Simulation and Analysis of the Impacts of Rising Temperature, Precipitation, and Nitrogen Application on Dryland Spring Wheat Yield and Biomass: Postprint

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Abstract

To explore the effects of precipitation and nitrogen application under elevated temperature on spring wheat yield and biomass in semi-arid regions, simulation experiments were conducted using APSIM based on meteorological data from Anding District, Dingxi City, Gansu Province from 1971-2018 and field experimental data from Anjiagou Village, Fengxiang Town, Anding District from 2014-2018. The experiments comprised 5 temperature gradients (0 ℃, 0.5 ℃, 1 ℃, 1.5 ℃, 2 ℃), 5 precipitation gradients (−20%, −10%, 0%, 10%, 20%), and 4 nitrogen treatments (0 $\mathrm{kg \cdot hm^{-2}}$, 55 $\mathrm{kg \cdot hm^{-2}}$, 110 $\mathrm{kg \cdot hm^{-2}}$, 220 $\mathrm{kg \cdot hm^{-2}}$). Spring wheat yield and biomass were analyzed through regression equations, single-factor analysis, and interaction analysis, and wheat yield was examined through the relationships among temperature increase, precipitation, and nitrogen application. The results showed: (1) The normalized root mean square error (NRMSE) for simulated wheat yield and biomass was 7.47% and 7.66%, respectively, and the model efficiency index (ME) was 0.91 and 0.85, respectively; the NRMSE for the grain-filling period was 1.73% with an ME of 0.98, indicating that the model adequately reflects the effects of temperature, precipitation, and nitrogen application on spring wheat yield and biomass. (2) With increasing temperature, spring wheat yield and biomass exhibited a negative upward-opening parabolic response; with increasing nitrogen application rate, yield and biomass showed a downward-opening parabolic response with thresholds of 122.11 $\mathrm{kg \cdot hm^{-2}}$ and 129.06 $\mathrm{kg \cdot hm^{-2}}$, respectively, and optimal values of 2574.86 $\mathrm{kg \cdot hm^{-2}}$ and 5777.39 $\mathrm{kg \cdot hm^{-2}}$, respectively; increased precipitation produced a positive upward-opening parabolic effect on yield and biomass. (3) The interaction between temperature and nitrogen application was negative; the interaction between temperature and precipitation was negative; the interaction between nitrogen application and precipitation was positive. (4) When yield reached optimum under temperature increases of 0 ℃, 0.5 ℃, 1 ℃, 1.5 ℃, and 2 ℃, precipitation should increase by 20% and nitrogen application rates should be 156.2 $\mathrm{kg \cdot hm^{-2}}$, 149.6 $\mathrm{kg \cdot hm^{-2}}$, 131.56 $\mathrm{kg \cdot hm^{-2}}$, 110.0 $\mathrm{kg \cdot hm^{-2}}$, and 107.8 $\mathrm{kg \cdot hm^{-2}}$, respectively. (5) The order of influence of the three factors on yield was precipitation > nitrogen application > temperature; reasonable water–nitrogen synergy can mitigate the negative effects of temperature increase on yield.

Full Text

Simulation and Analysis of the Effects of Precipitation and Nitrogen Application on Spring Wheat Yield and Biomass in Dryland Under Elevated Temperature

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Abstract

To explore the effects of temperature increase, precipitation variation, and nitrogen application on spring wheat yield and biomass in semi-arid regions, this study conducted simulation experiments using the APSIM model. Based on meteorological data from 1971-2018 for Anding District, Dingxi City, Gansu Province, and field experimental data from 2014–2018 in Anjiagou Village, Fengxiang Town, we designed five temperature gradients (0 °C, 0.5 °C, 1 °C, 1.5 °C, and 2 °C), five precipitation gradients (−20%, −10%, 0%, +10%, and +20%), and four nitrogen treatments (0 $\mathrm{kg \cdot hm^{-2}}$, 55 $\mathrm{kg \cdot hm^{-2}}$, 110 $\mathrm{kg \cdot hm^{-2}}$, and 220 $\mathrm{kg \cdot hm^{-2}}$). Regression analysis, single-factor analysis, and interaction analysis were employed to examine dryland spring wheat yield and biomass, with yield further analyzed through the relationships between temperature increase, precipitation, and nitrogen application.

The results showed that: (1) The normalized root mean square error (NRMSE) between simulated and observed values was 7.47% for yield and 7.66% for biomass, with model efficiency indices of 0.91 and 0.85, respectively. For grain dry matter during the filling period, NRMSE was 1.73% with a model efficiency index of 0.98, indicating that the APSIM model accurately simulated the effects of temperature, precipitation, and nitrogen on spring wheat yield and biomass. (2) Elevated temperature negatively affected yield and biomass following an upward-opening parabolic relationship. Increased nitrogen application showed a downward-opening parabolic effect, with thresholds of 122.11 $\mathrm{kg \cdot hm^{-2}}$ for yield and 129.06 $kg \cdot hm^{-2}$ for biomass; optimal values were 2574.86 $kg \cdot hm^{-2}$ and 5777.39 $kg \cdot hm^{-2}$, respectively. Increased precipitation positively affected yield and biomass following an upward-opening parabolic relationship. (3) The temperature–nitrogen interaction was negative, the temperature–precipitation interaction was negative, and the nitrogen–precipitation interaction was positive. (4) At optimal yield under 0 °C, 0.5 °C, 1 °C, 1.5 °C, and 2 °C, precipitation should increase by 20% and nitrogen application should be 156.2 $kg \cdot hm^{-2}$, 149.6 $kg \cdot hm^{-2}$, 131.56 $kg \cdot hm^{-2}$, 110.0 $kg \cdot hm^{-2}$, and 107.8 $kg \cdot hm^{-2}$, respectively. (5) The order of factor effects on yield was precipitation > nitrogen application > temperature. Rational water-nitrogen synergy can mitigate the negative effects of temperature increase on yield.

Keywords: APSIM; wheat; temperature; precipitation; nitrogen application; biomass; yield

1 Introduction

The impact of climate change on wheat yield is well-established, particularly for rain-fed wheat in Gansu Province. Previous research has extensively investigated the effects of temperature, fertilizer, and water on wheat growth. Studies have shown that appropriate nitrogen application can alleviate high-temperature stress during grain filling, though its effect on grain quality under heat stress is limited. Other research demonstrated that water and nitrogen promote wheat growth within certain ranges, but excessive application reduces water and fertilizer use efficiency. While most studies have focused on single or dual factors, research on the synergistic regulation of water and fertilizer under temperature change remains limited. Dingxi region exhibits rising temperatures and decreasing precipitation with strong interannual variability. Therefore, this study employed the APSIM model to simulate temperature increases and analyze the synergistic effects of precipitation and nitrogen on dryland spring wheat yield and biomass, focusing on the grain-filling stage when temperature impacts are most pronounced. The objectives were to determine optimal precipitation and nitrogen rates under different temperature scenarios and reveal the mechanisms of water-fertilizer synergy under elevated temperatures, providing a theoretical basis for future wheat production.

1.1 Study Area Description

The study area is located in Anjiagou Village, Fengxiang Town, Anding District, Dingxi City, Gansu Province (35°35 N, 104°37 E), in the Loess Plateau region. This mid-temperate semi-arid zone has an elevation of 2000 m, annual evaporation of 1531 mm, mean annual temperature of 6.4 °C, annual precipitation of 385.0 mm, and annual sunshine duration of 2400 h. Soils are loessal with a bulk density of 1.26 $g \cdot cm^{-3}$, total nitrogen content of 0.61 $g \cdot kg^{-1}$, organic matter content of 12.01 $g \cdot kg^{-1}$, and total phosphorus content of 1.77 $g \cdot kg^{-1}$.

Field experiments were conducted from 2014–2018 using spring wheat cultivar "Dingxi 35" in 6 m × 4 m plots with 0.5 m buffer zones. The no-tillage system typical of the region was employed without irrigation. Nitrogen (urea) was applied at rates of 0 $\mathrm{kg \cdot hm^{-2}}$ and 105 $\mathrm{kg \cdot hm^{-2}}$ (local conventional rate) as basal fertilizer. Sowing occurred in late March at local conventional seeding rates (105 $\mathrm{kg \cdot hm^{-2}}$) and 0.25 m depth. Three replications yielded average yield and biomass values, with 10 plants sampled per plot at harvest for measurement.

1.2 Data Sources and Processing

Field-measured yield and biomass data (aboveground dry biomass only) from 2014–2018 were used for model calibration and validation. Meteorological data (1971-2018) were obtained from the Dingxi Meteorological Bureau, including daily maximum temperature, minimum temperature, precipitation, and sunshine hours. Crop variety and physiological parameters were derived from previous studies by Li et al. . Field management parameters were set according to actual practices. APSIM simulation outputs were processed using Microsoft Excel 2010, with Matlab 2018 used for quadratic polynomial analysis to determine optimal precipitation and nitrogen rates for maximum yield.

1.3 APSIM Model Description

APSIM is a comprehensive model for simulating biophysical processes in agricultural systems, comprising crop, soil, management, input/output, and central engine modules. The model connects different sub-modules to the main engine as needed and allows user-developed modules. Parameter requirements include crop parameters, soil parameters, management parameters, and climate parameters, with crop variety parameters shown in .

1.4 Model Calibration and Validation

Model performance was evaluated using root mean square error (RMSE), normalized RMSE (NRMSE), and model efficiency (ME). Smaller RMSE and NRMSE indicate better fit, while ME values closer to 1 indicate higher simulation precision and stability.

$$\mathrm{NRMSE} = 100 \times \sqrt{\frac{\sum_{i=1}^{n}(Y_i - Y_j)^2}{n}} \Big/ \bar{Y}$$

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(Y_i - Y_j)^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}$$

where Y_i is the measured value, Y_j is the simulated value, and $\bar{Y}$ is the mean measured value.

1.5 Experimental Design

Using 1971-2018 meteorological data, simulation experiments were conducted with precipitation varying at −20%, −10%, 0%, +10%, and +20% of natural levels, and temperature varying at 0 °C, 0.5 °C, 1 °C, 1.5 °C, and 2 °C above actual values. Four nitrogen levels were established: N0 ($0\ \mathrm{kg \cdot hm^{-2}}$), N1 ($55\ \mathrm{kg \cdot hm^{-2}}$), N2 ($110\ \mathrm{kg \cdot hm^{-2}}$), and N3 ($220\ \mathrm{kg \cdot hm^{-2}}$). A completely randomized block design generated $5 \times 5 \times 4 \times 3 = 300$ treatment combinations, with averages calculated for each scenario. The control treatment used actual daily temperatures and $105\ \mathrm{kg \cdot hm^{-2}}$ nitrogen applied as basal fertilizer. Grain dry matter and daily yield during the filling period were simulated for different temperature and water-fertilizer combinations .

2 Results

2.1 Model Validation

Using 2014-2018 field data, linear regression between simulated and measured values showed NRMSE of 7.47% for yield and 7.66% for biomass, with model efficiency indices of 0.91 and 0.85, respectively. Grain dry matter during filling showed NRMSE of 1.73% and model efficiency of 0.98 [Figure 1: see original paper]. These results demonstrate that APSIM accurately simulates spring wheat yield and biomass under varying temperature, nitrogen, and precipitation conditions.

2.2 Regression Analysis of Water-Nitrogen Synergy Under Temperature Variation

Using yield (Y_{yield}) and biomass (Y_{biomass}) as dependent variables and temperature (X_1), precipitation (X_2), and nitrogen rate (X_3) as independent variables, quadratic polynomial stepwise regression was performed on $5 \times 5 \times 4 = 100$ samples. The resulting ternary quadratic regression equations showed correlation coefficients of 0.94 for yield and 0.96 for biomass, indicating strong relationships .

2.2.1 Main Effects Analysis The regression equations revealed that precipitation and nitrogen had positive linear coefficients while temperature had negative coefficients, indicating that increased precipitation and nitrogen enhance yield and biomass, whereas elevated temperature reduces them. The absolute coefficient values showed the effect order: precipitation > nitrogen > temperature for both yield and biomass.

2.2.2 Single-Factor Analysis With other factors held constant at intermediate levels, single-factor equations were derived . Temperature showed an upward-opening parabolic negative effect: each 0.5 °C increase reduced yield and biomass by maximum values of 4.11% and 0.76%, minimum values of 5.17% and 7.45%, and average values of 4.67% and 4.28%, respectively [Figure 2: see original paper]. Precipitation exhibited an upward-opening parabolic positive effect: each gradient increase enhanced yield and biomass by maximum values of 47.46% and 47.77%, minimum values of 26.45% and 26.88%, and average values of 35.53% and 35.94% [Figure 3: see original paper]. Nitrogen showed a downward-opening parabolic effect with thresholds of 122.11 $\text{kg} \cdot \text{hm}^{-2}$ for yield and 129.06 $\text{kg} \cdot \text{hm}^{-2}$ for biomass, beyond which yield and biomass declined. Optimal values occurred at 2574.86 $\text{kg} \cdot \text{hm}^{-2}$ yield and 5777.39 $\text{kg} \cdot \text{hm}^{-2}$ biomass when nitrogen was 129.06 $\text{kg} \cdot \text{hm}^{-2}$ [Figure 4: see original paper]. Each 55 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen increase enhanced yield and biomass by maximum values of 16.76% and 24.53%, minimum values of 11.38% and 16.42%, and average values of 9.03% and 6.01%.

2.2.3 Interaction Effects Analysis Interaction coefficients in the regression equations revealed: (1) negative temperature-precipitation interaction, indicating that precipitation' s positive effect exceeds temperature' s negative effect, resulting in net yield/biomass increase when both rise; (2) negative temperature-nitrogen interaction, where nitrogen' s positive effect surpasses temperature' s negative effect, increasing yield/biomass when both increase; and (3) positive precipitation-nitrogen interaction, where both factors synergistically enhance yield and biomass.

2.2.4 Temperature-Water-Nitrogen Relationships Substituting temperature values into the yield equation and optimizing with Matlab revealed optimal conditions at different temperatures: at 0.5 °C increase, precipitation should increase by 20% with 156.2 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen; at 1 °C, precipitation +20% with 149.6 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen; at 1.5 °C, precipitation +20% with 131.56 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen; at 2 °C, precipitation +20% with 110.0 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen; and at 2.5 °C, precipitation +20% with 107.8 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen.

2.3 Temperature-Water-Nitrogen Coupling During Grain Filling

Under baseline conditions (actual 2014-2018 temperatures, 105 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen), average grain dry matter was 1114.2 $\text{kg} \cdot \text{hm}^{-2}$. Simulations showed that increasing precipitation and nitrogen enhanced grain dry matter up to 1.8 times conventional levels, demonstrating strong promotional effects. At elevated temperatures, optimal nitrogen rates varied by precipitation: at 0.5 °C increase with 20% more precipitation, 220 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen maximized dry matter; at 1.5 °C increase with 20% more precipitation, 110 $\text{kg} \cdot \text{hm}^{-2}$ nitrogen was optimal. With constant precipitation and nitrogen, each 0.5 °C temperature increase reduced grain dry matter by minimum 6.20%, maximum 18.30%, and average 11.85% [Figure 5: see original paper].

3 Discussion

Model validation using 2014-2018 data confirmed APSIM' s suitability for the study region, with all NRMSE values within acceptable error ranges. The results demonstrate that nitrogen' s positive effect on wheat exceeds temperature' s negative effect, consistent with findings that elevated temperature inhibits starch synthesis while appropriate nitrogen increases spike number and grain protein content. The identified nitrogen thresholds (122.11 $\text{kg} \cdot \text{hm}^{-2}$ for yield, 129.06 $\text{kg} \cdot \text{hm}^{-2}$ for biomass) align with previous APSIM simulations in the region. The negative temperature-nitrogen interaction indicates that nitrogen can mitigate temperature stress by maintaining photosynthetic organ structure and chlorophyll content, as reported in pot and split-plot experiments.

The negative temperature-precipitation interaction reflects precipitation' s dominant positive effect over temperature' s negative effect, consistent with studies showing that increased precipitation improves soil water storage and yield in dryland wheat systems. The positive nitrogen-precipitation interaction demonstrates synergistic enhancement of yield and biomass, where adequate water prevents nitrogen leaching and insufficient water limits nitrogen efficacy. This aligns with research showing that high water and high fertilizer combinations produce maximum yields in semi-arid regions.

The study also revealed that grain dry matter decreases with temperature elevation under constant water and nitrogen, with average reductions of 11.85% per 0.5 °C increase. This is consistent with previous APSIM studies showing temperature increases of 0.5 °C reducing yield by 14.92% on average. The optimal solutions identified—precipitation increases of 20% across all temperature scenarios with nitrogen rates decreasing from 156.2 $\text{kg} \cdot \text{hm}^{-2}$ at +0.5 °C to 107.8 $\text{kg} \cdot \text{hm}^{-2}$ at +2.5 °C—provide practical guidance for maintaining wheat production under climate change. The APSIM model' s advantage in multi-factor scenario analysis enables comprehensive assessment of temperature, precipitation, and nitrogen interactions, offering theoretical support for climate adaptation strategies in dryland spring wheat production.

4 Conclusions

Validation with 2014-2018 data confirmed APSIM' s strong performance in simulating temperature, nitrogen, and precipitation effects on spring wheat yield and biomass. The factor effect order was precipitation > nitrogen application > temperature. Under future climate scenarios, optimal production requires nitrogen rates of 129.06 $\text{kg} \cdot \text{hm}^{-2}$, yielding 2574.86 $\text{kg} \cdot \text{hm}^{-2}$ grain and 5777.39 $\text{kg} \cdot \text{hm}^{-2}$ biomass. Rational water-nitrogen synergy can effectively mitigate negative temperature effects, providing a theoretical basis for sustainable dryland wheat production under climate change.

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Note: Figure translations are in progress. See original paper for figures.