Analysis of Optimal Sowing Dates for Winter Wheat over the Next 40 Years Based on the DSSAT CERES-Wheat Model (Postprint)

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Date: 2023-02-17T00:00:00+00:00

Abstract

Sowing within the suitable sowing window is a key management technique for promoting high and stable wheat yields. To mitigate adverse impacts of future climate change and improve winter wheat yields in major high-yield and high-quality production regions, this study selected the Huang-Huai-Hai and Jianghuai regions as the study area, choosing three representative stations within it. Using the DSSAT CERES-Wheat model, simulation experiments were conducted for the baseline period and the subsequent 40 years under four Representative Concentration Pathway (RCP) greenhouse gas emission scenarios with 51 sowing date treatments, aiming to characterize climate factor changes and optimal sowing period variations during future winter wheat growth periods, and to quantitatively analyze yield enhancement effects of optimal sowing period management. Analysis of experimental results indicates that: climate characteristics during future winter wheat growth periods show a warming and drying trend; growth period duration decreases with temperature rise, with the reduction incrementing from north to south across the study area; optimal sowing period delays with temperature increase and, under all periods and scenarios, delays with decreasing latitude; compared with the baseline period, maximum delay days of optimal sowing period at the three stations during the 2030s increase incrementally by 5 d, 8 d, and 13 d from north to south, respectively, and optimal sowing period in the 2050s is delayed to varying degrees compared with the 2030s, with the greatest delays under the RCP8.5 scenario in the 2050s at each station; adopting optimal sowing period management produces varying yield enhancement effects at all three stations, with the smallest effect in the northern Huang-Huai-Hai region, and relatively higher yield increase magnitudes in the southern Huang-Huai-Hai region and Jianghuai region, concentrated between 2% and 4%. Therefore, the Huang-Huai-Hai and Jianghuai regions can adopt management measures of delaying sowing dates and selecting suitable sowing

windows to cope with climate warming and improve winter wheat yields in the future.

Full Text

Optimum Sowing Date Analysis for Winter Wheat in the Next 40 Years Based on the DSSAT CERES-Wheat Model

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Abstract: Planting within the suitable sowing window is a key management practice for promoting high and stable wheat yields. To address the adverse effects of future climate change and improve winter wheat productivity in major high-yield and high-quality wheat-producing regions, this study selected the Huang-Huai-Hai and Jiang-Huai regions as the study area and chose representative stations within these regions. Using the DSSAT CERES-Wheat model, we conducted simulation experiments with 51 sowing date treatments under the baseline period and future 40-year period across four Representative Concentration Pathway (RCP) greenhouse gas emission scenarios. The objectives were to characterize changes in climate variables during the winter wheat growth period and identify optimal sowing dates, and to quantitatively analyze the yield benefits of adopting optimal sowing date management practices. The results demonstrate that future climate during the winter wheat growth period will exhibit a warming and drying trend. The number of days in the winter wheat growth period will decrease with rising temperatures, with the reduction increasing progressively from north to south across the study area. The optimal sowing date will be delayed as temperatures increase, showing a consistent pattern of later sowing with decreasing latitude across all periods and scenarios. Compared with the baseline period, the maximum delay in optimal sowing date during the 2030s increases from north to south. The optimal sowing dates in the 2050s are delayed to varying degrees compared with those in the 2030s, with the greatest delays occurring under the RCP8.5 scenario at each station. Implementing optimal sowing date management practices produces yield increases at all three stations, with the smallest effect in northern Huang-Huai-Hai region and relatively larger increases in southern Huang-Huai-Hai and Jiang-Huai regions, concentrated between 2% and 4%. Therefore, delayed sowing and selection of optimal sowing windows represent effective management strategies for the Huang-Huai-Hai and Jiang-Huai regions to cope with climate warming and improve winter wheat yields.

Keywords: winter wheat; optimum sowing date; climate change; RCPs; crop model; Huang-Huai-Hai; Jiang-Huai

Wheat is one of the most widely cultivated food crops worldwide. In China, wheat serves not only as a major staple food crop but also as an important commodity grain and strategic reserve grain, occupying a prominent position in national food security. As the regional production pattern of wheat has evolved, the Huang-Huai-Hai and Jiang-Huai winter wheat regions have become increasingly important as China' s main wheat-producing and advantageous areas, gradually emerging as high-quality wheat production zones. Statistical data show that in 2014, the total winter wheat production and planting area in the Huang-Huai-Hai and Jiang-Huai regions accounted for 88% and 83% of the national totals, respectively, highlighting their crucial role in China' s wheat production.

Since the Industrial Revolution, global average surface temperature has risen by 0.61°C compared with a century ago. Climate change and meteorological disasters have slowed the rate of agricultural productivity improvement, presenting a dual challenge for food crop production to meet population growth and ensure food security. Consequently, research on climate change impacts on crops has become a focal point, with studies on wheat impacts being among the most comprehensive in this field.

Adjusting sowing dates represents one of the most widely adopted measures globally to adapt to climate change. Olesen et al. found that European farmers have actively adapted to climate change by altering planting times over the past decades. Ruiz-Ramos et al. used crop models to simulate various adaptation measures at a single wheat planting site in Spain, concluding that the single adaptation measure of advancing sowing dates held high adaptation potential. In Australia, wheat yields can be increased simply by adopting earlier sowing adaptation measures. In China, however, delayed sowing has been the beneficial adaptation measure for wheat over the past 60 years. Thus, appropriate wheat sowing date adjustment strategies vary significantly across regions. Additionally, research indicates that rising temperatures shorten the wheat growth period and reduce yields. Timely sowing of winter wheat promotes growth and development throughout the entire growth period, ensures robust seedlings, and lays the foundation for high and stable yields. Increased pre-winter temperatures can cause excessive pre-winter growth in winter wheat, making it vulnerable to cold damage and affecting yields. Selecting appropriate sowing dates can mitigate risks from meteorological disasters.

Previous research on optimal sowing dates has primarily relied on field experiments, meteorological statistical analysis, and crop model simulation. Field experiment studies are often limited to 1-2 years due to large experimental workloads and long cycles. Some researchers have used statistical relationships between wheat and meteorological elements to calculate suitable sowing dates based on long-term historical meteorological observation data. Crop models serve as important tools for climate change impact assessment, enabling simulation of crop growth and development over the past 30 years to screen suitable adaptation measures. Crop models can effectively overcome limitations of field experiments and statistical analysis methods, making them applicable for studying the response relationship between different sowing date management practices and yield.

This study aims to address the adverse effects of future climate change and improve wheat yields in the Huang-Huai-Hai and Jiang-Huai regions by screening optimal sowing date management practices. Using the DSSAT CERES-Wheat model, we simulated and identified optimal sowing dates for high-yield winter wheat in the Huang-Huai-Hai and Jiang-Huai winter wheat regions over the next 40 years (2021-2060) under different RCP climate scenarios, providing theoretical basis and scientific reference for high and stable yields of winter wheat in these regions.

2. Data and Methods

2.1 Study Area and Data Sources

This study selected three winter wheat agrometeorological experimental stations representing the northern Huang-Huai-Hai, southern Huang-Huai-Hai, and Jiang-Huai wheat planting regions: Dingzhou in Hebei (HBDZ), Zhengzhou in Henan (HNZZ), and Macheng in Hubei (HBMC). These stations exhibit distinct geographic and climatic differences and possess complete field experiment data required for model input [Figure 1: see original paper].

Historical meteorological data for the study stations were obtained from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), including daily maximum temperature, minimum temperature, precipitation, and sunshine hours from 2005–2009. Solar radiation values were calculated from sunshine hours. Winter wheat field experiment data for the same period, including crop varieties, key growth stages, yield and its components, and agronomic management measures, were also obtained from the China Meteorological Data Sharing Service System. Farmland management measures at the agrometeorological stations were essentially the same as those used by local farmers. Soil texture, organic carbon, bulk density, field capacity, and other attribute data were derived from the 1:1 million Harmonized World Soil Database (HWSD) constructed by the International Institute for Applied Systems Analysis (IIASA). Future climate scenario data based on RCPs were obtained from the HadGEM2-ES global environmental model of the UK Met Office Hadley Centre, which participated in the Inter-Sectoral Impact Model Intercomparison Project. The RCP scenarios include low greenhouse gas emission scenario (RCP2.6), medium greenhouse gas emission scenarios

(RCP4.5, RCP6.0), and high greenhouse gas emission scenario (RCP8.5). The scenario data include daily maximum temperature, minimum temperature, precipitation, and solar radiation from 1984-2060, which were bias-corrected using the equidistant cumulative distribution function method.

2.2 DSSAT Model and Validation

The Decision Support System for Agrotechnology Transfer (DSSAT) is a widely used crop growth simulation model with over 30 years of application history. The latest version of the DSSAT model (v4.7.5) encompasses dynamic growth simulation models for 42 crops. This study employed the wheat model (CERES-Wheat) from DSSAT version 4.7.5 (https://dssat.net/) for simulation analysis. Required model inputs include the daily weather data, crop field experiment data, soil data, and crop variety parameters mentioned above. Model parameter estimation utilized the GenCalcV2.0 variety parameter estimation module in the model to calibrate and validate six winter wheat parameter values for each representative station. The variety parameters are: vernalization characteristic parameter (P1V, d); photoperiod parameter (P1D, %); grain filling duration accumulated temperature (P5, °C·d); grain number per unit canopy weight at anthesis (G1, grains/g); standard kernel weight under non-stressed conditions (G2, mg); total above-ground biomass per plant under non-stressed conditions at maturity (G3, g); and phyllochron interval (PHINT, °C·d).

2.3 Model Performance Evaluation Metrics

The accuracy of DSSAT model simulations for winter wheat growth period and yield in the study area was tested by comparing simulated and observed results using various statistical indicators. Statistical metrics include the coefficient of determination (R^2), normalized root mean square error (NRMSE), and index of agreement (D). The calculation formulas are as follows:

$$\mathrm{NRMSE} = [\sqrt{(\Sigma(S - O)^2/n)}] / \bar{O} \times 100\% \quad (1)$$

$$D = 1 - [\Sigma|S - O| / \Sigma(|S - \bar{O}| + |O - \bar{O}|)]$$

Where S and O are simulated and observed values, respectively; $\bar{O}$ is the mean of observed values; and n is the sample size. NRMSE values below 10% indicate small relative error between simulated and observed values and high simulation accuracy; values between 10% and 20% indicate good simulation performance; values between 20% and 30% indicate fair simulation performance; and values above 30% indicate poor simulation performance. R^2 and D values closer to 1 indicate higher consistency between simulated and observed values and better simulation performance.

2.4 Model Simulation Experimental Design and Optimum Sowing Date Identification

Using the calibrated and validated DSSAT model, we simulated and analyzed changes in optimal sowing dates for winter wheat at each representative station under different climate scenarios and the response of yield to sowing dates. The simulation experiment was designed with 51 sowing date treatments at 1-day intervals based on observed sowing date data from the three stations. Specifically, sowing dates were set between September 21 and November 10 for Dingzhou in Hebei, between October 1 and November 20 for Zhengzhou in Henan, and between October 11 and November 30 for Macheng in Hubei. Simulations were conducted for three periods: the baseline period (1985–2004), the 2030s (2021–2040), and the 2050s (2041–2060). Each period was simulated under four RCP scenarios. Each station ran 12,240 simulations (51 sowing date treatments × 4 RCP scenarios × 60 years). Crop varieties and water-fertilizer management levels in the simulation experiments were based on observations from each station, and the experiments considered the CO_2 fertilization effect.

Optimum sowing dates were identified by calculating the average yield under different sowing date treatments for each period and extracting the sowing date corresponding to the highest yield value.

3. Results and Analysis

3.1 DSSAT-CERES-Wheat Model Parameter Calibration

Using crop field experiment data, soil data, and daily weather observation data from meteorological stations concurrent with the field experiments, the DSSAT-CERES-Wheat model was calibrated and validated for the study area. Parameters were adjusted to make simulated values as close as possible to observed values, thereby achieving model localization. Model validation compared simulated and observed values for three aspects: anthesis date (sowing to anthesis), maturity date (sowing to maturity), and yield [Figure 2: see original paper]. The differences between simulated and observed growth stages were all less than 3 days. The relative errors for anthesis and maturity dates were 1.9% and 0.8%, respectively, with D-index values close to 1. The simulated and observed yield values also showed high agreement, with a relative error of less than 10% (6.8%) and D-index values greater than 0.9, though slightly lower than those for growth period simulation. These results demonstrate that the DSSAT model can reliably simulate winter wheat growth period and yield in the study area.

3.2 Climate Variables and Wheat Growth Period Characteristics

Based on simulation results, we extracted average temperature, total precipitation, and full growth period length during the winter wheat growth period under different sowing date treatments to analyze changes in the 2030s and 2050s relative to the baseline period. All values represent multi-year averages.

As shown in Table 1 , average temperatures during the winter wheat growth stage show an upward trend in the future. The temperature increase in the 2030s is mostly below 1°C, while the increase in the 2050s is greater than in the 2030s, with all RCP scenarios showing increases above 1°C. The temperature increase under RCP8.5 at the Dingzhou station exceeds 2°C. Total precipitation during the full growth period generally shows a decreasing trend. The precipitation reduction at the Macheng station in the 2050s is significantly greater than in the 2030s, while the differences between the two future periods are relatively small at the other two stations.

The full growth period of winter wheat is shortened in both future periods compared with the baseline period, with greater reductions in the 2050s than in the 2030s, and the reduction increasing progressively from north to south. Among the three stations, Macheng in Hubei shows the largest difference in growth period days between the 2030s and 2050s, with the 2050s period under RCP8.5 having 6–12 fewer days than the 2030s. Dingzhou in Hebei shows the smallest difference in growth period days between the two future periods.

3.3 Optimum Sowing Date Characteristics

Comparative analysis of optimum sowing dates for the crop model baseline period and four RCP scenarios in the 2030s and 2050s reveals significant differences among the three stations, showing a progressively later trend from north to south [Figure 3: see original paper]. In the 2030s, the optimum sowing date for Dingzhou ranges from September 21 to September 24, 2–5 days later than the baseline optimum of September 19. For Zhengzhou, the optimum sowing date ranges from October 11 to October 17, 6–8 days later than the baseline optimum of October 5. For Macheng, the optimum sowing date ranges from November 1 to November 6, 3–13 days later than the baseline optimum of October 19. The suitable sowing periods at Dingzhou and Zhengzhou in the Huang-Huai-Hai region show relatively small differences among RCP scenarios, while Macheng in the Jiang-Huai region shows larger differences among scenarios.

In the 2050s, the optimum sowing date for Dingzhou ranges from September 26 to October 13, for Zhengzhou from October 10 to October 17, and for Macheng from October 22 to November 2. The delays relative to baseline are most pronounced under the RCP8.5 scenario.

The full growth period of winter wheat is shortened in both future periods compared with the baseline, with greater reductions in the 2050s than in the 2030s, increasing from north to south. Macheng shows the largest difference between the 2030s and 2050s, with the 2050s under RCP8.5 having 6–12 fewer days than the 2030s, while Dingzhou shows the smallest difference between the two future periods.

3.4 Yield Increase from Optimum Sowing Dates

To quantify yield benefits, we extracted simulated yield values for the 2030s and 2050s using the baseline period optimum sowing dates (representing future production without sowing date adjustment) and compared them with simulated yields using the period-specific optimum sowing dates. This comparison yielded the yield increase amplitude from adopting optimum sowing date management under different RCP scenarios at each station in the two future periods [Figure 4: see original paper].

The yield increase amplitude in the 2050s is generally higher than in the 2030s. Among the three stations, Dingzhou in northern Huang-Huai-Hai shows the smallest increase, ranging from 0.15% to 0.7% in the 2030s. In the 2050s, all scenarios except RCP2.6 show higher increases than in the 2030s, with the highest increase reaching 1.98% under RCP8.5. For Zhengzhou in Henan, the 2050s yield increases are 3.12%, 2.39%, 3.17%, and 3.93% across scenarios, representing increases of 0.22% to 1.52% over the 2030s. For Macheng in Hubei, the 2050s yield increases under RCP2.6 and RCP4.5 are relatively high at 4.74% and 3.57%, respectively, significantly higher than the 2030s values. Under RCP6.0 and RCP8.5, the opposite pattern occurs, but differences between the 2030s and 2050s are small, ranging from 1.8% to 2.7%.

DSSAT crop models have been widely applied in China to assess climate change impacts and management effects on crop growth and yield. This study used the model to evaluate how changes in sowing date management under climate change affect wheat growth period and yield, thereby identifying optimal sowing dates. Conventional field experiment methods are limited by climate conditions, experimental design, and resource constraints, making it difficult to adequately reflect long-term climate change impacts on sowing dates. Meteorological statistical analysis methods lack consideration of actual crop physiological characteristics and can only identify potential long-term sowing date changes based on extensive climate data. Crop mechanism models can account for crop physiological and ecological effects while meeting temporal requirements for climate change impact assessment.

Changes in sowing dates alter the wheat growth period, resulting in differences in utilization of light, heat, and water resources during the growth period. Sowing at inappropriate times may exacerbate abiotic stress on crops. Research indicates that rising pre-winter temperatures favor delayed sowing of winter wheat, which can reduce adverse effects from early spring freezing damage. Wang et al. used the DSSAT model to assess winter wheat sowing dates and found that delayed sowing could mitigate negative climate impacts and improve yields. Ding et al. used the Root Zone Water Quality Model to demonstrate that delayed wheat sowing promotes nitrogen uptake and increases crop yield. Therefore, selecting optimal sowing dates can effectively improve winter wheat yield and reduce negative climate change impacts.

Global average temperature is projected to increase by 1.5°C and 2°C in the

2030s and 2050s under RCP2.6 and RCP4.5 scenarios, respectively, relative to pre-industrial levels. The temperature increase values during the winter wheat growth period at the three stations were added to the 0.61°C increase already observed from pre-industrial to baseline periods to obtain total warming relative to pre-industrial levels. Table 1 shows that future climate during the winter wheat growth period at the three stations will consistently exhibit warming and drying trends, with average temperature increases of 0.5°C to 2.3°C. The lowest temperature increases of 1.41°C in the 2030s under RCP2.6 and 1.91°C in the 2050s under RCP4.5 are consistent with many studies focusing on these warming levels. However, since the global community has not reached consensus on the 1.5°C warming target, this study adopted four RCP scenarios to comprehensively present potential future impacts. The model simulation analysis was conducted at three representative stations, and while the results cannot fully reflect regional patterns due to data limitations, spatial differences among stations were maximized to improve representativeness. Additionally, this study used climate scenario data from a single climate model and a single crop model, which introduces some uncertainty from not accounting for differences among climate models and crop models. These limitations should be addressed in future research to reduce uncertainty.

This study employed the DSSAT model to investigate optimal sowing dates for winter wheat in China’ s main production regions, including northern and southern Huang-Huai-Hai and Jiang-Huai areas. Three representative stations were selected, and climate observation data from agrometeorological stations, HadGEM2-ES global environmental model RCP scenario data, crop data, and soil data were used to validate the applicability of the DSSAT CERES-Wheat model in the study area. A simulation experiment with 51 sowing date treatments was conducted to assess climate change characteristics under different RCP scenarios and their impacts on suitable sowing dates for winter wheat.

The optimal sowing date for winter wheat in the baseline period, 2030s, and 2050s shows a consistent pattern of later sowing with decreasing latitude. Among the three stations, Zhengzhou shows the smallest adjustment magnitude, with optimal sowing dates shifting from mid-October in the baseline period to early-to-mid October in the 2030s and mid-to-late October in the 2050s. Dingzhou’ s optimal sowing date shifts from mid-to-late September in the baseline to late September in the 2030s and early October in the 2050s. Macheng’ s optimal sowing date shifts from mid-to-late October in the baseline to late October in the 2030s and early November in the 2050s. The RCP8.5 scenario shows the greatest delays across all stations. Yield improvements from optimal sowing date adoption vary considerably among stations, with minimal increases in Dingzhou in northern Huang-Huai-Hai, while Zhengzhou in southern Huang-Huai-Hai and Macheng in Jiang-Huai show significant yield increases of 2%–4%.

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