

# Quantitative Research on Drought Loss Sensitivity of Summer Maize Based on AquaCrop Model

Fawen Li (✉ [lifawen@tju.edu.cn](mailto:lifawen@tju.edu.cn))

Tianjin University

Manjin Zhang

Tianjin University <https://orcid.org/0000-0003-4647-9953>

Yaoze Liu

University at Albany

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## Research Article

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# Quantitative research on drought loss sensitivity of summer maize based on AquaCrop model

Li Fawen<sup>1</sup>, Zhang Manjing<sup>1</sup>, Liu Yaoze<sup>2</sup>

(1. State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, PR China; 2. Department of Environment and Sustainable Engineering, University at Albany, State University of New York, 1400 Washington Avenue, Albany, NY 12222, USA)

**Abstract:** In this study, the growth periods of summer maize was divided into seedling, booting and flowering-grain stage. Based on the simulation results of AquaCrop model, the drought loss sensitivity of summer maize in different growth periods was analyzed. The sensitivity curves fitting using the soil moisture content of the effective root zone and the fixed soil layer both indicated that the booting stage was the most sensitive to water stress, which was the critical period for irrigation, followed by the seedling stage. Compared with the curve parameters fitted by the soil water content of the effective root zone, the maximum Biomass Loss Rate fitted by the fixed soil layer water content was higher and the Drought Hazard Index corresponding to the disaster-causing point and the turning point in the seedling stage moved backward. Accordingly, the best irrigation opportunity may be missed and resulting in a large reduction in production if an irrigation scheme is formulated at the seedling stage based on the sensitivity curve of summer maize fitted by the water

content of a fixed soil layer. This study also adapted the Jensen model to calculate the normalized moisture sensitivity coefficient and studied the response of final crop yield to water deficit in different growth periods. The results showed that the normalized moisture sensitivity coefficients at the seedling stage, booting stage, and flowering-grain stage were 0.251, 0.524, 0.224 respectively, which verified the rationality and feasibility of using the cumulative loss of biomass to measure the final yield loss.

**Keywords:** AquaCrop model; growth period; effective root zone; drought loss sensitivity; moisture sensitivity coefficient

The corresponding author:

Li Fawen, Email: lifawen@tju.edu.cn; Liu Yaoze, Email: yliu46@albany.edu

## 1. Introduction

In recent years, drought has become one of the most serious natural disasters in the world as the global warming continues to intensify. The frequent occurrence and wide-ranging effects of drought have threatened the global social and economic development and the well-being of human beings, which have become a problem that cannot be ignored (Naumann et al. [2018](#); Ping et al. [2010](#)). China is one of the countries with frequent droughts. According to the statistics of China Statistical Yearbook and Flood and Drought Disaster Bulletin, China's average annual dry farmland area from 1949 to 2019 was about 20.483 million ha, accounting for approximately 57.2% of the farmland affected by various meteorological disasters.

Among them, the average disaster area is 919.2ha, accounting for nearly 6.5% of the sown area, and the annual loss of grain due to drought is 14.482 billion kg. Therefore, an in-depth understanding of the mechanism of agricultural drought risk formation and the transformation from passive drought resistance to active drought prevention are of great significance for ensuring national food security and increasing farmers' economic income.

Drought loss sensitivity is the core factor of agricultural drought vulnerability, which refers to the loss response of the disaster-bearing body completely exposed to the disaster-pregnant environment to the drought-causing factors. In agricultural drought, it is expressed as the response or sensitivity degree of crop growth to the loss of water deficit intensity in growth period (Xu et al. [2010](#)). At present, the research on agricultural drought mainly focuses on drought risk assessment (Hoque et al [2021](#); Jin et al. [2016](#)), drought vulnerability assessment (Cui et al. [2019](#); Tanago et al. [2018](#)), and drought warning (Kar et al. [2018](#); Ewbank et al. [2019](#)), but most of them are in view of the whole growth period, and the difference in water sensitivity of crops in different growth periods will lead to different drought losses. Huang et al. ([2019](#)) used crop model to simulate the effect of drought of different durations at the seedling, jointing, and filling stages on corn yield. The results showed that the reduction in corn yield at the jointing stage was greater than the seedling and filling stages under the same degree of drought. Study by Varga et al. ([2015](#)) in Europe indicated that the impact of winter wheat water deficit on the final yield was not only related to the length of the crop growth period, but also related to the growth period. The current

researches on agricultural drought concentrate on the impact of rainfall on drought, but insufficient attention is paid to the impact of soil and crops on drought in the process of agricultural drought, ignoring the differences in water sensitivity of crops in different growth stages. As a result, some agricultural drought evaluation indexes have obvious defects in expressing the mechanism and process of drought development, and there is a large gap between the evaluation results and reality. Therefore, as the core factor of agricultural drought disaster, drought loss sensitivity is necessary to be analyzed and discussed to study the response of crop yields at different growth stages to agricultural drought, so as to provide scientific basis for in-depth understanding of the formation mechanism of agricultural drought risk, improving agricultural drought indicators, formulating appropriate irrigation systems and guiding actual agricultural production.

Some studies on crop drought loss sensitivity have been carried out. Cui et al. (2019) evaluated the drought loss sensitivity of soybeans in the Huaibei Plain based on water deficit pot experiments; Wei et al. (2019) used the crop model to study the drought loss sensitivity of summer maize and develop different irrigation systems based on rainfall conditions in typical drought years; Based on the historical data from 1961 to 2017, Wang et al. (2019) compared the sensitivity of two crops through the yield loss of soybean and maize corresponding to the same degree of drought. Elisabeth et al. (2019) quantified the drought sensitivity and resilience of rice, wheat and maize, and proposed the concept of “crop-drought vulnerability typology”. Snowden et al. (2014) conducted field experiments in Texas to study the effects of the

time of drought on cotton growth and fiber quality. Puppala et al. (2005) compared different irrigation treatments on oilseed crops based on field experiments to study the most critical stage. The above studies on drought loss sensitivity were mostly based on pot experiment, field experiment or historical data. However, the number of samples obtained by pot experiment is limited and the accidental error is large. In the field experiment, the conditions are difficult to control, and the time and capital investment is large. In most areas of China, the data began to be monitored later with fewer stations and more missing years, so there are less available historical data. In addition, the soil water content data used to study crop disaster sensitivity are usually based on fixed soil layer, which does not change with the growth of crop roots and is different from the soil layer that actually absorbs water. The crop model based on the response of crop yield to water has mature theory and strong mechanism, and has high accuracy and applicability after calibration and verification, which can create sufficient sample conditions (Mkhabela and Bullock 2012). Therefore, AquaCrop crop model was used to simulate the 0-40cm fixed soil water content, soil water content in effective root zone and aboveground biomass accumulation of summer maize in Shijin Irrigation District from 1951 to 2016 under full irrigation and rainfed conditions to calculate the drought disaster index and biomass loss rate. The drought loss sensitivity curves of summer maize at different growth stages were plotted using the idea of constructing vulnerability curves. From the dynamic point of view, the biomass loss rate under different water stress intensity in each growth period was studied, and the difference of fitting curve between fixed soil layer water content and

effective root zone soil water content was compared.

Drought disaster sensitivity is a study on the loss rate of aboveground biomass under various drought intensities at different growth stages from a dynamic perspective, which is of great significance to accurately identify the critical water sensitive periods of summer maize growth and formulate accurate irrigation schemes. However, it is because of its dynamic nature that the expression form of applying it to the improvement of agricultural drought index is complex, which is not conducive to popularization and application. Therefore, it is necessary to study the response of crop final yield to water deficit at different growth stages and calculate crop moisture sensitivity coefficient by using crop water production function from a macro perspective, which lays the foundation for subsequent index improvement. The first part of this study was to discuss the drought disaster sensitivity by using the aboveground biomass accumulation, which was intended to reveal the physical causes of drought losses under the action of drought-induced factors from the perspective of aboveground growth. By comparing the results of moisture sensitivity coefficient and drought disaster sensitivity, the rationality and feasibility of using aboveground biomass accumulation loss to measure the final yield loss were verified. At present, the commonly used water production functions include Stewart model, Rao model, Jensen model, etc., among which Jensen model is the most widely used and the calculation result is relatively reliable (Han et al. [2009](#)). Igbadun et al. ([2007](#)) compared several water productivity models and recommended the Jensen model to predict maize yield. He et al. ([2016](#)) used potential evapotranspiration, actual

evapotranspiration, potential yield and actual yield to calculate the water sensitivity coefficient of winter wheat at different growth stages based on Jensen model and crop model, and formulated the corresponding irrigation scheme in Guanzhong area. Smilovic et al. (2016) obtained the moisture sensitivity coefficients of various crops at different growth stages based on the parameters provided by FAO, and drew the “crop kite” to help decision makers select the optimal irrigation system under different water inflow conditions. In this study, according to the crop evapotranspiration and final yield of summer maize under sufficient moisture and rainfed conditions simulated by AquaCrop crop model in Shijin Irrigation District from 1951 to 2016, the Jensen model was used to calculate the crop moisture sensitivity coefficient to verify the rationality and feasibility of selecting biomass accumulation as a measure in the study of drought sensitivity, and lay the foundation for the improvement of subsequent agricultural drought indicators.

## **2. Materials and Methods**

### **2.1 Study area**

As a large irrigation area in Haihe River Basin, the Shijin Irrigation District is located in the central and southern part of Hebei Province, between the Hutuo River and the Fuyang River. Geographical location is shown in Fig.1. The Shijin Irrigation District is situated in the temperate zone, dominated by typical temperate continental monsoon climate. The average annual evaporation is 1100mm and the average annual rainfall is 507.2mm. The annual rainfall distribution in the irrigation area is extremely

uneven, with June to August receiving nearly 70% of the annual rainfall and mostly in the form of torrential rain. The average temperature in January is the lowest, generally around  $-9^{\circ}\text{C}$ , with extreme lows reaching  $-22^{\circ}\text{C}$ . The average temperature in July is the highest, generally around  $32^{\circ}\text{C}$ , with extreme highs reaching  $41.9^{\circ}\text{C}$ . The total sunshine time throughout the year is about 2629.5 hours, and the sunshine rate is 59%. Summer maize is one of the main food crops in Shijin Irrigation Area. Controlling the adverse effects of drought on summer maize is of great significance to ensuring food security in Hebei and creating economic benefits.

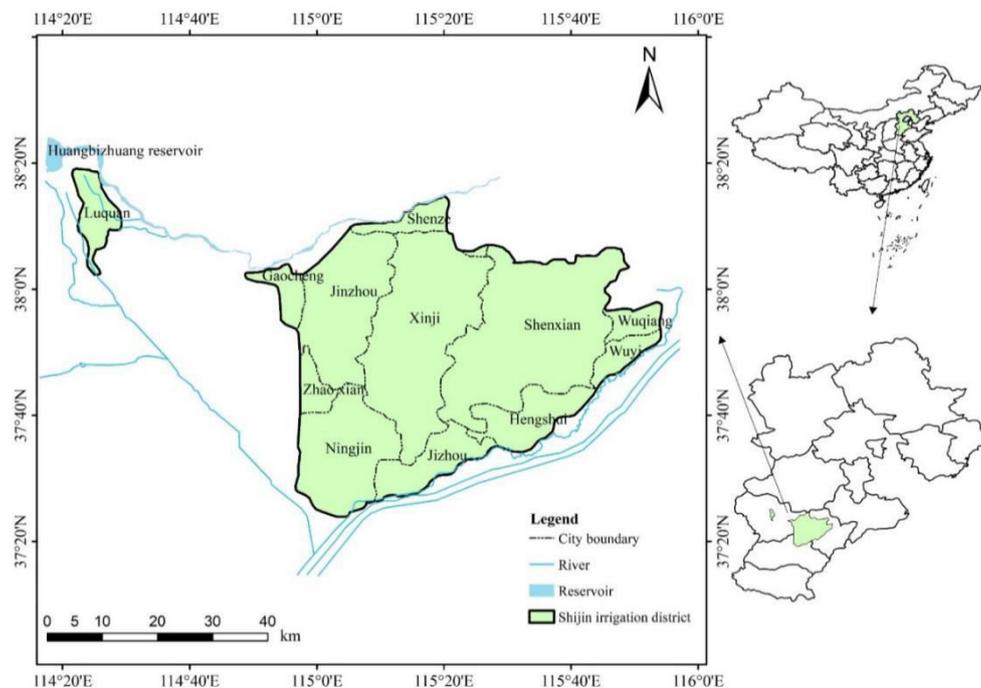


Fig. 1 Location of Shijin Irrigation District

## 2.2 Data

The meteorological data of Luancheng Meteorological Station from 1951 to 2016 and crop data used in this study are downloaded from China Meteorological Data Network (<http://www.nmic.cn/>), including daily average temperature, maximum

temperature, minimum temperature, sunshine hours, precipitation, wind speed. The field management parameters when calibrating and verifying the AquaCrop model are derived from the field data of Luancheng Experimental Station. The soil data is searched from the China Soil Database (<http://vdb3.soil.csdb.cn>).

### 2.3 AquaCrop model

AquaCrop model is a new crop model proposed by FAO in 2009 based on the response of crop yield to water. Compared with the widely used crop models such as APSIM, WOFOST and DSSAT, the AquaCrop model has fewer input parameters and a simpler interface. The model requires input parameters mainly meteorological data, crop parameters, management parameters, soil parameters and initial condition parameters, and all the above data information is generally easily available. Because of the complexity of crop response to water deficit, empirical equation is generally used in assessing crop yield response to water, and the basic principle of the traditional water-driven model operation is based on Eq. (1).

$$\left[ \frac{Y_x - Y_a}{Y_x} \right] = K_y \left[ \frac{ET_x - ET_a}{ET_x} \right] \quad (1)$$

Where  $Y_x$  and  $Y_a$  represent potential yield ( $\text{kg}\cdot\text{m}^{-2}$ ) and actual yield ( $\text{kg}\cdot\text{m}^{-2}$ ), respectively;  $ET_x$  and  $ET_a$  represent potential evapotranspiration (mm) and actual evapotranspiration (mm), respectively;  $K_y$  represents the ratio of relative yield loss to relative evapotranspiration reduction.

The above equation confuses ineffective soil evaporation with effective crop transpiration to a certain extent when evaluating crop yield response to water, especially in the case of low crop canopy cover, the model simulation error is larger. To solve the above problem, the AquaCrop model is improved in two ways: 1. transpiration is divided into soil ineffective evaporation and effective transpiration of the crop to make the simulation results more accurate. The product of water production efficiency and cumulative crop transpiration is used as biomass (Eq. 2), and the final yield is the multiply of biomass and harvest index (Eq. 3). 2. The traditional leaf area index describing the crop growth and development process is replaced by canopy cover, and the crop senescence process is described by canopy growth coefficient and canopy decay coefficient, which quantifies the crop growth and senescence process and greatly improves the simulation accuracy of the model (Steduto et al. 2009; Raes et al. 2009; Hsiao et al. 2009).

$$B = WP \times \sum Tr \quad (2)$$

$$Y = B \cdot HI \quad (3)$$

Where B is biomass ( $\text{kg}\cdot\text{m}^{-2}$ ); WP is water productivity ( $\text{kg}\cdot\text{m}^{-2}\cdot\text{mm}^{-1}$ );  $\sum Tr$  is cumulative transpiration (mm); HI is harvest index (%).

## **2.4 Calibration and validation of the model**

The method of calibration and validation has been described in our previous paper (Li et al. 2020). It is necessary to simplify the calibration process by determining parameter sensitivity before model calibration. The trial and error method

(Eq.4) was introduced to calculate the relative sensitivity of crop parameters (Wang and Wang 2010). Adjustments were made one parameter at a time during commissioning, within a range of  $\pm 10\%$ . It needs to make appropriate adjustments if the parameters were out of the range of reference parameters in the AquaCrop manual. For parameters with low relative sensitivity (RS), default it to fixed values recommended by FAO, and only adjust parameters with high RS.

$$RS = \left| \frac{x[y(x+\Delta x) - y(x)]}{y(x)\Delta x} \right| \quad (4)$$

where RS represents the relative sensitivity of the parameters;  $x$  and  $\Delta x$  represent the input values of a certain parameter and the input variation of the parameters;  $y(x)$  and  $y(x+\Delta x)$  represent the simulated output values of the model before and after the parameters are changed respectively.

Luancheng experimental station only has the field experimental data of summer maize from 2004 to 2013. Therefore, this study took 2004-2008 as the model calibration period, and 2009-2013 as the model validation period. Based on the measured and simulated soil water content at 10 cm, 20 cm and 50 cm and crop yield, The simulation results were evaluated using the relative error RE (Eq.5) and coefficient of residual mass CRM (Eq.6). When the relative error RE is within  $\pm 20\%$ , The simulation accuracy is considered high. CRM is used to verify the evaluation result of relative error which can be positive or negative, and the closer the CRM is to zero, the better the simulation effect is.

$$RE = \frac{|O_i - S_i|}{O_i} \quad (5)$$

$$\text{CRM} = \frac{(\sum_{i=1}^{i=n} O_i - \sum_{i=1}^{i=n} S_i)}{\sum_{i=1}^{i=n} O_i} \quad (6)$$

Where  $S_i$  represents the simulated value of production (kg/ha);  $O_i$  represents the observed value of production (kg/ha);  $n$  represents the sample size.

## **2.5 Sensitivity to drought loss of summer maize**

### **2.5.1 Growth stages division**

According to the primary and secondary relationships between roots, stems, leaves, spikes and grains of summer maize and the process of vegetative and reproductive growth, the whole growth process is divided into three stages: seedling stage, booting stage and flower-grain stage. The seedling stage, from the sowing to the jointing period, is also called the vegetative growth stage, which refers to the stage of rooting, growing leaves, and differentiation of the stems. Booting stage is also known as the stage where vegetative growth and reproductive growth go hand in hand, from jointing to tasseling period. At this stage, there are vigorous growth of roots, stems, and leaves, as well as rapid differentiation and development of male tassels. During this period, there are 3-5 layers of hyperplastic node roots, the stem nodes are elongated, thickened, and shaped, the leaves are all expanded, the tassels are drawn out, and the main axis blooms. The early stage is dominated by vegetative growth, and then turned to reproductive growth. The flowering-grain stage also known as the reproductive growth stage, which is the period from tasseling to maturity. The vegetative growth at this stage is basically over, and it enters the reproductive growth stage of flowering, fertilization, and fruit development. Grains

are rapidly formed and enriched, becoming the transfer center of photosynthetic products. The phenological data of Luancheng Meteorological Station determines the specific dates for the division of summer corn growth stages, as shown in Table 1.

Table 1 Division of growth stages of summer maize

Growth stage	seedling stage from sowing to jointing	booting stage from jointing to tasseling	flower-grain stage from tasseling to maturity
Date	11 June-10 July	July 11 – August 11	12 August-20 September

### 2.5.2 Index selection

In this study, Drought Hazard Index (DHI) was used to describe quantitatively the degree and duration of water stress at each growth stage, and the calculation formulas were as follows Eq.7 and Eq.8. The value range of DHI is 0-1, and the greater the value is, the more serious the water deficit or the longer the duration is. Crop Water Deficit ( $CWD_j$ ) was calculated according to the drought recognition theory based on the soil water content under rain-fed conditions simulating by the AquaCrop model, which describes the degree of water deficit on the  $j$ th day under specific growth stage of summer corn. The process of drought identification is shown in Fig.2. When the soil water content is lower than the threshold  $\theta_F$ , it is determined that the day is subjected to water stress. The b and d processes in the figure are subjected to water deficit. The accumulation of water deficit in crop growth period is the sum of shadow parts in the figure.

Li et al. (2010) found that the lower limit of soil moisture suitable for summer

maize growth is 70 % of field capacity, and the wilting point is the soil water content where the growth of summer corn is most inhibited. Therefore, the above two points are selected as the threshold for drought identification.

$$DHI = \frac{\sum_{j=1}^n CWD_j - \min CWD_j}{\max CWD_j - \min CWD_j} \quad (7)$$

$$CWD_j = \begin{cases} 1 & \theta_j < \theta_{WP} \\ \frac{\theta_j - \theta_{WP}}{\theta_F - \theta_{WP}} & \theta_{WP} \leq \theta_j \leq \theta_F \\ 0 & \theta_j > \theta_F \end{cases} \quad (8)$$

Where n is the number of days summer corn is exposed to water stress in a certain growth period;  $\min CWD_j$  and  $\max CWD_j$  represent the minimum and maximum value of accumulated crop water deficit in this growth period in all simulated years respectively;  $\theta_j$  represents the soil water content on the jth day of the growth stage under the rain-fed condition simulated by the AquaCrop model;  $\theta_{WP}$  is the water content at the wilting point, and  $\theta_F$  is 70% of the field capacity.

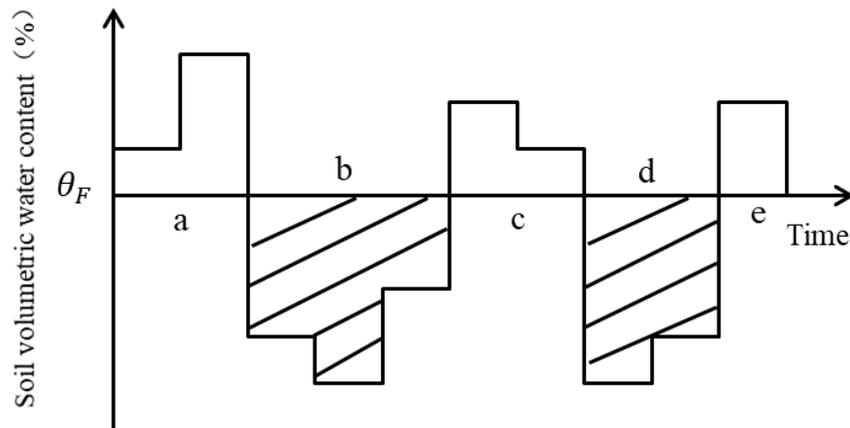


Fig.2 Drought process identification

Biomass accumulation dynamics is the most direct manifestation of crop growth,

and also an external indicator of summer maize growth and development at various growth stages. Aboveground biomass quality is an important material basis for yield formation, and has a noticeable positive correlation with crop yield (Zhu et al. 2008; Steduto et al.2007). Therefore, the aboveground Biomass Loss Rate (BLR) in each growth period was selected as an indicator to measure the impact of water deficit on the growth and development of crops, which was conducive to revealing the physical causes of drought loss of summer maize under the action of drought-induced factors from the perspective of aboveground growth. The calculation formula is shown in Eq.9.

$$BLR = 1 - \frac{B_R}{B_I} \times 100\% \quad (9)$$

Where  $B_I$  and  $B_R$  are the aboveground biomass accumulation at a certain growth stage simulated by the model under sufficient water and rain-fed conditions respectively. The accumulation of aboveground biomass in the  $i$ th growth stage is the difference between the quality at the end of this growth stage and the end of the previous growth stage ( $i-1$ ).

### 2.5.3 S-type sensitivity curve

Taking the DHI and the corresponding BLR as the abscissa and ordinate respectively, the S-shaped curve was used for fitting to compare the drought loss sensitivity of summer maize at each growth stage. The fitting form of the S-type sensitivity curve is shown in Eq.10, and each parameter has its physical meaning. The primary parameters are  $K$  and  $r$ .  $K$  reflects the upper limit of aboveground BLR of

summer maize under high drought disaster intensity.  $r$  reflects the speed of aboveground BLR approaching the upper limit  $K$  with the increase of drought disaster intensity (Chen et al. 2015). The conceptual model is shown in Fig.3. The main points of concern are disaster-causing point and turning point. The point with the maximum slope change rate is the disaster-causing point, and the third-order derivative of this point is 0. Substituting it into the S-type curve expression, the formula for calculating the DHI corresponding to this point is  $\ln[(2 - \sqrt{3})a]/r$ . When the loss rate of aboveground biomass reaches  $K/2$ , the corresponding point is the turning point of drought, and the loss rate of aboveground biomass reaches the maximum growth rate with the increase of drought disaster intensity. Substituting  $K/2$  into the S-shaped curve expression, the expression of DHI corresponding to this point is  $\ln(a)r$ .

$$y = \frac{K}{1 + \alpha e^{-rx}} \quad (10)$$

Where  $x$  is the drought hazard index in a certain growth stage;  $y$  is the corresponding above-ground biomass loss rate loss rate during the growth period;  $e$ 、 $\alpha$ 、 $r$ 、 $K$  are the parameters of the curve.

## 2.6 Normalized moisture sensitivity coefficient

The AquaCrop model was used to simulate the yield and evapotranspiration of summer maize under sufficient water and rainfed conditions from 1951 to 2016. Using the Jensen model, the response of summer corn yield to water deficit at each growth stage was expressed in the form of the multiplication of the ratio of actual soil moisture to the ideal soil water condition, and the moisture sensitivity coefficients of

summer corn at different growth stages were calculated (Eq.11).

$$\frac{Y_R}{Y_I} = \prod_{i=1}^n \left( \frac{W_R}{W_I} \right)_i^{\rho_i} \quad (11)$$

Where  $Y_R$  and  $Y_I$  represent the yield of summer maize under rainfed condition and sufficient water condition respectively.  $n$  is the number of growth stages of summer maize, which is set to 3 in this study;  $W_R$  and  $W_I$  represent the crop evapotranspiration under rainfed condition and sufficient water condition respectively;  $\rho_i$  is the moisture sensitivity coefficient of each growth stage.

Mathematical expansion and change of Jensen model:

$$\ln \frac{Y_R}{Y_I} = \rho_1 \ln \left( \frac{W_R}{W_I} \right)_1 + \rho_2 \ln \left( \frac{W_R}{W_I} \right)_2 + \rho_3 \ln \left( \frac{W_R}{W_I} \right)_3 \quad (12)$$

The simulation results of AquaCrop model are introduced into Eq.12 to form multiple linear regression equation:

$$\sum_{j=1}^k \ln \frac{Y_R}{Y_I}_j = \sum_{j=1}^k \left( \rho_1 \ln \left( \frac{W_R}{W_I} \right)_1 + \rho_2 \ln \left( \frac{W_R}{W_I} \right)_2 + \rho_3 \ln \left( \frac{W_R}{W_I} \right)_3 \right)_j \quad (13)$$

Where  $k$  is the number of multiple linear regression equations, that is the total number of simulation years, which is set to 66 in this study. The least square method is used to optimize the multiple linear regression equations to obtain the moisture sensitivity coefficients of summer corn in different growth stages.

F test (Eq.14 to Eq.17) was used to determine the significance of multivariate linear regression equations. This test was carried out at the significance level  $\alpha=0.05$ . The value of  $F_{\alpha}(n, k - n - 1)$  is found from the F value table. If  $F > F_{\alpha}$ , the fitting

equation is significantly effective at this level.

$$F = \frac{U/n}{Q/(k-n-1)} \quad (14)$$

$$U = \sum_{j=1}^k (\hat{Y}_j - \bar{Y})^2 \quad (15)$$

$$Q = \sum_{j=1}^k (\hat{Y}_j - Y_j)^2 \quad (16)$$

$$\bar{Y} = \frac{1}{k} \sum_{j=1}^k Y_j \quad (17)$$

Where  $\hat{Y}_j$  is the crop yield (t/ha) calculated by the Jensen model;  $Y_j$  is the crop yield (t/ha) simulated by the AquaCrop model; and  $\bar{Y}$  is the annual average yield (t/ha) simulated by the crop model.

Normalize  $\rho_1$ 、 $\rho_2$  and  $\rho_3$  to calculate the normalized moisture sensitivity coefficient  $\gamma_i$ :

$$\gamma_i = \rho_i / (\rho_1 + \rho_2 + \rho_3) \quad (18)$$

### 3. Results and discussion

#### 3.1 Calibration and validation of the model

The relative sensitivity analysis of summer corn parameters in the AquaCrop model and their rated values are shown in Table 2. The main sensitive parameters were canopy growth coefficient (CGC), crop coefficient when canopy is complete but prior to senescence (kcb), water productivity normalized for ET<sub>0</sub> and CO<sub>2</sub> (WP), reference harvest index (Hio) and soil water depletion factor for canopy expansion-lower threshold (plexp).

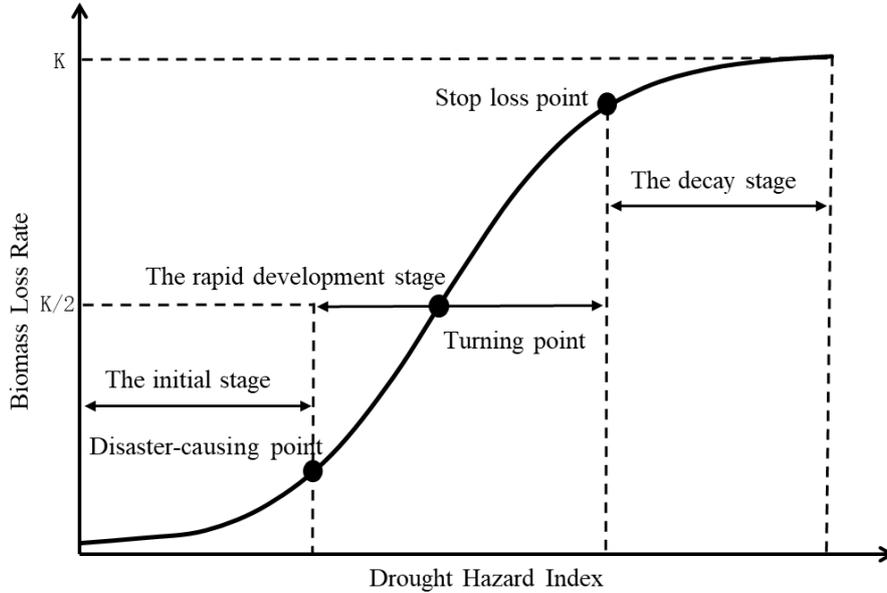


Fig.3 Conceptual model of crop drought sensitivity curve

Table 2 Sensitivity analysis results and calibration values of summer maize parameters

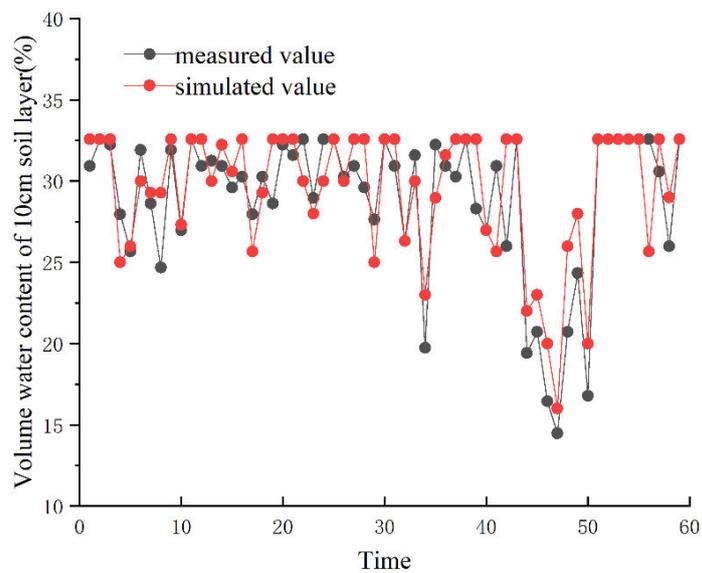
Crop parameters	The relative sensitivity	calibration value
plexp	0.76	2.08
kcb	0.58	0.92
WP	0.94	1.00
CGC	0.84	1.24
Hio	0.91	1.00

The multi-year relative errors between the simulated and measured values of summer maize yield were within 10% as shown in Tables 3. The residual coefficients of the calibration period and the validation period were -0.0089 and 0.0343, respectively, which were close to 0. The dynamic variation trends of simulated and measured soil volumetric water contents in different soil layers were consistent. As shown in Fig.4, the maximum errors of simulated and measured soil volumetric water contents in 10, 20 and 50cm soil layers were 6.9, 4.3 and 4.9cm<sup>3</sup>/cm<sup>3</sup>, respectively,

and the average errors were 0.59, 1.22 and 0.06cm<sup>3</sup>/cm<sup>3</sup>. The simulation accuracy of AquaCrop model is high, which can be used in Shijin irrigation area.

Table 3 Yield calibration and verification results of summer maize

	year	Measured yield (t/ha)	Simulated yield (t/ha)	RE (%)	CRM
the calibration period	2004	6942	7196	3.66	
	2005	7066	7121	0.78	
	2006	7083	7065	0.25	-0.0089
	2007	7078	7087	0.13	
	2008	7216	7231	0.21	
the validation period	2009	6800	6899	1.46	
	2010	7288	7025	3.61	
	2011	7816	7278	6.88	0.0343
	2012	7667	7368	3.90	
	2013	7552	7281	3.59	



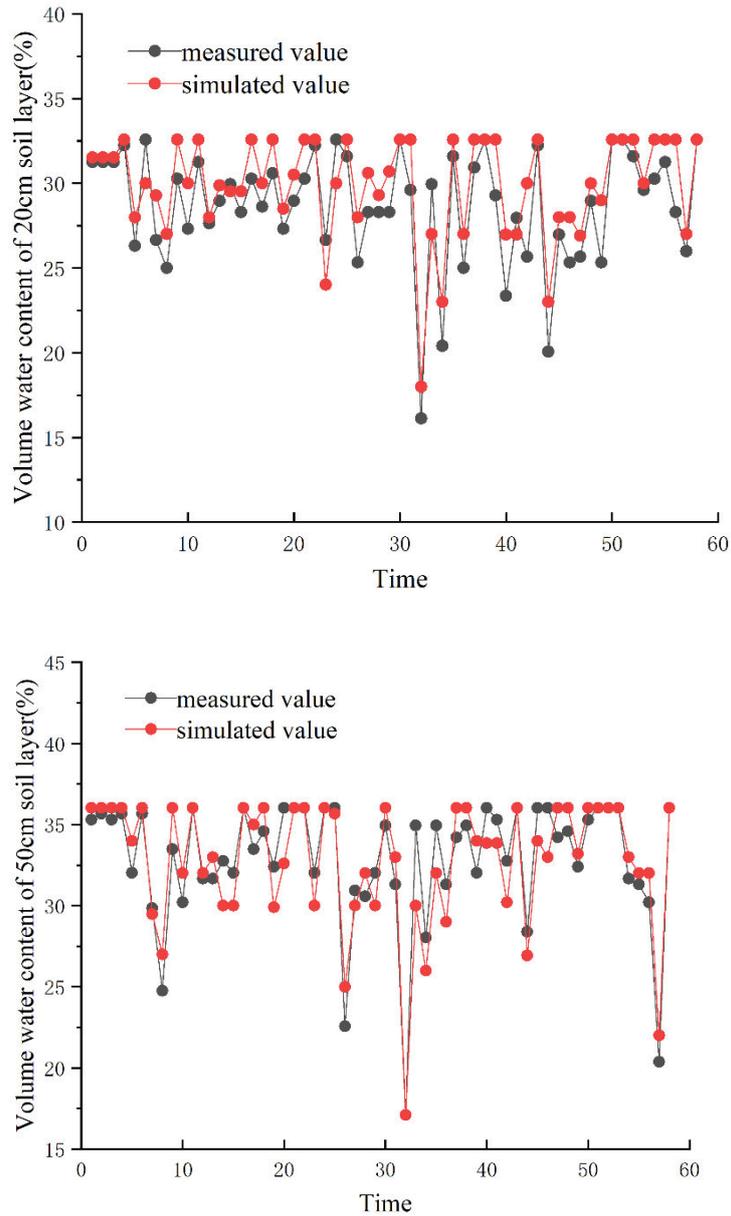


Fig.4 Measured and simulated soil volumetric water content

### 3.2 Drought loss sensitivity curve

The drought loss sensitivity curves of summer maize in different growth stages fitted with 0-40cm fixed soil layer and effective root zone soil moisture are shown in columns a and b in Fig.5. It indicated that summer maize aboveground BLR increases with the increase of DHI. Combined with the physical meaning of each parameter of

S-type sensitivity curve and the corresponding values of simulated growth stages, it could be seen that the maximum aboveground BLR at seedling stage, booting stage and flower-grain stage corresponding to DHI calculated by soil water content data in effective root zone was 38.06%, 56.21% and 11.00%, respectively. The maximum BLR occurred at booting stage, demonstrating that this growth stage was most sensitive to water stress, and the biomass loss was the most serious under the same drought stress. The booting stage is the most exuberant growth stage of summer maize. The vegetative organs such as leaves and stem nodes grow vigorously. The male and female spike precursors begin to differentiate, and the young spikes grow rapidly. During this period, the metabolism is strong, and the growth of reproductive organs is extraordinary sensitive to water response. The maximum LBR at seedling stage ranked the second. When the vegetative growth of summer maize is subjected to water stress, the plant growth is affected and the leaf development is insufficient, thus affecting the light interception and photosynthesis of the canopy. During this period, drought stress would reduce the plant height, leaf area index and the growth rate of aboveground biomass, resulting in the decrease of dry matter accumulation. The maximum BLR at flowering-grain stage was the smallest. At this stage, the roots, stems and leaves of summer maize have basically stopped growing. The supplied water is mainly used to prolong the photosynthesis time of leaves and ensure that the plants transported the accumulated nutrients from leaves to fruits, so that the maize kernel develops more fully and the 100-grain weight increases. At this time, the demand for water is small, so the drought stress has little impact on the biomass

accumulation of crops (Ge et al. 2012). Parameter  $r$  reflects the speed at which the aboveground BLR tends to the upper limit with the increase of DHI. The  $r$  values at seedling stage, booting stage and flowering-grain stage were 2.24, 3.68 and 9.26 respectively, indicating that the flowering-grain stage reached the maximum biomass loss rate in the shortest time. Therefore, although the maximum BLR at this stage was the lowest, it is still necessary to strictly control the soil moisture content. The above discussion shows that it is very important to keep summer maize from water stress at booting stage and strictly control the water deficit intensity at seedling stage and flowering-grain stage to maintain the development of summer maize and ensure crop yield. This conclusion is consistent with the previous study of summer maize water demand (Wei et al. 2020; Cao et al. 2003).

The disaster-causing point of S-shaped curve is the point of the maximum slope change rate. At this point, the growth rate of BLR of summer maize is the fastest with the increase of DHI. Since then, the adverse effect of drought on crops has entered a rapid development period from the initial period. The DHI corresponding to the disaster-causing points at seedling stage, booting stage and flowering-grain stage fitted by soil water content in the effective root zone were 0.09, 0.18 and 0.05, respectively, and the cumulative crop water deficit values were 0.01, 0.02 and 0.01, respectively. In order to avoid the rapid development of drought damage, when the drought disaster intensity or cumulative water deficit value at each growth stage reached the corresponding critical value, disaster warning should be established to guide farmers to conduct irrigation in time.

When the aboveground BLR reaches  $K/2$ , the corresponding point is the turning point of drought. With the increase of DHI, the growth rate of aboveground BLR reaches the maximum and the adverse effects of drought on crops have changed from prosperity to decline in this point. The DHI corresponding to the drought turning points of seedling stage, booting stage and flowering-grain stage fitted by soil moisture content in the effective root zone was 0.68, 0.54 and 0.20, respectively, and the cumulative crop water deficit values were 0.06, 0.06 and 0.05, respectively. In the actual drought resistance process, irrigation is carried out in time according to soil moisture to ensure that the drought disaster intensity is always lower than the critical value of the turning point, so as to control the adverse effects of drought on crops and maintain the yield loss within an acceptable range.

The maximum BLR corresponding to seedling stage, booting stage and flowering-grain stage were 39.92%, 47.94% and 12.35% fitted with the fixed soil moisture content. Compared with the curve plotted with the effective root zone soil moisture content, the former maximum BLR of seedling stage and flowering-grain stage were greater than the latter. Although the maximum BLR fitted with the fixed soil moisture content at booting stage was lower than that fitted with the effective root zone moisture content, it can be seen from Fig.6 that when the DHI was in the range of 0.11-0.94, the BLR of the former was greater than that of the latter. Overall, the disaster sensitivity curve fitted with the fixed soil moisture content would overestimate the BLR.

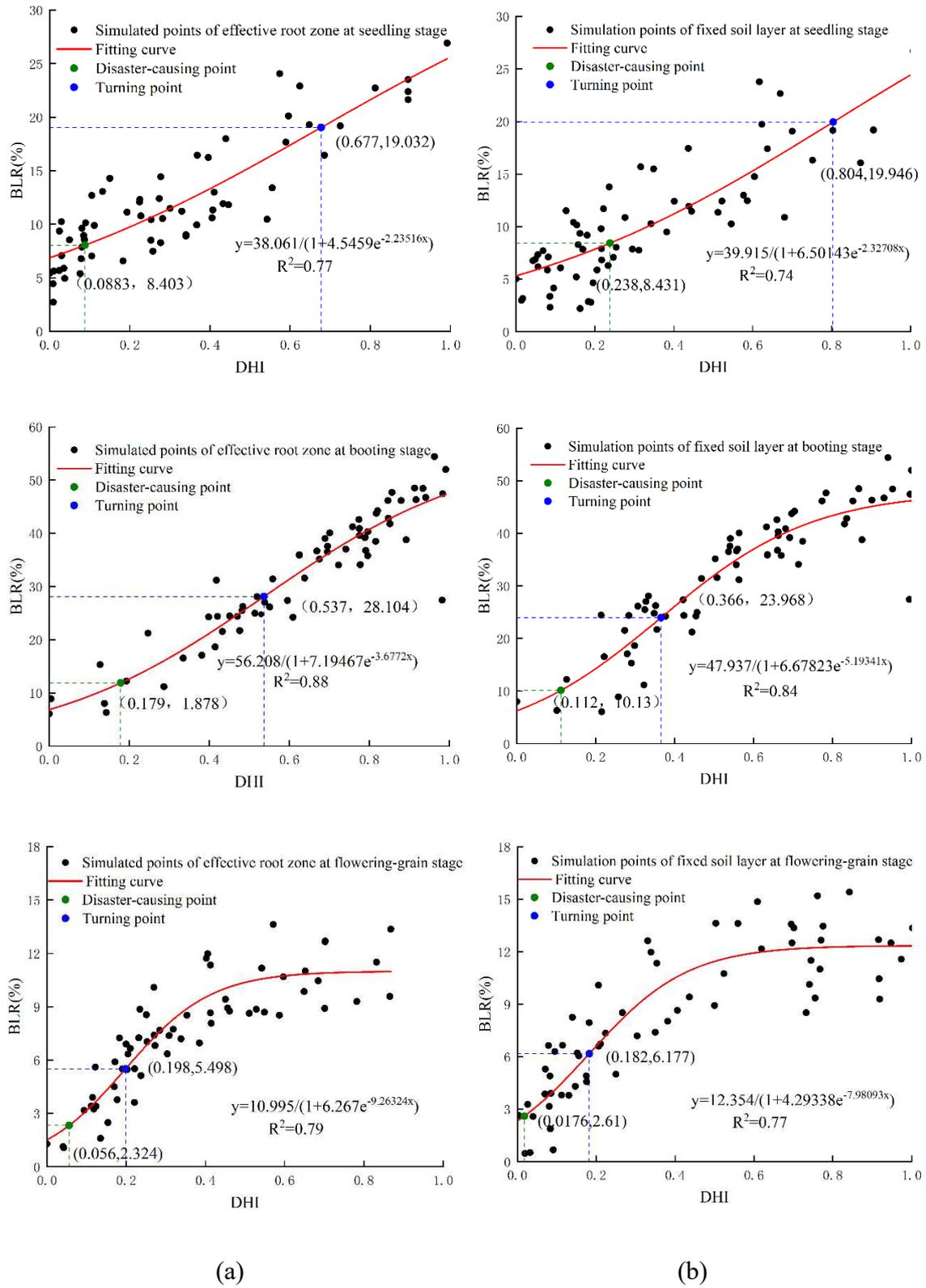


Fig.5 Curve fitting results of drought loss sensitivity in different growth stages of summer maize

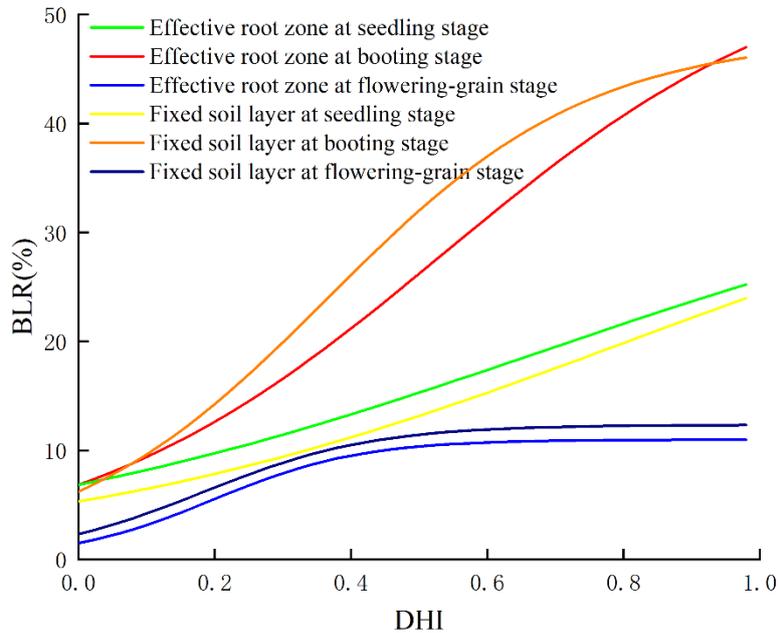


Fig.6 Comparison of drought sensitivity in different growth stages of summer maize

The DHI corresponding to the disaster-causing points at seedling stage, booting stage and flowering-grain stage of the disaster sensitivity curve fitted by the fixed soil layer water content data were 0.24, 0.11 and 0.02 respectively, and the DHI corresponding to the turning point were 0.80, 0.37 and 0.16 respectively. Compared with the curve parameters fitted by the soil water content data in the effective root zone, the DHI corresponding to the disaster-causing point and the turning point at seedling stage fitted by the fixed soil layer water content increased by 0.15 and 0.12, respectively. The DHI corresponding to the disaster-causing point and the turning point at booting stage decreased by 0.07 and 0.17, at flowering-grain stage decreased by 0.04 and 0.02 respectively. It is mainly due to the strong correlation between the water content of surface soil and climatic conditions such as temperature, sunshine

and wind speed. The evaporation of surface soil is large, and the water content changes frequently. However, the water content of deep soil is relatively stable, and the lag time for meteorological drought is long (Gao et al. 2015). In the early stage of summer maize sowing and vegetative growth, root depth is usually between 0-20cm soil layer, 0-40cm fixed soil layer water content is usually greater than the actual available soil water content. Therefore, under the same drought intensity, the BLR in the seedling stage fitted by the fixed soil layer was lower than that of the effective root zone, and the corresponding critical point of drought disaster intensity postponed. The root system of summer maize is developed at booting stage and flowering-grain stage, and the root depth was usually greater than 40cm, even up to 2m. At this stage, summer maize could not only absorb the water near the root system, but also obtain the water in deeper soil through capillary force. The water content of fixed soil layer at 0-40cm was less than the actual available soil water content. Therefore, under the same disaster-causing drought intensity, the fitting BLR at booting stage and flowering-grain stage of fixed soil layer was higher than that of the effective root zone, and the corresponding critical point of drought hazard index advanced. It can be seen from the above results that if the irrigation scheme of the seedling stage is formulated according to the drought loss sensitivity curve of summer maize fitted by the fixed soil moisture content, the optimal irrigation time will be missed and lead to massive reduction in summer maize yield.

### **3.3 Moisture sensitivity coefficient**

Based on the yield and evapotranspiration of summer maize under sufficient

water and rainfed conditions from 1951 to 2016 simulated by AquaCrop model, the crop sensitivity coefficients at seedling stage, booting stage and flowering-grain stage calculated by Jensen model were 0.281, 0.587 and 0.251, respectively, and the normalized moisture sensitivity coefficients were 0.251, 0.524 and 0.224, respectively. Look up the table and get  $F_{0.05}(3, 62)=2.6$ . The calculation results of sensitivity coefficient showed that the booting stage was the pivotal period affecting the yield of summer maize, followed by the seedling stage, which was consistent with the results of disaster sensitivity curve fitted by crop biomass accumulation. If summer maize suffers drought at seedling stage, the plant height and leaf area index decrease significantly, aboveground biomass accumulation slows down, resulting in incomplete fruit development, and eventually led to a significant reduction in yield. If water deficiency occurs at booting stage, biomass accumulation decreases during this period, and the spikes of male and female can't be pulled out on schedule. Thus prolong the flowering distance between male and female, resulting in poor pollination and showing less quantity per spike, and ultimately inducing serious balding and yield reduction. Water stress at the flowering-grain stage will inhibit the accumulation of biomass in the kernel part, which will cause the corn kernels to become shriveled, reduce the 100-grain weight, and conclusively lead to a decline in yield. This study verified the rationality of using biomass accumulation loss to reveal the physical causes of summer maize yield loss under drought disaster-causing factors from the perspective of upper land growth.

## 4. Conclusions

(1) The maximum aboveground BLR at seedling stage, booting stage and flowering-grain stage corresponding to DHI calculated by soil water content data of effective root zone were 38.06%, 56.21% and 11.00%, respectively. The maximum dry matter loss rate occurred at booting stage, followed by seedling stage. Therefore, it is necessary to ensure that summer maize is free from water stress at booting stage, and strictly control the water deficit intensity at seedling stage and flowering-grain stage.

(2) The DHI corresponding to the disaster-causing point at the seedling stage, booting stage and flower-grain stage were 0.09, 0.18, and 0.05 respectively. In order to avoid the rapid development of drought damage, when the DHI of each growth period reached the corresponding critical value, disaster warning should be established to guide farmers to irrigation in time.

(3) The DHI corresponding to drought turning points at seedling stage, booting stage and flowering-grain stage was 0.68, 0.54 and 0.20, respectively. In the actual drought resistance process, it is necessary to ensure that the DHI is always below the turning point to control the adverse effects of drought on crops.

(4) On the whole, compared with the curve fitted by the soil water content data in the effective root zone, the disaster sensitivity curve fitted by the water content data of the fixed soil layer overestimated the BLR. The DHI corresponding to the disaster-causing point and the turning point at the seedling stage moved backward, and the

DHI corresponding to the disaster-causing point and the turning point at the booting and flowering stages moved forward. In the seedling stage, the disaster sensitivity curve fitted by the water content data of the fixed soil layer should be carefully selected as a reference for the formulation of irrigation schemes.

(5) The normalized moisture sensitivity coefficients of seedling, booting and flowering-grain stages calculated by Jensen model were 0.251, 0.524 and 0.224 respectively, which were consistent with the results of disaster sensitivity curve fitting by crop biomass accumulation. The results verified the rationality of using biomass accumulation loss to reveal the physical causes of drought yield loss in summer maize from the perspective of aboveground growth.

## **5. Declarations**

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**Data Availability** Not applicable.

**Code availability** Not applicable.

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**Consent to Participate** Not applicable.

**Consent to Publish** Not applicable.

**Conflict of Interest** The authors declare that they have no conflicts of interest.

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