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Quantification Assessment of Winter Wheat Sensitivity under Different Drought Scenarios during Growth

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Abstract: To effectively reveal the disaster-causing mechanism between water stress and yield loss under different drought combinations during multiple growth periods of winter wheat, based on biennial wheat drought experiments, a crop growth analysis method was used to quantitatively identify and assess wheat yield loss sensitivity. The results showed that there was a significant negative correlation between the total dry matter relative growth rate (RGR) of wheat and the daily average degree of drought stress. The average determination coefficients of logarithmic fitting for 2017 and 2018 were 0.7935 and 0.7683, respectively. Wheat dry matter accumulation differed under the different drought combination scenarios. The yield loss sensitivity response relationship between the decrease in the RGR of wheat dry matter (relative to no drought stress) and the daily average degree of drought stress could be quantitatively identified by an *S*-shaped curve, and the 2017 and 2018 average coefficients of determination R^2 were 0.859 and 0.849, respectively. Mild drought stress at the tillering stage stimulates adaptability and has little effect on yield. The soil water content (SWC) can be controlled to 65–75% of the field water holding capacity; the SWC at the jointing and booting stage can be controlled to be higher than the field water holding capacity of 55%. The SWC was maintained at a level higher than 75% of the field water holding capacity during the heading and flowering stages and the grain-filling and milky stages to achieve a harmonization of yields and water savings. In addition, during the production process, continuous severe drought during the jointing and booting stage and the heading and flowering stage should be avoided. This study elucidates the response relationship between drought intensity and drought-induced losses from the perspective of physical genesis, provides effective irrigation guidance for regional wheat planting, lays the foundation for the construction of quantitative agricultural drought loss risk curves, and provides technical support for predicting the trend of yield losses in wheat under different drought stresses.

Keywords: wheat; yield loss sensitivity; sensitivity identification; drought stress experiment; crop growth analysis method

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Citation: Jiang, S.; Li, Z.; Yuan, H.; Jin, J.; Xiao, C.; Cui, Y. Quantification Assessment of Winter Wheat Sensitivity under Different Drought Scenarios during Growth. *Water* **2024**, *16*, 2048. https://doi.org/10.3390/w16142048

Academic Editor: Steven G. Pueppke

Received: 6 May 2024
Revised: 11 July 2024
Accepted: 17 July 2024
Published: 19 July 2024

1. Introduction

Drought is a natural phenomenon in which the amount of natural water resources in the study area, which is composed of surface water, groundwater, soil water, and atmospheric water in the Earth's surface hydrosphere, is continuously and significantly lower than the long-term average level [1,2]; it is the front-end input of the drought disaster process and is also called the drought disaster factor [3]. Drought disasters (referred to as drought) are adverse effects of drought on regional hazard-bearing bodies consisting of the anthroposphere, biosphere, and geosphere [4]. In agricultural production, agricultural drought refers to a phenomenon in which an insufficient water supply during the crop-growing season leads to an imbalance between the supply and demand of farmland water, which prevents the normal growth and development of crops [5–7]. This type of drought has the widest impact and the highest frequency [8], and it is also the meteorological disaster that has the most severe impact on agricultural production, posing a serious risk to global food security, sustainable economic and societal development, and the ecological environment [9]. According to the *Drought In Numbers 2022* report from the United Nations Convention to Combat Desertification (UNCCD), the number and duration of droughts have increased by 29% since 2000. According to the *China Drought and Water Hazard Defence Bulletin*, between 1950 and 2022, the average annual area of crops destroyed by drought was 1.95×10^7 hectares; the average annual area of crops affected by drought reached 8.78×10^6 hectares, and the average annual grain loss due to drought reached 1.58×10^{10} kg. During a 10-year period from 2013 to 2022, the average annual direct economic loss due to agricultural drought reached 55.8 billion yuan.

Wheat is one of the most important food crops in the world and one of the staple food crops in many countries [10]. India, Russia, and China are the three countries with the largest wheat planting areas in the world. Wheat is an important food crop in China, and its planting area and total output are second only to those of rice. The development of the wheat industry is directly related to China's food security and social stability [11]. Most wheat in China is planted in arid and semiarid areas in the north, and drought and water scarcity have always been important constraints restricting wheat production in China [12]. The quantitative analysis of the formation process and the physical genesis of crop yield loss under water stress are important parts of current systematic drought risk assessments, which aim to shift drought management from "passive" and "crisis-based" methods to 'proactive' and 'risk-based' approaches from the perspective of physical genesis mechanisms. The drought yield loss sensitivity of hazard-bearing bodies refers to the relationship between different levels of drought stress under natural conditions and drought loss in hazard-bearing bodies [13].

Jia et al. [14] used the crop coefficient method and water balance model to estimate the crop water demand of winter wheat in the middle reaches of the the Yarlung Zangbo River and its two tributaries from 1981 to 2015. Crop water requirement (CWR) shows relatively high sensitivity to sunshine duration and wind speed, indicating that these factors are more likely to lead to changes in CWR, with wind speed being the determining factor for CWR changes as its sensitivity is high and significantly reduced. Although the increase in temperature leads to an increase in CWR, its impact is relatively limited and offset by the effects of other factors. In a study by Wu et al. [15], the loss of net primary production (NPP) in seasonal winter wheat was evaluated through an analysis of the changes in frequency and probability of exceeding NPP loss. Within the study period, the frequency of winter wheat NPP loss due to drought in the North China Plain was within the range of 30% to 40%, with higher sensitivity to drought occurring during the middle growth period of winter wheat and in the North China Plain's dry subhumid region. Xiang et al.'s [16] research indicated that as the severity of drought increased, the wheat yield loss probability also increased. Yield loss probability varied among the study shires, mainly due to the various climate conditions of each region.

The yield loss sensitivity of drought hazard-bearing bodies is a core link in determining the quantitative relationship between drought frequency and corresponding crop growth due to drought, that is, the risk function of agricultural drought loss [2,13]. At present, some studies have established the relationship between crop yield and water use by constructing a sensitivity index [17,18], thus revealing the sensitivity of crop yield formation at different growth stages to water deficit. However, the process of crop growth and development and yield formation is very complex, and a single sensitivity index based on a single model cannot accurately and quantitatively describe responses to different water deficits, nor does the approach offer a physical genesis mechanism. In addition, the implications of yield loss sensitivity still need further clarification. Some studies have focused on the response relationship between the degree of drought stress in a single growth period of crops and the crop growth and formation of yield [19,20]. While the physical mechanisms of responses may be clear, little attention has been given to the effect of drought stress on different combinations of scenarios with multiple growth periods. The sensitivity of crop growth and yield formation and the mechanism of this process are closely related to crop variety, the intensity of drought stress at each growth period, and the growth stage at the time of drought stress. Therefore, it is necessary to examine crops with different growth periods. A combined drought scenario experiment can analyze the complex response process of crops under drought stress. Some researchers have used historical data statistical methods to perform sensitivity assessments [21]. Based on the historical series of regional hydrological elements or water resources, the agricultural drought disaster rate was obtained by the typical year method, and the curve between drought frequency and agricultural disaster rate was established. This method has not focused on the response process under drought stress; therefore, its physical meaning is lacking. In addition, this method still needs to establish the relationship between the current annual disaster rate and the historical typical annual disaster rate under different drought frequencies to determine the drought disaster impact conversion factor and to accurately quantify this coefficient. Some researchers have used the indicator-driven systematic evaluation method to identify and assess sensitivity [22]. This method achieves sensitivity assessment from the perspective of a drought risk system but cannot reflect the response process of crop physiological growth and yield formation under drought stress. It is also difficult to determine the variation pattern of crop yield loss sensitivity under drought stress with different combinations of multiple growth periods. In summary, it is necessary to go beyond historical data statistical methods, index-driven comprehensive evaluation methods, and model-based sensitivity index methods to focus on drought stress in crops under different drought combination scenarios during multiple growth periods. Drought losses in crops and water deficit experiments on actual crops need to be carried out. Quantitatively identifying and evaluating the sensitivity of crop drought loss must be conducted based on simulations and experiments.

Therefore, this paper takes wheat disaster sensitivity, a major food crop in the Huaibei Plain of China, as the research object. Through drought stress experiments under different drought combination scenarios during multiple wheat growth periods, the connotation of crop yield loss sensitivity was first clarified. Then, the relative growth rate (RGR) of the total dry matter and RGR reduction in total dry matter were used as indicators to measure yield formation and yield loss. The crop growth analytical method was used to reveal the different drought stresses of wheat during the single-growth period, double-growth period, and three-growth period. Finally, different drought combination scenarios were constructed to reveal the response relationship between drought loss and drought stress degree, that is, wheat yield loss sensitivity, which was then quantitatively compared and analyzed under the scenarios of different drought combinations with multiple growth periods. This study provides effective irrigation guidance for regional wheat planting and improved water resource use efficiency, as well as a theoretical basis and technical support for drought risk management. It also provides a way to further construct agricultural drought loss risk curves between drought frequency and the corresponding crop growth damage indexes from the perspective of causation mechanisms.

2. Test Protocols

2.1. Test Locations and Materials

The data used in this study were measured between October 2016 and May 2018 at the Xinmaqiao Agricultural and Water Comprehensive Test Station. This station is located in Bengbu city, Anhui Province, on the Huaibei Plain, China, with a longitude of E 117°22′ and latitude of N 33°09′. The Anhui Provincial Irrigation Test Central Station is affiliated with the Academy of Water Conservancy located at the Water Resources Research Institute of Anhui Province and Huaihe River Commission, Ministry of Water Resources. It has a typical transitional zone with a north–south climate and high and low latitudes, with an average annual rainfall of approximately 900 mm and a shallow groundwater depth, generally less than 3 m. The temperature is moderate, the sunshine is sufficient, and the agricultural production conditions are superior [23] (Figure 1).

The soil in the experimental area is Shajiang black soil, which belongs to the typical medium and low-yield field soil. Its physico-chemical characteristics are all poor, and its texture is sticky (the volume content of silt and clay particles in the cultivated layer is more than 95%), with poor permeability and easy flooding and drought. The field water holding capacity and withering water content of the soil are 28.0% and 11.2% (weight water content), respectively, and the soil bulk density is 1.36–1.50 g/cm^3 [24]. The potted plant testing buckets were plastic buckets with an average inner diameter of 24 cm and a height of 27 cm. The wheat variety used was Yannong 19. In the two-year drought stress experiment, the same chemical fertilizer (7.2 g/barrel of compound fertilizer and 2.7 g/barrel of urea) was applied to all samples at the time of wheat sowing, and no top dressing was applied in the later stage. To ensure that the SWC of each treatment sample at different growth stages was within the corresponding control range, all potted wheat from the two years were placed inside an automatically opened and closed rainproof canopy, and precipitation was isolated during the whole wheat drought test.

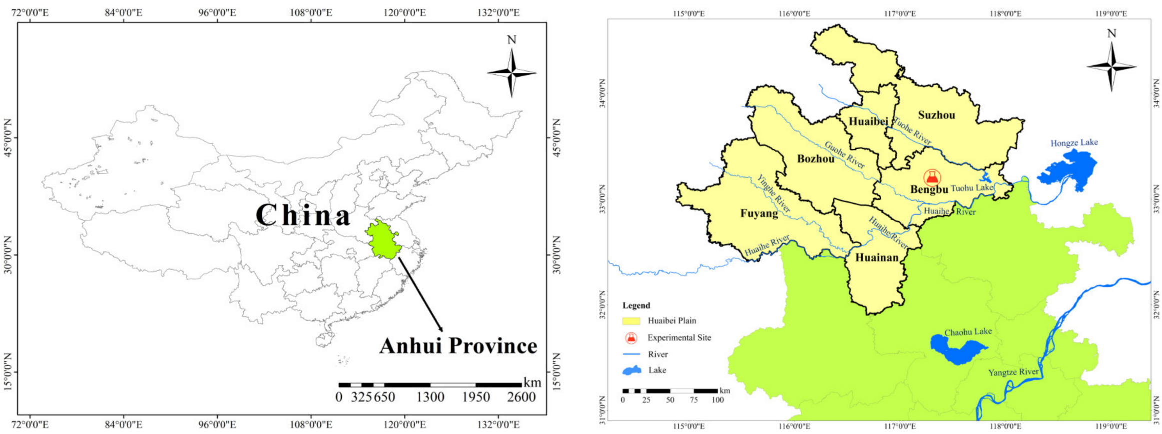

Figure 1. Location of test sites.

2.2. Experimental Design

The growth periods of wheat under drought stress were as follows: tillering stage, jointing and booting stage, heading and flowering stage, and grain-filling and milky stage. Two drought stress levels, mild and severe, were used for each growth stage. Other growth stages were treated with full irrigation. The percentage of soil water content (SWC) in the field water holding capacity was used as the control index to determine the lower limit of SWC for each treatment sample as follows: 75% for the control with no water stress, 55% for mild drought stress, and 35% for severe drought stress [19,20]. To analyze in depth the response mechanism of wheat plants under continuous drought conditions during the critical water requirement growth period, a special experiment under wheat drought stress was carried out. A total of 13 treatments and 170 bucket samples were included. The experimental design is shown in Table 1. The three combinations of T_1, T_3, and T_5 constituted one scenario. T_1 represented light drought at the tillering stage; T_3 represented light drought at the tillering stage and severe drought at the jointing and booting stage; and T_5 represented light drought at the tillering stage and severe drought at the jointing and booting stage. Similarly, T_2, T_4, and T_6 constituted one scenario. T_2 represented severe drought at the tillering stage; T_4 represented severe drought at the tillering stage and light drought at the jointing and booting stage; and T_6 represented severe drought at the tillering stage, light drought at the jointing and booting stage, and light drought at the heading and flowering stage. T_7, T_9, and T_{11} constituted one scenario, with T_7 representing light drought at the jointing and booting stage; T_9 representing light drought at the jointing and booting stage and severe drought at the heading and flowering stage; and T_{11} representing light drought at the jointing and booting stage, severe drought at the heading and flowering stage, and severe drought at the grain-filling and milky stage. T_8, $T_{10,}$ and T_{12} constituted one scenario: T_8 represented severe drought at the jointing and booting stage; T_{10} represented severe drought at the jointing and booting stages and light drought at the heading and flowering stage; and T_{12} represented severe drought at the jointing and booting stage, light drought at the heading and flowering stage, and light drought at the grain-filling and milky stage. At the end of each growth period and at harvest, the drought stress and control treatments were subjected to a destruction test (5 barrels were destroyed for each treatment) to measure the changes in the growth indicators of each treatment during the corresponding growth period. In referring to the drought stress test programs described in references [25,26], combined with results of the long-sequence wheat irrigation test at the Xinmaqiao Agricultural and Water Comprehensive Test Station and practical experience from field irrigation, the irrigation methods were as follows: when the SWC of the potted wheat sample was lower than the lower limit of the corresponding growth period, the soil was irrigated to 90% of the field water holding capacity, and the cycle continued until the end of the corresponding growth period. During the experiment, except for water control conditions, other field management and protection measures were the same among the treatments and were not affected by factors such as pests and diseases.

Table 1. Design of the drought stress experiment on potted wheat.

Treatment	Lower Control Limit of SWC in Each Growth Period (% of Field Water Holding Capacity)/%						Remarks
	Seedling Stage	Tillering Stage	Jointing and Booting Stage	Heading and Flowering Stage	Grain-Filling and Milky Stage	Number of Repeats	
T_1	75%	55%	75%	75%	75%	20	Light drought at tillering stage
T_2	75%	35%	75%	75%	75%	20	Severe drought at tillering stage
T_3	75%	55%	35%	75%	75%	15	Light drought at tillering stage; severe drought at jointing and booting stage
T_4	75%	35%	55%	75%	75%	15	Severe drought at tillering stage; light drought at jointing and booting stage
T_5	75%	55%	35%	35%	75%	10	Light drought at tillering stage, severe drought at jointing and booting stage, and severe drought at heading and flowering stage
T_6	75%	35%	55%	55%	75%	10	Severe drought at tillering stage, light drought at jointing and booting stage, and light drought at heading and flowering stage
T_7	75%	75%	55%	75%	75%	15	Light drought at jointing and booting stage
T_8	75%	75%	35%	75%	75%	15	Severe drought at jointing and booting stage
T_9	75%	75%	55%	35%	75%	10	Light drought at jointing and booting stage; severe drought at heading and flowering stage
T_{10}	75%	75%	35%	55%	75%	10	Severe drought at jointing and booting stage; light drought at heading and flowering stage

Table 1. *Cont.*

Treatment	Lower Control Limit of SWC in Each Growth Period (% of Field Water Holding Capacity)/%						Remarks
	Seedling Stage	Tillering Stage	Jointing and Booting Stage	Heading and Flowering Stage	Grain-Filling and Milky Stage	Number of Repeats	
T_{11}	75%	75%	55%	35%	35%	5	Light drought at jointing and booting stage, severe drought at heading and flowering stage, and severe drought at grain-filling and milky stage
T_{12}	75%	75%	35%	55%	55%	5	Severe drought at jointing and booting stage, light drought at heading and flowering stage, light drought at grain-filling and milky stage
T_{13}	75%	75%	75%	75%	75%	20	No drought stress (control)

The sowing date of winter wheat in 2017 was 5 December 2016, and the harvest date was 20 May 2017. The average temperature during its growth period was 9.66 °C; the sowing date of winter wheat in 2018 was 9 November 2017, and the harvest date was 20 May 2018. The average temperature during its growth period was 8.80 °C, as shown in the experiment equipment (Figure 2).

Figure 2. Picture of the experiment equipment.

2.3. Measurement Items and Methods

2.3.1. Weighing the Potted Wheat Plants and Calculating Their SWC

To accurately obtain the daily average SWC of each wheat pot treatment, all potted wheat samples were weighed at approximately 17:00 every day using an electronic balance (model YP30KN) with an accuracy of 0.01 g. To reduce the error caused by the growth and development of the wheat plants in each treatment, the mean wet weight of the wheat plants at the end of the previous growth period of the corresponding treatment was subtracted from the weighed weight of each pot treatment.

SWC is a key parameter of the hydrological cycle and energy exchange between the surface and atmosphere [27] and is an important condition affecting the growth and development of crops. SWC has important basic significance for the systematic assessment of drought risk, especially for sensitivity identification and assessment [28,29]. Considering the dynamic variability in the wheat pot SWC, the mean of the initial SWC and the final SWC of the potted samples on the day were used to represent the mean SWC on the current day. The specific calculations were as follows: ① the SWC when weighing at the $i - 1$ day for potted plant j plus the amount of irrigation water for the i-th day was the initial SWC on the i-th day; ② the SWC when weighing at the i-th day for potted plant j was the final

SWC of day i; and ③ the mean of the initial and final SWC of pot j on the i-th day was the average SWC on the i-th day.

2.3.2. Irrigation Water Volume for Potted Plants

The irrigation water amount for pot j on the i-th day was determined according to the lower limit of SWC corresponding to the different experimental treatments [26]:

$$Q_{i,j} = \begin{cases} 0 & \theta''_{i-1,j} \geq \theta_{\mathrm{m}\ j} \\ (0.9 \times \theta_f - \theta''_{i-1,j}) \times Ws_j & \theta''_{i-1,j} < \theta_{\mathrm{m}\ j} \end{cases} \quad (1)$$

where Q_i and j are the irrigation volumes of potted plant j on the i-th day, kg; θ_f is the field water holding capacity of the soil tested; $\theta''_{i-1,j}$ is the SWC at the end of day $i-1$, kg/kg; and Ws_j is the dry soil weight of pot j, kg. In this experiment, the dry soil weight of each pot sample was 16 kg, and the weight of the barrel for pot j was 0.435 kg; $\theta_{\mathrm{m}\ j}$ is the lower control limit of SWC in the design of the pot j experiment. When the SWC at the end of the $i-1$ day of pot j was lower than the lower control limit of the SWC of the corresponding treatment, the water content was precisely irrigated with a graduated cylinder to 90% of the field water holding capacity at approximately 7:00 on the i-th day [26].

3. Construction of an RGR-Based Quantitative Assessment Model of Wheat Yield Loss Sensitivity

3.1. Calculation of the Degree of Drought Stress in Wheat Based on the SWC

Research has shown that the SWC can effectively characterize the water exchange relationships among farmland soil, plants, and the atmosphere, and it is widely used in the identification, assessment, forecasting, and early warning of agricultural drought [24]. However, most existing results can only statically determine whether crops are drought-stricken and cannot quantitatively describe the cumulative process and extent of crop drought treatments. In actual agricultural production, SWC of farmland significantly and dynamically changes under the action of rainfall and irrigation. Therefore, based on the results of sequential crop drought and irrigation at the Xinmaqiao Agricultural and Water Comprehensive Test Station, this study used the concept and calculation formula proposed in [26] for the drought stress degree of dry crops for the Huaibei Plain of Anhui Province based on SWC:

$$DS_{i,j} = \begin{cases} 0 & \theta_s \leq \theta_{i,j} \leq \theta_f \\ \frac{\theta_s - \theta_{i,j}}{\theta_s - \theta_w} & \theta_w < \theta_{i,j} < \theta_s \\ 1 & \theta_{i,j} \leq \theta_w \end{cases} \quad (2)$$

where $DS_{i,j}$ is the drought stress degree of pot j on the i-th day; $\theta_{i,j}$ is the average SWC of pot j on the i-th day; θ_s is the lower limit of suitable SWC for the crop; θ_f is the field water holding capacity; and θ_w is the withering water content. With reference to the range of SWC suitable for crop growth in the design of relevant experiments and research results [19,23,30] and the multiyear crop deficit irrigation experiment at our experimental station, the present study revealed that when the SWC reached only 75% of the field water holding capacity θ_f, it was deemed highly suitable for crop growth, but it did not need to completely reach θ_f. That is, the lower limit of the most suitable SWC for crop growth should be 75% of θ_f. At the same time, when the SWC is lower than the water content at the withering point, that is, 40% of θ_f, it is difficult for plants to absorb water from the soil.

In this study, Equation (2) was used to calculate the daily $DS_{i,j}$ of each wheat pot test sample, and the average drought stress degree of the potted samples during the growth period or time period was obtained. The calculation formulas were [26,31]:

$$SD_j = \frac{\sum_{i=t_0}^{t_1} DS_{i,j}}{t_1 - t_0} \quad (3)$$

where t_0 is the initial time of the calculated growth period or time period, d; t_1 is the calculated end time of the growth period or time period, d; and SD_j is the average drought stress degree of potted plant j during the calculated growth period or time period.

3.2. Crop Growth Analysis Method

The crop growth analysis method was proposed by the British scholar Blachman in 1919 [32]. He believed that the process of crop dry matter accumulation could characterize the basic characteristics of crop growth and development and that revealing the pattern of crop dry matter accumulation could be used to effectively analyze the reproductive process and the response of crops to the growing environment [33,34]. He constructed a series of growth functions [35], including the RGR and crop growth rate (CGR) [35], which could be used to analyze crop growth characteristics and quantitatively characterize crop responses to changes in the growth environment. The growth function method has rich physical meaning, is simple to use, and has reasonable and reliable application results. It has been widely used to quantitatively describe the effect of natural disasters on crop growth [35]. To this end, in the present study, a wheat drought stress experiment was combined with the RGR, and experiments and simulations were used to reveal the response pattern of total dry matter to the degree of drought stress under different drought combination scenarios during multiple growth periods of wheat and to quantitatively identify and evaluate wheat yield loss sensitivity. The growth rate of dry matter per unit of dry matter per unit time is the RGR or relative growth speed, and its differential expression is as follows [26,33,36]:

$$R = \frac{1}{w}\mathrm{d}w/\mathrm{d}t \tag{4}$$

where R is the RGR, g/(g·d); w is the total dry matter amount of the crop, g; and t is time, d.

After integrating both sides of Equation (4) and performing logarithmic operations, the following basic formula for calculating the RGR can be obtained [36]:

$$R = \frac{\ln w_1 - \ln w_0}{t_1 - t_0} \tag{5}$$

where t_0 is the initial time of the period, d; t_1 is the end time of the period, d; w_0 is the total dry matter amount of the crop at time t_0, g; w_1 is the total dry matter amount of the crop at time t_1, g; and R is the RGR of total crop dry matter during the period t_0~t_1, g/(g·d).

3.3. Construction of the Wheat Yield Loss Sensitivity Relationship Based on the Crop Growth Analytical Method

From the perspective of physical genesis, drought risk is a complex system formed by six linked and interacting elements that include the risk of the disaster-formed environment, disaster prevention and reduction ability (drought resistance), drought risk, drought yield loss sensitivity of the hazard-bearing body, exposure of the hazard-bearing body, and loss risk of the hazard-bearing body; this is called the drought risk system [2,13,37]. The drought yield loss sensitivity, exposure, and drought resistance of the hazard-bearing body interact with each other and are collectively referred to as the vulnerability of the hazard-bearing body, which reflects the relationship between the losses of the hazard-bearing body and droughts of different intensities [2,38]. From the perspective of the physical process of drought risk formation under a specific disaster-forming environment and drought resistance capacity in a study area, the basic structure of the drought risk system was formed by the chain transfer effect of drought risk, vulnerability of hazard-bearing bodies, and drought loss risk [2,39,40], deemed ternary chain transfer structure for short. In other words, the risk of drought loss is the input of the drought risk system, and after the chain transfer of the system conversion of the vulnerability of the hazard bearer, the obtained system output is the drought loss of the hazard bearer [11,41]. For agricultural drought systems, the hazardous bearers are crops such as wheat and soybeans. The drought yield loss sensitivity of the hazard bearer refers to the relationship between drought intensity (different levels of drought stress, such as severe drought and light drought) and natural conditions. Regarding the response relationship between the drought losses of the hazard-bearing bodies, the experiments in this study designed different drought intensities to simulate the drought scenarios under natural conditions and achieved different degrees of drought in wheat by controlling the duration during which the SWC reached the lower limit. Under the severe drought level, the time to reach the lower limit of the SWC was longer than that under the light drought level. Crop drought tolerance can be determined by different irrigation levels (e.g., 100%, 75%, and 50% irrigation requirements). Therefore, a reasonable and quantitative assessment of the sensitivity of agricultural drought systems is an important premise and basis for revealing the mechanisms of drought and achieving quantitative drought risk assessment.

At present, the key issues that need to be resolved in the crop-oriented quantitative assessment of the yield loss sensitivity of hazard-bearing bodies are as follows: (1) the connotation of crop yield loss sensitivity still needs to be further clarified; and (2) the revelation of the mechanism of drought system sensitivity under different drought combination scenarios for multiple crop growth periods. Most current studies have focused on the response relationship between the degree of drought stress in a single growth period of crops and the growth and yield of crops, and the physical mechanisms of the responses are relatively clear. However, very little attention has been given to the sensitivity of crop growth and yield formation under different scenarios of drought stress during multiple growth periods. The mechanism of this process is very complicated and is closely related to crop variety, the intensity of drought stress at each growth stage, and the growth stage at drought stress. In addition, the determination of a single sensitivity index based on modeling alone cannot accurately and quantitatively describe its response to different water deficits. This process does not involve a physical genesis. Therefore, drought experiments under different scenarios during multiple growth periods are urgently needed, and in-depth analyses of crops under drought stress based on experiments and simulations are needed. (3) The crop yield loss sensitivity assessment methods are mostly biased towards historical statistical methods. Based on the historical series of regional hydrological elements or water resources, the agricultural drought disaster rate is obtained through the typical year method; in this way, the drought frequency and agricultural disaster rate curve were established. This method does not focus on the response process under drought stress and lacks physical meaning. In addition, this method needs to establish the relationship between the current annual disaster rate and the historical typical annual rate under different drought frequencies to determine the impact of drought disasters. Accurate quantification of this coefficient is difficult, and an indicator-driven comprehensive evaluation method is preferred. This method achieves a sensitivity assessment from the perspective of a drought risk system but cannot reflect the response of crop physiological growth and yield formation under drought stress. Moreover, it is not easy to determine the variation pattern of crop yield loss sensitivity under drought stress under different combinations of multiple growth periods. There is an urgent need for quantitative damage sensitivity assessment research that describes the quantitative relationship between drought intensity and crop loss indicators from the perspective of crop yield loss mechanisms.

To this end, in the present study, based on our previous study, we conducted a special wheat drought experiment and proposed using the decrease in the RGR of total dry matter as the response variable to construct different drought combination scenarios. We quantitatively identified and assessed yield loss sensitivity during multiple growth periods of wheat based on experiments and simulations and established the response relationship between drought intensity and drought-induced losses under the scenario of different drought combinations during multiple growth periods. The construction of the wheat yield loss sensitivity function included the quantification of drought intensity, the quantification of crop yield response to drought intensity, and the construction of a sensitivity relationship function between drought intensity and drought loss. The specific construction process is as follows:

(1) Quantify the intensity of hazards. The daily drought stress degree of each potted wheat sample was calculated by Equation (2), which reflects the daily drought stress degree of the potted samples. Therefore, the average degree of drought stress in the potted samples during the drought stress growth period was calculated via Equation (3). This essentially reflects the intensity of drought disaster-causing factors for potted samples during the drought stress growth period. In this study, the daily average drought stress during the wheat growth period was used to quantitatively characterize the intensity of drought disaster-causing factors.

(2) Quantify the response of crop yield to the intensity of hazards. Equation (5) was used to calculate the RGR of each wheat pot sample, which could quantitatively describe the growth and development status of wheat under the action of drought disaster-causing factors. To this end, this study used the difference between the RGR of the samples subjected to drought stress and the RGR of the samples without drought stress to quantitatively describe the response of wheat yield to the intensity of disaster-causing factors.

(3) Construct a sensitivity relationship function between drought intensity and drought-related losses. Different drought combination scenarios were constructed. The daily average drought stress degree of the repeated samples from the wheat pot experiment is shown on the horizontal axis, and the reduction in the total dry matter RGR of the wheat sample corresponding to the daily average relative stress degree is shown on the vertical axis. Based on drought stress experiments and simulations, a wheat yield loss sensitivity function under different drought combination scenarios during multiple growth periods was constructed.

4. Results and Analysis

4.1. Correlation Analysis between the Total Amount of Wheat Matter Accumulation and Yield

Based on the results of wheat drought stress experiments in 2017 and 2018 at the Xinmaqiao Agricultural and Water Comprehensive Test Station, the correlation between the yield of 130 potted wheat samples and the corresponding total dry matter was statistically analyzed (Figure 3).

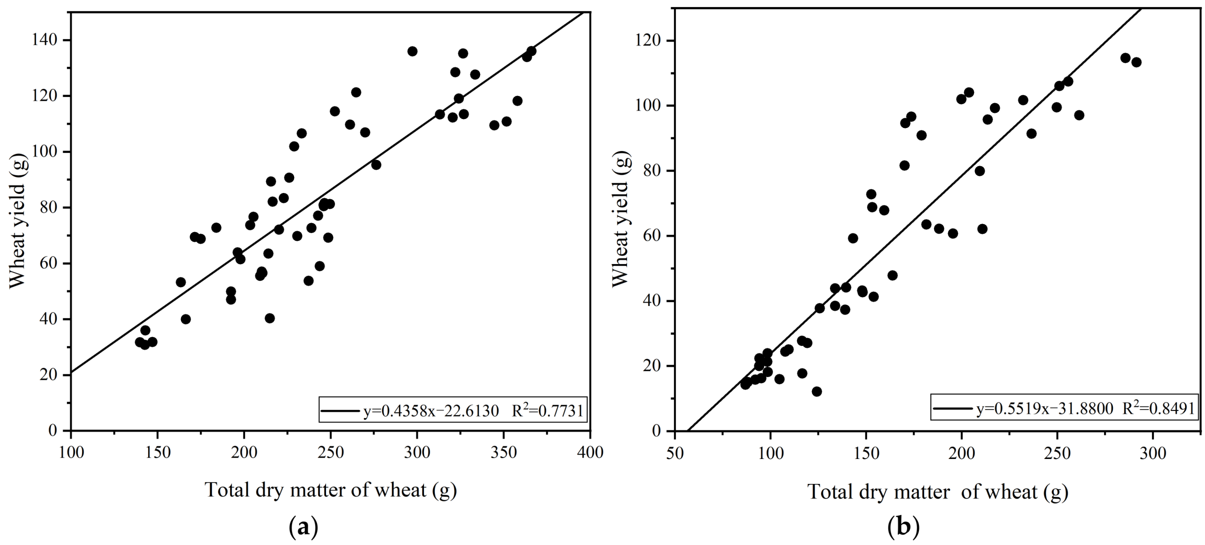

Figure 3. Correlations between total dry matter and yield of wheat under different drought scenarios. (**a**) 2017; (**b**) 2018.

As shown in Figure 3, among the 260 samples harvested in the special experiment under wheat drought stress in 2017 and 2018, the final harvest yield of wheat had a significant positive correlation with the corresponding total dry matter; the coefficient of determination of yield and the corresponding total dry matter R^2 for 2017 and 2018 were 0.7731 and 0.8491, respectively. The reason for the different R^2 may be due to the chance error in the experimental process, and from the correlation coefficient R, it was

0.879 in 2017 and 0.921 in 2018, which were both greater than 0.85, indicating that there is a good correlation between the total dry matter and yield. Therefore, it is reasonable and effective to determine changes in wheat growth characteristics and yield by studying changes in total dry matter under drought stress.

4.2. Analysis of the Growth Characteristics of Wheat under Drought Stress Based on the Crop Growth Analysis Method

According to the experimental design parameters, the SWC for the wheat pots was calculated via the gravimetric method. Considering the dynamic changes in wheat pot SWC during the day, the mean values of the initial SWC and the final SWC of the potted samples on the day were used to characterize the SWC on the current day. The RGR of total dry matter for each potted wheat sample in 2017 and 2018 was then calculated by Equation (2), which quantitatively describes the response of wheat growth and development under specific drought stresses to the degree of drought stress. On this basis, the daily average degree of drought stress for each potted wheat sample in 2017 and 2018 was obtained according to Equation (3), which quantitatively described the degree of water stress, i.e., drought intensity. Based on this, different drought combination scenarios were constructed, with the daily average drought stress degree of the wheat pot samples on the horizontal axis and the RGR of the total dry matter corresponding to the daily average drought stress degree on the vertical axis. Logarithmic fitting was performed on the sample data of 2017 and 2018 to quantitatively reveal the response relationship between the daily average level of drought stress and the growth characteristics of wheat under different drought combinations during multiple growth periods (Figure 4).

As shown in Figure 4, (1) the drought treatments corresponding to T_1, $T_{3,}$ and T_5 were light drought at the tillering stage; light drought at the tillering stage and severe drought at the jointing and booting stage; and light drought at the tillering stage and severe drought at the jointing and booting stage, respectively, and the average daily drought stress degree showed an increasing trend. The drought treatments corresponding to T_2, T_4, and T_6 were severe drought at the tillering stage; severe drought at the tillering stage and light drought at the jointing and booting stage; and severe drought at the tillering stage, light drought at the jointing and booting stage, and light drought at the heading and flowering stage, respectively, and the average daily drought stress degree also showed an increasing trend, but the initial average daily drought stress degree of the latter was greater than that of the former because the latter suffered severe drought stress during the tillering stage, while the former was subjected to light drought stress. The calculation method used in this study to quantitatively describe the degree of drought stress of crops can accurately identify the daily variation in the degree of drought stress of each potted wheat plant during the experiment and is reasonable and effective. (2) The drought treatments corresponding to T_7, $T_{9,}$ and T_{11} were light drought at the jointing and booting stage; light drought at the jointing and booting stage and severe drought at the heading and flowering stage; and light drought at the jointing and booting stage, severe drought at the heading and flowering stage, and severe drought at the grain-filling and milky stage, respectively. The drought treatments corresponding to T_8, $T_{10,}$ and T_{12} were severe drought at the jointing and booting stage; severe drought at the jointing and booting stages and light drought at the heading and flowering stage; and severe drought at the jointing and booting stage, light drought at the heading and flowering stage, and light drought at the grain-filling and milky stage, respectively. The daily average drought stress degree showed an increasing trend, but the initial value of the latter's average daily drought stress degree was greater than that of the former because the latter was subjected to severe drought stress at the jointing and booting stages, while the former was under light drought stress. In addition, the former had a greater range of variation in daily average drought stress than did the latter. This is because the former were subjected to severe drought stress at both the heading and flowering stage and the grain-filling and milky stage, the degree of drought stress varied significantly, while the latter was subjected to light drought stress at both the heading and flowering stage and the grain-filling and milky stage. (3) The RGR of total dry matter of wheat under different drought combinations over multiple growth periods had a significant negative correlation with the daily average degree of drought stress. The average *R* values of the logarithmic fittings for 2017 and 2018 were 0.7935 and 0.7683, respectively. Through two-year wheat pot experiments, the RGR of total dry matter and the daily average drought stress degree under the scenario of different drought combinations during multiple growth periods could be quantitatively described by logarithmic curves. This is consistent with the research results in Ref. [17]. (4) The two-year drought experiments in 2017 and 2018 showed that when the total dry matter RGR was equal, the different drought combination treatments exhibited differences in drought tolerance. Taking the T_1, T_3, T_5, and T_2, T_4, and T_6 combinations as examples, when the RGRs of the two drought combinations were the same, the T_2, T_4, and T_6 drought combinations could withstand greater degrees of drought stress than that of T_1, T_3, and T_5, indicating that their drought tolerance was better than that of the combination of T_1, T_3, and T_5. Similarly, the drought tolerance of the T_7, T_9, and T_{11} drought combinations was greater than that of the T_8, T_{10}, and T_{12} combinations.

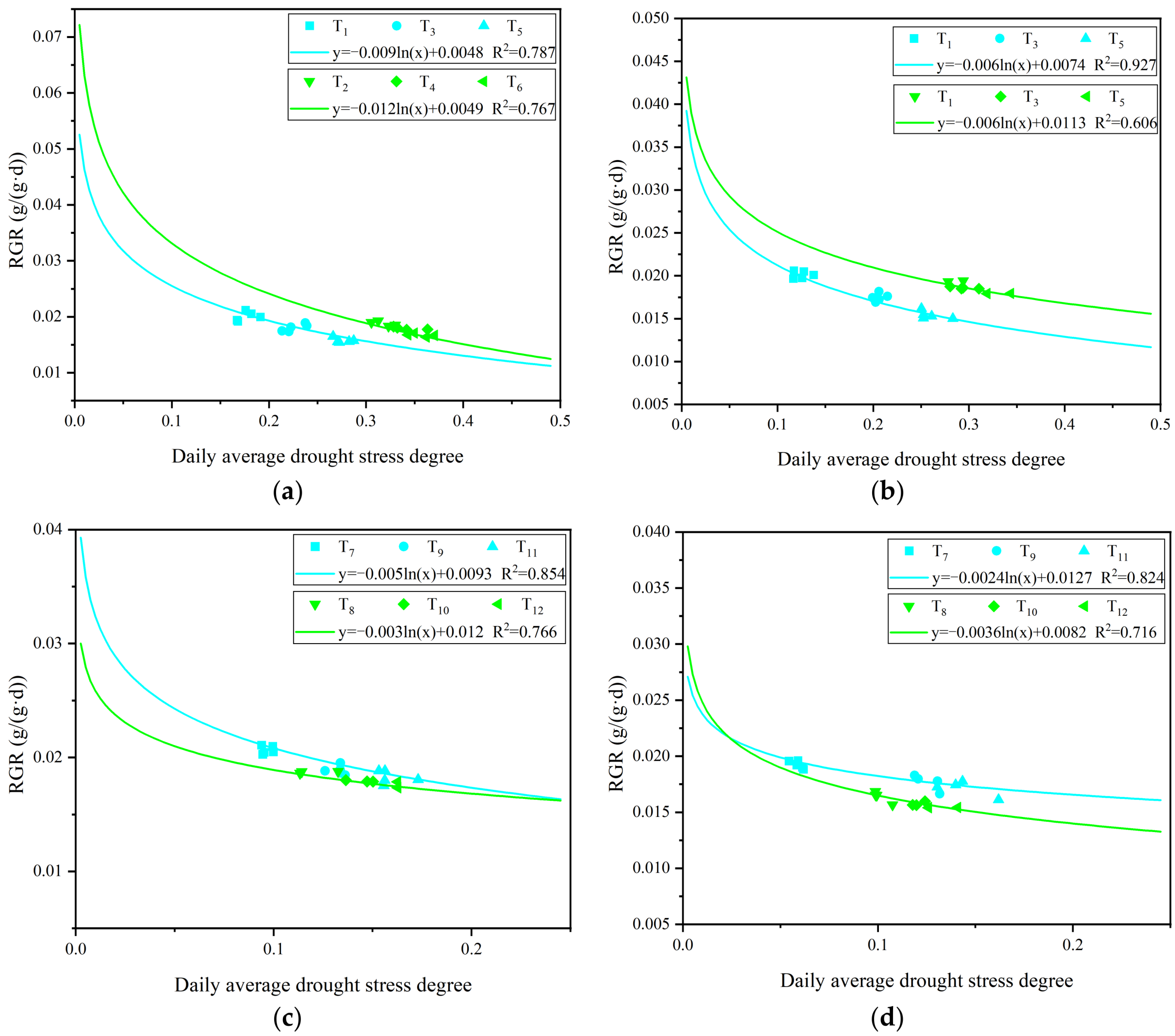

Figure 4. Effect of drought stress at different growth stages on the RGR of total dry matter. (**a**) The 2017 treatment for T_1, T_3, and T_5 (blue) and T_2, T_4, and T_6 (green). (**b**) The 2018 treatment for T_1, T_3, and T_5 (blue) and T_2, T_4, and T_6 (green). (**c**) The 2017 treatment for T_7, T_9, and T_{11} (blue) and T_8, T_{10}, and T_{12} (green). (**d**) The 2018 treatment for T_7, T_9, and T_{11} (blue) and T_8, T_{10}, and T_{12} (green).

4.3. Construction of the Wheat Yield Loss Sensitivity Relationship Based on the Crop Growth Analytical Method

Equations (3) and (5) were used to calculate the daily average drought stress and the corresponding reduction in the total dry matter RGR for each treatment in 2017 and 2018, respectively. With the daily average drought stress degree of the T_1, $T_{3,}$ and T_5 drought combinations as the horizontal axes and the corresponding reduction in the total dry matter RGR as the vertical axis, an *S*-shaped curve for 2017 and 2018 was constructed (logistic function). The parameters of the *S*-shaped curve were optimized using the accelerated genetic algorithm to determine the *S*-shaped curve function relationship between the daily average drought stress degree and the decrease in the RGR of total dry matter (i.e., the sensitivity function) under different drought combination scenarios during multiple growth periods. The same applies to the combination scenarios of T_2, T_4, T_6, T_7, T_9, T_{11}, T_8, T_{10}, and T_{12} (Table 2 and Figure 5).

Table 2. Wheat yield loss sensitivity function based on the crop growth analytical method.

Year	Treatment	Logistic Fitting Parameters				Sensitivity Function
		a	*b*	*c*	Determination Coefficient R^2	
2017	T_1, T_3, T_5	0.054	365.412	13.407	0.873	$y = 0.054/(1 + 365.412 \times e^{-13.407x})$
	T_2, T_4, T_6	0.012	506.547	15.667	0.909	$y = 0.012/(1 + 506.547 \times e^{-15.667x})$
	T_7, T_9, T_{11}	0.047	322.944	19.592	0.799	$y = 0.047/(1 + 322.944 \times e^{-19.592x})$
	T_8, T_{10}, T_{12}	0.053	219.065	17.697	0.856	$y = 0.053/(1 + 219.065 \times e^{-17.697x})$
2018	T_1, T_3, T_5	0.032	396.365	14.695	0.858	$y = 0.032/(1 + 396.365 \times e^{-14.695x})$
	T_2, T_4, T_6	0.038	493.715	11.873	0.828	$y = 0.038/(1 + 493.715 \times e^{-11.873x})$
	$T_{7,}$ T_9, T_{11}	0.071	187.956	17.525	0.756	$y = 0.071/(1 + 187.956 \times e^{-17.525x})$
	T_8, T_{10}, T_{12}	0.007	222.958	56.942	0.953	$y = 0.007/(1 + 222.958 \times e^{-56.942x})$

As shown in Table 2 and Figure 5, (1) in 2017 and 2018, the average coefficients of determination R^2 for the S-curve fitting of the average daily drought stress degree to the corresponding total dry matter RGR reductions (relative to the no drought stress treatment) for wheat were 0.859 and 0.849 for 2017 and 2018, respectively, indicating that it was reasonable and accurate to use the S-curve to describe the sensitivity of the wheat drought system. The crop drought sensitivity function based on the *S*-shaped yield loss curve can accurately describe the quantitative relationship between the amount of crop growth loss due to drought and the variation in water deficit intensity in a certain stage and has a causal mechanism.

(2) In Figure 5a,b, mild drought stress at the tillering stage and full irrigation during the remaining three growth periods (T_1) caused a certain decrease in the total dry matter RGR relative to no drought stress, but the inhibition of wheat dry matter accumulation was not significantly enhanced. In addition, mild drought stress stimulated the adaptive ability of wheat, and the subsequent restoration of irrigation had a compensatory effect [12,42], promoting the vertical growth of the root system, which is beneficial for growth and development in the later stage. Therefore, during this growth period, under the premise of ensuring the completeness of wheat seedlings, a nonsufficient water supply mode can be implemented, such as maintaining the SWC at 65–75% of the field water holding capacity. Severe drought stress at the tillering stage and full irrigation (T_2) during the remaining three growth periods also significantly increased the reduction in total dry matter RGR, which reduced the effective tillering of wheat and significantly increased the loss due to drought.

(3) In Figure 5a,b, even though the drought-induced loss of wheat under severe drought stress (T_2) at the tillering stage was greater than that under light drought stress at the tillering stage (T_1), under severe drought stress (T_1, T_3, and T_5) at the booting stage and heading and flowering stage, the increase rate of the decrease in the total dry matter

RGR was greater than that under mild drought stress at the jointing and booting stage and heading and flowering stage (T_2, T_4, and T_6). This is because the jointing and booting stage and the heading and flowering stage are the key growth periods of wheat; the severe water deficit resulted in a more significant yield reduction and increased RGR reduction.

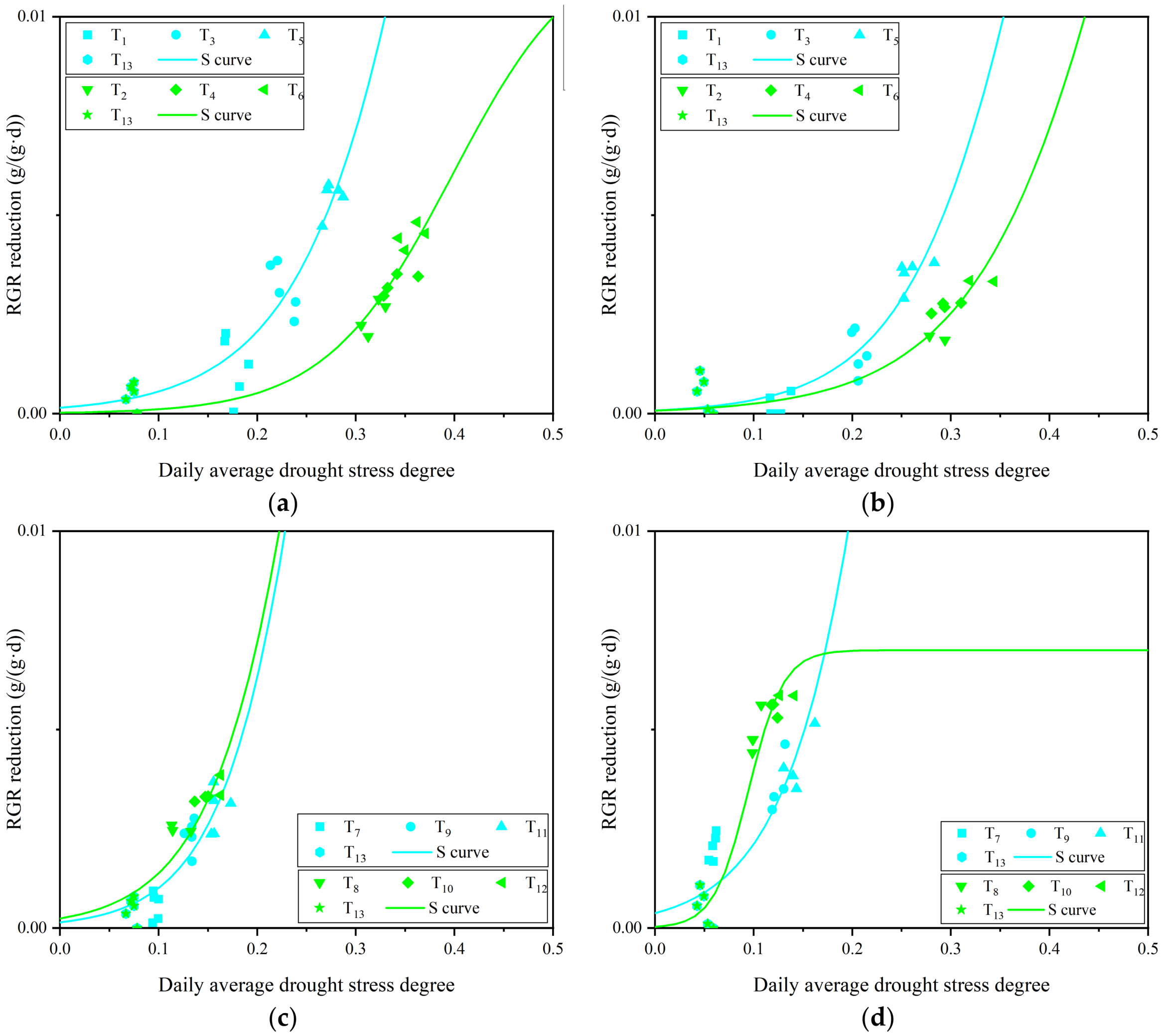

Figure 5. Wheat yield loss sensitivity function based on the crop growth analytical method. (**a**) The 2017 treatment for T_1, T_3 and T_5 (blue) and T_2, T_4 and T_6 (green). (**b**) The 2018 treatment for T_1, T_3, and T_5 (blue) and T_2, T_4, and T_6 (green). (**c**) The 2017 treatment for T_7, T_9, and T_{11} (blue) and T_8, T_{10}, and T_{12} (green). (**d**) The 2018 treatment for T_7, T_9, and T_{11} (blue) and T_8, T_{10}, and T_{12} (green).

(4) In Figure 5c,d, wheat was subjected to mild drought stress at the jointing and booting stage, and the three growth stages were fully irrigated (T_7) at the tillering stage, heading and flowering stage, and the grain-filling and milky stage. The increase in the reduction in the RGR was not significant (relative to no drought stress). This is because the roots of wheat during the jointing and booting stages were deep-set, the mass was the greatest, and the root activity was the greatest. Water supply had almost no effect on plant dry matter accumulation. On the other hand, when wheat was subjected to severe drought stress at the jointing and booting stage and fully irrigated at the three growth stages (T_8), water loss in the wheat body affected cell division, and as a result, the wheat growth rate slowed. Short stature significantly affected dry matter accumulation, resulting in a faster rate of decrease in the total dry matter RGR of the T_8, T_{10}, and T_{12} combinations than that of the T_7, T_9, and T_{11} combinations. The jointing and booting stage of wheat is the most sensitive to soil water. Mild drought stress during this growth period has little

effect on the growth and development of wheat. However, system sensitivity is greatest under severe drought stress. Therefore, it should be ensured that the SWC is high during this growth period. A total of 55% of the field water holding capacity should be used to ensure sufficient dry matter accumulation in the wheat.

(5) In Figure 5c,d, T_7, T_9, and T_{11} correspond to light drought at the jointing and booting stage; light drought at the jointing and booting stage and severe drought at the heading and flowering stage; and light drought at the jointing and booting stage, severe drought at the heading and flowering stage, and severe drought at the grain-filling and milky stage, respectively, and the RGR of total dry matter decreased significantly. This is mainly due to the reduction in the number of fruit-bearing spikelets due to water stress during the spike-flowering stage, which reduced the effective number of spikes and grains per spike of the wheat plants. The system is more sensitive during this growth period, and severe drought stress will have a greater impact on wheat growth. The growth stage is a critical period for yield formation. During this growth period, wheat photosynthetic compounds are converted to wheat grains and are sensitive to water stress [8]. Even mild drought stress during the current period significantly affects plant dry matter accumulation. Therefore, during the heading and flowering stages, it should be ensured that the SWC at this growth stage is greater than the appropriate water content, that is, greater than 75% of the field water holding capacity. During the grain-filling and milky stage, it should be fully ensured that the SWC in the milky stage is greater than 75% of the field water holding capacity to ensure the plumpness and quality of the wheat grains. After the yellow maturity stage, the stems, roots, and leaves of wheat gradually senesce and fall off, and the water demand significantly decreases, so we can reduce or not provide a water supply.

(6) As the average daily drought stress gradually increased, the decrease in RGR of the total dry matter peaked [43]. This result was consistent with the actual physical process and provided a basis for the prediction of drought losses. For example, in Figure 5d, when the daily average drought stress degree reached 0.3, the sensitivity function curve could be used to calculate the decrease in the RGR of total dry matter and thus determine the amount of drought loss.

(7) When different drought combinations suffer the same yield loss, the levels of drought stress they can withstand are different. Taking T_1, T_3, T_5, and T_2, T_4, T_6 as examples, when the reduction in the RGR of the two drought combinations was 0.005, the maximum drought that the T_2, T_4, and T_6 drought combinations could withstand was approximately 0.38, while the maximum degree of drought stress that the T_1, T_3, and T_5 drought combinations could withstand was approximately 0.27. These results suggest that the T_2, T_4, and T_6 drought combinations responded slowly to drought stress. The T_1, T_3, and T_5 combinations were more sensitive to drought stress. Similarly, the drought tolerance of the T_7, T_9, and T_{11} drought combinations was greater than that of the T_8, T_{10}, and T_{12} combinations. The above analysis agreed well with the correlation analysis in Section 3.2.

(8) From the perspective of drought at different growth stages, the mean values of reductions in the RGR of total dry matter in 2017 and 2018 were 0.0045 and 0.0047, respectively, while those of T_6 and T_{11} were 0.0039 and 0.0036, respectively. The main reason is that T_5 and T_{12} suffered severe drought at the jointing and booting stage, and T_5 experienced severe drought stress at the heading and flowering stage; the jointing and booting stage is an important stage of simultaneous vegetative growth and reproductive growth of wheat, and the heading and flowering stage is an important stage of grain formation. The core growth period of wheatgrass is a critical period that determines growth and development, the number of grains set, the weight of the grains, and the quality of the wheat [44,45]. Therefore, during the growth of wheat, continuous severe drought at the jointing and booting stage and the heading and flowering stage should be avoided as much as possible.

5. Conclusions

To elucidate the genetic mechanism underlying the conversion of the risk of drought disaster-causing factors to drought losses through the vulnerability of disaster-bearing bodies during the growth and development of wheat, a special experiment under wheat drought stress was carried out at the Xinmaqiao Agricultural and Water Comprehensive Test Station. In response to the changes in total dry matter under different intensities of drought stress, the crop growth analysis method was comprehensively used to quantitatively reveal the growth characteristics of wheat under drought stress during multiple growth periods. A drought damage sensitivity function for wheat with different drought combinations at multiple growth periods was constructed based on drought stress test and crop growth analysis, and the quantitative identification and assessment of wheat damage sensitivity was achieved. The main conclusions are as follows:

(1) The RGR of total dry matter was used as the evaluation index to measure the wheat yield. The RGR of the total dry matter of wheat had a significant negative correlation with the daily average degree of drought stress. The average R^2 values of the logarithmic fitting for 2017 and 2018 were 0.7935 and 0.7683, respectively. Wheat dry matter accumulation differed under the different drought combination scenarios.

(2) The RGR reduction in total dry matter was used as the evaluation index to measure the degree of wheat yield loss. The difference between the reduction in the RGR of total dry matter (relative to no drought stress treatment) and the daily average drought stress degree was determined. The yield loss sensitivity response relationship can be quantitatively identified by the *S*-shaped curve, and the average determination coefficients R^2 for 2017 and 2018 were 0.859 and 0.849, respectively. When the yield loss caused by different drought combinations was equal, the levels of drought stress they could withstand differed.

(3) Mild drought stress at the tillering stage in wheat stimulates self-adaptation and has little effect on yield. The SWC can be controlled to 65%–75% of the field water holding capacity; the SWC can be controlled at the jointing booting stage at a rate higher than 55% of the field water holding capacity. To ensure that the loss of the effective number of spikes, the number of grains per spike, and the yield of wheat were low, the SWC was maintained at a level higher than 75% of the field water holding capacity during the heading and flowering stages and the grain-filling and milky stages. Water savings, stable production, and increased efficiency are achieved. In addition, the jointing and booting stage is an important stage in which the vegetative growth and reproductive growth of wheat go hand in hand, and the heading and flowering stage is the core growth period for grain formation. During the production process, continuous severe drought at the jointing and heading stage and the heading and flowering stage should be avoided as much as possible. This study provides effective irrigation guidance for regional wheat planting.

(4) The *S*-shaped curve characterizing the response relationship between drought stress and drought loss showed that when the average daily drought stress gradually increased, the decrease in the RGR of total dry matter reached the peak value, which is consistent with the actual physical process. These results provide a basis for the prediction of drought loss under different drought stresses and also provide a theoretical basis and technical support for drought risk management. This approach also provides a way to further construct agricultural drought loss risk curves between drought frequency and the corresponding crop growth damage indexes from the perspective of causation mechanisms.

Author Contributions: Writing—Original Draft, Methodology, Formal Analysis, Validation, S.J.; Investigation, Writing—Review and Editing, Resources, Funding acquisition, Z.L.; Data curation, Visualization, Software, H.Y.; Data curation, Conceptualization, Writing—Review and Editing, J.J.; Funding acquisition, Conceptualization, C.X.; Investigation, Writing—Review and Editing, Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Natural Science Foundation of Anhui Province, China (Grant Nos. 2208085US03, 2208085US09, 2208085US15, 2308085US06), the National Natural Science Foundation of China (Grant Nos. 52209002, 42271037), the Outstanding Young Water Resources Talents in the Ministry of Water Resources, China, and the Youth Science and Technology Innovation Program of the Water Resources Research Institute of Anhui Province and Huaihe River Commission, Ministry of Water Resources (KY202203).

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

Acknowledgments: The authors would like to thank the handling editor and the reviewers for their reviews and valuable comments that significantly improved the quality of this paper.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gholami, F.; Amerian, M.R.; Asghari, H.R.; Ebrahimi, A. Assessing the effects of 24-epibrassinolide and yeast extract at various levels on cowpea's morphophysiological and biochemical responses under water deficit stress. *BMC Plant Biol.* **2023**, *23*, 593. [CrossRef] [PubMed]
2. Jin, J.L.; Zhou, L.G.; Cui, Y.; Jiang, S.M.; Wu, C.G.; Zhou, R.X. Discussion on some problems of regional drought risk assessment. *J. Hydraul. Eng.* **2023**, *54*, 1267–1276. (In Chinese) [CrossRef]
3. Li, D.; Li, X.X.; Li, Z.S.; Fu, Y.; Zhang, J.T.; Zhao, Y.J.; Wang, Y.F.; Liang, E.Y.; Rossi, S. Drought limits vegetation carbon sequestration by affecting photosynthetic capacity of semi-arid ecosystems on the Loess Plateau. *Sci. Total Environ.* **2023**, *912*, 168778. [CrossRef] [PubMed]
4. Zhang, H.; Sun, X.P.; Dai, M.Q. Improving crop drought resistance with plant growth regulators and rhizobacteria: Mechanisms, applications, and perspectives. *Plant Commun.* **2022**, *3*, 100228. [CrossRef] [PubMed]
5. Wang, X.F.; Luo, P.P.; Zheng, Y.; Duan, W.L.; Wang, S.T.; Zhu, W.; Zhang, Y.Z.; Nover, D. Drought disasters in China from 1991 to 2018: Analysis of spatiotemporal trends and characteristics. *Remote Sens.* **2023**, *15*, 1708. [CrossRef]
6. Cohen, I.; Zandalinas, S.I.; Huck, C.; Fritschi, F.B.; Mittler, R. Meta-analysis of drought and heat stress combination impact on crop yield and yield components. *Physiol. Plantarum.* **2021**, *171*, 66–76. [CrossRef] [PubMed]
7. Zahra, N.; Hafeez, M.B.; Wahid, A.; Al Masruri, M.H.; Ullah, A.; Siddique, K.H.M.; Farooq, M. Impact of climate change on wheat grain composition and quality. *J. Sci. Food Agric.* **2023**, *103*, 2745–2751. [CrossRef] [PubMed]
8. Daryanto, S.; Wang, L.; Jacinthe, P.A. Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. *Agric. Water Manag.* **2017**, *179*, 18–33. [CrossRef]
9. Bhat, M.A.; Mishra, A.K.; Jan, S.; Bhat, M.A.; Kamal, M.A.; Rahman, S.; Shah, A.A.; Jan, A.T. Plant growth promoting rhizobacteria in plant health: A perspective study of the underground interaction. *Plants* **2023**, *12*, 629. [CrossRef]
10. Sallam, A.; Alqudah, A.M.; Dawood, M.F.A.; Baenziger, P.S.; Boerner, A. Drought stress tolerance in wheat and barley: Advances in physiology, breeding and genetics research. *Int. J. Mol. Sci.* **2019**, *20*, 3137. [CrossRef]
11. Yue, Y.J.; Wang, L.; Li, J.; Zhu, A.X. An EPIC model-based wheat drought risk assessment using new climate scenarios in China. *Clim. Chang.* **2018**, *147*, 539–553. [CrossRef]
12. Yu, H.Q.; Zhang, Q.; Sun, P.; Song, C.Q. Impact of droughts on winter wheat yield in different growth stages during 2001–2016 in Eastern China. *Int. J. Disaster Risk Sci.* **2018**, *9*, 376–391. [CrossRef]
13. Jin, J.L.; Song, Z.Z.; Cui, Y.; Zhou, Y.L.; Jiang, S.M.; He, J. Research progress on the key technologies of drought risk assessment and control. *J. Hydraul. Eng.* **2016**, *47*, 398–412. (In Chinese) [CrossRef]
14. Jia, K.; Yang, Y.Z.; Dong, G.L.; Zhang, C.; Lang, T.T. Variation and determining factor of winter wheat water requirements under climate change. *Agric. Water Manag.* **2021**, *254*, 106967. [CrossRef]
15. Wu, J.J.; Wang, N.; Xing, X.G.; Ma, X.Y. Loss of Net primary production of seasonal winter wheat due to multiple drought types in the main Grain-Producing area of China. *J. Hydrol.* **2023**, *625*, 130093. [CrossRef]
16. Xiang, K.Y.; Wang, B.; Liu, D.L.; Chen, C.; Waters, C.; Huete, A.; Yu, Q. Probabilistic assessment of drought impacts on wheat yield in south-eastern Australia. *Agric. Water Manag.* **2023**, *284*, 108359. [CrossRef]
17. Igbadun, H.E.; Tarimo, A.K.P.R.; Salim, B.A.; Mahoo, H.F. Evaluation of selected crop water production functions for an irrigated maize crop. *Agric. Water Manag.* **2007**, *94*, 1–10. [CrossRef]
18. Smilovic, M.; Gleeson, T.; Adamowski, J. Crop kites: Determining crop-water production functions using crop coefficients and sensitivity indices. *Adv. Water Resour.* **2016**, *97*, 193–204. [CrossRef]
19. Cui, Y.; Jiang, S.M.; Jin, J.L.; Ning, S.W.; Feng, P. Quantitative assessment of soybean drought loss sensitivity at different growth stages based on S-shaped damage curve. *Agric. Water Manag.* **2019**, *213*, 821–832. [CrossRef]
20. Wei, Y.; Jin, J.; Li, H.; Zhou, Y.; Cui, Y.; Commey, N.A.; Zhang, Y.; Jiang, S. Assessment of agricultural drought vulnerability based on crop growth stages: A case study of Huaibei Plain, China. *Int. J. Disaster Risk Sci.* **2023**, *14*, 209–222. [CrossRef]
21. Wu, R.J.; Shi, J.Q.; Guan, F.L.; Yao, S.R. Integrated index construction and zoning of drought risk: A case study of winter wheat area in Hebei Province. *J. Nat. Disasters* **2013**, *22*, 145–152. (In Chinese) [CrossRef]
22. Yuan, B.B.; Wang, S.D.; Guo, L.H. Drought vulnerability assessment of winter wheat using an improved entropy-comprehensive fuzzy evaluation method: A case study of Henan Province in China. *Atmosphere* **2023**, *14*, 779. [CrossRef]

23. Chen, M.; Ning, S.; Cui, Y.; Jin, J.; Zhou, Y.; Wu, C. Quantitative assessment and diagnosis for regional agricultural drought resilience based on Set Pair Analysis and Connection Entropy. *Entropy* **2019**, *21*, 373. [CrossRef] [PubMed]
24. Bai, X.; Jin, J.; Wu, C.; Zhou, Y.; Zhang, L.; Cui, Y.; Tong, F. Construction of a time-variant integrated drought index based on the GAMLSS Approach and Copula Function. *Water* **2023**, *15*, 1653. [CrossRef]
25. Cui, Y.; Ning, S.; Jin, J.; Jiang, S.; Zhou, Y.; Wu, C. Quantitative lasting effects of drought stress at a growth stage on soybean evapotranspiration and aboveground BIOMASS. *Water* **2021**, *13*, 18. [CrossRef]
26. Jiang, S.M.; Yuan, H.W.; Cui, Y.; Jin, J.L.; Zhang, Y.L.; Zhou, Y.L. Quantitative evaluation of soybean drought system sensitivity based on relative growth rate. *Soybean Sci.* **2018**, *37*, 92–100. (In Chinese)
27. Oleszczuk, R.; Jadczyszyn, J.; Gnatowski, T.; Brandyk, A. Variation of moisture and soil water retention in a lowland area of central poland-solec site case study. *Atmosphere* **2022**, *13*, 1372. [CrossRef]
28. Zhang, J.; Zhou, Z.; Yao, F.; Yang, L.; Hao, C. Validating the modified perpendicular drought index in the North China region using In situ soil moisture measurement. *IEEE Geosci. Remote Sens. Lett.* **2015**, *12*, 542–546. [CrossRef]
29. Chen, H.L.; Zhang, H.W.; Shen, S.H.; Yu, W.D.; Zou, C.H. A real-time drought monitoring method: Cropland Soil Moisture Index (CSMI) and application. In Proceedings of the SPIE—The International Society for Optical Engineering, Berlin, Germany, 1–3 September 2009.
30. Wei, Y.Q.; Jin, J.L.; Cui, Y.; Ishidaira, H.; Li, H.C.; Jiang, S.M.; Zhou, R.X.; Zhou, L.G. Agricultural drought risk assessment based on crop simulation, risk curves, and risk maps in Huaibei Plain of Anhui Province, China. *Stoch. Environ. Res. Risk Assess.* **2022**, *36*, 3335–3353. [CrossRef]
31. Wei, Y.Q.; Jin, J.L.; Cui, Y.; Ning, S.W.; Fei, Z.Y.; Wu, C.G.; Zhou, Y.L.; Zhang, L.B.; Liu, L.; Tong, F. Quantitative assessment of soybean drought risk in Bengbu city based on disaster loss risk curve and DSSAT. *Int. J. Disaster Risk Reduct.* **2021**, *56*, 102126. [CrossRef]
32. Blackman, V. The Compound Interest Law and Plant Growth. *Ann. Bot.* **1919**, *33*, 353–360. [CrossRef]
33. Xiang, D.B.; Wei, W.; Ouyang, J.Y.; Le, L.Q.; Zhao, G.; Peng, L.X.; Wan, Y. Nitrogen alleviates seedling stage drought stress response on growth and yield of tartary buckwheat. *Int. J. Agric. Biol.* **2020**, *24*, 1167–1177. [CrossRef]
34. Polley, H.W.; Tischler, C.R.; Johnson, H.B.; Derner, J.D. Growth rate and survivorship of drought: CO_2 effects on the presumed tradeoff in seedlings of five woody legumes. *Tree Physiol.* **2002**, *22*, 383–391. [CrossRef]
35. Bo, S.H. Influence of Vesicular-Arbuscular Mycorrhiza on Growth and Drought Resistance of Selected Ground Cover Roses. Master's Thesis, Texas A&M University, College Station, TX, USA, 1992.
36. Awanis, S.; Purwanto, E.; Rahayu, M. The potential of Central Java local black rice and red rice as drought tolerant cultivars. *E3S Web Conf.* **2022**, *361*, 04007. [CrossRef]
37. Hussain, M.; Farooq, S.; Hasan, W.; Ul-Allah, S.; Tanveer, M.; Farooq, M.; Nawaz, A. Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. *Agric. Water Manag.* **2018**, *201*, 152–166. [CrossRef]
38. Lamaoui, M.; Jemo, M.; Datla, R.; Bekkaoui, F. Heat and drought stresses in crops and approaches for their mitigation. *Front. Chem.* **2018**, *6*, 26. [CrossRef] [PubMed]
39. Cheng, L.; Jin, J.L.; Li, J.Q.; Wang, Z.Z.; Li, L.; Yuan, X.C. Advance in the study of drought frequency analysis. *Adv. Water Sci.* **2013**, *24*, 296–302. (In Chinese) [CrossRef]
40. Sun, K.K.; Chen, J.; Jin, J.L.; Li, J.Q.; Xu, J.J.; Fei, Z.Y. Calculation method of agricultural drought loss risk curve under the actual drought resistance ability condition in Southern China. *J. Hydraul. Eng.* **2014**, *45*, 809–814. (In Chinese) [CrossRef]
41. Jin, J.L.; Zhou, L.G.; Jiang, S.M.; Zhou, T.; Cui, Y.; Bai, X.; Zhang, Y.L. Quantitative assessment method and its application modes of drought actual risk based on chain transfer structure. *J. Catastrophol.* **2023**, *38*, 1–6. (In Chinese) [CrossRef]
42. Dong, S.; Jiang, Y.Z.; Dong, Y.C.; Wang, L.B.; Wang, W.J.; Ma, Z.Z.; Yan, C.; Ma, C.M.; Liu, L.J. A study on soybean responses to drought stress and rehydration. *Saudi J. Biol. Sci.* **2019**, *26*, 2006–2017. [CrossRef]
43. Zhang, J.P.; Zhao, Y.X.; Wang, C.Y.; Yang, X.G.; Wang, J. Evaluation technology on drought disaster to yields of winter wheat based on WOFOST crop growth model. *Acta Ecol. Sin.* **2013**, *33*, 1762–1769. [CrossRef]
44. Potopova, V.; Boroneant, C.; Boincean, B.; Soukup, J. Impact of agricultural drought on main crop yields in the Republic of Moldova. *Int. J. Climatol.* **2016**, *36*, 2063–2082. [CrossRef]
45. Ma, J.; Li, R.Q.; Wang, H.G.; Li, D.X.; Wang, X.Y.; Zhang, Y.C.; Zhen, W.C.; Duane, H.J.; Yan, G.J.; Li, Y.M. Transcriptomics analyses reveal wheat responses to drought stress during reproductive stages under field conditions. *Front. Plant Sci.* **2017**, *8*, 592. [CrossRef] [PubMed]