Simulated Impacts of Climate Change on Potential and Rain-fed Yields of Winter Wheat in Southwest China, 1961–2010: Postprint

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Abstract

Using crop and soil data from agrometeorological experimental stations, the adaptability of the APSIM-Wheat model in Southwest China was evaluated, and the model was applied to analyze spatiotemporal variation characteristics of winter wheat potential and rain-fed yields in the region from 1961 to 2010, with stepwise regression analysis employed to reveal the impacts and relative contribution rates of major meteorological factors during the wheat growth season on potential and rain-fed yields. The results indicate that the APSIM model performed well in simulating five commonly used wheat varieties in the region: the root mean square error (RMSE) between simulated and observed growth periods was within 7.0 days, and the normalized root mean square error (NRMSE) between simulated and observed aboveground biomass and yield values was below 25%, demonstrating good model adaptability in Southwest China. From 1961 to 2010, total radiation during the winter wheat growth season decreased significantly at 36% of stations in the study area, most pronounced in the northern, southeastern, and south-central regions; effective accumulated temperature 0 ℃ during the growth season increased significantly at 68% of stations, with notable warming in the western region; the mean diurnal temperature range during the growth season decreased significantly at 30% of stations, most notably in the south-central region; and total precipitation during the growth season decreased over a large area across the entire region, though not significantly, with reduction areas mainly located in the southernmost and southeastern parts. Simulated winter wheat potential yield exhibited a significant decreasing trend at 65% of stations, with the most pronounced changes in the south-central and northern regions; rain-fed yield decreased significantly at 25% of stations, with the northern region showing more obvious reductions, while the yield reduction trend across the entire region was relatively weak. At stations with significant yield reductions, the contribution rates of decreased radiation, increased temperature, and reduced diurnal temperature range during the growth season to potential yield reduction were 45%, 36%, and 2%, respectively, while their contribution rates to rain-fed yield reduction were 36%, 39%, and -8%, respectively; decreased precipitation contributed 7% to rain-fed yield reduction. The combined effects of decreased radiation, increased temperature, and reduced precipitation during the winter wheat growth season in Southwest China collectively led to significant declines in both potential and rain-fed yields, while the reduction in diurnal temperature range exhibited negative and positive effects on winter wheat potential and rain-fed yields, respectively; overall, radiation and temperature had the greatest influence.

Full Text

Preamble

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Impact Simulation of Climate Change on Potential and Rainfed Yields of Winter Wheat in Southwest China from 1961 to 2010*

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Abstract

Using crop and soil data from agro-meteorological observational stations together with meteorological data from meteorological stations, this study evaluated the adaptability of the APSIM-Wheat (Agricultural Production Systems sIMulator-Wheat) model in winter wheat planting zones in Southwest China (SWC). The model was then applied to calculate the potential and rainfed yields of winter wheat from 1961 to 2010 in SWC. The relative contribution rates of changes in main climatic factors during the crop growing season to the changes in simulated potential and rainfed yields of winter wheat were determined using the stepwise regression method. The results showed that the APSIM-Wheat model performed well in simulating phenology, above-ground biomass, and yield of five representative winter wheat varieties in SWC. Root Mean Square Error (RMSE) between simulated and observed wheat phenology was less than 7.0 d for all varieties. Normalized Root Mean Square Error (NRMSE) between simulated and observed above-ground biomass and yield was lower than 25% and 21%, respectively, for all varieties. Total solar radiation during the wheat growing season decreased significantly at 36% of the study stations, concentrated in the northern, southeastern, and mid-southern SWC. The effective accumulative temperature of not less than 0 ℃ during the wheat growing season increased significantly at 68% of the study stations, concentrated in the western SWC, while average diurnal temperature range during the wheat growing season decreased significantly at 30% of study stations, concentrated in the mid-southern SWC ($P < 0.05$). Total precipitation during the wheat growing season decreased at most study stations, concentrated in the southern and southeastern SWC from

1961 to 2010, though the trend was not statistically significant. As a result, simulated potential yield of winter wheat showed a significant decline at 65% of study stations, especially in the mid-southern and northern SWC. Simulated rainfed yield showed a significant decline at 25% of study stations, especially in the northern SWC. The contribution rates of the decrease in solar radiation and diurnal temperature range, and the increase in temperature during the wheat growing season were 45%, 2%, and 36%, respectively, to the reduction in simulated potential yield, and 36%, 39%, and -8%, respectively, to the reduction in simulated rainfed yield. The contribution rate of decreasing precipitation during the wheat growing season was 7% to the reduction in simulated rainfed yield. In general, solar radiation and temperature had the most obvious effects on simulated yield variations of winter wheat in SWC from 1961 to 2010. The decrease in solar radiation and precipitation, and the increase in temperature during the winter wheat growing season led to a decline in both simulated potential and rainfed yields at most study stations in SWC, while the decreased diurnal temperature range had both negative and positive effects on potential and rainfed yields, respectively. Quantifying the impacts of light, temperature, and precipitation on wheat production using the APSIM model provides a sound foundation for developing countermeasures to adapt to climate change and improve wheat yield in Southwest China.

Keywords
Winter wheat; APSIM model; Climate change; Climatic factor; Potential yield; Rainfed yield; Stepwise regression; Contribution rate

Introduction

Southwest China is one of China' s important grain production regions. As the third largest grain crop in Southwest China, wheat not only meets local food consumption demand but also provides raw materials for industrial uses such as brewing. The region' s annual wheat planting area and total production account for 11% and 9% of the national totals, respectively [1]. Agriculture is highly dependent on climatic conditions, and climate change significantly affects crop growth and development, pest and disease occurrence, and resource use efficiency. Therefore, quantifying the degree of climate change and its impacts on winter wheat yield in this region is of great significance under global warming. Current methods for assessing climate change impacts on wheat yield mainly include climate simulation experiments in laboratories or fields [2-3], statistical models based on regression relationships between meteorological factors and wheat yield [4], crop potential productivity models [3], and crop growth models. Among these, crop growth models can dynamically simulate crop growth, development, and yield formation processes, and can more accurately express the relationship between crop growth and climate factor changes. These models have become effective tools in agricultural production [5]. Since its introduction to China, the APSIM model has undergone parameter calibration and validation in multiple major crop production regions and has been used to assess climate change impacts on wheat production. Studies in the North China Plain have shown that climate change generally has negative effects on winter wheat yield, with reduced radiation and increased temperature being the main meteorological factors causing yield decline, though these adverse effects can be mitigated or offset through adjustments in sowing date, variety improvement, and improved field management measures [6-11]. In the Loess Plateau of Northwest China, increased temperature shortens the wheat growth period while increasing evapotranspiration from wheat fields, causing water deficits that adversely affect spring wheat yield, though these effects can be alleviated through no-tillage and mulching measures [12-13].

Compared with the major wheat production regions in North and Northwest China, research reports on climate change impacts on wheat yield in Southwest China are scarce [14-15], providing weak theoretical support for local decision-makers. Therefore, this study aims to analyze the spatiotemporal distribution characteristics of potential and rainfed yields of winter wheat in Southwest China from 1961 to 2010 based on a validated APSIM model, quantify the degree of influence of light, temperature, and precipitation resources during the growing season, and provide references for evaluating future climate change impacts on winter wheat production.

Materials and Methods

1.1 Study Area and Data Sources

Southwest China lies between 21°08 -34°19 N and 97°21 -110°11 E, including Sichuan, Yunnan, Guizhou provinces and Chongqing municipality. The terrain slopes from high in the north and west to low in the south and east, featuring diverse landforms including basins, plateaus, plains, mountains, and hills, making it one of the most topographically complex regions in the world. Most of the region is in the subtropical zone with abundant rainfall and favorable heat conditions. The Qinling and Daba mountains block cold wave invasion, resulting in mild winters and long growing seasons. Except for a few high mountains, rice and wheat can be double-cropped, and subtropical perennial plants can be widely cultivated, making it an important agricultural and forestry region in China [16-17].

Daily meteorological data from 1961-2010 for 64 research stations in Sichuan, Yunnan, Guizhou, and Chongqing were obtained from the National Meteorological Information Center of the China Meteorological Administration. Winter wheat growth, development, yield components, and field management data were obtained from agro-meteorological experimental stations. Soil data were referenced from the National Soil Survey (Volume 6) [18]. Based on the characteristics of Southwest China, its agro-climatic features, and local winter wheat sowing periods and growth period lengths, the region was divided into one non-planting area and five planting districts at the county level. The winter wheat planting districts are shown in Figure 1 [Figure 1: see original paper]. Soil types are complex in Southwest China; according to the Chinese soil distribution map, the region' s soils were classified into five types (Table 1).

1.2 APSIM Model Description

The APSIM model is a mechanistic model developed by the Australian Agricultural Production Systems Research Unit (APSRU) to simulate biophysical processes in agricultural production systems. Its distinctive feature is that it considers crop rotation, fallow, and residue management from the perspective of agricultural production systems, and has been widely used in farming system management, climate change impact assessment, climate forecast value evaluation, and climate risk management [19-20].

The core modules of the APSIM model include: a crop module, soil module, and management module. The crop module simulates crop growth, development, and yield formation, with parameters 主要包括作物参数和品种遗传参数. The soil module simulates soil water movement, nutrient transport, and soil erosion, with basic soil water parameters including saturated water content ($\mathrm{mm}^3 \cdot \mathrm{mm}^{3}$), field capacity ($\mathrm{mm}^3 \cdot \mathrm{mm}^{3}$), and wilting coefficient ($\mathrm{mm}^3 \cdot \mathrm{mm}^{3}$) for each soil layer. The management module handles module calls, crop sowing and harvest dates, fertilization and irrigation management settings, and input and output variable configurations.

APSIM is a daily time-step model. Input meteorological data include daily maximum temperature (℃), minimum temperature (℃), precipitation (mm), and total radiation ($\mathrm{MJ} \cdot \mathrm{m}^{2} \cdot \mathrm{d}^{1}$), where total radiation is estimated from sunshine data using the Ångström-Prescott formula [21-22]. Main output variables include key growth stages (emergence, flowering, and maturity), above-ground biomass, and yield.

1.3 Model Parameter Calibration and Validation Methods

This study previously evaluated the adaptability of the APSIM-Wheat model in Chongqing [23]. This paper further expands the evaluation by including additional stations in Southwest China to assess the model' s simulation capability. Model calibration and validation primarily used Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), coefficient of determination (R^2), and index of agreement (D-index) to compare simulated and observed values. Smaller RMSE and NRMSE values and R^2 and D-index values closer to 1 indicate better simulation performance. During the parameter calibration phase, the "trial-and-error method" was used to determine genetic parameters for typical wheat varieties (Table 2). The model' s adaptability in Southwest China was evaluated by comparing absolute and relative errors and consistency between simulated and observed values for growth stages, above-ground biomass, and yield during validation years (Table 3).

1.4 Model Scenario Design

The APSIM model was used to simulate potential and rainfed yields of winter wheat in Southwest China from 1961-2010. Potential yield is defined as the yield determined by light and temperature resources under adequate water conditions, while rainfed yield is the yield determined by natural light, temperature, and precipitation resources under non-irrigated conditions. Both scenarios assumed adequate nitrogen application and no pests or diseases. To study the impact of single-factor climate change, varieties were held constant during the simulation period, with varieties having longer continuous planting years in each district selected as typical varieties, and sowing dates set according to wheat planting zones (Table 2). Sowing density was set at 300 plants • m ^{2}, sowing depth at 5.0 cm, and soil water parameters were input according to soil type (Table 1).

1.5 Contribution Rate of Climate Factors to Yield Changes

Under climate change, the main meteorological factors significantly affecting wheat growth and development are temperature, precipitation, and sunshine [6-10]. Since diurnal temperature range and average temperature together reflect changes and impacts of maximum and minimum temperatures, this paper analyzed the effects of four meteorological factors—radiation, temperature, diurnal temperature range, and precipitation—on wheat yield. Based on stations where APSIM-simulated winter wheat potential and rainfed yields showed significant changes, the stepwise regression method was used to eliminate non-significant factors. Contribution rates were then used to represent the individual impact degree of significant factors among radiation, temperature, diurnal temperature range, and precipitation on yield, with standardized regression coefficients used to compare the effects of different meteorological factors. The contribution rate was calculated as the percentage of the product of the factor’ s change magnitude from 1961-2010 and its partial regression coefficient relative to the total yield change magnitude. Partial regression coefficients from multiple regression analysis represent the rate of change in the dependent variable caused by a change in one independent variable while holding all other variables constant. Standardized regression coefficients are estimated by subtracting the mean and dividing by the standard deviation of variables in linear regression, eliminating errors caused by different magnitudes and units of independent variables [24].

Since the model assumes constant varieties and management practices, simulated rainfed yield approximates actual yield affected only by meteorological conditions. To verify whether the APSIM model could capture the impact of meteorological conditions on yield, agro-meteorological observation stations with longer continuous wheat planting years were selected (Table 8). The 5-year moving average method [4] was used to fit trend yield, from which meteorological yield was extracted from actual winter wheat yield. Climate years were classified as good (>10%), normal (-10% to 10%), and poor (<-10%) based on the meteorological yield change rate (percentage of meteorological yield to trend yield). Meteorological yield change rates were then compared with simulated rainfed yield anomaly change rates (percentage of rainfed yield deviation from average yield) for different year types.

Results

2.1 APSIM Model Parameter Calibration and Validation

The crop genetic parameters determined during the calibration process are shown in Table 2. For the five simulated winter wheat varieties, RMSE values for simulated versus observed days to emergence, flowering, and maturity were within 1.0 d, 7.0 d, and 5.0 d, respectively. NRMSE values for aboveground biomass and yield were below 25% and 21%, respectively (Table 3). These results demonstrate that the APSIM model accurately simulated winter wheat phenology, biomass, and yield, indicating good adaptability in Southwest China.

2.2 Climate Factor Trends During Winter Wheat Growing Season

Climate tendency rates for meteorological elements during the winter wheat growing season in Southwest China from 1961-2010 are shown in Table 4 . Total radiation during the growing season decreased most in District III, while District V showed an increasing trend. Effective accumulated temperature 0 ℃ increased most in District II, followed by District I, with the smallest increase in District III. Diurnal temperature range decreased most significantly in District I, with weaker changes in District III. Total precipitation decreased most in District I, followed by District IV, while District II showed a slight increasing trend.

Across the entire region, 75% of study stations showed decreasing trends in total radiation during the winter wheat growing season, with 48% passing significance tests ($P<0.05$). Decreases were most pronounced in the northern, southeastern, and mid-southern planting areas, with an average regional change rate of -14.3 $MJ \cdot m^{2} \cdot 10a^{1}$. Effective accumulated temperature 0 ℃ showed increasing trends at 95% of stations, with 72% passing significance tests ($P<0.05$). Warming was more significant in western areas, with an average regional warming rate of [value missing in original] $℃ \cdot d \cdot 10a^{1}$. Diurnal temperature range showed decreasing trends at 78% of stations, with 38% passing significance tests, most notably in the mid-southern area, with an average regional change rate of -0.13 $℃ \cdot 10a^{1}$. Total precipitation showed decreasing trends at 69% of stations, though most changes were not significant region-wide, with an average change rate of -4.8 $mm \cdot 10a^{1}$. Spatially, precipitation increased in the northwest but decreased in the southern and southeastern areas (Figure 2 [Figure 2: see original paper]).

2.3 Characteristics of Winter Wheat Potential and Rainfed Yield Changes

Simulated multi-year average values and changing trends of potential and rainfed yields of winter wheat in Southwest China are shown in Table 5 . From 1961-2010, District II had the highest potential yield, followed by District III. After considering precipitation effects, District III had the highest rainfed yield, followed by District II, while District V had the lowest potential and rainfed yields. Potential and rainfed yields decreased most significantly in Districts III and IV, respectively, while Districts I and V showed smaller negative impacts from climate change, with rainfed yields even showing slight increasing trends.

Region-wide, winter wheat potential yield ranged from 2,386 to 10,146 kg · hm^{2}, with a regional mean of 5,697 kg · hm^{2}, showing a spatial pattern of high values in the northwest and low values in the south and east. From 1961-2010, 86% of stations showed decreasing potential yield trends, with 76% showing significant reductions ($P<0.05$), most notably in the northern and mid-southern planting areas, with an average regional yield change rate of -110 kg · hm^{2} · 10a^{1}. Rainfed yield ranged from 2,386 to 8,774 kg · hm^{2}, with a regional mean of 4,605 kg · hm^{2}, showing a spatial pattern of low values in the west and high values in the east. Over the past 50 years, 61% of stations showed decreasing rainfed yield trends, with 41% showing significant reductions ($P<0.05$), most notably in the northeastern planting area, with an average regional yield change rate of -31 kg · hm^{2} · 10a^{1} (Figure 3 [Figure 3: see original paper]). Compared with potential yield, the rainfed yield reduction was smaller.

At 45 stations with significant potential yield changes, the average yield reduction was 723 kg · hm^{2} · 10a^{1}. From 1961-2010, average daily radiation during the growing season decreased by 0.63 MJ · m^{2}, average temperature increased by 1.22 ℃, and average diurnal temperature range decreased by 0.70 ℃, contributing 45%, 36%, and 2% to yield reduction, respectively. Overall, reduced radiation contributed most to potential yield decline, followed by temperature, with diurnal temperature range having the smallest effect. Standardized regression analysis showed that radiation, temperature, and diurnal temperature range significantly affected 98%, 82%, and 11% of the 45 stations, respectively. Reduced radiation and increased temperature both had negative effects on yield, while reduced diurnal temperature range had negative effects at Panxian and Gongshan but positive effects at Wenjiang, Qianxi, and Meitan (Table 6).

At 18 stations with significant rainfed yield changes, the average yield reduction was 529 kg · hm^{2} · 10a^{1}. From 1961-2010, average daily radiation decreased by 0.47 MJ · m^{2}, average temperature increased by 1.11 ℃, total precipitation decreased by 49 mm, and average diurnal temperature range decreased by 0.26 ℃, contributing 36%, 39%, 7%, and -8% to yield reduction, respectively. Unlike potential yield, increased temperature contributed most to rainfed yield decline, followed by radiation and precipitation, with diurnal temperature range having the smallest effect. Standardized regression analysis showed that radiation, temperature, diurnal temperature range, and precipitation significantly affected 83%, 67%, 39%, and 17% of stations, respectively. Reduced radiation and precipitation and increased temperature all had negative effects, while reduced diurnal temperature range had positive effects on yield (Table 7).

Comparison of meteorological yield change rates and simulated rainfed yield anomaly change rates showed that, overall, simulated rainfed yield anomaly change rates were similar to observed meteorological yield change rates. Rainfed yield anomalies were low in poor meteorological yield years and high in good meteorological yield years, with 基本一致 years for extreme values of meteorological and rainfed yields. These results demonstrate that the model accurately reflected the impacts of meteorological factor changes on wheat yield (Table 8).

Discussion and Conclusions

In Chinese model adaptability studies, simulation effects are generally considered acceptable when NRMSE values for yield and biomass are below 30%. For example, Wang et al. [25] reported NRMSE values of 24%-28% for winter wheat-summer maize biomass simulation in Yucheng, Shandong, while Liu [26] reported NRMSE values of 10% and 37% for winter wheat biomass simulation in Luancheng, Hebei and Zhengzhou, Henan. Therefore, compared with previous studies, our results indicate that the APSIM model also has good adaptability in Southwest China. Based on previous research, typical values for wheat variety genetic parameters are: vernalization sensitivity of 1.5-2.9, photoperiod sensitivity of 2.0-3.9, effective accumulated temperature required from grain-filling to maturity of 420-600 ℃·d, and grains per unit dry matter of stem of 23.0-33.0 [4-5,10,27-28]. The four crop genetic parameters determined in this study were 1.5-3.0, 2.0-3.5, 420-800 ℃·d, and 18.0-28.0, respectively, all within reasonable ranges. Compared with the North China Plain, winter wheat varieties in Southwest China tend to be more spring-type.

This study shows that climate change trends during the winter wheat growing season in Southwest China from 1961-2010 were generally consistent with those in major winter wheat production regions such as the North China Plain, middle and lower reaches of the Yangtze River, and Northwest China, showing trends of decreasing radiation, increasing temperature, and decreasing precipitation [6-7,29-30], but with the smallest magnitude of change in Southwest China. The spatial distribution of meteorological factor changes during the winter wheat growing season was similar to that for spring maize, with decreasing radiation concentrated in the mid-southern and eastern areas, warming concentrated in the western area, and decreasing diurnal temperature range mainly in the southern and southeastern areas. However, due to seasonal differences in water and heat resources, the warming magnitude was greater during the winter wheat growing season (October to May), and precipitation reduction was concentrated in the southern and southeastern areas, whereas precipitation reduction during the spring maize growing season was only distributed in a few central stations

[31-34].

Regarding the entire wheat growth period, reduced total radiation decreases crop net photosynthetic rate and grain-filling rate, leading to reduced assimilate accumulation. Therefore, the decline in radiation during the growing season in Southwest China caused significant wheat yield reductions. Increased temperature shortens the crop growth period, reducing dry matter accumulation time and causing yield decline. Precipitation is relatively low during the winter wheat growing season from October to May in Southwest China, and precipitation reduction causes water stress that limits yield. Increased nighttime temperature enhances respiration, which is unfavorable for assimilate accumulation, but increased average temperature that does not exceed the optimum temperature is beneficial for photosynthesis. Therefore, the interaction of these two effects leads to different impacts of reduced diurnal temperature range on yield at different stations. Studies in North China [7,10,29], Northwest China [35], and the Huang-Huai-Hai region [36-37] have also shown that, in recent decades, radiation and precipitation generally had positive effects on winter wheat yield, while temperature had negative effects, with reduced radiation and increased temperature being the main factors causing simulated yield decline, consistent with our conclusions. Climate change in Southwest China shows significant spatial variation. Although radiation decreased in most areas during the wheat growing season, some stations showed increased radiation, leading to increasing trends in both potential and rainfed yields at 14% and 39% of stations, respectively.

Our results show that both simulated potential and rainfed yields of winter wheat showed decreasing trends, indicating that climate change has overall negative impacts on winter wheat yield, consistent with studies in North China [5,8,26,28,38] and Northwest China [35]. However, related studies have shown that variety improvement and improved field management measures such as water and fertilizer application can mitigate or offset the negative impacts of climate change and reduce crop yield risk [6,9,29,39]. For Southwest China, to cope with increasing temperature and decreasing precipitation trends, future production could adopt new high-yield and heat-resistant varieties, use longer-growth-period varieties without affecting the sowing time of subsequent crops, appropriately delay winter wheat sowing dates, and optimize winter wheat irrigation systems.

The APSIM model still has some uncertainties in reflecting actual field crop growth conditions. First, in terms of model parameter determination, although this study divided different winter wheat planting districts and main soil types, considering different agro-climatic characteristics and actual crop growth conditions, the complex climate, terrain, and soil conditions in Southwest China still lack corrections for environmental parameters such as slope and water runoff. Second, the model lacks functions to simulate the effects of pests, diseases, and weeds, and meteorological disasters on crop growth processes, which may introduce potential biases in model validation and application [40]. Third, observed crop growth period and yield data have inaccuracies, and multi-year measured data sequences from different regions may not be independent, leading to errors in comparisons between simulated and observed values based on simple linear regression models [41]. Therefore, future research should strengthen analysis of model error sources and further improve the model.

Additionally, this study only analyzed climate change impacts on winter wheat in Southwest China based on a single model. Previous studies have shown that although individual crop growth models can simulate crop growth, development, and yield formation well within certain ranges, assessment results from single models have uncertainties due to differences in model structure and parameterization processes when evaluating future climate change impacts on wheat production. Multi-model ensembles can reduce uncertainties in climate change impact assessment results [42]. Therefore, future research should integrate multiple crop growth models to assess climate change impacts on winter wheat production in Southwest China.

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