.0(1)	84.0(3)	93.2(5)	233.2(10)
	$F_{2/3}R_{2/3}$	28.0(1)	56.0(3)	93.2(5)	205.2(10)
	$F_{2/3}R_{1/3}$	28.0(1)	56.0(3)	46.6(5)	158.6(10)
	$F_{1/3}R_{2/3}$	28.0(1)	28.0(3)	93.2(5)	177.2(10)
	$F_{1/3}R_{1/3}$	28.0(1)	28.0(3)	46.6(5)	130.6(10)
	CK	28.0(1)	84.0(3)	139.8(5)	279.8(10)

[a] Numbers in the brackets indicate irrigation times for the respective growth stage.
[b] Irrigation amount and times of the whole season include transplanting water.

and Qiu et al. (2013). A summary of weather data during various growth stages in 4 growing seasons is present in Table 4.

2.1.6. Yield and fruit quality parameters measurement

During fruit ripening period, in order to minimize border effect, in every harvest the same two middle rows of crop plants in each plot were harvested for individual fruit weight, fruit number and fresh yield. Individual fruit weight was measured using electronic balance (accuracy of 0.01 g). At the end of the cropping season, the fresh yield of each harvest was summed up as the total yield (Y).

Twenty ripe fruits were chosen from the harvested fruits in each plot for fruit quality measurement every 7–10 days from the first

Table 4
The average daily mean solar radiation (*Rs*), air temperature (*Ta*), relative humidity (*RH*), vapor pressure deficit (*VPD*) and cumulative reference evapotranspiration (ET_0) for various growth stages in four growing seasons.

Cropping season	Growth stage	*Rs* (W/m^2)	*Ta* (°C)	*RH* (%)	*VPD* (kPa)	ET_0 (mm)
2008/09	*Stage I*	105.1	16.0	58.4	1.14	80.8
	Stage II	86.8	15.0	84.4	0.44	108.5
	Stage III	128.1	15.4	85.6	0.41	146.4
2009/10	*Stage I*	116.0	18.0	61.9	0.99	103.5
	Stage II	82.5	12.5	83.8	0.31	79.4
	Stage III	90.0	14.7	86.5	0.33	128.4
2011	*Stage I*	89.8	16.9	73.8	0.80	62.2
	Stage II	128.6	19.0	83.0	0.68	135.3
	Stage III	188.4	22.7	73.1	1.23	249.5
2012/13	*Stage I*	93.8	17.0	77.8	0.63	71.4
	Stage II	83.2	13.5	87.3	0.35	91.8
	Stage III	142.4	19.0	74.0	1.04	209.6

harvest. The size, shape and color of these fruits were firstly measured. Then, 10 fruits were used to measure the fruit firmness, and the other 10 fruits were homogenized in a blender for measuring the fruit contents of total soluble solids (*TSS*), reducing sugars (*RS*), organic acids (*OA*), and vitamin C (*VC*).

The color of fruits was measured with a spectrophotometer (SP60, X-rite, Incorporated, MI, USA). The CIE (Commission Internationale de I'Éclairage) color space coordinates *L*, *a*, *b* values were obtained from 4 equatorial orientations of each fruit. The average values were used to calculate color index (*CI*) of the fruit with the following equation (Hobson et al., 1983; Intelmann et al., 2005):

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

where *CI* is the fruit color index; *L* is the lightness ranging from 0 (black) to 100 (white); *a* is a scale ranging from −100 (green) to +100 (red); and *b* is a scale ranging from −100 (blue) to +100 (yellow).

Fruit firmness (*Fn*) was measured on four equatorial orientations with the fruit firmness tester (FHR-5, Takemura electric works, Ltd., Japan). *TSS* was determined using the electronic handheld refractometer (PR-32, Co., Ltd., Tokyo, Japan) with automatic temperature compensation. *VC* was measured using the 2, 6-dichloroindophenol titrimetric method and expressed as percentage content of ascorbic acid of fresh mass (AOAC, 1984). *RS* was measured with 3,5-dinitrosalicylic acid reagent colorimetric (DNS) method (Miller, 1959). *OA* was titrated with 0.1 mol L^{-1} NaOH and calculated as equivalents of citric acid expressed as percentage of fresh mass (AOAC, 1990). Sugar/acid content ratio (*SAR*) of the fruit was calculated as the ratio of *RS* to *OA*. All these fruit quality parameters were totally measured 6, 5, 5 and 3 times during the fruit ripening period for each plot in the 2008/09, 2009/10, 2011 and 2012/13 season, respectively. The average values of these measurements were used as the values of fruit quality parameters for each season.

2.2. Models description

2.2.1. Water-yield models

Water-yield models were described as the dated crop water production functions. In the present study, Jensen model, Stewart model and Minhas model were used to simulate the relationship of tomato yield with *ET* deficit during various growth stages.

The Jensen model developed by Jensen (1968) is given as the following equation:

$$\frac{Y_a}{Y_{ck}} = \prod_{i=1}^{n} \left(\frac{ET_{ai}}{ET_{cki}}\right)^{\lambda_t} \tag{4}$$

where Y_a is the crop yield of deficit irrigation treatments; Y_{ck} is the crop yield of full irrigation treatment; ET_{ai} is actual crop evapotranspiration at the growth stage '*i*' of deficit irrigation treatments; ET_{cki} is maximum crop evapotranspiration at the growth stage '*i*' of full irrigation treatment; λ is Jensen's water deficit sensitivity index of crop yield; *i* is the growth stage; *n* is the number of growth stages.

The Stewart model developed by Stewart et al. (1976) is given as

$$\frac{Y_a}{Y_{ck}} = 1 - \sum_{i=1}^{n} Ky_i \left(1 - \frac{ET_{ai}}{ET_{cki}}\right) \tag{5}$$

where *Ky* is Stewart's water deficit sensitivity index of crop yield, and the other parameters as previously defined.

The Minhas model developed by Minhas et al. (1974) is given as

$$\frac{Y_a}{Y_{ck}} = \prod_{i=1}^{n} \left(1 - \left(1 - \frac{ET_{ai}}{ET_{cki}}\right)^2\right)^{\delta_i} \tag{6}$$

where δ is Minhas' water deficit sensitivity index of crop yield, and the other parameters as previously defined.

2.2.2. Water-fruit quality models

Using the multiplicative or additive type of the water-yield models for reference, multiplicative model and additive model were developed to simulate the effects of water deficit at various growth stages on fruit quality parameters.

The multiplicative model adapted from the model by Jensen (1968) is given as

$$\frac{Q_a}{Q_{ck}} = \prod_{i=1}^{n} \left(\frac{ET_{ai}}{ET_{cki}}\right)^{\gamma_i} \tag{7}$$

where Q_a represents a certain fruit quality parameter, e.g. *TSS*, *RS*, *OA* et al. from deficit irrigation treatments; Q_{ck} represents a certain fruit quality parameter, e.g. *TSS*, *RS*, *OA* et al. from full irrigation treatment; γ is the water deficit sensitivity index of fruit quality parameters for multiplicative model; the other parameters as previously defined.

The additive model adapted from the model by Stewart et al. (1976) is given as

$$\frac{Q_a}{Q_{ck}} = 1 + \sum_{i=1}^{n} Kq_i \left(1 - \frac{ET_{ai}}{ET_{cki}}\right) \tag{8}$$

where *Kq* is the water deficit sensitivity index of fruit quality parameters for additive model, and the other parameters as previously defined.

In addition, exponential model was also developed because the logarithm of the relative values of fruit quality parameters were found linearly correlated with the relative *ET* deficit of *Stage II* and *Stage III* according to the pre-analysis (data not shown). The exponential model is given as

$$\frac{Q_a}{Q_{ck}} = EXP\left(\sum_{i=1}^{n}\psi_i\left(1-\frac{ET_{ai}}{ET_{cki}}\right)\right) \quad (9)$$

where ψ is the water deficit sensitivity index of fruit quality parameters for exponential model, and the other parameters as previously defined.

2.3. Determination of water deficit sensitivity indexes of the models

The water deficit sensitivity indexes for each model were estimated using field observed data from 2008/09, 2009/10 and 2011 seasons. Each model was firstly transformed into a multiply linear equation, in which the relative values of yield (Y_a/Y_{ck}) or fruit quality parameters (Q_a/Q_{ck}) and the relative *ET* (ET_{ai}/ET_{cki}) or *ET* deficit ($1 - ET_{ai}/ET_{cki}$) were the dependent and independent variables, respectively, and the sensitivity indexes were the coefficients of the multiply linear equation. The field measured Y_a/Y_{ck} or Q_a/Q_{ck} and ET_{ai}/ET_{cki} or $1 - ET_{ai}/ET_{cki}$ were used to solve the coefficients of the multiply linear equations with the method of multiply linear regression. The obtained values were regarded as the base water deficit sensitivity indexes, and the statistical analysis of the multiply linear regression was also investigated.

2.4. Evaluation of models' performance

The base water deficit sensitivity indexes were incorporated into their respective models and the performance of the models in simulating relative values of yield or fruit quality parameters was tested using the field measured data from 2012/13 season. The simulated relative values of yield or fruit quality parameters (S_i in the equations that follow) were compared with the measured values (M_i in the equations that follow). In order to assess the goodness of fit of the models, linear regressions forced to the origin relating simulated values and measured values were performed and the coefficients of regression (b) and determination (R^2) were analyzed. In addition, the indicators of estimation errors and quality of modeling were also calculated: the root mean square error (*RMSE*), average absolute error (*AAE*), the Nash and Sutcliffe (1970) modeling efficiency (*EF*) and the Willmott (1981) index of agreement (d_{IA}).

RMSE which characterizes the variance of the errors is calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2} \quad (10)$$

AAE which expresses the size of estimation errors is calculated as follows:

$$AAE = \frac{1}{n}\sum_{i=1}^{n}\left|S_i - M_i\right| \quad (11)$$

EF defined by the ratio of the mean square error to the variance in the measured data is calculated as follows:

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2} \quad (12)$$

EF values close to 0 or negative indicate that the measured mean value, $\overline{M}$, is as good or better predictor than the model (Legates and McCabe, 1999; Moriasi et al., 2007).d_{IA} which presents the agreement between the measured and simulated values is given as follows:

$$d_{IA} = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2} \quad (13)$$

when $d_{IA} = 1$, a perfect agreement between the measured and simulated value is attained; when $d_{IA} = 0$, there is no agreement (Legates and McCabe, 1999; Moriasi et al., 2007).

2.5. Sensitivity analysis

A sensitivity analysis was conducted to identify the response of the models to the variations of some factors. The investigated factors included relative *ET* (ET_{ai}/ET_{cki}) and water deficit sensitivity index ($\lambda_i/Ky_i/\delta_i$ and $\gamma_i/Kq_i/\psi_i$)) at each growth stage. The initial values of ET_{ai}/ET_{cki} were 0.7 for all growth stages, and the initial values of water deficit sensitivity indexes were the respective base values obtained in Section 2.3. Only one factor was adjusted at a time up to ±20% at incremental interval of ±5%, while holding the other factors constant. The sensitivity of the model to a given variation of one factor was quantified by the normalized sensitivity coefficient (*SC*), defined as the following equation (Liu et al., 2007):

$$SC = \frac{\Delta S/S}{\Delta P/P} \quad (14)$$

where ΔS is the variation of simulated relative value of yield or a certain fruit quality parameter; S is the relative value of yield or fruit quality parameters simulated with the initial values of the factors; ΔP is the variation of the factor; P is the initial value of the factor. Then the average value of *SC* over the whole range of variation was calculated as the final value of *SC* for the factor.

2.6. Data analysis

At the end of each cropping season, tomato yield and fruit quality parameters of different irrigation treatments were determined. They were subjected to one-way analysis of variance (*ANOVA*) using the Least Significant Differences (*LSD*) test at the 5% probability level ($P < 0.05$). All statistical procedures involved in this study were done using SPSS 13.0 version software (SPSS Inc., USA).

3. Results

3.1. Crop evapotranspiration, tomato yield and fruit quality parameters

The actual crop evapotranspiration (ET_a) for various growth stages and whole season in 4 growing seasons is given in Table 5. The seasonal ET_a varied from 171.3 to 329.9 mm, corresponding to the seasonal irrigation depth of 130.6–321.5 mm (Table 3) for different irrigation treatments. In each season, the highest seasonal ET_a was recorded in full irrigation treatments (*CK*), except that in 2008/09 season; the lowest seasonal ET_a was recorded in the treatments which received the least seasonal irrigation volume, e.g. $R_{1/3}$ in 2008/09 and 2009/10 seasons, $F_{4/9}R_{4/9}$ in 2011 season and $F_{1/3}R_{1/3}$ in 2012/13 season. The ET_a of each growth stage was closely linked to the amount of water applied to the stage. The ET_a of *Stage II* were 36.6%, 51.5% and 36.7% smaller in $F_{1/3}$ than *CK* for 2008/09, 2009/10 and 2012/13 seasons, respectively. Compared to *CK*, the ET_a of *Stage III* was reduced by 47.1–54.9% in $R_{1/3}$ and 21.9–29.6% in $R_{2/3}$ for above three seasons. Severe deficit irrigation during consecutive stages of *Stage II* and *Stage III* caused huge seasonal ET_a depression; compared to *CK*, seasonal ET_a was reduced by 41.8% in $F_{4/9}R_{4/9}$ for 2011 season

Table 5
Actual crop evapotranspiration (ET_a) and total yield (Y) for different irrigation treatments in four growing seasons.

Cropping season	Treatment	ET_a (mm)			Whole season	Y (t ha^{-1})
		Stage I	*Stage II*	*Stage III*		
2008/09	$V_{1/3}$	56.1	61.8	141.5	259.4	118.2ab[a]
	$V_{2/3}$	42.1	83.9	144.5	270.5	119.2a
	$F_{1/3}$	52.2	40.2	134.9	227.3	103.6d
	$F_{2/3}$	58.3	64.7	139.9	262.9	109.6bcd
	$R_{1/3}$	53.0	74.1	74.1	201.2	102.2d
	$R_{2/3}$	71.7	59.4	100.7	231.8	106.5cd
	CK	65.2	63.4	140.0	268.6	113.8abc
2009/10	$F_{1/3}$	68.8	39.8	126.8	235.4	114.7b
	$F_{2/3}$	67.9	66.6	134.0	268.6	121.5ab
	$R_{1/3}$	69.3	82.2	61.0	212.5	111.0b
	$R_{2/3}$	71.2	80.1	94.4	245.7	120.7ab
	CK	68.4	82.1	134.0	284.5	128.1a
2011	$F_{8/9}R_{8/9}$	26.1	85.3	189.8	301.2	136.9a
	$F_{7/9}R_{7/9}$	28.8	80.1	185.1	294.0	119.4b
	$F_{6/9}R_{6/9}$	27.0	76.5	158.4	261.8	110.3b
	$F_{5/9}R_{5/9}$	26.3	67.0	125.7	218.9	97.5c
	$F_{4/9}R_{4/9}$	26.9	61.7	103.5	192.0	88.2c
	CK	28.9	95.9	205.0	329.9	138.0a
2012/13	$F_{1/3}$	58.8	62.2	140.9	262.0	84.2b
	$F_{2/3}$	52.6	78.2	146.6	277.4	95.2a
	$R_{1/3}$	57.8	98.7	66.1	222.7	75.6c
	$R_{2/3}$	51.6	97.3	114.4	263.3	92.2a
	$F_{2/3}R_{2/3}$	59.6	74.1	98.4	232.0	84.6b
	$F_{2/3}R_{1/3}$	59.4	74.8	80.4	214.6	80.6bc
	$F_{1/3}R_{2/3}$	54.6	57.2	100.3	212.2	81.4bc
	$F_{1/3}R_{1/3}$	56.8	53.8	60.8	171.3	64.6d
	CK	58.3	98.2	146.6	303.1	96.9a

[a] Values followed by the same letter within columns and each cropping season are not significantly different at 0.05 *P* level by *LSD* test.

and 43.5% in $F_{1/3}R_{1/3}$ for 2012/13 season. The higher seasonal ET_a in 2011 season was consistent with its higher ET_0 (Tables 4 and 5).

The total yield of different irrigation treatments in 4 growing seasons is presented in Table 5. Statistical analysis of variance (*ANOVA*) indicated that there was a statistical difference among the yields of different treatments at $P < 0.05$ level in each season. Except that in 2008/09 season, the highest yield was recorded in *CK*, ranging from 96.9–138.0 t ha^{-1}. In 2008/09 season, the yields of $V_{1/3}$ and $V_{2/3}$ were a little higher than *CK*, but without statistical difference. Among the treatments with deficit irrigation at one growth stage (*Stage II* or *Stage III*), different levels of yield reduction were observed in 2008/09, 2009/10 and 2012/13 seasons. In the three seasons, compared to *CK*, the yields were significantly lower in $F_{1/3}$ and $R_{1/3}$ with a reduction by 8.9–13.1% and 10.1–22.0%, respectively; a lower yield was found in $F_{2/3}$ and $R_{2/3}$, but there was no significant difference. Tomato yield was significantly decreased by the treatments with deficit irrigation during consecutive stages of *Stage II* and *Stage III*, except $F_{8/9}R_{8/9}$ in 2011 season. The yield reduction ranged from 12.7% to 36.1% for these treatments in 2011 and 2012/2013 seasons.

Table 6 shows the results of effects of different irrigation treatments on tomato fruit quality. In 2008/09 season, no significant difference was found in any fruit quality parameter between *CK* and $V_{1/3}$ or $V_{2/3}$. In general, tomato fruit quality was improved by deficit irrigation treatments with the increased *TSS*, *RS*, *OA*, *VC*, *Fn*, *CI* and *SAR* of tomato fruit. In 4 growing seasons, *TSS*, *RS* and *OA* were recorded from 4.66 to 5.55 °Brix, 2.60–3.38 g 100 g^{-1} FW, and 0.283–0.402 g 100 g^{-1} FW for *CK*, respectively. They were significantly increased by $F_{1/3}$, $R_{1/3}$ and $R_{2/3}$ in 2008/09 and 2009/10 seasons and by $F_{1/3}$ and $R_{1/3}$ in 2012/13 season, but no significant difference was found between $F_{2/3}$ and *CK* in 2008/09, 2009/10 and 2011 seasons and between $R_{2/3}$ and *CK* in 2012/13 season. *VC* varied from 72.8 to 166.4 mg kg^{-1} FW for *CK* in 4 growing seasons. Compared to *CK*, higher *VC* was found in $F_{1/3}$, $R_{1/3}$ and $R_{2/3}$, but no significant difference was found in $F_{2/3}$ in 2008/09, 2009/10 and 2012/13 seasons. *Fn* was also enhanced by the deficit irrigation, though no significant difference was found in 2009/10 season. It was significantly increased by $F_{1/3}$, $F_{2/3}$, $R_{1/3}$ and $R_{2/3}$ in 2008/09 season and by $F_{1/3}$, $F_{2/3}$ and $R_{1/3}$ in 2012/13 season. *CI* was significantly influenced by the deficit irrigation, with an increase for $F_{1/3}$, $F_{2/3}$, $R_{1/3}$ and $R_{2/3}$ in 2008/09, 2009/10 and 2012/13 seasons. *SAR* was significantly enhanced by $R_{1/3}$ and $R_{2/3}$ in 2008/09, 2009/10 and 2012/13 seasons due to the higher increase of *RS* than *OA*. For the treatments with deficit irrigation during consecutive stages of *Stage II* and *Stage III*, except $F_{8/9}R_{8/9}$ in 2011 season, all the fruit quality parameters were increased by different degrees, compared with those of *CK*.

3.2. Water-yield relationships and water-fruit quality relationships

The relationship of relative tomato yield (Y_a/Y_{ck}) with relative seasonal *ET* (ET_a/ET_{ck}) and the relationships of relative yield reduction ($1 - Y_a/Y_{ck}$) with relative *ET* deficit at *Stage II* and *Stage III* ($1 - ET_{a2}/ET_{ck2}$ and $1 - ET_{a3}/ET_{ck3}$) were studied, considering the pooled data of 4 growing seasons. The results are presented in Fig. 1a and b, respectively. The relationship of Y_a/Y_{ck} with ET_a/ET_{ck} was best fitted with a linear function with the slope value and determination coefficient (R^2) of 0.78 and 0.85, respectively. The treatments with deficit irrigation during only one growth stage (*Stage II* or *Stage III*) were used to evaluate the relationships of $1 - Y_a/Y_{ck}$ with $1 - ET_{a2}/ET_{ck2}$ and $1 - ET_{a3}/ET_{ck3}$. The correlation analysis showed that the relative yield reduction was significantly correlated with $1 - ET_{a2}/ET_{ck2}$ and $1 - ET_{a3}/ET_{ck3}$. The relationships were well fitted using a linear regression forced to the origin with the regression coefficients of 0.21 and 0.28, respectively.

The relationships of relative values of fruit quality parameters (TSS_a/TSS_{ck}, RS_a/RS_{ck}, OA_a/OA_{ck}, SAR_a/SAR_{ck}, VC_a/VC_{ck}, Fn_a/Fn_{ck}, CI_a/CI_{ck}) with ET_a/ET_{ck}, $1 - ET_{a2}/ET_{ck2}$ and $1 - ET_{a3}/ET_{ck3}$ are presented in Fig. 1c–p, considering the pooled data of 4 growing seasons. The observed data showed good negative linear relationships between TSS_a/TSS_{ck}, RS_a/RS_{ck}, OA_a/OA_{ck}, SAR_a/SAR_{ck}, VC_a/VC_{ck},

Table 6
Tomato quality parameters for different irrigation treatments in 4 growing seasons (*TSS*—total soluble solids, *RS*—reducing sugars, *OA*—organic acids, *VC*—vitamin C, *Fn*—fruit firmness, *CI*—color index, *SAR*—sugar/acid content ratio).

Cropping season	Treatment	*TSS* (°Brix)	*RS* (g 100 g FW^{-1})	*OA* (g 100 g FW^{-1})	*VC* (mg kg FW^{-1})	*Fn* (kg cm^{-2})	*CI*	*SAR*
2008/09	$V_{1/3}$	4.57cd [a]	3.44b	0.432c	73.6c	5.25d	32.3bc	7.96bc
	$V_{2/3}$	4.50cd	3.47b	0.436bc	73.6c	5.36d	33.9abc	7.96bc
	$F_{1/3}$	5.06a	4.08a	0.486a	85.8b	5.93b	35.0a	8.40a
	$F_{2/3}$	4.64c	3.60b	0.449bc	78.1bc	5.62c	34.3ab	8.02b
	$R_{1/3}$	4.98ab	4.07a	0.482a	101.1a	6.19a	36.5a	8.44a
	$R_{2/3}$	4.88b	3.67b	0.454b	86.8b	5.64c	35.9a	8.06b
	CK	4.66c	3.38b	0.438bc	72.8c	5.23d	30.2c	7.72c
2009/10	$F_{1/3}$	6.02b	2.91b	0.311a	183.6bc	8.26a	35.8a	9.36bc
	$F_{2/3}$	5.44c	2.55c	0.273cd	176.4bc	7.90ab	33.5b	9.34bc
	$R_{1/3}$	6.16a	3.29a	0.300b	217.4a	8.37a	35.4a	10.99a
	$R_{2/3}$	5.91b	2.82b	0.285c	199.2ab	7.96ab	33.8b	9.91b
	CK	5.55c	2.60c	0.283c	163.2c	7.39ab	31.3c	9.20c
2011	$F_{8/9}R_{8/9}$	4.86d	2.45d	0.374d	167.5d	5.45b	33.4c	6.53c
	$F_{7/9}R_{7/9}$	5.51c	2.59cd	0.398c	179.1cd	5.84a	35.8b	6.52c
	$F_{6/9}R_{6/9}$	5.67bc	2.86bc	0.407c	185.5bc	5.94a	36.3ab	7.01bc
	$F_{5/9}R_{5/9}$	5.76b	3.17b	0.423b	198.7ab	5.92a	36.7ab	7.50ab
	$F_{4/9}R_{4/9}$	6.11a	3.64a	0.440a	204.9a	6.05a	37.4a	8.27a
	CK	4.99d	2.46d	0.376d	166.4d	5.43b	32.5c	6.55c
2012/13	$F_{1/3}$	5.70bc	3.76bc	0.452ab	143.6a	4.58abc	37.8bc	8.32de
	$F_{2/3}$	5.33c	3.39c	0.417de	120.7bc	4.27cde	36.5cd	8.15e
	$R_{1/3}$	6.33ab	4.63a	0.435bc	150.2a	4.71ab	41.1a	10.24a
	$R_{2/3}$	5.28c	3.44c	0.400e	136.4ab	4.00e	36.4cd	8.58de
	$F_{2/3}R_{2/3}$	5.90abc	3.83bc	0.431cd	141.1a	4.16de	39.1abc	8.89cd
	$F_{2/3}R_{1/3}$	5.78bc	4.20ab	0.457a	150.6a	4.75ab	38.9abc	9.48bc
	$F_{1/3}R_{2/3}$	6.22ab	4.42ab	0.445abc	148.4a	4.49bcd	39.1abc	9.93ab
	$F_{1/3}R_{1/3}$	6.63a	4.79a	0.452ab	151.7a	4.91a	40.1ab	10.59a
	CK	5.22c	3.34c	0.402e	117.6c	3.95e	35.1d	7.98e

[a] Values followed by the same letter within columns and each cropping season are not significantly different at 0.05 *P* level by *LSD* test.

Fn_a/Fn_{ck} and ET_a/ET_{ck} (Fig. 1c, e, g, i, k, m and o). Linear regression analysis was performed to evaluate the relationships of TSS_a/TSS_{ck}, RS_a/RS_{ck}, OA_a/OA_{ck}, SAR_a/SAR_{ck}, VC_a/VC_{ck}, Fn_a/Fn_{ck} and CI_a/CI_{ck} with $1-ET_{a2}/ET_{ck2}$ and $1-ET_{a3}/ET_{ck3}$ using the data from the treatments with deficit irrigation during only one growth stage (*Stage II* or *Stage III*). The results showed that significant positive linear relationships were found between relative values of all the fruit quality parameters and $1-ET_{a3}/ET_{ck3}$. And the coefficients of determination (R^2) and the test of significance of regression (*P* value) imply that the goodness of fit is fairly good. However, only VC_a/VC_{ck}, Fn_a/Fn_{ck} and CI_a/CI_{ck} were significantly related with $1-ET_{a2}/ET_{ck2}$, though the other fruit quality parameters showed a rising trend with the increase of $1-ET_{a2}/ET_{ck2}$.

3.3. Water deficit sensitivity indexes of the models

The field experimental data obtained from 2008/09, 2009/10 and 2011 seasons were used to calculate water deficit sensitivity indexes of the models with the method of multiply linear regression. Table 7a shows the tomato yield water deficit sensitivity indexes ($\lambda/Ky/\delta$) at various growth stages for water-yield models like Jensen, Stewart and Minhas models. The test of significance of regression coefficients indicated that tomato yield water deficit sensitivity indexes of *Stage I* was not significant for all the three models at the 5% of probability level, but those of *Stage II* and *Stage III* were significant at the 1% and 0.1% of probability level, respectively. For all the three models, the largest water deficit sensitivity indexes were observed at *Stage III*, followed by those of *Stage II*, and *Stage I* had the least. Moreover, the sensitivity indexes were close to 0 at *Stage I*, much smaller than those of *Stage II* and *Stage III* for all the three models.

The water deficit sensitivity indexes of fruit quality parameters ($\gamma/Kq/\psi$) at various growth stages for three water-fruit quality models (multiplicative, additive and exponential models) are given in Table 7b. Like the water-yield models, the test of significance of regression coefficients showed that the water deficit sensitivity indexes of all the fruit quality parameters (*TSS*, *RS*, *OA*, *SAR*, *VC*, *Fn*, *CI*) of *Stage I* were not significant at the 5% of probability level for all the three models, but those of *Stage II* and *Stage III* were significant at the 5% and 0.1% of probability level, respectively. The water deficit sensitivity indexes of multiplicative model were negative for all the fruit quality parameters while those of additive and exponential model were positive. The largest water deficit sensitivity indexes of *TSS*, *RS*, *SAR*, *VC*, *Fn* and *CI* were recorded at *Stage III* for all the three models, followed by those of *Stage II*, and *Stage I* had the least. But for OA, the sensitivity indexes were observed larger at *Stage II* than *Stage III* for all the three models, though the values were close to each other. The sensitivity indexes of *Stage II* and *Stage III* were also observed close to each other for both *Fn* and *CI*. For all three models, the sensitivity indexes of all the fruit quality parameters of *Stage I* were close to 0, much smaller than those of *Stage II* and *Stage III*.

3.4. Performance of the models in prediction

The field experimental data obtained in 2012/13 season was used to validate the models and their water deficit sensitivity indexes calculated from the field data in 2008–2009, 2009–2010 and 2011 seasons. The performance of the models in predicting tomato yield and fruit quality parameters was evaluated by comparing field measured data with simulated values obtained from the models. Fig. 2a shows the comparisons between measured relative values of tomato yield and simulated ones obtained from Jensen, Stewart and Minhas models, and Table 8a shows the goodness of fit indicators for the comparisons. There was a close agreement between measured relative yields and the simulated values of each model (Fig. 2a). For Minhas model, regression coefficient (*b*) was 0.99 and coefficient of determination (R^2) was 0.94 (Table 8a); thus, the simulated values were close to the measured ones and most of the variation of the measured values was explained by the model. For Jensen and Stewart models, the values of *b* were both 0.97, indicating the simulated values slightly underestimated the measured ones, while R^2 were 0.93 and 0.88, thus showing a high explanation of the variance by the models. For all the three models errors

Table 7
(a) The water deficit sensitivity indexes of tomato yield at various growth stages for different models.

Model	Sensitivity index ($\lambda/Ky/\delta$)			R^2
	Stage I[ns]	*Stage II*[**]	*Stage III*[***]	
Jensen	0.0868	0.2561	0.3086	0.85
Stewart	0.0593	0.2939	0.3520	0.90
Minhas	0.0552	0.6721	0.8176	0.75

(b) The water deficit sensitivity indexes of tomato fruit quality parameters at various growth stages for different models.

Quality parameters	Model	Sensitivity index ($\gamma/Kq/\psi$)			R^2
		Stage I[ns]	*Stage II*[*]	*Stage III*[***]	
TSS	Multiplicative	−0.0006	−0.1163	−0.1666	0.82
	Additive	0.0091	0.1557	0.2387	0.84
	Exponential	0.0007	0.1442	0.2238	0.84
RS	Multiplicative	−0.0961	−0.1950	−0.3260	0.92
	Additive	0.1099	0.2804	0.4901	0.90
	Exponential	0.0913	0.2474	0.4274	0.92
OA	Multiplicative	−0.0100	−0.1261	−0.1154	0.85
	Additive	0.0061	0.1694	0.1607	0.85
	Exponential	0.0045	0.1590	0.1525	0.85
SAR	Multiplicative	−0.0417	−0.1042	−0.2470	0.88
	Additive	0.0576	0.1496	0.3643	0.86
	Exponential	0.0484	0.1364	0.3248	0.88
VC	Multiplicative	−0.0531	−0.1253	−0.3677	0.90
	Additive	0.0663	0.1430	0.5694	0.90
	Exponential	0.0625	0.1463	0.4948	0.91
Fn	Multiplicative	−0.0368	−0.1429	−0.1549	0.87
	Additive	0.0424	0.1888	0.2189	0.87
	Exponential	0.0418	0.1804	0.2051	0.88
CI	Multiplicative	−0.0544	−0.1617	−0.1659	0.91
	Additive	0.0595	0.2160	0.2363	0.93
	Exponential	0.0577	0.2046	0.2217	0.93

[ns] The test of significance of regression coefficients is not significant at 0.05 *P* level.
[*] The test of significance of regression coefficients is significant at 0.05 *P* level.
[**] The test of significance of regression coefficients is significant at 0.01 *P* level.
[***] The test of significance of regression coefficients is significant at 0.001 *P* level.

Table 8
(a) Goodness of fit indicators for the comparisons between measured relative values of tomato yield and those simulated by various models in 2012/13 season.

Model	*b*	R^2	*RMSE*	*AAE*	*EF*	d_{IA}
Jensen	0.97	0.93	0.038	0.031	0.85	0.96
Stewart	0.97	0.88	0.043	0.036	0.81	0.95
Minhas	0.99	0.94	0.030	0.024	0.90	0.98

(b) Goodness of fit indicators for the comparisons between measured relative values of fruit quality parameters and those simulated by various models in 2012/13 season.

Quality parameters	Model	*b*	R^2	*RMSE*	*AAE*	*EF*	d_{IA}
TSS	Multiplicative	0.98	0.77	0.039	0.032	0.82	0.94
	Additive	0.98	0.58	0.045	0.037	0.76	0.91
	Exponential	0.98	0.63	0.044	0.036	0.77	0.92
RS	Multiplicative	1.00	0.86	0.054	0.046	0.88	0.97
	Additive	1.00	0.74	0.062	0.049	0.84	0.95
	Exponential	1.00	0.78	0.060	0.046	0.85	0.95
OA	Multiplicative	1.00	0.61	0.035	0.026	0.53	0.88
	Additive	1.00	0.63	0.030	0.023	0.65	0.90
	Exponential	1.00	0.63	0.031	0.024	0.63	0.90
SAR	Multiplicative	0.99	0.89	0.037	0.023	0.90	0.97
	Additive	0.99	0.79	0.043	0.032	0.86	0.95
	Exponential	0.98	0.80	0.043	0.030	0.86	0.95
VC	Multiplicative	1.00	0.66	0.088	0.057	0.26	0.87
	Additive	1.00	0.75	0.064	0.041	0.62	0.92
	Exponential	1.00	0.73	0.070	0.045	0.54	0.91
Fn	Multiplicative	0.98	0.60	0.049	0.040	0.65	0.89
	Additive	0.98	0.40	0.053	0.045	0.60	0.86
	Exponential	0.98	0.45	0.052	0.044	0.60	0.87
CI	Multiplicative	1.02	0.67	0.051	0.031	0.03	0.84
	Additive	1.02	0.71	0.043	0.032	0.31	0.86
	Exponential	1.02	0.69	0.047	0.034	0.18	0.85

estimation indicators were low, with *RMSE* ranging from 0.030 to 0.048 and *AAE* from 0.024 to 0.036. The lowest *RMSE* and *AAE* were both observed in Minhas model. The indicators on the quality of modeling were good for all the models: *EF* was 0.81–0.90, implying that the models' simulated values could fit the measured data very well; d_{IA} were 0.95–0.98, indicating a fairly good agreement between the simulated values with the measured ones. The highest *EF* and d_{IA} were both found in Minhas model.

The comparisons between the measured relative values of fruit quality parameters and the simulated ones obtained from multiplicative, additive and exponential models are presented in Fig. 2b–h, and the goodness of fit indicators for the comparisons are

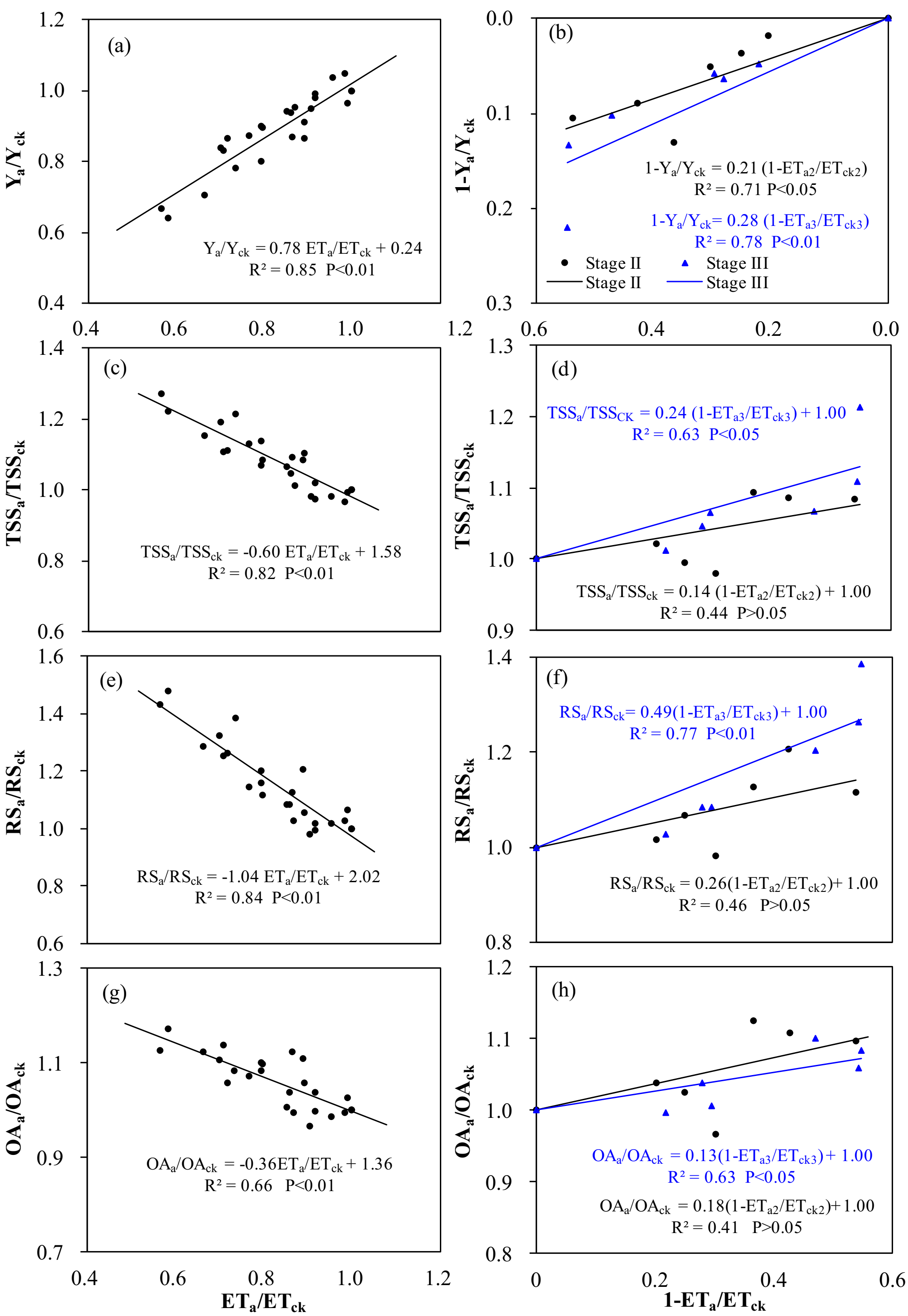

Fig. 1. The relationships between relative values of tomato yield (Y_a/Y_{ck}), fruit quality parameters (TSS_a/TSS_{ck}, RS_a/RS_{ck}, OA_a/OA_{ck}, SAR_a/SAR_{ck}, VC_a/VC_{ck}, Fn_a/Fn_{ck}, CI_a/CI_{ck}) and relative seasonal *ET* (ET_a/ET_{ck}), and the relationships between relative yield reduction ($1 - Y_a/Y_{ck}$), relative values of fruit quality parameters and relative *ET* deficit at *Stage II* and *III* ($1 - ET_{a2}/ET_{ck2}$ and $1 - ET_{a3}/ET_{ck3}$).

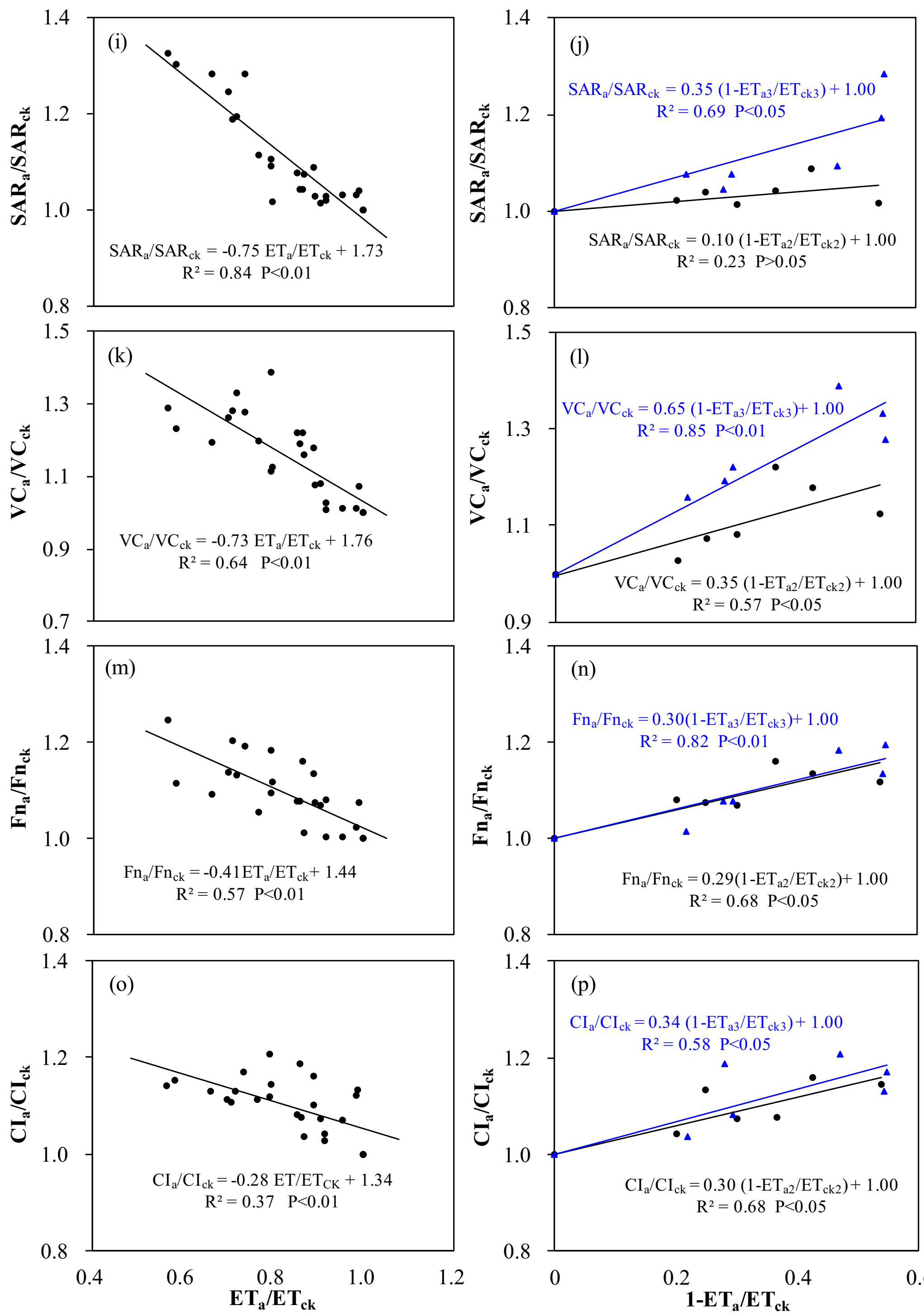

Fig. 1. (*Continued*).

given in Table 8b. There was a good agreement between the measured relative values of *TSS*, *RS*, *SAR* and the ones simulated by the three models (Fig. 2b, c, e). For these three fruit quality parameters, the simulated relative values of the three models were statistically close to the measured ones with the values of *b* ranging from 0.98 to 1.00; and the models could explain most of the variation of the measured data with R^2 of 0.58–0.89 (Table 8b). The best modeling performance in simulating *TSS*, *RS* and *SAR* was observed in multiplicative model, which had the lowest *RMSE* and *AAE* and the highest *EF* and d_{IA} among the three models (Table 8b).

A good agreement was also observed between the measured relative values of *OA*, *VC*, *CI* and the simulated ones obtained from the three models with *b* of 1.00–1.02 and R^2 of 0.61–0.75 (Fig. 2d, h and f; Table 8b). Among the three models, additive model performed better than the other two models in predicting *OA*, *VC* and *CI* because of the lowest *RMSE* and *AAE* and the highest *EF* and d_{IA}. The largest discrepancies between measured and simulated relative values of *VC* were in $F_{1/3}$ and $F_{1/3}R_{1/3}$ treatments, and that of *CI* was in $F_{1/3}R_{1/3}$ treatment. Compared to the field measured values, the simulated ones were much lower in $F_{1/3}$

for *VC* but much higher in $F_{1/3}R_{1/3}$ for both *VC* and *CI*. When the treatments were excluded from the comparisons between the measured and simulated values, the models' performance on *VC* and *CI* would be greatly improved; the *RMSE* in the comparisons for *VC* would decrease from 0.088 to 0.034, from 0.070 to 0.021 and from 0.064 to 0.020 for multiplicative model, exponential and additive model, respectively; the d_{IA} in the comparisons for *CI* would increase from 0.03 to 0.73, from 0.31 to 0.62 and from 0.18 to 0.60 for multiplicative, additive and exponential model, respectively. As for *Fn*, there was a good agreement between the measured data and the values simulated by multiplicative model with *b* value of 0.98 and R^2 of 0.60; the modeling performance of the other two models was not so good because of the low R^2 (0.40 and 0.45) (Fig. 2g).

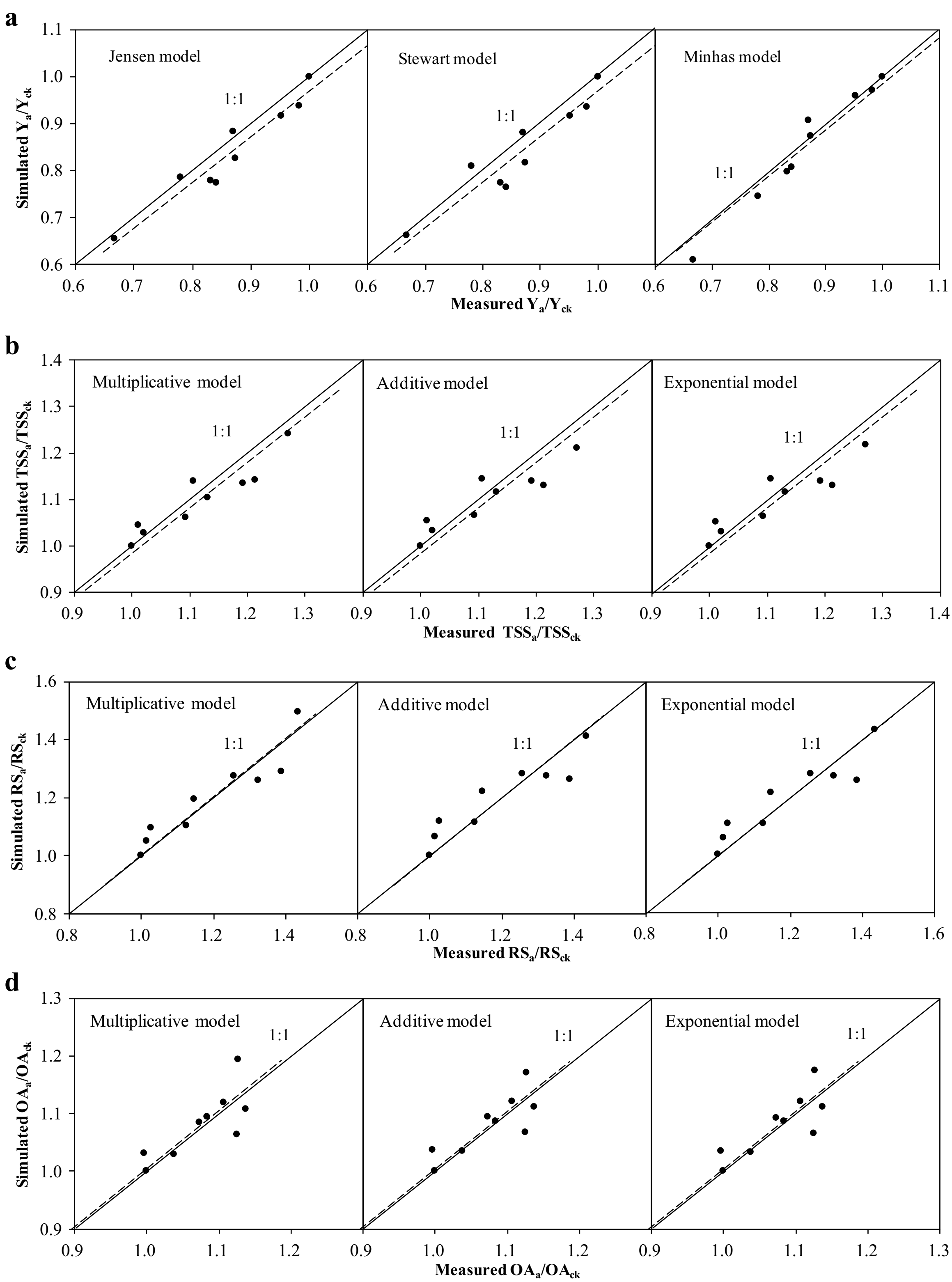

Fig. 2. Comparison between simulated and measured relative values of *Y* (a), *TSS* (b), *RS* (c), *OA* (d), *SAR* (e), *VC* (f), *Fn* (g), *CI* (h) for various models in 2012/13 season.

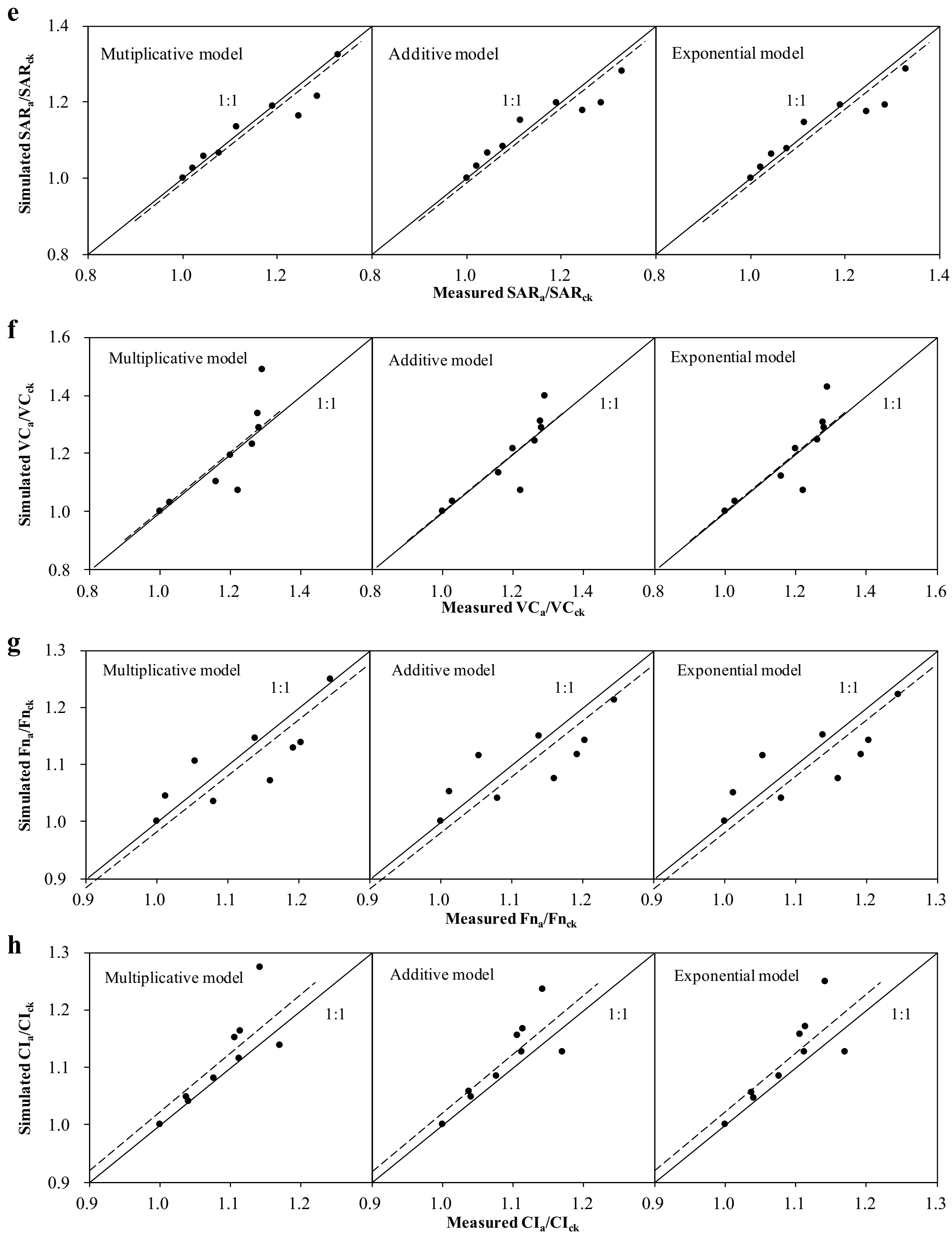

Fig. 2. (*Continued*).

3.5. Sensitivity analysis

To understand the response of the models to fluctuations of the inputs, a sensitivity analysis to relative *ET* (ET_{ai}/ET_{cki}) and water deficit sensitivity indexes ($\lambda_i/Ky_i/\delta_i$ or $\gamma_i/Kq_i/\psi_i$) at each growth stage was performed. The mean normalized sensitivity coefficients (*SC*) for the relative yield obtained from Jensen, Stewart and Minhas models are given in Fig. 3a. The negative values of *SC* mean that the calculated relative yields decrease with the increase of the inputs, and the positive values indicate the otherwise. Models are more sensitive to the inputs with higher absolute values of *SC*. Results showed that all the three water-yield models were mainly sensitive to the relative *ET* at *Stage II* and *Stage III* (ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}), which had *SC* ranged from 0.257 to 0.311 and from 0.310 to 0.378, respectively. The sensitivity of the three models to $\lambda_2/Ky_2/\delta_2$ and $\lambda_3/Ky_3/\delta_3$ was low with the absolute values of *SC* ranged from 0.063

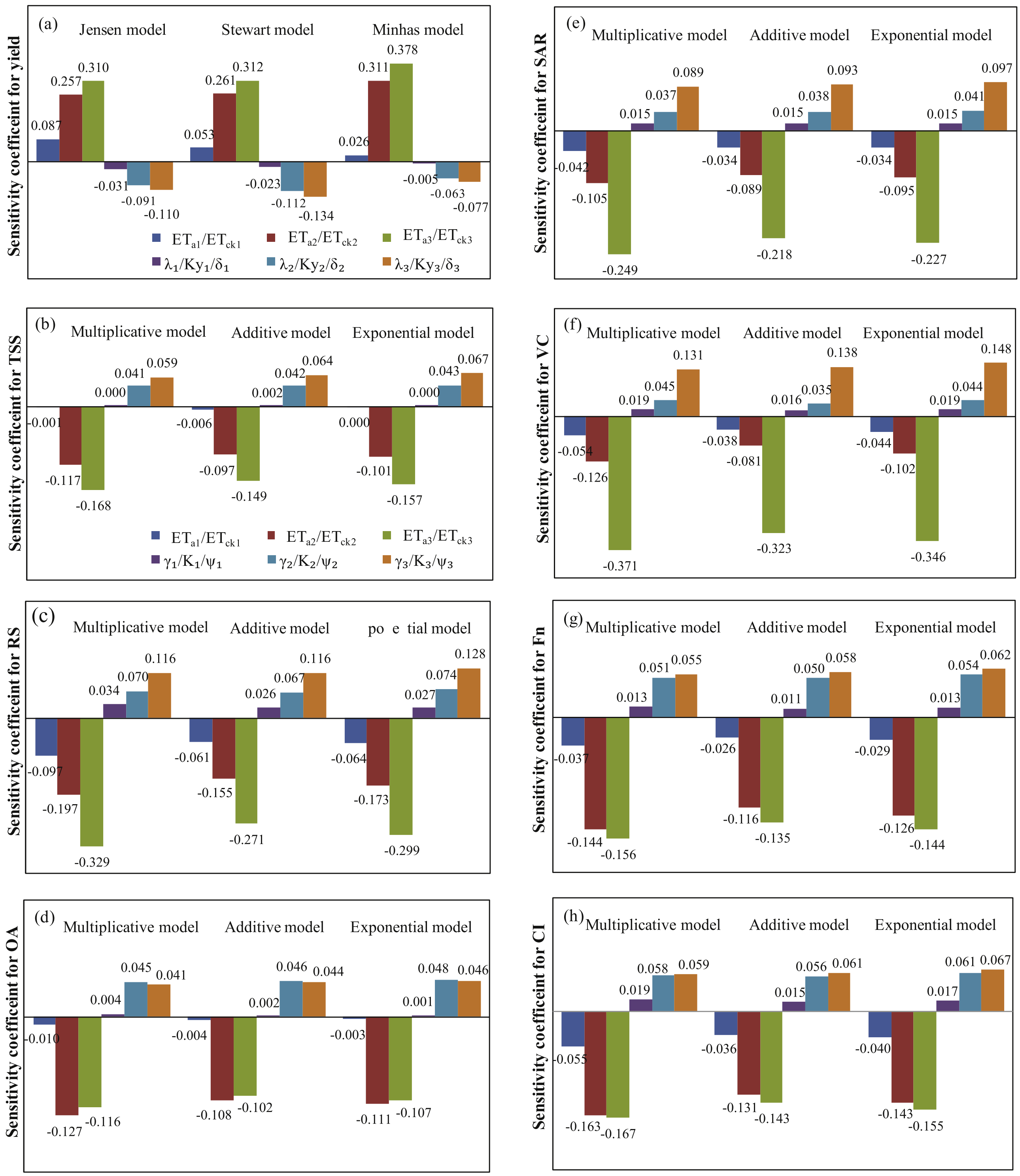

Fig. 3. Mean normalized sensitivity coefficients for the relative values of yield (a), *TSS* (b), *RS* (c), *OA* (d), *SAR* (e), *VC* (f), *Fn* (g), *CI* (h) calculated from different models according to given variations of ET_{ai}/ET_{cki}, $\lambda_i/Ky_i/\delta_i$ and $\gamma_i/Kq_i/\psi_i$.

to 0.112 and from 0.077 to 0.134, respectively. All the models were hardly sensitive to ET_{a1}/ET_{ck1} and $\lambda_1/Ky_1/\delta_1$. Among the three models, Minhas model had higher absolute values of *SC* for ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}, and lower absolute values of *SC* for ET_{a1}/ET_{ck1} and $\lambda_i/Ky_i/\delta_i$ than the other two models.

Fig. 3b–h presents the *SC* for relative values of *TSS*, *RS*, *OA*, *SAR*, *VC*, *Fn*, CI obtained from multiplicative, additive and exponential models. All the three water-fruit quality models had negative *SC* values of ET_{ai}/ET_{cki} but positive values of $\gamma_i/Kq_i/\psi_i$ for the fruit quality parameters, indicating that the fruit quality parameters increased with the decrease of ET_{ai}/ET_{cki} and the rise of the absolute values of $\gamma_i/Kq_i/\psi_i$. As for *TSS*, *RS*, *SAR* and *VC* (Fig. 3b, c, e and f), the three water-fruit quality models were found the most sensitive to ET_{a3}/ET_{ck3}, followed by ET_{a2}/ET_{ck3} and $\gamma_3/Kq_3/\psi_3$; the sensitivity of the models to ET_{a1}/ET_{ck1} and $\gamma_2/Kq_2/\psi_2$ was low; and all the models were hardly sensitive to $\gamma_1/Kq_1/\psi_1$. But for *OA*, *Fn* and *CI* (Fig. 3d, g and h), all the models were mainly sensitive to ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}, whose values of *SC* were similar to each other; the sensitivity of the models to $\gamma_2/Kq_2/\psi_2$ and $\gamma_3/Kq_3/\psi_3$ was low with *SC* in the range of 0.045–0.061 and 0.041–0.067, respectively, and that to ET_{a1}/ET_{ck1} and $\gamma_1/Kq_1/\psi_1$ was almost nil. In general, the *SC* values of additive model were similar to those of exponential model for each fruit quality parameter, and multiplicative model had higher absolute *SC* values of ET_{ai}/ET_{cki} and lower *SC* values of $\gamma_i/Kq_i/\psi_i$ than the other two models.

4. Discussion

Tomato is one of the most water demanding crops (Peet, 2005). The irrigation is the only source of water supply for crops in greenhouses, thus making it one of the most critical factors influencing tomato production in greenhouses. It has been widely reported that deficit irrigation depressed tomato yield but enhanced some fruit quality parameters, depending on period and degree of water deficit (Mitchell et al., 1991; Pulupol et al., 1996; Nuruddin et al., 2003; Zegbe et al., 2006; Marouelli and Silva, 2007; Favati et al., 2009; Patanè and Cosentino, 2010). The fact was confirmed by the results presented in this study; tomato yield was reduced by the treatments with deficit irrigation during flowering and fruit development stage (*Stage II*), e.g. $F_{1/3}$, fruit ripening stage (*Stage III*), e.g. $R_{1/3}$ and $R_{2/3}$, and both the stages, e.g. $F_{7/9}R_{7/9}$–$F_{4/9}R_{4/9}$ and $F_{2/3}R_{2/3}$–$F_{1/3}R_{1/3}$, while the fruit quality parameters (e.g. *TSS*, *RS*, *SAR*, *VC* etc.) of these treatments were increased. There were no significant differences in tomato yield, fruit quality parameters such as *TSS*, *RS*, *OA* and *VC* between $F_{2/3}$ and *CK* in 2008/09, 2009/10 and 2012/13 seasons, which is probably because the reduction of 1/3 full irrigation amount at *Stage II* did not cause enough water stress to affect the tomato yield and fruit quality significantly. It is perhaps the similar situation that the reduction of irrigation amount in $F_{8/9}R_{8/9}$ of 2011 season did not affect the tomato yield and fruit quality significantly. It is in expectation that $V_{1/3}$ and $V_{2/3}$ did not influence tomato yield and fruit quality significantly since water limitation at the vegetative stage is too early to affect fruit quality, which was in agreement with the previous findings (Zegbe et al., 2006; Marouelli and Silva, 2007).

Information about relationships between tomato yield and crop water consumption is useful for efficient irrigation management. In the present study, a linear model best fitted the relationship of relative yield with relative seasonal *ET*, indicating that relative yield increased linearly with relative seasonal *ET*. The linear relations between tomato yield and seasonal *ET* were also reported in other studies (Zheng et al., 2013; Kuscu et al., 2014). However, the relationships were not always linear, which may depend on the range of relative seasonal *ET*. The linear regression equation of this study indicated that a relative yield of 0.24 could be achieved even without seasonal *ET* (Fig. 1a), which is obviously invalidated. Therefore, it was supposed that the relations of relative yield with relative seasonal *ET* may be curvilinear when the relative seasonal *ET* is beyond the range of 0.55–1.00. Patanè et al. (2011) reported that an exponential curve best fitted the relationship of tomato yield with seasonal *ET*.

The differential influence of water deficit during various growth stages on tomato yield was quantified by the relationships of relative yield reduction with relative *ET* deficit at flowering and fruit development stage (*Stage II*) and fruit ripening stage (*Stage III*) (Fig. 1b). The regression and determination coefficients of the linear equations indicated that *Stage II* and *Stage III* were both sensitive to water deficit in terms of yield. Rudich et al. (1977) reported that the period of fruit growth was most responsible for the improvement of tomato yield, which was also confirmed by Nuruddin et al. (2003). In this study, due to the indeterminate nature of the tomato crop, fruit development and fruit ripening stage overlaps; thus when the first truss of fruits start to ripe, the other trusses are still growing. Consequently, tomato yield was depressed by the water deficit during either *Stage II* or *Stage III*.

The reduction of tomato yield under deficit irrigation was accompanied by the improvement of fruit quality, indicating the contradictory relationship between yield and fruit quality. Linear regressions of processing tomato quality parameters vs seasonal irrigation volume by Favati et al. (2009) indicated that *TSS*, *VC* and lycopene were negatively correlated with seasonal irrigation volume. A similar study by Patanè and Cosentino (2010) showed curvilinear rise of *TSS*, *RS*, *OA*, *Fn* and fruit color with the soil water deficit. As one of the most important tomato fruit quality parameters, *TSS* indicates the proportion (%) of dissolved solids in a solution, which includes about 65% sugars (sucrose and hexoses), 13% acids (citrate and malate) and 12% other minor components (phenols, amino acids, soluble pectins, ascorbic acid and minerals) in the tomato fruit pulp (Balibrea et al., 2006; Kader, 2008). In this study, *TSS*, *RS* and *OA* decrease with the rise of relative seasonal *ET*. As previously reported in other studies, *TSS* was negatively correlated with water supplied (Cahn et al., 2002; Machado and Oliveira, 2005; Ozbahce and Tari, 2010; Kuscu et al., 2014). With water stress, the flux of the phloem sap supplied to the fruit decrease but the concentration of solute in sap increase (Ehret and Ho, 1986; Ho et al., 1987), which results in a reduced water uptake from fruits and a low dilution in the fruits but not an accumulation of fruit compounds such as sugars and acids (Ehret and Ho, 1986; Mitchell et al., 1991; Guichard et al., 1999). This would lead to an increase in the concentration of dry matter and of various components (e.g. sugars, acids) of the fruit (Ehret and Ho, 1986; Mitchell et al., 1991).

Many studies stated that water deficit seems generally to tend to increase *VC* in tomato fruit (Veit-Köhler et al., 1999; Dumas et al., 2003; Favati et al., 2009; Patanè et al., 2011). Positive correlations between *VC* and sugars content have been well described in fruit (Causse et al., 2003; Stevens et al., 2007), though the pathway of *VC* synthesis in plants and its regulation remain unknown (Conklin et al., 1998; Wheeler et al., 1998). This correlation between *VC* and sugars content could be linked to the role of sugars as a substrate for *VC* biosynthesis (Wheeler et al., 1998), but also to the well-known role of sugars acting as a signal that promote gene expression (Smeekens, 2000; Hanson and Smeekens, 2009). In the present study, both *RS* and *VC* were found to be significantly and negatively correlated with seasonal *ET*. It was assumed that *VC* synthesis was promoted during fruit ripening by the higher sugars concentration in the fruits with the lower water supply (Veit-Köhler et al., 1999). In addition light is reported to be a major factor influencing *VC* content in fruits (Dumas et al., 2003), and its role seemed to be predominant in the absence of substrate limitation (Gautier et al., 2009; Massot et al., 2010). But it may be not the case in this study since the study area is rich in light resource and fruits of all the treatments were supposed to received nearly the same sunlight (Table 4).

Tomato fruit with high *Fn* is favored by both growers and consumers due to the longer storage duration (Kader, 1986; Shewfelt, 2000). In the present study, *Fn* was enhanced by water deficit, which is in agreement with the findings by Patanè and Cosentino (2010) that the increasing soil water deficit during fruit enlargement and maturity improved fruit firmness. The increase in *Fn* under water deficit may be associated with a decrease of internal turgor which could lead to a lower pressure on the cell walls and then to a higher epidermal elasticity (Guichard et al., 2001).

The color of red tomatoes is mainly associated with lycopene content in tomato fruit (Arias et al., 2000); it is reported that the color values (a/b) were highly correlated with the lycopene content (Johjima and Matsuzoe, 1995). *CI* was found to increase with the degrees of water deficit in this study, just like the previous findings that *CI* was positively affected by water stress during fruit growth and fruit ripening stages (Nuruddin et al., 2003). This result may be attributed to a rise of tomato fruit ethylene content under water stress (Basiouny et al., 1994), which in turn may increase the lycopene content of tomato fruit (Ishida et al., 1993; Pulupol et al., 1996), thus enhancing the fruit color. Zushi and Matsuzoe (1998) also found that soil water deficit tended to increase the lycopene content of red and pink large-fruited tomatoes.

At the onset of fruit ripening, many reactions take place which ultimately are responsible for high fruit quality (Ishida et al., 1993). In the present study, significant and positive linear relationships were found between tomato fruit quality parameters e.g. *TSS*, *RS*, *OA*, *VC* et al. and $1-ET_{a3}/ET_{ck3}$, demonstrating that tomato fruit quality was mainly influenced by water deficit during fruit ripening stage. The fact was confirmed by the findings that tomato fruit quality was improved by water deficit during fruit ripening period (Veit-Köhler et al., 1999; Nuruddin et al., 2003; Johnstone et al., 2005; Marouelli and Silva, 2007; Favati et al., 2009).

The water-yield models, also known as dated crop water production function (*DCWPF*), were widely used to evaluate the relationships between water deficit and the grain yield of cereal crops, e.g. rice, maize and wheat (Mao et al., 1994; Zhang and Oweis, 1999; Zhang et al., 1999; Igbadun et al., 2007). But few studies were conducted on tomato crops (Xu et al., 2001). As it was mentioned above, due to the indeterminate nature of the tomato crop, the overlaps of fruit development and fruit ripening lead to many times of harvest during the fruit ripening stage. When the early ripen fruits were harvested, the water deficit would not affect them but the rest of fruits which were still developing and ripening. In the present study, at the end of the cropping season the yield of each harvest was summed up as the total yield (*Y*) which was used to calibrate and validate the water-yield models. That is, the models investigated the overall influence of the water deficit during fruit ripening stage on the total yield. The water deficit sensitivity indexes ($\lambda_i/Ky_i/\delta_i$) quantify the sensitivity of tomato yield to the water deficit at each growth stage and tomato yield is more sensitive to water deficit at the growth stage with larger sensitivity index. In this study, Jensen, Stewart and Minhas models had similar patterns of the seasonal change of the $\lambda/Ky/\delta$ values. For all the models, the largest values were observed at *Stage III*, implying that *Stage III* was the most sensitive stage to water deficit in terms of yield; the $\lambda/Ky/\delta$ values of *Stage II* were a little smaller than those of *Stage III*, which was consistent with the condition of the regression coefficients of linear equations given in Fig. 1b (0.21 for *Stage II* and 0.28 for *Stage III*); in spite of the insignificance of the test of regression coefficients, the $\lambda/Ky/\delta$ values of *Stage I* were the least and close to 0, indicating that tomato yield was not sensitive to water deficit at *Stage I*. The pattern of seasonal change of the $\lambda/Ky/\delta$ values was in accordance with the nature growth law of tomato crop since fruit growth was the most sensitive to water deficit (Rudich et al., 1977; Nuruddin et al., 2003).

Despite the differences among the three water-yield models, the performance of Jensen, Stewart and Minhas models in simulating the relationships of tomato yield with water deficit was fairly good, in view of the fact that empirical models rarely perfectly simulate field data due to some inherent variability in field data that models may not capture. By assessing the coefficients of regression (*b*), estimation errors (*RMSE* and *AEE*) and quality of modeling (*EF* and d_{IA}) of the comparisons for the three models (Table 8a), it could be found that Minhas model had the best performance on simulating the relationships of tomato yield with water deficit, followed by Jensen model, then by Stewart model. Xu et al. (2001) reported that Jensen model could simulate the water-yield relations of greenhouse tomato very well, but in the present study Minhas model could be a better choice. According to the sensitivity analysis of the models, the small *SC* value of ET_{a1}/ET_{ck1} demonstrated that the models was not sensitive to the variations of ET_{a1}/ET_{ck1}, which was in agreement with the fact that tomato yield was not sensitive to the water deficit at *Stage I*. And all the three models were sensitive to the variations of ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}, implying the models could very well simulate the yield response to variations of water consumption during tomato fruit growth and ripening. Besides, due to the smaller absolute values of *SC* of $\lambda_i/Ky_i/\delta_i$ the models were less sensitive to the water deficit sensitivity indexes, which is beneficial for the models to predict tomato yield with the calculated water deficit sensitivity indexes. In general, the models with high sensitivity to inputs like ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3} and high robustness or low sensitivity to inputs like ET_{a1}/ET_{ck1} and $\lambda_i/Ky_i/\delta_i$ tend to be applied to predict tomato yield under deficit irrigation conditions, since they could better simulate the response of tomato yield to water deficit with the calculated water deficit sensitivity indexes. Compared to Jensen and Stewart models, Minhas model had larger *SC* values of ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3} and smaller absolute *SC* values of ET_{a1}/ET_{ck1} and $\lambda_i/Ky_i/\delta_i$. Therefore, considering the performance and sensitivity analysis, Minhas model would be recommended to simulate water-yield relationship of tomato in this study.

So far as the researches that have been reported, unlike the water-yield relationships, no modeling equations were developed to simulate water-fruit quality relationships. Using the types of water-yield models for reference, attempts were made to simulate tomato fruit quality parameters by three models (multiplicative, additive and exponential models) in this study. Among the three models, the water deficit sensitivity indexes of multiplicative model were negative while those of the other two models were positive, which was relevant to the types of the models. Just like that of the water-yield models, the larger absolute values of water deficit sensitivity indexes ($\gamma/Kq/\psi$) mean the higher sensitivity of the fruit quality parameters to water deficit. *TSS, RS, SAR* and *VC* were sensitive to water deficit at *Stage II*, but much more to water deficit at *Stage III*; *OA*, *Fn* and *CI* were sensitive to water deficit at *Stage II* as well as that of *Stage III* with similar water deficit sensitivity indexes for the two stages; all the quality parameters were hardly sensitive to water deficit at *Stage I*. The fact is consistent with the results of linear regression analysis in Fig. 1d, f, h, j, l, n and p. Concerning the absolute values of the sensitivity indexes for different quality parameters, *RS, SAR* and *VC* were more sensitive to water deficit than *TSS, OA, Fn, and CI*, which is in agreement with the findings about the slope values of the linear equations in Fig. 1c, e, g, i, k, m and o.

Though the water-fruit quality models did not performed as well as the water-yield models, their performance in simulating water-fruit quality relationships were considered adequate. By comparing the goodness of fit indicators among the three models (Table 8b), it could be found that the performance of additive model was very similar to that of exponential model for all the fruit quality parameters, which may be highly relevant to the same additive type of $1-ET_{ai}/ET_{cki}$ in these two models; multiplicative model performed differently from the other two models, and as for *TSS*, *RS*, *SAR* and *Fn* it performed better than the other two models, but for *OA*, *VC* and *CI* it performed worse. According to the sensitivity analysis of the models, the small *SC* value of ET_{a1}/ET_{ck1} indicated that the models were not sensitive to the variations of ET_{a1}/ET_{ck1}, which was in agreement with the fact that tomato fruit quality was not sensitive to water deficit at *Stage I*. All the three models were sensitive to the inputs like ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}, but less sensitive to $\gamma_i/Kq_i/\psi_i$, which is an advantage for the models to predict tomato fruit quality parameters with the calculated water deficit sensitivity indexes. Just like that of water-yield models, generally, the models with high sensitivity to ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3} and low sensitivity to ET_{a1}/ET_{ck1} and $\gamma_i/Kq_i/\psi_i$ tend to be applied to predict tomato fruit quality under deficit irrigation conditions because they could better simulate the response of fruit quality to water deficit. As for the three water-fruit quality models, the *SC* values of additive model were similar to those of exponential model for each fruit quality parameter, but multiplicative model had higher absolute *SC* values of ET_{ai}/ET_{cki} and lower *SC* values of $\gamma_i/Kq_i/\psi_i$ than the other two models. Considering performance and sensitivity analysis of the models, multiplicative model would be selected to simulate the relationships of *TSS, RS, SAR*, and *Fn* with water deficit, while additive model seems to be more suitable for *OA, VC* and *CI* owing to its easier use than exponential model.

The water-yield models and water-fruit quality models have potential use in optimizing irrigation water allocation during the growth season, thus achieving efficient production of greenhouse tomato with high fruit quality in consideration of the compromise between tomato yield and fruit quality. The good performance of the models in simulating tomato yield and fruit quality parameters shows that the calculated water deficit sensitivity indexes of various growth stages in each model could appropriately quantify the effects of deficit irrigation on the yield and fruit quality of greenhouse tomato. However, care must be taken in applying the water deficit sensitivity indexes obtained from this study to simulate relative yield or fruit quality parameters of tomato in other studies due to different environmental conditions and definitions of growth stages. In addition, since the water-yield models and water-fruit quality models are all empirical models, their application may be limited to the location where the study is conducted or that with similar environmental conditions. Therefore, in the next study, physiological knowledge about the response of tomato yield and fruit quality to water deficit should be taken into account for the improvement of the models.

5. Conclusion

Four years of experiments were conducted to investigate water-yield and water-fruit quality relations of greenhouse tomato under deficit irrigation. Tomato yield and fruit quality were significantly influenced by deficit irrigation; the relative yield decreased linearly with the drop of seasonal *ET*, mainly due to the yield depression caused by *ET* deficit at flowering and fruit development stage (*Stage II*) and fruit ripening stage (*Stage III*); the relative values of fruit quality parameters (*TSS, RS, OA, SAR, VC, Fn, CI*) increased with the drop of seasonal *ET*, mostly because of the enhancement by *ET* deficit at *Stage III*. The water deficit sensitivity indexes of various growth stages in water-yield models (Jensen, Stewart and Minhas) and water-fruit quality models (multiplicative, additive and exponential) appropriately quantified the effects of water deficit during specific growth stages on the tomato yield and fruit quality: (1) the yield was sensitive to water deficit at *Stage II* and at *Stage III*, but not at *Stage I*; (2) *RS*, *SAR* and *VC* were much more sensitive to water deficit than *TSS*, *OA*, *Fn* and *CI*; (3) *TSS*, *RS*, *SAR* and *VC* were sensitive to water deficit at *Stage II*, but much more sensitive to that at *Stage III*; (4) *OA*, *Fn* and *CI* were sensitive to water deficit at *Stage II* as well as that of *Stage III* with similar water deficit sensitivity indexes for the two stages; (5) all the fruit quality parameters were hardly sensitive to water deficit at *Stage I*.

The levels of performance of the models in simulating the relative values of tomato yield and fruit quality parameters were good, with Minhas model ranking the first for yield, multiplicative model ranking the first for TSS, *RS*, *SAR* and *Fn*, and additive model ranking the first for *OA*, *VC* and *CI*. All the models are sensitive to the inputs like ET_{a2}/ET_{ck2} and ET_{a3}/ET_{ck3}, but less sensitive to the water deficit sensitivity indexes of different growth stages ($\lambda_i/Ky_i/\delta_i$ or $\gamma_i/Kq_i/\psi_i$), which is beneficial for the models to predict relative values of tomato yield and fruit quality parameters using the sensitivity indexes obtained in this study. The Minhas model with its water deficit sensitivity indexes was recommended to simulate water-yield relations of greenhouse tomato in the study area; multiplicative model and additive model with their water deficit sensitivity indexes were, respectively, recommended to simulate the relationships of fruit quality parameters like *TSS*, *RS*, *SAR*, *Fn* and fruit quality parameters like *OA*, *VC*, *CI* with water deficit at various growth stages. The water-yield models and water-fruit quality models would be helpful to optimize irrigation water allocation during the growth season, thus achieving efficient production of greenhouse tomato considering the compromise between tomato yield and fruit quality.

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