Quantitative response of oil sunflower yield to evapotranspiration and soil salinity with saline water irrigation

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Abstract: Appropriate application of water-salt-crop function model can optimize agricultural water management in regions with declining water supply, such as the Hetao district. Appropriate use of saline water is also based on the effects of irrigation water demand and water quality on crop growth quantitatively. Therefore, oil sunflower growth testing under both water and salt stress was completed from 2013 to 2014. Water salinity levels at 1.7 ds/m, 4 ds/m, 6 ds/m and 8 ds/m were used in the experiments. Two water deficit levels were reported, 60% and 80% of the irrigation quota, which were considered moderate and mild deficit levels, respectively. All treatments were applied in planting the oil sunflower in critical growing periods, namely, floral initiation, anthesis and maturity. Linear, Cobb-Douglas, quadratic and transcendental function models were used to simulate the relative yield, evapotranspiration (ET) and electrical conductivity (EC). The predictive ability and sensitivity of each model were then evaluated. Compared with salt stress, water stress exerted a more significant effect on the oil sunflower yield; the water parameters (a_1 and a_3) were most sensitive in the water-salt-crop function model. Oil sunflower was most sensitive to water and salt stress during anthesis. The transcendental function generally showed a relatively high sensitivity coefficient and a relatively small statistical error. Therefore, the transcendental function is the most appropriate model for simulating and predicting the yield of oil sunflower irrigated with saline water. Applying the water-salt-crop function model in planting of oil sunflower can help in the development and utilization of saline water in the Hetao district.

Keywords: irrigation, water-salt production functions, saline water, water stress, salt stress, oil sunflower, evapotranspiration
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1 Introduction

Fresh water shortage in the Hetao irrigation district has become severe as the allocated water intake from the Yellow River continues to decrease. However, sufficient underground saline water was measured in the Hetao irrigation district, reaching 8.86 billion m^3 with 2-5 g/L mineralization. Therefore, extreme water shortage prompted the rational development and utilization of underground saline water, as well as the application of deficit irrigation, as a significant method to relieve agricultural water shortage. However, either the water stress caused by deficit irrigation or the stress caused by saline water inhibits soil water usage. Therefore, accurately predicting crop yield under this circumstance presents a problem.

Many studies have investigated the response of crops to salinity and water stress. The linear dependence of relative crop yield on relative evapotranspiration under water stress has been validated for various climates and

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irrigation conditions[1-3]. Similarly, numerous studies have proposed a linear relationship between crop yield and salinity[4-6]. Despite the large number of research[7-10], the simultaneous effects of water and salt stress on crop yield remain poorly defined because of the complexity involved. Shani and Dudley[7] reported a piecewise linear relationship, which provided a different view of the relative effects of salt and water stress. This relationship varies from the functions proposed in the study by Letey et al.[4], which predicted that yield response to combined stress is additive. Kiani and Mirlatifi[10] and Singh et al.[9] also assumed a curvilinear relationship between grain yield and applied water at a given salinity level. Therefore, the quantitative relationship among crop yield, salinity and water use must be elucidated.

A considerable number of studies, mostly based on models, have been conducted to develop proper irrigation management of saline water[10-13]. Production functions can most conveniently explain the relationship of mutative environmental variables[14]. Russo and Baker[15] reported that yield production functions for cotton and sweetcorn should be described using a nonlinear form rather than the piecewise linear expression by Maas and Hoffman[16]. Datta, et al.[8] demonstrated that wheat yield is directly influenced by quantity and salinity of the irrigation water and can more suitably illustrate the response of wheat yield to stresses as quadratic functions compared with linear and Cobb-Douglas forms. An analytical dominated factor model representing the complex interaction of water and salt stress was evaluated in the study by Shani, et al.[17], which claimed that both the dominant factor approach and notions of compensative plant response to multiple stresses simplify complex plant response. Crop production functions for wheat grown under saline condition were obtained by pot experiments in North Golestan Province, Iran[18]. In this study, the wheat yield response to both water and salinity stress could be best predicted by transcendental functions, with a larger yield reduction in matric potential than in osmotic potential. Consequently, crop production functions, such as linear, Cobb-Douglas, quadratic, and transcendental forms, are widely used to simulate the relationship between some crop yield and water-salt stress, for example, cotton, wheat and maize. However, the current studies rarely involve economic crops, such as oil sunflower. Meanwhile, these studies mainly use soil water potential or applied water as water variables and rarely use evapotranspiration to explain the relation.

The mathematical response of crop yield to water and salt stress could be estimated using the water-salt production function. Oil sunflower has the largest planting areas among all economic crops in the Hetao irrigation region because its strong drought resistance and salt tolerance can adopt deficit irrigation with saline water. Therefore, oil sunflower yield should be accurately predicted using the water-salt production function model, and appropriate irrigation management should be provided for its plantation.

Modeling equations should be established to simulate the relationship between oil sunflower yield and saline water under deficit irrigation to improve the utilization of saline water by precise deficit irrigation. In the present study, two years of deficit irrigation with saline water experiments in Hetao District were investigated. This study mainly aimed to (1) evaluate evapotranspiration and soil salinity and their effects on crop yield by using deficit irrigation with saline water, (2) apply production function models (linear, Cobb-Douglas, quadratic and transcendental functions) to simulate the response of oil sunflower yield to relative evapotranspiration (ET) and electrical conductivity of soil water (EC_{sw}), and (3) evaluate the capability and performance of water-salt-crop production function models during the growth period by using deficit irrigation with saline water. The results of this study could elucidate the water-salt-crop production functions and guide irrigation management using saline water in the Hetao district.

2 Material and methods

2.1 Experiment Area

The experiment was accomplished at the Shuguang experimental station in Linhe District of Bayannaoer City (latitude 40°46′N, longitude 107°24′E, altitude 1039.9 m). The station is located midstream of the Hetao irrigation district which is illustrated in Figure 1, with an average temperature of 6.9℃, wind speed of 2.71 m/s, sunshine time of 3189 h, and relative humidity of 51%. The maximum frost depth of soil is 1.31 m, the average frost-free period is 160 d (with a minimum of 129 d), the average annual rainfall is 142.1 mm, and the average annual evaporation capacity is 2306.5 mm.

Figure 1 Location of the experimental station

2.2 Experiment design

To examine the response of oil sunflower yield to deficit irrigation using saline water, the pot experiments were accomplished in 2013 and 2014, respectively. The pots used in the experiment consisted of plastic buckets 36 cm in diameter and 30 cm in height. The soil used in the experiment was collected from the soil surface layer at the Shuguang station. The soil was packed with a bulk density of 1.35 g/cm^3 with three layers after air drying and sieving through a 2 mm mesh. During the trial, the soil moisture was measured by weighing the buckets every other day.

Water EC, deficit degree, and their occurring time were factors considered in the experiment. Four types of saline water with EC of 1.7 ds/m, 4 ds/m, 6 ds/m and 8 ds/m were used, among which EC=1.7 ds/m used local shallow groundwater, while the other treatments mixed local groundwater with NaCl.

The oil sunflower crops were irrigated at 90% field water capacity (FC) for the full irrigation treatment (CK) when its average soil moisture content at the 0-30 cm soil layer decreased to 60%±2% of FC. Deficit irrigation treatment received two levels of irrigation amount (Ⅰ) reduction, moderate deficit (60%Ⅰ) and mild deficit (80%Ⅰ).

Water deficit occurred only in the specified floral initiation (Stage Ⅰ), anthesis (Stage Ⅱ), and maturity stages (Stage Ⅲ); the other two stages were completely irrigated. Oil sunflower exhibited weak salt and drought tolerance during the seeding stage; thus, they were irrigated with local groundwater (EC=1.7 ds/m). The experiment involved orthogonal testing with 3 factors, including 24 treatments. In addition, four completely irrigated treatments were set as contrast. The 28 treatments each had 11 replications. Table 1 presents the descriptions of oil sunflower and the irrigation schedule of all treatments. Given the limitations of the experimental condition in 2013, only 17 treatments, without the mild deficit treatments of EC=1.7 ds/m and 4 ds/m and the moderate deficit treatments of 8 ds/m, as well as completely irrigated treatments of EC=4 ds/m and 8 ds/m. In addition, the experiment in 2014 was improved to lay pots under the soil to avoid the effects of sunshine and temperature and lower their effects on crop water consumption and yield. Meanwhile, rain-proof measurements were conducted in 2013 and 2014 to ensure irrigation precision.

Table 1 Descriptions of oil sunflower growth stage and treatments in the experiment in 2013-2014

	Description
Stage Ⅰ	Floral initiation Stage
Stage Ⅱ	Anthesis Stage
Stage Ⅲ	Maturity Stage
$CK_{1.7}$-CK_8	Full irrigation with saline water of 1.7-8 ds/m
$S_{1.7}$-S_8	saline water of 1.7-8 ds/m
F_{60}, F_{80}	60% full irrigation at floral initiation stage, 80% full irrigation at floral initiation stage
A_{60}, A_{80}	60% full irrigation at anthesis stage, 80% full irrigation at anthesis stage
M_{60},M_{80}	60% full irrigation at maturity stage, 80% full irrigation at Maturity stage

The oil sunflower was T012244, which was resistant to lodging, and seeded in summer with high oil content. In 2013, the oil sunflower was planted on June 10 and emerged on June 15, and the seeding stage ended on July 20. The floral initiation period started on July 21 and ended on August 12. The anthesis period ended on August 24, and the maturity period ended on September 8. Similarly, the oil sunflower was planted on July 11, 2014, and irrigation started on July 19. The seedling stage lasted for 43 days and ended on July 26; the squaring stage started on July 27 and ended on August 18. The anthesis stage lasted from August 19 to September 2. The maturity period lasted for 18 days, and oil sunflower was harvested on September 16.

2.3 Measurement and methods

2.3.1 Crop consumption

Crop water consumption was calculated using the water balance method, which measures the variation in soil water content at a certain time with the following equation[19]:

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

where, ET_c is crop water consumption, mm; P is rainfall, mm; I is irrigation amount, mm; ΔW is the variation in soil water content; R is the overland runoff, mm; D is the deep leakage, mm. Given that the experiment used pots to avoid water, the rainfall, overland runoff and deep leakage were negligible; thus, P=0, R=0 and D=0. Therefore, the equation could be simplified as:

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

The soil water content was measured by weighing the pot with the oil sunflower crop. The variation was then calculated.

2.3.2 Soil salinity

Soil samples of each treatment were collected every 10 days to evaluate the soil salinity, and soil samples were collected from three layers with 10 cm intervals. After drying and grinding through 2 mm mesh, the soil and water were mixed at a ratio of 1:5 to test for soil salinity.

2.3.3 Yield and water use efficiency

After oil sunflower maturity, each treatment collected samples to evaluate the yield. After manual harvesting and air drying, the seeds were weighed after scraping. The seeds of five replications were weighed, and their average was considered as the final result. From each treatment, five batches of samples including 100 seeds were selected randomly to obtain the 100-grain weight.

Water use efficiency was calculated using the following:

$$WUE = Y / ET \times 100 \tag{3}$$

where, WUE is the water use efficiency, kg/m^3; Y is the total yield, t/hm^2.

2.4 Model description

2.4.1 Water-salt-crop production function model

In the present study, the water-salt-crop production functions of the entire growing stage were used to simulate the relationship among yield, ET and EC. The factors that affect the yield were only ET and EC_{sw}; the other possible factors were assumed to be constant. The aforementioned relationship is expressed as follows:

$$Y = f(ET, EC_{sw}, X) \tag{4}$$

where, X is the constant vector for considering other factors affecting the yield. EC_{sw} is the electrical conductivity of soil water.

Based on previous water-salt production functions, the functions used in this study were linear, Cobb-Douglas, quadratic and transcendental functional forms.

Linear: $R(Y) = a_0 + a_1 R(ET) + a_2 R(EC_{sw})$ (5)

Cobb-Douglas: $R(Y) = a_0 R(ET)^{a_1} R(EC_{sw})^{a_2}$ (6)

Quadratic:

$$\begin{aligned} R(Y) = a_0 + a_1 R(ET) + a_2 R(ET)^2 + a_3 R(EC_{sw}) + \\ a_4 R(EC_{sw})^2 + a_5 R(ET) \cdot R(EC_{sw}) \end{aligned} \tag{7}$$

Transcendental: $Y = a_0 ET^{a_1} EC_{sw}^{a_2} Exp(a_3 ET + a_4 EC_{sw})$ (8)

where, $R(Y)$, $R(ET)$ and $R(EC_{sw})$ are standardizations of dimensionless variables; $R(Y)$ is the relative yield; $R(ET)$ is the relative ET, and $R(EC_{sw})$ is the relative EC_{sw}.

First, each model was transformed into a multiple linear equation, and the coefficients of the four water-salt production functions were estimated by multiple linear regression, using the measured data of $R(Y)$, $R(ET)$ and $R(EC_{sw})$. Meanwhile, the F-value, R^2, root mean squared error ($RMSE$), and standard error (SE) were estimated to compare the four functions.

From the 45 sets of data between 2013 and 2014, 35 sets were randomly selected for parameterizing the models as group A and the others as group B to evaluate the model performance.

2.5 Evaluation of model performance

The fitted coefficients were incorporated into their respective models, and the model performance, in simulating the relative yield, was validated with the 10 sets of data from the B group. The simulated relative yield was compared with the observed yield. To assess the fitting effects of the models, linear regressions forced to the origin were applied, relating simulated and measured values. The regression coefficient (b) and the determination coefficient (R^2) were analyzed. The indicators of quality and estimation errors of the models were also calculated, including the root mean square error ($RMSE$), average absolute error (AAE), modeling efficiency[20] (EF), and index of agreement[20] (d_{IA}). EF with a negative or nearly 0 value implied that compared with the model, the measured mean value was a better predictor. When d_{IA}=1, the perfect agreement between the measured and simulated values was obtained; when d_{IA}=0, no agreement was indicated. The calculation methods are as follows:

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(RY_s-RY_m\right)^2} \tag{9}$$

$$AAE=\frac{1}{n}\sum_{i=1}^{n}\left|RY_s-RY_m\right| \tag{10}$$

$$EF=1-\frac{\sum_{i=1}^{n}\left(RY_s-RY_m\right)^2}{\sum_{i=1}^{n}\left(RY_m-\overline{RY_m}\right)^2} \tag{11}$$

$$d_{IA}=1-\frac{\sum_{i=1}^{n}\left(RY_i-RY_m\right)^2}{\sum_{i=1}^{n}\left(\left|RY_s-\overline{RY_m}\right|+\left|RY_m-\overline{RY_m}\right|\right)^2} \tag{12}$$

2.6 Sensitivity analysis

Sensitivity analysis was evaluated to determine the response of the models to the most influential factors. The investigated factors contained the relative ET, relative EC_{sw}, and fitted coefficient. The sensitivity of the model to the variation was quantified by the normalized sensitivity coefficient (SC), calculated using the following equation[21]:

$$SC=\frac{\Delta Y/\overline{Y}}{\Delta F/\overline{F}} \tag{13}$$

where, ΔY is the variation of the simulated relative yield; $\overline{Y}$ is the relative yield simulated with the initial values of the factors; ΔF is the variation of the factor and $\overline{F}$ is the initial value of the factor.

3 Results

3.1 Effect of water deficit and salt stress on oil sunflower evapotranspiration

Table 2 shows the ET of oil sunflower in different growing stages and the entire season from 2013 to 2014 using saline water deficit irrigation. The ET generally varied from 244.52 mm to 301.42 mm and from 283.05 mm to 448.26 mm in 2013 and 2014, respectively. In 2013-2014, the highest ET during the growing period was observed in treatment $CK_{1.7}$, whereas the lowest was obtained in S_8F_8 and S_8F_{60}. The ET in the floral initiation stage was significantly higher than those in the anthesis and maturity stages. During the entire growing period, the ET of treatments with water deficit in the floral initiation stage was significantly lower than those in other growing stages. As for the full irrigation treatments, the ET decreased with increasing water EC irrigated (e.g., the ET in CK_4, CK_6 and CK_8 were 7.3%, 14.6% and 24.3% lower than that in $CK_{1.7}$, respectively). Both water deficit and salinity strongly influenced ET, and the effect of water deficit was more pronounced when water EC of irrigated water was lower than 4 ds/m.

Table 3 presents the average EC_{sw} of each treatment during the entire growing period in the soil with 0-30 cm. In general, the EC_{sw} in 2014 varied from 1.933 ds/m to 2.525 ds/m, and was significantly higher than that in 2013 (0.952-1.559 ds/m). The lowest EC_{sw} was observed in $S_{1.7}F_{60}$ and $S_{1.7}F_{80}$ (treatments with the strongest water deficit) in 2013 and 2014, respectively; meanwhile, the highest EC_{sw} was obtained by S_8M_8 and CK_8, indicating that the increase in soil EC_{sw} may be attributed to the accumulation of salt from the saline water irrigation.

3.2 Influences of water deficit and salt stress on oil sunflower yield and water use efficiency

Table 4 presents the oil sunflower yield and WUE under different treatments in 2013 and 2014. The yields of full irrigation treatments ($CK_{1.7}$, 1.69 and 3.21 t/hm^2 in 2013 and 2014, respectively) were significantly (p<0.05) higher than those of other treatments under water deficit and salt stress. Compared with that of $CK_{1.7}$, the yield decreased by 18.4%, 26.6% and 36.4% in CK_4, CK_6 (two-year average) and CK_8, respectively. However, no significant difference in yield was found between CK_4 and CK_6 in 2014. The yield also varied as water deficit occurred during different growing stages. Treatment with water deficit in the anthesis stage generally exhibited a significantly lower yield, compared with those in the floral initiation and maturity stages. These results suggest that the anthesis stage was the most sensitive stage, requiring less water deficit and salinity stress. The yields under treatments with similar water deficit levels were reduced significantly when the *EC* of the irrigation water was higher than 4 ds/m.

The highest *WUE* values were observed in $CK_{1.7}$ (0.55 kg/m^3) and $S_{1.7}F_{60}$ (0.76 kg/m^3) in 2013 and 2014, respectively. Notably, S_6F_{80} had a relatively high *WUE*, indicating that less negative influence on *WUE* can be expected in treatments with mild water deficit; meanwhile, a relatively higher *EC* (6 ds/m) was observed in the irrigation water. However, high-EC irrigation water and moderate water deficit showed significantly lower *WUE*.

3.3 Crop-water-salinity production functions of oil sunflower

To eliminate the effect of climate, soil and other factors on the yield during the experiments from 2013 to 2014, the yield, *ET* and EC_{sw} were generalized on a relative basis (R_{ET}, R_Y and R_{EC}). R_Y and R_{ET} were acquired through dividing by the largest yield and *ET* of the $CK_{1.7}$ treatment. R_{EC} was transformed, with 1 as maximum EC_{sw} from all treatments.

Table 2 Effect of irrigation treatments on evapotranspiration (*ET*) in different growth stages and the total season

Treatment	*ET*/mm						Total season	
	Floral initiation Stage		Anthesis Stage		Maturity Stage			
	2013	2014	2013	2014	2013	2014	2013	2014
$CK_{1.7}$	132.53	167.77	43.70	98.49	51.51	104.44	301.42	448.26
$S_{1.7}F_{80}$	nm	132.78	nm	100.07	nm	104.14	nm	414.69
$S_{1.7}A_{80}$	nm	164.65	nm	75.73	nm	107.48	nm	423.72
$S_{1.7}M_{80}$	nm	165.47	nm	96.77	nm	88.32	nm	428.28
$S_{1.7}F_{60}$	91.38	99.59	52.45	91.47	51.13	94.75	268.53	363.96
$S_{1.7}A_{60}$	130.63	168.97	24.98	56.79	48.17	108.27	277.88	412.37
$S_{1.7}M_{60}$	131.49	163.04	43.17	88.7	33.08	77.76	282.15	407.89
CK_4	nm	150.01	nm	88.8	nm	100.27	nm	415.63
S_4F_{80}	nm	118.29	nm	91.45	nm	103.99	nm	390.36
S_4A_{80}	nm	143.46	nm	69.99	nm	100.22	nm	389.75
S_4M_{80}	nm	145.32	nm	87.19	nm	79.27	nm	388.16
S_4F_{60}	87.99	88.72	43.76	90.46	46.42	95.24	251.64	351.23
S_4A_{60}	121.09	151.8	23.81	52.49	46.74	99.54	265.77	380.62
S_4M_{60}	119.52	148.71	35.80	86.46	26.71	72.62	256.85	384.86
CK_6	119.21	141.69	35.40	80.09	42.83	84.2	271.45	383.03
S_6F_{80}	112.62	110.4	45.89	79.72	46.74	71.9	278.28	339.19
S_6A_{80}	119.10	136.56	27.70	63.73	40.41	65.34	261.50	341.61
S_6M_{80}	119.72	138.59	35.74	78.34	32.47	62.23	261.68	356.21
S_6F_{60}	83.84	82.8	39.12	78.04	43.41	70.16	264.50	308.49
S_6A_{60}	117.45	138.09	21.18	47.8	45.92	69.11	258.61	332.57
S_6M_{60}	119.02	135.08	34.67	80.55	23.53	50.48	251.39	343.85
CK_8	nm	130.74	nm	69.39	nm	61.8	nm	339.39
S_8F_{80}	96.93	101.46	37.39	67.1	36.13	62.89	244.52	308.93
S_8A_{80}	116.13	124.96	25.31	53.46	36.04	65.49	251.26	321.03
S_8M_{80}	116.50	126.52	33.94	64.14	29.08	48.27	253.24	315.97
S_8F_{60}	nm	76.1	nm	70.77	nm	59.85	nm	283.05
S_8A_{60}	nm	128.18	nm	40.1	nm	64.68	nm	310.2
S_8M_{60}	nm	123.73	nm	66.95	nm	44.76	nm	312.75

Note: nm=not measured.

Table 3 Average EC of each treatment in the whole growth period at 0-30 cm soil depth in 2013-2014

Treatment	EC_{sw}		Treatment	EC_{sw}	
	2013	2014		2013	2014
$CK_{1.7}$	0.980	2.084	CK_6	1.484	2.376
$S_{1.7}F_{80}$	nm	1.933	S_6F_{80}	1.410	2.213
$S_{1.7}A_{80}$	nm	2.095	S_6A_{80}	1.457	2.382
$S_{1.7}M_{80}$	nm	2.082	S_6M_{80}	1.451	2.395
$S_{1.7}F_{60}$	0.952	1.951	S_6F_{60}	1.301	2.221
$S_{1.7}A_{60}$	0.963	2.082	S_6A_{60}	1.491	2.372
$S_{1.7}M_{60}$	0.958	2.074	S_6M_{60}	1.487	2.387
CK_4	nm	2.261	CK_8	nm	2.525
S_4F_{80}	nm	2.077	S_8F_{80}	1.379	2.376
S_4A_{80}	nm	2.250	S_8A_{80}	1.542	2.406
S_4M_{80}	nm	2.283	S_8M_{80}	1.559	2.507
S_4F_{60}	0.993	2.077	S_8F_{60}	nm	2.340
S_4A_{60}	1.022	2.235	S_8A_{60}	nm	2.450
S_4M_{60}	1.009	2.263	S_8M_{60}	nm	2.495

Note: nm=not measured.

Table 4 Effect of irrigation treatment on oil sunflower yield and water use effiviency (WUE) in 2013-2014

Treatment	Yield/t·hm^{-2}		WUE/kg·m^{-3}	
	2013	2014	2013	2014
$CK_{1.7}$	1.69a	3.21a	0.55a	0.72ab
$S_{1.7}F_{80}$	nm	3.02b	nm	0.73ab
$S_{1.7}A_{80}$	nm	2.88bc	nm	0.68bcde
$S_{1.7}M_{80}$	nm	3.03b	nm	0.71abc
$S_{1.7}F_{60}$	1.49b	2.76cd	0.42b	0.76a
$S_{1.7}A_{60}$	1.25c	2.6de	0.33c	0.63efg
$S_{1.7}M_{60}$	1.55b	2.76cd	0.44b	0.68bcde
CK_4	nm	2.62de	nm	0.63efg
S_4F_{80}	nm	2.52ef	nm	0.65def
S_4A_{80}	nm	2.37fgh	nm	0.61fghi
S_4M_{80}	nm	2.51ef	nm	0.65def
S_4F_{60}	1.12cdef	2.43efg	0.30cde	0.69bcd
S_4A_{60}	1.04cdefg	2.31gh	0.27cdef	0.61fghi
S_4M_{60}	1.11cdef	2.37fgh	0.29cde	0.62fgh
CK_6	1.18cde	2.48efg	0.29cde	0.65de
S_6F_{80}	1.27cd	2.46efg	0.32cd	0.72ab
S_6A_{80}	1.02efgh	2.21hi	0.23cdefg	0.65de
S_6M_{80}	1.16cdefg	2.35fgh	0.28cdef	0.66cdef
S_6F_{60}	0.88fgh	1.92jk	0.22defg	0.62efg
S_6A_{60}	0.82gh	1.83k	0.18ef	0.55j
S_6M_{60}	0.90efgh	1.93jk	0.21efg	0.56ij
CK_8	nm	2.04ij	nm	0.60fghij
S_8F_{80}	0.83efgh	1.87jk	0.22defg	0.60fghi
S_8A_{80}	0.65h	1.78k	0.17g	0.55j
S_8M_{80}	0.93efgh	1.84k	0.24cdefg	0.58ghij
S_8F_{60}	nm	1.6l	nm	0.56hij
S_8A_{60}	nm	1.44l	nm	0.47k
S_8M_{60}	nm	1.49l	nm	0.48k

Note: values followed by different letters are satistically different at 0.05p level according to LSD test.

nm = not measured.

Table 5 Estimated coefficients for each of the examined oil sunflower water-salt production functions

Variables	Linear 2013-2014	Cobb-Douglas 2013-2014	Quadratic 2013-2014	Transcendental 2013-2014
Constant (a_0)	0.585	0.819	13.077	93.808
a_1	1.021	1.211	−9.562	3.774
a_2	−0.778	−0.946	2.175	0.397
a_3			−19.517	−3.218
a_4			6.963	−1.590
a_5			8.043	
R^2	0.90*	0.88*	0.92*	0.89*
F	117.69	93.22	51.99	46.01
$RMSE$	0.045	0.047	0.041	0.046
SE	0.048	0.077	0.046	0.078

Note: *Significant at level $p<0.05$ by LSD range.

The A group data obtained from the two-year experiment were used to calculate the model coefficients by using multiple linear regression. Table 5 shows the estimated coefficients and statistical analyses of the four functions. The determination coefficients (R^2) of the linear, Cobb-Douglas, quadratic and transcendental functions were 0.90, 0.88, 0.92 and 0.89, respectively, with significant correlation ($p<0.05$). In addition, the quadratic function had the smallest $RMSE$ and SE, as well as the smallest F-value, suggesting low significance of the regression equation but high estimated coefficient accuracy. Compared with the estimated coefficients of functions, a_1 and a_2 of the linear and Cobb-Douglas were positive and negative, respectively. The influence of R_{ET} on R_Y is beneficial, whereas the effect of R_{EC} on R_Y is adverse. Meanwhile, a_1 and a_3 of the quadratic function, as well as a_4 and a_5 of the transcendental function were negative, indicating the negative correlation between the yield and the synergistic effect of water and salt stress.

3.4 Model performance in predicting oil sunflower yield

Ten sets of B group data from the 2013-2014 experiments were used to validate the models. The performance of the models in predicting oil sunflower yield was estimated by comparing the field data with the simulated values obtained using the models. Figure 2 presents comparisons between the relative yield of oil sunflower and those of simulated ones obtained using the linear, Cobb-Douglas, quadratic and transcendental models. Table 7 shows the fit indicators of the comparisons.

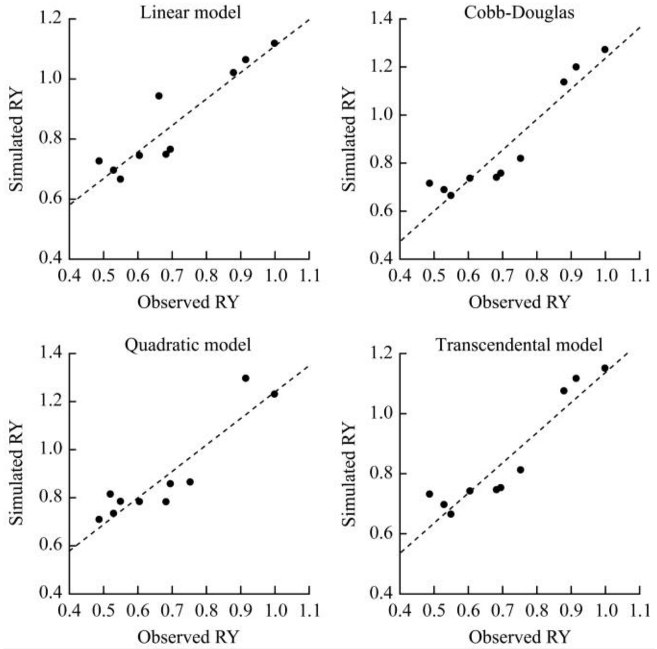

Figure 2 Comparison between simulated and observed relative yields obtained using the four models

The regression coefficients obtained using the four models were larger than 1; thus, the simulated values were larger than the measured ones. The reason was that eight sets of 2013 data were used for the prediction; the yields were low because of poor experimental conditions. However, all R^2 values obtained using the models were higher than 0.81, except for the linear model; the highest R^2 was 0.89, which was obtained using the Cobb-Douglas model.

Table 6 Goodness of fit indicators for the comparisons between measured relative values of oil sunflower yield and those simulated by four models

Model	b	R^2	$RMSE$	AAE	EF	d_{IA}
Linear	1.19	0.75	0.160	0.147	0.071	0.805
Cobb-Douglas	1.23	0.89	0.182	0.161	−0.204	0.808
Quadratic	1.30	0.81	0.224	0.210	−0.858	0.736
Transcendental	1.18	0.85	0.150	0.137	0.180	0.835

All estimation errors of the four models were low, with $RMSE$ varying from 0.150 to 0.224 and AAE from 0.137 to 0.210. Both the highest $RMSE$ and the highest AEE were observed in the quadratic model. However, both the lowest EF and the lowest d_{IA} were observed in the quadratic model. The highest EF and d_{IA} were obtained using the transcendental model, indicating that the transcendental and Cobb-Douglas models exhibited a good fit between the simulated and measured values. Therefore, among the four models, the transcendental and Cobb-Douglas models were the better water-salt production functions for oil sunflower under combined water and salt stress.

3.5 Sensitivity analysis

Sensitivity analysis was conducted for the selected transcendental and Cobb-Douglas models to examine the response of the models to fluctuations in the input variable and estimated coefficients. The mean normalized SC of the relative yield obtained using the transcendental and Cobb-Douglas models are given in Figure 3. The positive values of SC for R_{ET} and the negative values for R_{EC} indicated that the calculated relative yields were reduced with increasing EC_{sw} and enhanced with decreasing ET; these effects were consistent with the aforementioned results.

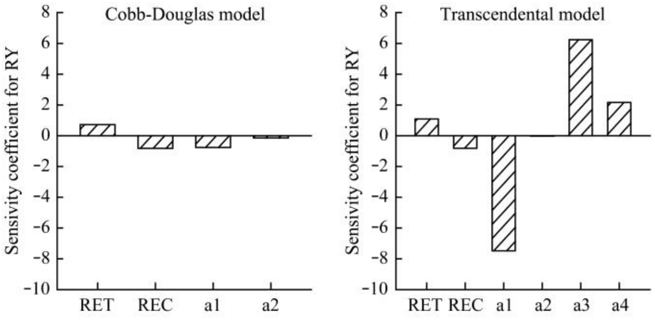

Figure 3 Mean normalized sensitivity coefficients for the relative values of yield calculated using different models according to given variations in RET, REC, a_1, a_2, a_3 and a_4

In addition, the SC for a_1 and a_2 were negative (a_2 was −0.026 in the transcendental model), whereas the SC for a_3 and a_4 were positive, with considerably higher absolute values of SC for a_1 and a_3. These results indicate that the influence of ET on yield was dominant under combined water and salt stress because a_1 and a_3 were the coefficient of ET.

4 Discussion

Evapotranspiration is affected by climate factors, plant growth, and soil surface properties[22]. In this study, the ET in 2013 was much higher than that in 2014. This difference was attributed to meteorological factors, such as higher water surface evaporation (611.7 mm) in 2014 than that (543.5 mm) in 2013. In addition, the pots were buried in the soil, weakening the adverse effect of high temperature and illumination on the root system, and the leaf area was larger than that in 2013 (data not given).

The *ET* in the total growing stage was below 546-677 mm, which was previously presented[23,24]. First, deficit irrigation would decrease oil sunflower water consumption[25]. Compared with the field experiment, the root growth of oil sunflower was severely inhibited, and no water and nutrients were supplied from deep soil. In addition, salt accumulated with increasing water because of the salinity of irrigation water, resulting in markedly restricted vegetative growth before anthesis. Decreases in leaf number, leaf area and stem diameter significantly reduced crop evapotranspiration after anthesis, which was consistent with the decreasing *ET* in the whole stage. Consequently, the percentage of total crop *ET* during the floral initiation was about 40.46%, which was higher than the percentage (20%) stated in the previous study[24].

Salinity always affects crop evapotranspiration; higher salinity results in lower evapotranspiration[26]. The salinity decreased the soil osmotic potential and the water utilization of crops, leading to severe water stress. Anabatic stress can significantly affect stomata conductance, leaf growth and photosynthesis. It also proved that the floral initiation period was the salt sensitive period and that salt input should be minimized. Under combined water and salt stress, the inhibition caused by water deficit was greater than that caused by salt stress. The main reason was that salt stress inhibited water uptake from the soil, requiring more energy from plants and redistributing photosynthetic products[29]; salt stress reduced the basic energy required for organ formation, resulting in the loss of crop growth and reduction in water consumption.

Among the treatments with *EC*=1.7 ds/m, the water deficit during the anthesis period significantly reduced the oil sunflower yield, without significantly affecting the floral initiation and maturity periods, which was consistent with the findings by Childs and Hanks[30]. Water stress and limited irrigation in the flowering period significantly reduced seed yield, and the limitation of irrigation water during the flowering period should be avoided.

When the water salinity increased by 1 ds/m, the oil sunflower yield reduced significantly and decreased by 5.67% as 1 ds/m increased; the result was close to 5% of the prior preferences made under field conditions[31,32].

Changing the interactive proportion of water deficit and salt stress during different stages exerted different effects on yield. With salt stress as the key controlling factor, the anthesis stage was more sensitive to salinity and yield decreased further. Meanwhile, the floral initiation stage was more sensitive to water stress when it was major; thus, an appropriate deficit could control the reduction in production. The reason was that the anthesis stage was a critical period for the yield. High osmotic stress would consume more energy to water absorption, and assimilated product would be assigned to the root, leading to much less production. Given the lower crop water consumption in the floral initiation period[25], the appropriate water deficit would not exert a stronger effect on crop growth and late reproductive development.

The water-salt-crop production functions, including the quadratic, Cobb-Douglas, and transcendental models, are widely used to simulate the yield-water-salt relationship of other crops, such as wheat, maize and cotton. In this study, the synergistic effects of water and salt stress were not simply linearly additive, but in present of a threshold value of *EC*. When the *EC* was below the threshold, the effect of water stress was more pronounced, and by contrast, the effect was converse. The results were consistent with the results in the study by Shani, et al.[17], which reported that the crop responds more to severe stress rather than to the combined stresses. Kiani and Abbasi[18] also found that transcendental production functions predicted reasonably well the yield under salinity and water stress conditions, indicating that the reductions in yield due to joint salinity and water stress were not confirmed by simple linear additive and multiplicative concepts. However, Russo and Bakker[15] and Datta, et al[8]. suggested a quadratic form of the production function under salinity and water stress for cotton, corn and wheat; the results obtained were different from the current results.

The difference could be attributed to the matric potential of soil treated as the water variable in those studies, which was not only affected by the amount of irrigation water. The Cobb-Douglas and transcendental models could simulate the relative yield response to relative *ET* and relative EC_{sw}; however, compared with the Cobb-Douglas model, the transcendental model obtained smaller *RMSE* and *AEE* but larger *EF* and d_{IA}. Therefore, the transcendental model is the best model to simulate the yield-water-salt relationship of oil sunflower in this study.

5 Conclusions

On the basis of the 2013-2014 pot experiments, this study investigated the quantitative relationship among oil sunflower yield, water consumption, and soil *EC* by using saline water for deficit irrigation. The following conclusions were drawn:

1) The combined water and salt stress would significantly decrease the *ET* of oil sunflower during the reproductive stage. In addition, the effect of water stress on *ET* would decrease with increasing water *EC* (>4 ds/m).

2) Oil sunflower yield exhibited a negative linear relationship with salinity; the reduction in yield was particularly significant when the *EC* of saline water was higher than 6 ds/m. Meanwhile, the yield responded more strongly to water deficit than to salinity because of the additive effect of salt stress, indicating the most sensitive parameters in the water-salt function model (a_1 and a_3). In addition, anthesis was the most sensitive stage to water and salt stress.

3) Both the transcendental and Cobb-Douglas function models could satisfactorily predict the yield of oil sunflower irrigated with saline water. In addition, the transcendental function, which showed a higher sensitivity to water deficit and salinity, was recommended to simulate the relationship between oil sunflower production as well as *ET* and EC_{sw}. The simulation can help in the development and utilization of irrigated saline water during the growth season in the Hetao district.

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