Postprint: DSSAT-Based Simulation of Potential Winter Wheat Yield in the Middle and Lower Reaches of the Yangtze River

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Abstract

To investigate the impacts of climate change on the potential yield of winter wheat in the middle and lower reaches of the Yangtze River, this study utilized daily simulated data of major meteorological elements under various Representative Concentration Pathway (RCP) scenarios (baseline period, RCP 2.6, RCP 4.5, and RCP 8.5) output from the BCC-CSM1-1 (Beijing Climate Center Climate System Model version 1-1) climate system model proposed by the Intergovernmental Panel on Climate Change (IPCC) AR5, along with historical observation data. The DSSAT model was employed to simulate the phenological stages and yield of winter wheat during the historical period (2001-2009), and the root mean square error and consistency index between simulated and observed data were calculated (the relative root mean square errors of flowering, maturity, and yield simulation results were between 0.83%-2.98% and below 7%, respectively, with the agreement index D approaching 1) to determine optimal genetic parameters, which were then applied in validation simulations to complete regionalization of model parameters. By integrating the trends of major meteorological elements in the historical stage (1961-1990) and future period (2021-2050), the DSSAT model was utilized to simulate and analyze the impacts and trends of climate change on wheat yield in the middle and lower reaches of the Yangtze River over the next 30 years, aiming to provide a theoretical basis for future crop production. The results indicated that after localization of the DSSAT-CERES-Wheat cultivar genetic parameters, the model could accurately simulate the growth, development, and yield potential of winter wheat. Compared with the baseline year, under RCP scenarios during 2021-2050, the accumulated temperature 10℃ during the winter wheat growth period showed a gradual increasing trend, except under the RCP 2.6 scenario, with the magnitude of increase being RCP 8.5 > RCP 2.6 > RCP 4.5; interannual precipitation fluctuations were substantial with significant regional differences; total solar radiation decreased compared with the baseline year, but the magnitude of decrease gradually diminished with increasing years, with change rates showing significant or extremely significant increasing trends. Except for Kunshan, the flowering and maturity stages of winter wheat were advanced compared with the baseline year, with the days from flowering to maturity consequently shortened. When considering only climatic conditions, the yield potential of winter wheat in the middle and lower reaches of the Yangtze River decreased compared with the baseline year, with the decline magnitude in Kunshan and Yingshan being greater than that in Chuzhou and Zhongxiang (3%-59%), and regional differences were significant. Analysis revealed that within a certain range, winter wheat yield gradually increased with increasing accumulated temperature, but decreased when exceeding a certain threshold, and increases or decreases in other climatic factors could not compensate for the negative effects of excessively low accumulated temperature.

Full Text

Simulation of Winter Wheat Potential Yield in the Middle and Lower Reaches of the Yangtze River Based on the DSSAT Model

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Abstract

This study investigated the impacts of climate change on winter wheat potential yield in the middle and lower reaches of the Yangtze River. Using daily meteorological simulation data from the BCC-CSM1-1 climate system model under different RCP scenarios (baseline, RCP 2.6, RCP 4.5, and RCP 8.5) from the IPCC AR5, combined with historical observation data, the DSSAT-GLUE module was employed to optimize parameters and validate model performance for winter wheat phenology and yield during the historical period (2001–2009). Model performance was evaluated using normalized root mean square error (NRMSE) and consistency index (D). After parameter optimization, the NRMSE for flowering and maturity duration ranged from 0.83% to 2.98%, while yield NRMSE remained below 7%, with D values approaching 1, indicating high accuracy. The calibrated model was then applied to simulate winter wheat phenology and yield trends for the future period (2021–2050).

Results showed that under RCP 2.6, accumulated temperature (>10℃) decreased significantly compared to baseline, but increased under RCP 4.5 and RCP 8.5 scenarios. Precipitation exhibited large interannual fluctuations with obvious regional differences, while total solar radiation decreased in all three RCP scenarios, with the reduction rate diminishing over time. When considering only climate factors (excluding CO concentration effects, variety substitution, soil changes, and management optimization), winter wheat flowering and maturity stages were advanced in most regions (except Kunshan), shortening the grain-filling period. Potential yields declined across all scenarios, with reduction magnitudes varying regionally: Kunshan and Yingshan showed greater declines than Chuzhou and Zhongxiang (3%-59%). Under RCP 2.6, despite the smallest reduction in solar radiation, yield declined most severely due to accumulated temperature limitations, demonstrating that solar radiation increases could not compensate for low temperature effects. Yield initially increased with accumulated temperature up to a threshold, beyond which it decreased. Excessive temperatures delayed phenology, prolonging vegetative growth, inhibiting reproductive development, increasing tillering, and reducing spike rates, ultimately lowering yields. These findings provide a theoretical basis for future crop production adaptation strategies.

Keywords: winter wheat; potential yield; DSSAT; RCP (Representative Concentration Pathway); middle and lower reaches of the Yangtze River

Introduction

Climate change has become a focal issue for scholars worldwide, with impacts across all sectors that cannot be ignored. The IPCC Fifth Assessment Report Working Group I confirms that global warming is an undeniable fact, resulting from both natural and anthropogenic factors. The climate system has undergone unprecedented changes, with nearly all regions experiencing warming. Global average temperature increased by 0.65-1.06°C between 1880-2012, and surface temperatures are projected to continue rising. Agriculture is particularly sensitive to climate change, and as a major agricultural country, China’ s food security faces significant threats from climate change.

Wheat is a major global food crop, and the middle-lower Yangtze winter wheat region is one of China’ s principal production areas. Climate change will significantly alter regional climate and agro-climatic resources, causing crop yield fluctuations. Temperature shows an increasing trend, with RCP 8.5 scenario showing particularly significant warming. The middle-lower Yangtze region exhibits the largest reduction in annual sunshine hours nationally. Annual precipitation shows a significant increasing trend, but the proportion of spring and autumn rainfall to annual totals is decreasing. Future climate production potential for winter wheat is projected to increase, but changing climate conditions will significantly affect crop growth, development, and yield formation, potentially altering cropping patterns, systems, and agricultural techniques, thereby increasing production instability.

The combination of future climate scenarios with crop dynamic growth models has become an important method for assessing climate change impacts on agriculture. DSSAT (Decision Support System for Agrotechnology Transfer) is a widely used crop model system that integrates data, analysis, and tool modules, providing computational methods to systematically predict future crop yields and analyze influencing factors. DSSAT simplifies agro-ecosystem research while offering valuable tools for future agricultural decision-making. The model has been widely applied to simulate crop yields under climate change and disaster stress, develop adaptation strategies, optimize irrigation scheduling, and determine optimal fertilization rates.

Previous studies using DSSAT-CERES-Wheat have shown that climate change accelerates wheat development, shortens growth periods, and reduces grain yield. Research indicates that developing new wheat varieties with more grains per spike is crucial for mitigating climate change impacts. Studies in the U.S. and Canada demonstrate that while CO increases can enhance photosynthesis and yield by 30–40% under optimal temperatures, yield declines occur under combined temperature and precipitation changes. Most existing research focuses on historical periods or national/旱作 (dryland) regions, with few studies quantitatively describing future wheat yield potential and underlying meteorological mechanisms in the middle-lower Yangtze region using crop models combined with future climate scenarios.

This study addresses this gap by using DSSAT-GLUE to calibrate and validate crop genetic parameters, then simulating winter wheat potential yields for 2021–2050 under three RCP scenarios (RCP 2.6, RCP 4.5, RCP 8.5) using downscaled daily meteorological data. The objectives are to characterize potential yield changes, evaluate climate change impacts, and provide scientific basis for adaptation strategies.

1. Study Area

The middle-lower Yangtze winter wheat region is a major Chinese wheat production area, bounded by the Qinling-Huaihe River and Huang-Huai winter wheat region to the north, adjacent to the Wuyi Mountains and South China winter wheat region to the south, extending to the East China Sea coast (27°33 -34°9 N, 110°49 -122°30 E). The region features diverse topography with low mountains, hills, and plains, including the Jianghan Plain, Poyang and Dongting Lake plains, Taihu Plain, and coastal plains. With a north subtropical monsoon climate, the region has abundant heat resources (annual mean temperature 14–18°C), 210–270 frost-free days, and 2000–2200°C accumulated temperature during the wheat growth period. Precipitation ranges 340–960 mm, solar radiation 193–226 kJ/cm^2, with a predominantly rice-wheat rotation system. The suitable sowing period is mid-to-late October, with maturity in late May to early June in the north.

2. Data and Methods

2.1 Meteorological Data

Meteorological simulation data were obtained from the National Meteorological Administration' s BCC-CSM1-1 model, including daily gridded data (0.5° × 0.5°) for baseline (1961–2010) and future (2021–2050) periods under RCP 2.6, RCP 4.5, and RCP 8.5 scenarios. The dataset includes precipitation (mm), maximum temperature (°C), minimum temperature (°C), and sunshine hours (h). Sunshine hours were converted to total solar radiation using the internationally recognized empirical formula:

[Figure 1: see original paper] Location of typical stations in the middle and lower Yangtze River Basin

$$Q = Q_0(a + b\frac{n}{N})$$

where Q is daily total radiation, Q is daily astronomical radiation, a and b are empirical coefficients (0.15 and 0.65 for the middle-lower Yangtze region), n is sunshine hours, and N is maximum possible sunshine duration.

Historical meteorological observations were obtained from the China Meteorological Data Network (http://data.cma.cn/). Four representative stations (Kunshan, Chuzhou, Yingshan, Zhongxiang) were selected based on: (1) even distribution across the study area, (2) regional representativeness, and (3) complete management records.

2.2 Soil Data

Soil data were obtained from the Chinese Soil Database (http://vdb3.soil.csdb.cn/), including soil type, physical and chemical properties, clay percentage, organic matter content, cation exchange capacity, and soil water retention characteristics for each layer.

2.3 Crop Management Data

Local main cultivars were selected as research objects. Sowing dates, irrigation amounts/methods, and fertilization types/rates were collected for representative stations.

2.4 Crop Model

DSSAT (Decision Support System for Agrotechnology Transfer) version 4.6 is a widely used dynamic crop growth model that simulates crop development and yield based on meteorological, genetic, soil, and management data. The model includes integrated data, analysis, and tool modules for seasonal, rotation, and spatial analysis. While not yet fully operational for production, DSSAT offers broad application prospects for simplifying agro-ecosystem research and supporting agricultural decision-making.

2.5 Genetic Parameter Calibration

Model parameter localization is critical for simulation accuracy. The DSSAT-GLUE (Generalized Likelihood Uncertainty Estimation) module was used to calibrate winter wheat genetic parameters. A three-round calibration process was applied: (1) initial parameter estimation, (2) phenological parameter estimation, and (3) growth parameter estimation. Model performance was evaluated using:

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

$$NRMSE = \frac{RMSE}{\overline{obs}} \times 100\%$$

$$D = 1 - \frac{\sum_{i=1}^{n}(sim_i - obs_i)^2}{\sum_{i=1}^{n}(|sim_i - \overline{obs}| + |obs_i - \overline{obs}|)^2}$$

where sim and obs are simulated and observed values, n is sample size, and $\overline{obs}$ is the mean observation. NRMSE < 10% indicates excellent fit, 10-20% good, 20-30% moderate, and >30% poor. D ranges 0-1, with values closer to 1 indicating better consistency.

3. Results

3.1 Parameter Calibration and Validation

Using observed data from typical stations (2001-2009), genetic parameters were calibrated for local varieties (Yangmai, Emain, Emai). After calibration, NRMSE for flowering and maturity dates ranged 0.83%-2.98%, and yield NRMSE was below 7% (Table 1). Consistency index D approached 1, indicating high accuracy. Validation using independent years showed NRMSE of 0.57%-2.81% for phenology and 4.68%-9.99% for yield, confirming the calibrated parameters reliably simulate local variety characteristics.

Comparison of observed and simulated values for variety parameters, anthesis stage, maturity stage, and yield of winter wheat at four selected stations

[Figure 2: see original paper] Comparison of observed and simulated values for flowering duration, maturity duration, and yield of winter wheat varieties

3.2 Future Climate Element Changes

Under future RCP scenarios, accumulated temperature (>10°C), precipitation, and solar radiation showed distinct trends compared to baseline (1961-1990). In RCP 2.6, accumulated temperature decreased significantly (-12% to -34%), while RCP 4.5 and RCP 8.5 showed increasing trends, with RCP 8.5 > RCP 4.5. Precipitation exhibited large interannual fluctuations with no significant trend. Solar radiation decreased in all scenarios, with reduction rates diminishing over time (40%-52% in early years, decreasing later).

Main meteorological elements and their variation rates under future RCP scenarios at each station

[Figure 3: see original paper] Variations of main meteorological elements under three RCP scenarios over the middle and lower Yangtze River during 2021-2050 compared with baseline

3.3 Future Phenology Changes

Simulated flowering and maturity dates for 2021-2050 showed advanced phenology under most scenarios (Table 3, Table 4). Baseline flowering occurred at day-of-year 157-216 and maturity at 190-244. Under RCP scenarios, most sites showed 2-13 days advancement in flowering and 3-36 days in maturity, except Kunshan where phenology was delayed. The flowering-to-maturity period shortened by 3-12 days across scenarios.

Changes in winter wheat flowering duration under future climate scenarios compared with baseline

Changes in winter wheat maturity duration under future climate scenarios compared with baseline

3.4 Future Yield Changes

Under future RCP scenarios, winter wheat potential yield showed declining trends across all four typical stations (Figure 4). Yield reduction magnitudes followed the order RCP 2.6 > RCP 8.5 > RCP 4.5, with regional differences: Yingshan showed greater declines than Chuzhou and Zhongxiang (3%-59%). Under RCP 2.6, despite the smallest solar radiation reduction, yield declined most severely due to accumulated temperature limitations, demonstrating that radiation increases could not compensate for low temperature effects. When accumulated temperature was consistent, yield reduction decreased as solar radiation reduction increased.

[Figure 4: see original paper] Changes in winter wheat potential yields under future RCP scenarios (2021-2050) compared with baseline

4. Discussion

The middle-lower Yangtze region has relatively high temperatures and low solar radiation totals. Most areas lack irrigation habits, as precipitation meets crop water demand. Under future scenarios, precipitation changes are not significant, so its impact on yield is minor. Accumulated temperature and solar radiation are the main factors affecting yield changes.

Winter wheat is a low-temperature, long-day crop requiring vernalization. Excessive temperatures during the vernalization stage delay phenology, prolong vegetative growth, and inhibit reproductive development, resulting in excessive tillering, reduced spike rates, and lower yields. While CO fertilization effects can enhance photosynthesis, the model simulations excluding CO effects show that temperature and radiation changes alone reduce yield potential.

The DSSAT-CERES-Wheat model has been widely validated internationally and showed good performance in this study. However, it contains simplified processes and semi-empirical parameters, and does not adequately account for disasters like waterlogging and extreme weather. Future research should incorporate multi-factor interactions, extend experimental duration, and include greenhouse gas effects to improve simulation realism.

5. Conclusions

1. After genetic parameter calibration, simulated flowering, maturity, and yield showed NRMSE of 0.83%-2.98% and consistency index D approaching 1, indicating high parameter accuracy and reliable simulation capability.
2. During 2021-2050, accumulated temperature (>10°C) will increase gradually with rates following RCP 8.5 > RCP 2.6 > RCP 4.5. Precipitation will show large interannual fluctuations with no significant trend. Solar radiation will decrease compared to baseline, with reduction rates diminishing over time.
3. DSSAT-CERES-Wheat simulations show that except for Kunshan, flowering and maturity dates will advance compared to baseline, shortening the grain-filling period. The advancement magnitude follows RCP 8.5 > RCP 4.5 > RCP 2.6.
4. Considering only climate resource changes, winter wheat potential yield in the middle-lower Yangtze region will decrease compared to baseline, with greater reductions in Yingshan than Chuzhou and Zhongxiang. Other climate factors cannot compensate for negative effects of low accumulated temperature. Yield initially increases with accumulated temperature up to a threshold, then decreases. Excessive temperatures delay maturity, block reproductive growth, reduce spike rates, and lower yields.

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