Calculating the water salt production function parameters of seed maize under water salt combination stress

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Abstract: In order to explore the relationship between crop yield and water salt stress, field experiments were conducted under deficit irrigation with saline water in Shiyang River Basin. It introduced into the crop-water-salt production function. The crop-water-salt production function parameters were calibrated and validated based on the field experiments measured data. The results showed that the simulated evapotranspiration and yield agreed well with the measured values of seed maize at different growth stages. The crop-water-salt production function parameters after calibration and validation were $b=6.72$, $k_{y1}=0.43$, $k_{y2}=0.82$, $k_{y3}=1.41$, $k_{y4}=0.65$, $k_{y5}=0.24$, respectively. The yield response factor ($k_y$) reflected sensitivity to the seed maize at different growth stages under water salt combination stress. The crop-water-salt production function can well simulate the seed maize evapotranspiration and yield under water salt combination stress after calibration and validation.

1. Introduction

The climate is drought and rare rainfall and the ecological environment is wicked in Northwest China. Agricultural production mainly uses groundwater for irrigation in Northwest China. Because of long-term groundwater over exploitation, the groundwater depth gradually increases and groundwater salinity also increases year by year\[^1\]. In order to make agricultural production develop steadily, saline water irrigation and deficit irrigation technology have gradually become important irrigation modes in arid areas. It is also effective way to alleviate the shortage of freshwater resources and maintain the sustainable agricultural development\[^2\]. However, salt water irrigation and deficit irrigation have some disadvantage effects on crop growth and yield due to the existence of water and salt stress. Researchers have done a lot of qualitative and quantitative research on the relationship between crop yield and soil water content and soil salt content. It established various forms of crop-water-salt production functions. Crop-water-salt production function is a mathematical model reflecting the relationship between soil water-salt and crop yield. It is an important basis for establishing salt water irrigation and deficit irrigation schedule. Wang et al. established the crop-water-salt response model by carrying out brackish water irrigation experiment and established the maize water-salt production function based on the crop water production mode\[^3\]. Tan et al. established the water-salt production function through drip irrigation experiment under brackish water irrigation condition\[^4\]. Guo et al. established the soil water-salt transport model and zucchini water-salt production function of drip
irrigation under brackish water condition[6]. This study were to consider the effects of soil water content and soil salt content on the growth and yield of maize seed production under deficit irrigation with saline irrigation in Shiyang River Basin. The parameters of crop water-salt production function were calculated and the water-salt production function of seed maize was constructed deficit irrigation with saline irrigation, which provided theoretical basis for rational utilization of ground saline water resources and water-saving irrigation in the study area.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in 2013 and 2014 at Shiyang River Experimental Station of China Agricultural University (North latitude 37°52′, East longitude 102°52′, Elevation 1581 m). The station is located in Wuwei City, Gansu Province of Northwest China. It has a typical continental temperate dry climate with annual average precipitation of 164.5 mm and annual average pan evaporation 2000 mm[6]. The average ground water table is below 40 m in study area. Eighteen non-weighing lysimeters were used for the experiments, each with an area of 6.66 square meters (3.33 m×2 m) having a depth of 3 m. Two non-weighing lysimeters were separated by cement concrete and the bottom was a cement floor. The soil physical and chemical properties before experiments are shown in Table 1.

| Soil depth (cm) | Sand (%) | Silt (%) | Clay (%) | Organic content (g·kg⁻¹) | Soil bulk density (g·cm⁻³) | Field capacity (cm·cm⁻¹) | International soil textural
|-----------------|----------|----------|----------|--------------------------|---------------------------|------------------------|-------------------------|
| 0-20            | 59.46    | 28.58    | 11.96    | 2.60                     | 1.49                      | 0.27                   | Sandy loam              |
| 20-60           | 58.33    | 29.47    | 11.21    | 2.64                     | 1.50                      | 0.30                   | Sandy loam              |
| 60-120          | 43.35    | 42.63    | 14.02    | 5.69                     | 1.52                      | 0.32                   | Loam                    |

Irrigation was performed with three water amount levels of 1\(\frac{ETc}{(w1)}\), 2/3\(\frac{ETc}{(w2)}\) and 1/2\(\frac{ETc}{(w3)}\) \(\frac{ETc}{(w3)}\) was the average evapotranspiration of seed maize. The average evapotranspiration of seed maize was 555 mm, which was calculated by Penman-Monteith method [7]. Irrigation was performed with three salinity levels of 0.71 g·L⁻¹ (s1), 3 g·L⁻¹ (s2), 6 g·L⁻¹ (s3), which represented groundwater salinity of the upstream, midstream and downstream of Shiyang River, respectively. The experiment was laid out in split plot arrangement. There was 9 treatments with two replicates in the experiment, w1s1 (control group), w1s2, w1s3, w2s1, w2s2, w2s3, w3s1, w3s2 and w3s3, respectively. Fresh water with water salinity of 0.71 g·L⁻¹ was obtained from a local well. According to composition of the local groundwater, irrigation water salinity of 3 g·L⁻¹ and 6 g·L⁻¹ was prepared artificially by dissolving NaCl, MgSO₄ and CaSO₄ in fresh water at a mass ratio of 2:2:1, respectively. Seed maize of the variety of “Golden northwest No. 22” was sowed with 56 plants in each experiment plot. Seed maize was sown on April 24 and April 20, and harvested on September 23 and September 13 in 2012 and 2013, respectively. Irrigation water quota refers to local actual situation of seed maize and the irrigation schedule of seed maize is shown in Table 2. Agricultural measures were executed following local experience.

| Treatment | Irrigation water salinity (g·L⁻¹) | Seedling–jointing stage (mm) | Jointing–booting stage (mm) | Booting–tasseling stage (mm) | Tasseling–filling stage (mm) | Filling–maturity stage (mm) | Total irrigation water quota (mm) |
|-----------|----------------------------------|--------------------------------|----------------------------|----------------------------|----------------------------|-----------------------------|--------------------------------|
| w1s1      | 0.71                             | 120                           | 120                        | 105                        | 105                        | 105                         | 555                            |
| w1s2      | 3.00                             | 120                           | 120                        | 105                        | 105                        | 105                         | 555                            |
| w1s3      | 6.00                             | 120                           | 120                        | 105                        | 105                        | 105                         | 555                            |
| w2s1      | 0.71                             | 80                            | 80                         | 70                         | 70                         | 70                          | 370                            |
| w2s2      | 3.00                             | 80                            | 80                         | 70                         | 70                         | 70                          | 370                            |
The soil samples were taken before seed maize seeding, after seed maize harvest, before and after irrigation using soil auger during the growth period of seed maize at the depth of 0-10, 10-20, 20-40, 40-60, 60-80, 80-100 and 100-120 cm in 2012 and 2013, respectively. The soil water content was measured using gravimetric method. Electrical conductivity, EC1:5 was measured using SG-3 conductivity meter (SG3-ELK742) at soil-to-water ratio of 1:5. The ears of seed maize were threshed and dried after harvest. The seed maize yield of each experiment plot was measured to determine yield per hectare. Total effective precipitation during the seed maize growth stage in 2012 and 2013 was 130 mm and 64.5 mm, respectively.

2.2. Crop-water-salt production function

The crop-water-salt production function was based on the water production function and established by Stewart et al in this study. It was used to represent crop yield with ET/ETm ratio at different growth stages[8]. The formula for calculation is as follows:

\[
\frac{Y_a}{Y_m} = \prod_{j} \left(1 - k_{ij} \left(1 - \frac{E_{T_a}}{E_{T_m}}\right)\right)
\]

(1)

Where \(Y_a\) is the actual yield (kg·hm\(^{-2}\)); \(Y_m\) is the maximum yield (kg·hm\(^{-2}\)); Index \(n\) is the growing stage, \(n=5\). Index \(j\) is the actual growing stage; \(K_{ij}\) is the yield response factor of growing stage; \(E_{T_a}\) is the actual evapotranspiration (mm); \(E_{T_m}\) is the maximum evapotranspiration (mm).

Due to water stress and salt stress, evapotranspiration under water stress (\(E_{Taw}\)), salt stress (\(E_{Tss}\)) and water and salt stress (\(E_{Tawss}\)) should be calculated separately under deficit irrigation with saline water. However, the formula (1) does not consider salt stress and water-salt stress, so it is necessary to modify the crop water production function. The crop-water-salt production function is modified by the following methods by consulting relevant reference in this study[9,10].

The crop evapotranspiration is directly related to soil water content in the crop root zone. If soil water content is higher than \(p\) (the proportion of soil water consumption in the crop root zone to total available soil water before the occurrence of water stress), the crops will not be subject to water stress. \(E_{Taw}\) is judged and estimated by the following method:

If \(TAW - Dr \geq (1-p)TAW = TAW - RAW\), that is \(E_{Taw} = E_{Tm}\). Otherwise:

\[
E_{Taw} = \frac{E_{Taw} - Dr}{(1-p)TAW}
\]

(2)

Where \(D_r\) is the consumption quantity of crop root zone in a given time, mm; \(TAW\) is the total available soil water quantity; \(RAW\) is the actual available soil water quantity, mm.

If it has soluble salt in the crop root zone, the crop transpiration capacity will decline, which soil saturated extract conductivity (\(EC_s\)) is higher than that of the threshold (\(EC_{sw}\)). The following formulas are used to calculate crop evapotranspiration (\(E_{Taw}\)) under salt stress and water-salt combination stress.

\[
\frac{E_{Taw}}{E_{Tm}} = K_{aw} = K_{aw}K_{sw} = \left[1 - \frac{b}{k_{sw}}(EC - EC_{aw})\right] \frac{TAW - Dr}{(1-p)TAW}
\]

(3)

Where \(E_{Taw}\) is the crop evapotranspiration under water-salt combination stress, mm; \(K_{aw}\) is the transpiration reduction factor dependent on \(K_{aw}\) and \(K_{sw}\), dimensionless; \(K_{aw}\) is the transpiration reduction factor dependent on soil saturated extract conductivity, dimensionless; \(K_{sw}\) range from 0 to 1, if \(EC < EC_{aw}\), that is \(K_{sw} = 1\); \(K_{aw}\) is the transpiration reduction factor dependent on soil available water, dimensionless; \(K_{aw}\) range from 0 to 1, if \(D_s < RAW\), that is \(K_{aw} = 1\). \(EC\) is the average soil saturated extract conductivity in the crop root zone dS·m\(^{-1}\); \(EC_{sw}\) is the threshold of soil saturated extract conductivity and \(EC_{sw}\) is 4.0 dS·m\(^{-1}\) according to the relevant reference[11]; \(b\) is a specific parameter description crop yield reduction rate of per unit excess salt.
2.3. Calculation parameters of crop-water-salt production function

2.3.1 Crop evapotranspiration
Crop evapotranspiration is calculated by the following equation:

\[ ET = P_0 + I - W \times R - L + D \]  

(4)

\[ W = 10 \times rH(W_1 - W_0) \]  

(5)

where, \( ET \) is crop evapotranspiration, mm; \( P_0 \) is the total effective rainfall, mm; \( I \) is the irrigation water quota, mm; \( AW \) is the soil water depletion, mm; \( W_0 \) is soil water content before maize sowing, cm\(^3\)·cm\(^{-3}\); \( W_1 \) is soil water content after maize harvest, cm\(^3\)·cm\(^{-3}\); \( R \) is surface runoff and it is 0 in this study, mm; \( L \) is soil water side penetration and it is 0 in this study, mm; \( r \) is soil bulk density, g·cm\(^{-3}\); and \( D \) is the bottom water flux of 0-100 cm and it was estimated according to Darcy’s equation, and was negative when downwards and positive when upwards.

2.3.2 Total available soil water quantity
The total available soil water quantity is calculated by the following equation:

\[ TAW = 10 \times (\theta_{fc} - \theta_{wp}) \times Z_r \]  

(6)

\[ RAW = p \times TAW \]  

(7)

Where \( TAW \) is the total available soil water quantity, mm; \( \theta_{fc} \) is field capacity, cm\(^3\)·cm\(^{-3}\); \( \theta_{wp} \) is wilting coefficient and it is 0.075 cm\(^3\)·cm\(^{-3}\) in this study; \( Z_r \) is the depth of crop root zone and it is 100 cm in this study; \( RAW \) is the actual available soil water quantity, mm; \( p \) is the proportion of soil water consumption in the crop root zone to total available soil water before the occurrence of water stress and it is 0.55 for maize according to the relevant reference\(^{[12]}\).

2.3.3 Soil consumption quantity in crop root zone
The soil consumption quantity in crop root zone is calculated by the following equation:

\[ D_r = 10 \times (\theta_{fc} - \theta_i) \times Z_r \]  

(8)

Where \( D_r \) is soil consumption quantity in crop root zone, mm; \( \theta_i \) is the average soil water content in calculating period, cm\(^3\)·cm\(^{-3}\).

3. Results and discussion

3.1. Calibration of crop-water-salt production function parameters
The crop evapotranspiration (\( ET_o \)), total available soil water quantity (\( TAW \)), actual available soil water quantity (\( RAW \)) and soil consumption quantity in crop root zone (\( D_r \)) was calculated by formula (4)-(8) based on field experiment data in 2012, respectively. The parameters \( b \) and \( k_{ij} \) were unknown in the calculation crop-water-salt production and these parameters needed to be calculated in this study. It was assumed that measured seed maize yield and actual evapotranspiration were the maximum yield (\( Y_m \)) and maximum evapotranspiration (\( ET_m \)) under sufficient irrigation with fresh water (w1s1 treatment) in 2012, respectively. The measured seed maize yield (\( Y_o \)) and actual evapotranspiration (\( ET_o \)) of each treatment were introduced into formula (1)-(3). The crop-water-salt production parameters were calculated and calibrated based on the above method.

Comparison of the simulated and measured \( ET_o \) and seed maize yield in calibration are shown in Figure 1. The simulated evapotranspiration and yield agreed well with the measured values of seed maize at different growth stages and most of the points were near the 1:1 line in calibration. The calibration results were basically consistent with the growth cycle of seed maize. Seed maize grown slowly and its evapotranspiration were little in seedling-jointing stage. Seed maize grown fast and its evapotranspiration gradually increased in jointing-booting stage and booting-tasseling stage. Seed maize was mainly reproductive growth and its evapotranspiration was also large in booting-tasseling stage. Seed maize matured and gradually withered and its evapotranspiration gradually decreased in
tasseling-filling stage. The statistically evaluated results that the RMSE were all lower than 10 mm and the MRE were lower than 25% within the allowable error range in seed maize evapotranspiration calibration. The RMSE were all lower than 600 kg·hm⁻² and the MRE were lower than 15% within the allowable error range in seed maize yield calibration. The crop-water-salt production parameters after calibration were

\[ b=6.72, \ k_{v1}=0.43, \ k_{v2}=0.82, \ k_{v3}=1.41, \ k_{v4}=0.65, \ k_{v5}=0.24 \]

respectively.

3.2. Validation of crop-water-salt production function parameters

The measured seed maize yield (\( Y_a \)) and actual evapotranspiration (\( ET_a \)) of each growth stages were validated crop-water-salt production parameters based on field experiment data in 2013. Comparison of the simulated and measured \( ET_a \) of each growth stages and maize yield in validation are shown in Figure 2. The simulated evapotranspiration and yield agreed well with the measured values of seed maize at different growth stages and most of the points were near the 1:1 line in validation. The statistically evaluated results that the RMSE were all lower than 10 mm and the MRE were lower than 25% within the allowable error range in seed maize evapotranspiration validation. The RMSE were all lower than 800 kg·hm⁻² and the MRE were lower than 15% within the allowable error range in seed maize yield validation. The results of calibrating and validating crop-water-salt production parameters showed that \( k_{v1}, k_{v2}, k_{v3}, k_{v4}, k_{v5} \), which was similar to the change rule of seed maize growth cycle. It could be concluded that the effects on seed maize yield were different under water-salt combination stress at different growth stages. The calibration and validation results showed that the calculating parameters of crop-water-salt production parameters were basically reliable.
4. Conclusions

Field experiments were conducted under deficit irrigation with saline water in Shiyang River Basin. It introduced into the crop-water-salt production function. The crop-water-salt production function parameters were calibrated and validated based on the field experiments measured data in 2012 and 2013. The following conclusions can be drawn from this study:

1. The simulated evapotranspiration and yield agreed well with the measured values of seed maize at different growth stages. The RMSE values were all lower than 10 mm and the MRE values were lower than 25% within the allowable error range in seed maize evapotranspiration calibration and validation. The RMSE values were all lower than 800 kg·hm$^{-2}$ and the MRE values were lower than 15% within the allowable error range in seed maize yield calibration and validation. The crop-water-salt production function parameters after calibration and validation were $b=6.72$, $k_{y1}=0.43$, $k_{y2}=0.82$, $k_{y3}=1.41$, $k_{b0}=0.65$, $k_{b5}=0.24$, respectively.

2. The results of calibrating and validating crop-water-salt production parameters showed that $k_{y3}>k_{y2}>k_{y4}>k_{y1}$, which was similar to the change rule of seed maize growth cycle. The yield response factor ($k_y$) reflected sensitivity to the seed maize at different growth stages under water salt combination stress. The crop-water-salt production function can well simulate the seed maize evapotranspiration and yield under water salt combination stress after calibration and validation. It provides scientific basis for making deficit irrigation with saline water schedule for seed maize in study area.

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