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Simulation Study on the Response of Dryland Spring Wheat Yield to Drought Stress in the Longzhong Loess Plateau Region: Postprint

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Abstract

To further elucidate the response mechanism of rainfed spring wheat yield formation to different drought stresses in the Loess Plateau region of central Gansu, this study validated the suitability of the Agricultural Production Systems Simulation (APSIM) model for simulating rainfed spring wheat yield and its components under different drought stresses, based on field water control experiment data from 2016-2018 and meteorological data from 1971-2018 in Anjiagou Village, Fengxiang Town, Anding District, Dingxi City, Gansu Province. The APSIM model was then used to analyze the effects of drought stress at different growth stages and of different severities on grain number, thousand-grain weight, and yield of rainfed spring wheat, and multiple stepwise regression equations were employed to determine the optimal irrigation timing and amount for rainfed spring wheat in the Loess Plateau region of central Gansu. The results showed that: (1) The Root Mean Square Error (RMSE) of the APSIM model in simulating growth duration, grain number, thousand-grain weight, and yield of rainfed spring wheat in the Loess Plateau region of central Gansu were all less than 3.67 d, 300.52 grains $\cdot$ m^{-2}, 2.56 g, and 267.43 kg $\cdot$ hm^{-2}, respectively; the Normalized Root Mean Square Error (NRMSE) were all less than 3.89%, 2.86%, 9.71%, and 11.58%, respectively; and the Model Efficiency Index (ME) were all greater than 0.62, 0.78, 0.60, and 0.66, respectively, indicating that the APSIM model exhibited good applicability for simulating rainfed spring wheat yield formation under drought stress conditions in the Loess Plateau region of central Gansu. (2) Under drought stress at different growth stages, drought stress at the jointing stage had the greatest impact on wheat grain number, followed in descending order by emergence stage, tillering stage, no stress, heading stage, flowering stage, and grain-filling stage; drought stress at the grain-filling stage had the greatest impact on wheat thousand-grain weight, followed in descending order by flowering stage, heading stage, no stress, jointing stage, emergence stage, and tillering stage; and drought stress at the jointing stage had the greatest impact on wheat yield, followed in descending order by grain-filling stage, heading stage, flowering stage, emergence stage, no stress, and tillering stage. (3) Under different drought stress severities, the maximum yield of rainfed spring wheat was 4866.19 kg $\cdot$ hm^{-2} at an irrigation amount of 300.00 mm, which represented increases of 283.53%, 39.65%, 0.46%, and 15.58% compared with the other four irrigation treatments, respectively. (4) When irrigation was applied on days 1, 47, 60, 82, and 86 after emergence, with the irrigation amount reaching 343.09 mm, the maximum yield of rainfed spring wheat was 5578.91 kg $\cdot$ hm^{-2}. The timing and severity of drought stress had significant interactive effects on wheat yield formation in the study area; moderate drought stress at the tillering stage was beneficial for improving rainfed spring wheat yield in the Loess Plateau region of central Gansu, while the jointing and grain-filling stages were critical growth periods for field water management of rainfed spring wheat, and water management during these growth periods should be strengthened to improve food production in the Loess Plateau region of central Gansu.

Full Text

Simulation Study on the Response of Dryland Spring Wheat Yield to Drought Stress in the Loess Plateau Region of Central Gansu

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Abstract

To further elucidate the response mechanisms of dryland spring wheat yield formation to different drought stress scenarios in the Loess Plateau region of central Gansu, this study utilized field water control experimental data from Anjiagou Village, Fengxiang Town, Anding District, Dingxi City, Gansu Province (2016-2018) along with meteorological data from Anding District, Dingxi City (1971-2018) to validate the suitability of the Agricultural Production Systems Simulation (APSIM) model for simulating dryland spring wheat yield and its components under various drought stress conditions. Based on the APSIM model, we analyzed the effects of drought stress at different growth stages and severity levels on grain number, thousand-grain weight, and yield of dryland spring wheat, and determined the optimal irrigation timing and amount using multiple stepwise regression equations. The results showed that the root mean square error (RMSE) values for wheat phenology, grain number, thousand-grain weight, and yield were less than 3.67 days, 300.52 grains m^{-2}, 2.56 g, and 267.43

kg hm^{-2}, respectively. The normalized root mean square error (NRMSE) values were less than 3.89%, 2.86%, 9.71%, and 11.58%, respectively, while the model effectiveness index (ME) values exceeded 0.62, 0.78, 0.60, and 0.66, respectively. These metrics demonstrate that the APSIM model exhibits good fitting performance and adaptability for simulating spring wheat production under drought stress in the study region. Under drought stress at different growth stages, jointing-stage drought had the greatest impact on wheat grain number, followed in descending order by emergence, tillering, no stress, heading, flowering, and grain-filling stages. Grain-filling-stage drought most severely affected thousand-grain weight, followed by flowering, heading, no stress, jointing, emergence, and tillering stages. Jointing-stage drought had the most significant impact on wheat yield, followed by grain-filling, heading, flowering, emergence, no stress, and tillering stages. Under varying drought severity levels, an irrigation amount of 300.00 mm produced the maximum yield of 4866.19 kg hm^{-2}, representing increases of 283.53%, 39.65%, 15.58%, and 0.46% compared with irrigation amounts of 100.00 mm, 200.00 mm, 400.00 mm, and 500.00 mm, respectively. The optimal irrigation schedule was identified as 1, 47, 60, 82, and 86 days after emergence, with a total irrigation amount of 343.09 mm, achieving a maximum yield of 5578.91 kg hm^{-2}. A significant interaction existed between the timing and severity of drought stress. Moderate drought stress during the tillering stage was beneficial for increasing dryland spring wheat yield in the Loess Plateau region of central Gansu, while the jointing and grain-filling stages represent critical periods for field water management. Enhanced water management during these growth stages is essential for improving grain production in this region.

Keywords: drought stress; wheat yield; yield component; APSIM model; Loess Plateau of central Gansu

Introduction

Wheat is a crucial grain crop in the Loess Plateau region, contributing approximately [1] of national wheat production. However, severe water deficits have significantly impacted wheat production in this area [2-3]. In recent years, increased precipitation variability, seasonal mismatch between precipitation and crop water demand, and more frequent extreme weather events have led to more pronounced yield reductions and even total crop failures [4]. Implementing appropriate management measures for preemptive intervention and remediation has proven effective. Numerous studies have attempted to determine optimal field water management practices through extensive field experiments, but variations in climate, soil, crop characteristics, and management practices can severely affect experimental outcomes, requiring substantial time and labor resources [5].

With continuous advances in crop simulation technology, crop growth models have provided effective new approaches for addressing these challenges. These models can quantitatively reflect the impacts of various environmental factors on crop growth and development, simulate field experiments under different conditions, analyze interactive effects among multiple factors, and thereby determine optimal field management practices [6-7]. Researchers worldwide have conducted extensive simulation studies on wheat yield response mechanisms to drought stress at different growth stages using crop models. Zhang Jianping et al. [8] employed the World Food Studies (WOFOST) model to investigate the effects of drought stress during the jointing, heading, and grain-filling stages on winter wheat yield in Henan Province. Xu Jianwen et al. [9] used the Decision Support System for Agrotechnology Transfer (DSSAT) model to study the impacts of different irrigation amounts during the jointing and grain-filling stages on wheat yield in the Huang-Huai-Hai region. Flohr et al. [10] utilized the APSIM model to examine the effects of water and temperature stress on wheat flowering time in southeastern Australia. Wu et al. [11] applied the APSIM model to study the impacts of long-term drought stress on wheat yield in southwestern China. Overall, previous research has primarily focused on single growth stage drought stress effects using crop models, while studies on the coupled effects of drought stress at different growth stages and severity levels on wheat yield formation processes remain relatively limited and warrant further investigation.

This study aims to further reveal the response mechanisms of different drought stress scenarios on dryland spring wheat yield formation in the Loess Plateau region of central Gansu. Using long-term field experimental data, we validated the suitability of the APSIM model for simulating spring wheat yield formation under various drought stress conditions. Building upon this validation, we employed the model to simulate yield components and yield characteristics under coupled scenarios of different growth stages and drought severity levels, thereby elucidating the response mechanisms of dryland spring wheat yield formation to different drought stress conditions and determining optimal irrigation timing and quotas for spring wheat production in the Loess Plateau region of central Gansu.

1.1 Study Area Description

The long-term field experiment was conducted in Anjiagou Village, Fengxiang Town, Anding District, Dingxi City, Gansu Province, located in a typical hilly-gully region of the Loess Plateau at an elevation of 1879 m. The area has a mean annual precipitation of 395.00 mm, with an average precipitation of 286.70 mm during the spring wheat growing season. The maximum precipitation within the growing season is 2935.10 mm, while the minimum is 189.86 mm. The region has a mean annual temperature of 6.50 °C, with $ $10 °C accumulated temperature of 2240.20 °C and $ 0°*Caccumulatedtemperatureof*2935.10°*C.Themeanannualsolarradiationis*570.12*kJcm*{-2}, *andthemeanannua*

3}$ in the plow layer, organic carbon content of 6.21 g kg^{-1}, and total nitrogen content of 0.61 g kg^{-1}.

1.2 Experimental Design

1.2.1 Field Water Control Experiment To validate the suitability of the APSIM model for simulating dryland spring wheat yield and yield components under different drought stress conditions, a field water control experiment was conducted in Anjiagou Village, Fengxiang Town, Anding District, Dingxi City, Gansu Province from 2016 to 2018. The experimental design was based on the maximum and minimum precipitation during the spring wheat growing season in the study area from 1971 to 2018. Using the maximum growing season precipitation of 300.00 mm as the upper limit and the minimum of 50.00 mm as the lower limit, five irrigation levels were established: 50.00 mm, 100.00 mm, 150.00 mm, 200.00 mm, and 250.00 mm. Equal amounts of water were applied during the tillering, jointing, and flowering stages of wheat (Table 1). The field experiment included three sowing dates: normal sowing (March 20), early sowing (March 15), and late sowing (March 25). The plot size was 20 m × 4 m, arranged in a randomized complete block design with three replications. Plastic barriers were installed between plots to prevent lateral soil water movement. The spring wheat cultivar "Dingxi 35" was used with a seeding rate of 187.50 kg hm^{-2}, row spacing of 30 cm, and sowing depth of 0.25 m. Pure nitrogen (105.00 kg hm^{-2}) and P_2O_5 (105.00 kg hm^{-2}) were applied as basal fertilizer at sowing. A rain shelter was used to exclude precipitation, and supplemental irrigation was applied using a water meter to control irrigation amounts. Other management practices followed local production standards.

1.2.2 Simulation Experiment Design To determine the response thresholds of dryland spring wheat yield and yield components to different drought stress scenarios, simulation experiments were designed combining different growth stages and irrigation amounts. The simulation experiments consisted of combinations of irrigation timing and amount to simulate coupled drought stress at different growth stages and severity levels. To investigate the effects of different drought severity levels on spring wheat yield and yield components, five irrigation gradients were established: 100.00 mm, 200.00 mm, 300.00 mm, 400.00 mm, and 500.00 mm. Additionally, drought stress at different growth stages was simulated by withholding irrigation during any one of six main growth stages (emergence, tillering, jointing, heading, flowering, and grain-filling). The simulation experiment design is detailed in Table 2.

1.3 APSIM Model

The APSIM model, developed by the Agricultural Production Systems Research Unit (APSRU) in Australia, exhibits strong applicability and has been widely applied in agricultural production research under climate change scenarios [12]. The model comprises crop, soil, weather, and management modules that are processed through a central model engine to simulate crop growth and development on a daily time step. The modular "plug-and-pull" design allows users to select appropriate modules based on specific needs, ultimately obtaining results through the crop growth process [13]. Meteorological data for Dingxi City from 1971 to 2018 were obtained from the Gansu Provincial Meteorological Bureau. Crop cultivar parameters were adapted from Li Guang et al. [14] regarding APSIM model applicability in the Loess hill-gully region of central Gansu (Table 3). Soil parameters were based on measured data from the study area (Table 4), and management parameters were set according to the water control experimental design.

1.4 Phenology Prediction Model

The APSIM model calculates spring wheat phenology using adjusted thermal time ( ). When the accumulated thermal time reaches the target for a specific growth stage, wheat development progresses to the next stage. Adjusted thermal time represents the sum of daily thermal time modified by vernalization, photoperiod, and other environmental factors. The adjusted thermal time is calculated as:

$$= \sum [\Delta TT \times \min(f_V) \times \min(f_P) \times \min(f_W, f_N, f_P)]$$

where ΔTT is daily thermal time calculated based on three cardinal temperatures; f_V and f_P are vernalization and photoperiod coefficients, respectively; and f_W, f_N, and f_P are coefficients for soil water, nitrogen, and phosphorus effects on wheat growth (default value = 1).

Wheat growth is primarily influenced by: - Temperature and soil moisture from sowing to germination - Sowing depth and temperature from germination to emergence - Temperature and vernalization coefficient (f_V) from emergence to tillering - Photoperiod coefficient (f_P), temperature, and cultivar characteristics from tillering to booting - Temperature from heading to flowering - Temperature and grain-filling factors from flowering to maturity

The vernalization coefficient is calculated as:

$$V = 1 - (0.0054545 \times V_c + 0.0003) \times (50 - D_v)$$

where V_c is the vernalization sensitivity coefficient and D_v is the vernalization days.

The photoperiod coefficient is:

$$P = 1 - 0.002 \times P_c \times (20 - D_p)$$

where P_c is the photoperiod sensitivity coefficient and D_p is day length, calculated using standard astronomical formulas based on local latitude (35°58 N), day of year, and twilight parameters.

The total vernalization index (V_{total}) is calculated as the difference between daily vernalization index (V_{daily}) and de-vernalization index. The daily vernalization index is related to daily minimum and maximum temperatures. When daily minimum temperature is below 15°C and maximum temperature is below 20°C, the vernalization index is calculated using formula (3). However, when total vernalization index is less than 10 and daily maximum temperature exceeds 30°C, de-vernalization occurs, calculated using formula (4).

1.5 APSIM Model Validation

The study utilized field water control experimental data from 2016–2018 to validate APSIM model suitability. Validation employed three statistical indicators: root mean square error (RMSE), normalized root mean square error (NRMSE), and model effectiveness index (ME). Generally, RMSE and NRMSE indicate error between simulated and observed values (smaller values are better), while ME indicates model performance (values closer to 1 are better). The formulas are:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}$$

$$NRMSE = 100 \times \frac{RMSE}{\bar{O}}$$

$$ME = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

where P_i represents the ith simulated value, O_i represents the ith observed value, $\bar{O}$ is the mean observed value, and n is the number of observations.

Results

2.1 APSIM Model Validation

2.1.1 Phenology Simulation Performance The emergence, jointing, heading, and flowering stages are critical and easily observable periods in spring wheat development. The APSIM model demonstrated relatively high simulation accuracy for key phenological stages under different drought stress conditions. For the emergence stage, simulated and observed values showed NRMSE of 1.59%-3.89% and ME of 0.62-0.86. For the jointing stage, RMSE was 2.28-3.34 days with NRMSE of 2.75%. For the heading stage, RMSE was 0.76-0.94 days with NRMSE of 1.29%-3.02% and ME of 0.71-0.95. For the flowering stage, RMSE was 1.98-2.94 days with NRMSE of 1.09%-2.68% and ME of 0.75-0.95. Comparison with measured data revealed that simulation accuracy was higher for irrigation amounts of 100.00-200.00 mm, and later growth stages showed better simulation performance than earlier stages.

2.1.2 Yield and Yield Component Simulation Performance **Grain Number Simulation.** Validation using 2016-2018 field data showed that simulated and observed grain numbers were uniformly distributed within $±15^{-2}$, mean NRMSE was 2.32%, and mean ME was 0.78 (Table 6). These results indicate that APSIM can effectively simulate spring wheat grain number under various drought stress conditions in the study area.

Thousand-Grain Weight Simulation. Validation results showed that simulated and observed thousand-grain weights were uniformly distributed within $±$15% of the 1:1 line (Figure 3). The mean RMSE was 2.07 g, mean NRMSE was 8.15%, and mean ME was 0.60 (Table 7). These results demonstrate that APSIM can satisfactorily simulate spring wheat thousand-grain weight under different drought stress conditions.

Yield Simulation. Simulated and observed yields were uniformly distributed within $±15^{-2}$, mean NRMSE was 7.80%, and mean ME was 0.66 (Table 8). These results confirm that APSIM can adequately simulate spring wheat yield under various drought stress conditions in the study region.

2.2 Effects of Different Drought Stress on Yield and Yield Components

2.2.1 Effects of Drought Stress at Different Growth Stages Drought stress at different growth stages affected grain number, thousand-grain weight, and yield differently in the Loess Plateau region of central Gansu. Treatments T1-T5 represented emergence-stage drought, T6-T10 tillering-stage drought, T11-T15 jointing-stage drought, T16-T20 heading-stage drought, T21-T25 flowering-stage drought, and T26-T30 grain-filling stage drought, with T31-T35 representing no stress (Table 9).

Grain Number. Grain-filling stage drought produced the highest average grain number (1268.78 grains m^{-2}), while jointing-stage drought resulted in the lowest (100.00 mm treatment: 1219.75 grains m^{-2}). The ranking of growth stage effects on grain number from most to least severe was: jointing > emergence > tillering > no stress > heading > flowering > grain-filling.

Thousand-Grain Weight. Tillering-stage drought produced the maximum average thousand-grain weight (43.50 g at 300.00 mm irrigation), while grain-filling stage drought resulted in the minimum (34.75 g at 100.00 mm irrigation). The ranking of growth stage effects on thousand-grain weight was: grain-filling > flowering > heading > no stress > jointing > emergence > tillering.

Yield. Tillering-stage drought produced the highest average yield (3897.30 kg hm^{-2}), while jointing-stage drought resulted in the lowest yield. The ranking of growth stage effects on yield was: jointing > grain-filling > heading > flowering > emergence > no stress > tillering.

These results indicate that jointing-stage drought is the primary factor causing yield reduction by significantly decreasing grain number, while moderate tillering-stage drought can increase thousand-grain weight and improve yield.

2.2.2 Effects of Different Drought Severity Levels Under varying drought severity levels, significant differences were observed in yield and yield components. An irrigation amount of 300.00 mm produced the maximum grain number (5150.04 grains m^{-2}), thousand-grain weight (42.54 g), and yield (4866.19 kg hm^{-2}). Compared with other irrigation amounts, the 300.00 mm treatment increased yield by 283.53%, 39.65%, 15.58%, and 0.46% relative to 100.00 mm, 200.00 mm, 400.00 mm, and 500.00 mm treatments, respectively. These results demonstrate that 300.00 mm is the optimal irrigation amount for dryland spring wheat in this region.

2.2.3 Optimal Irrigation Timing and Amount Using days after emergence for five irrigation events (x_1-x_5) and total irrigation amount (x_6) as independent variables, and APSIM-simulated grain number, thousand-grain weight, and yield as dependent variables, multiple stepwise regression equations were established (Table 10). All three equations had determination coefficients (R^2) above 0.50, indicating good model fit.

Multi-objective optimization identified the optimal irrigation schedule as 1, 47, 60, 82, and 86 days after emergence, with a total irrigation amount of 343.09 mm, achieving maximum yield of 5578.91 kg hm^{-2}. At this optimal schedule, grain number reached 5150.04 grains m^{-2} and thousand-grain weight reached 46.29 g. These results indicate that 343.09 mm is the optimal irrigation amount for dryland spring wheat in the Loess Plateau region of central Gansu.

Discussion

Previous studies have validated APSIM model performance for simulating wheat phenology under different regions, sowing dates, and planting densities, showing high simulation accuracy [15]. Fan Dongliang et al. [16] used APSIM to simulate phenology, biomass, and yield of different wheat varieties in Inner Mongolia, demonstrating high model precision. Li Guang et al. [14] showed that APSIM performed well in simulating wheat yield under different tillage practices in the Loess hill-gully region. Li Yan et al. [17] used APSIM to study irrigation effects on reducing wheat yield risk. Our study confirms that APSIM exhibits high simulation accuracy and good adaptability for phenology, grain number, thousand-grain weight, and yield of dryland spring wheat under various drought stress conditions in the Loess Plateau region of central Gansu.

Previous research indicates that grain-filling stage drought has relatively small effects on wheat spike number but significantly reduces thousand-grain weight by affecting grain filling [18]. Thousand-grain weight is primarily influenced by drought during the grain-filling period, with pre-grain-filling drought having relatively minor effects [19]. However, Kaur and Behl [20] found that short-term drought stress before and after flowering shortened grain-filling duration and affected thousand-grain weight. Our study shows that tillering-stage drought with 300.00 mm irrigation in other stages produced maximum thousand-grain weight, likely because early-season mild drought stress can increase average grain-filling rate [21]. Grain-filling stage drought with 100.00 mm irrigation in other stages produced minimum thousand-grain weight, consistent with previous findings [22-23].

Research demonstrates that pre-booting drought reduces effective spikelet and grain numbers [22]. Wang Min et al. [24] found that moderate drought at the jointing stage significantly reduced spike number and grain number per spike. Li Yanbin et al. [25] showed that any degree of jointing-stage drought reduced fertile spikelets and effective spikes. Our results confirm that jointing-stage drought is the critical factor affecting grain number and yield in the study region, consistent with Xu Jianwen et al. [9] and Lü Dianqing [32]. Moderate tillering-stage drought was beneficial for yield, as mild drought during this stage can significantly increase grain number per spike, grain-filling rate, and thousand-grain weight [33]. The finding that tillering-stage drought with 400.00 mm irrigation in other stages produced maximum yield aligns with previous research [34].

The ranking of growth stage effects on yield (jointing > grain-filling > heading > flowering > emergence > no stress > tillering) reflects the critical water demand periods for wheat. Studies show that drought effects on wheat yield depend on stress severity and timing, with significant differences in compensation effects from irrigation at different growth stages [35-36]. Huang Caixia et al. [37] found that irrigating 105.00 mm at the jointing, heading, and grain-filling stages produced maximum grain yield. Yao Ning et al. [38] showed that irrigation at heading and grain-filling stages increased thousand-grain weight with relatively minor effects on spike number and grains per spike. Zhou Shiwei et al. [39] used the Root Zone Water Quality Model (RZWQM) to optimize irrigation scheduling for spring wheat in the Shiyang River basin, finding that irrigation at emergence, jointing, heading, and grain-filling stages with 323.70 mm total amount was appropriate. Our study identified 343.09 mm as the optimal irrigation amount, similar to the reported water requirement of 325.30 mm for spring wheat in this region [40]. Excessive irrigation can increase ineffective tillers, reduce leaf area per plant, inhibit photosynthesis, and ultimately cause yield reduction [41].

Conclusions

1. The APSIM model demonstrates good fitting performance and adaptability for simulating phenology, grain number, thousand-grain weight, and yield of dryland spring wheat under drought stress conditions in the Loess Plateau region of central Gansu.
2. Under drought stress at different growth stages, jointing-stage drought is the primary cause of yield reduction in this region, while moderate tillering-stage drought is beneficial for increasing yield. The ranking of growth stage effects on yield from most to least severe is: jointing > grain-filling > heading > flowering > emergence > no stress > tillering.
3. Under different drought severity levels, an irrigation amount of 300.00 mm produced maximum yield of 4866.19 kg hm^{-2}, representing increases of 283.53%, 39.65%, 15.58%, and 0.46% compared with 100.00 mm, 200.00 mm, 400.00 mm, and 500.00 mm treatments, respectively.
4. The optimal irrigation schedule was identified as 1, 47, 60, 82, and 86 days after emergence, with a total irrigation amount of 343.09 mm, achieving maximum yield of 5578.91 kg hm^{-2}. This represents the optimal irrigation timing and amount for dryland spring wheat in the Loess Plateau region of central Gansu.

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