Impacts of Climate Change During Main Growth Periods on Winter Wheat Growth and Yield in Henan Province: Postprint

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Abstract

To analyze the impacts of climate change during different growth stages on winter wheat growth and yield, this study selected meteorological data from 30 agrometeorological observation stations in Henan Province from 1961-2014, together with winter wheat developmental period and yield data from 1981-2014. Using a combined method of mathematical statistics and DSSAT-CERES Wheat model simulation, we analyzed the characteristics of climate change during three periods—sowing-regreening, regreening-heading, and heading-maturity—and their effects on growth duration and yield. The results showed that the prominent feature of climate change in the study area was a significant decrease in sunshine hours during the sowing-regreening period at a rate of 40.09 h · (10a) 1 ($P<0.05$), while both average daily maximum and minimum temperatures increased substantially during the regreening-heading period. Winter wheat spikelet differentiation ended progressively earlier with increasing pre-heading daily minimum temperature at a rate of 2.9 d · (10a) 1. Climate change before regreening exerted sustained influences on subsequent developmental processes, with meteorological factors being predominantly negatively correlated with the duration of sowing-heading and sowing-maturity periods. Both analytical methods indicated that climate change during the sowing-regreening period currently has minimal impact on yield in the Henan wheat region, even demonstrating a yield-enhancing effect within certain ranges, with an average contribution rate of meteorological factors of 0.758. Climate change during the regreening-heading period reduced spike density and grains per spike by an average of 2.74% and 3.94%, respectively, which was greater than that during the heading-maturity period. Under climate change scenarios during different growth stages, both high yield and yield stability of winter wheat were affected, with representative stations showing average yield reductions of 1.6%, 6.3%, and 4.8% during the sowing-regreening, regreening-heading, and heading-maturity periods, respectively. The key meteorological factors affecting yield were daily maximum temperature during the sowing-regreening and heading-maturity periods, and daily minimum temperature during the regreening-heading period.

Full Text

Preamble

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Effect of Climate Change on Growth and Yield of Winter Wheat in Henan Province During Key Growth Periods*

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Abstract: To analyze the impacts of climate change on winter wheat growth and yield during different growth periods, this study utilized meteorological data from 1961-2014 and winter wheat development and yield data from 1981-2014 at 30 agro-meteorological observation stations in Henan Province. By combining mathematical statistics with DSSAT-CERES Wheat model simulations, we examined climate change characteristics during three growth periods—planting to greening, greening to heading, and heading to maturity—and their effects on phenology and yield. The results revealed that the most significant climate change feature in the study area was a substantial decline in sunshine hours during the planting-greening period at a rate of 40.09 h · (10a)^{1} ($P<0.05$), accompanied by simultaneous increases in both average daily maximum and minimum temperatures during the greening-heading period. Panicle differentiation in winter wheat advanced by 2.9 days per decade in response to rising pre-heading minimum temperatures. Climate change before greening exerted a persistent influence on subsequent developmental processes, with meteorological factors showing predominantly negative correlations with the duration from planting to heading and planting to maturity. Both analytical approaches demonstrated that current climate change during the planting-greening period had minimal impact on yield in Henan's wheat region, even exhibiting a slight yield-enhancing effect within certain ranges, with meteorological factors contributing an average rate of 0.758. In contrast, climate change during the greening-heading period reduced kernel density and kernel number per spike by 2.74% and 3.94%

on average, respectively—greater impacts than during the heading-maturity period. Under climate change scenarios for different growth periods, both high and stable yields were affected, with representative stations showing average yield reductions of 1.6%, 6.3%, and 4.8% during planting-greening, greening-heading, and heading-maturity periods, respectively. The key meteorological factor affecting yield was daily maximum temperature during planting-greening and heading-maturity periods, while daily minimum temperature was critical during the greening-heading period.

Keywords: Winter wheat; Main growth periods; Climate change; DSSAT-CERES Wheat model; Meteorological variable; Daily minimum air temperature

Introduction

Over the past century, global warming driven by changes in greenhouse gas concentrations has attracted widespread attention from scholars worldwide[1]. Agricultural production systems, being among the most sensitive to climate change, directly impact human survival[2]. Numerous studies have confirmed that since observational records began, China' s agricultural climate conditions have undergone significant changes, affecting agro-climatic resources, agricultural meteorological disasters, cropping systems, and production potential[3-4]. Winter wheat (*Triticum aestivum*), one of China' s most important food crops, warrants in-depth investigation into how climate change affects its production processes to scientifically understand both the beneficial and detrimental impacts and to formulate appropriate adaptation measures.

Since the 1990s, China has produced substantial research on climate change impacts on winter wheat production. Consistent conclusions indicate that during the winter wheat growth period, winter and spring warming trends are significant while solar energy resources decline, with warming causing a general shortening of the growth period[5-6], particularly pronounced advancement of the jointing and heading stages[7]. In some regions, the climatic production potential of winter wheat shows a slight increasing trend with fluctuations, though water constraints have become more limiting[8-10]. Most simulation results combining crop models with regional climate models suggest that the climate system will cause obvious yield reductions in winter wheat over the next 30–50 years[11].

Climate change and its impacts constitute a systematic and extensive research topic. While abundant research findings have gradually deepened our understanding, several uncertainties remain: the advantages, disadvantages, and magnitude of historical climate change impacts on production are not yet fully determined; although methods for projecting future climate change impacts on yield are relatively mature, against the background of continuously increasing social yields, there are differing perspectives on how historical climate change has affected yields in terms of both methodology and conclusions[12]. More-over, few studies have identified which growth stage is most affected by climate change, how different developmental periods respond to climate change, or the underlying mechanisms of these responses.

This paper takes Henan Province—China' s primary winter wheat production region—as a case study. By combining mathematical statistics with crop simulation modeling, we characterize the main features of climate change during different winter wheat growth periods, identify critical periods when climate change affects growth processes and yield, and determine key influencing factors during each growth period. Our objective is to elucidate the patterns of climate change impacts on winter wheat and provide a scientific basis for agricultural production to maximize benefits and minimize harm while adapting to climate change.

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1. Materials and Methods

1.1 Data Sources

Thirty agro-meteorological observation stations in Henan Province were selected as study sites [Figure 1: see original paper]. Daily meteorological data for the winter wheat growing season from 1961-2014, including maximum temperature, minimum temperature, mean temperature, sunshine hours, and precipitation, were obtained from the Henan Provincial Meteorological Bureau. Winter wheat yield data for each station from 1981-2014 were sourced from Henan Provincial statistical departments, while crop development period data came from the Henan Provincial Meteorological Bureau. Soil data for each region were referenced from *Soils of Henan*[13].

1.2 Statistical Methods

Based on the progression of winter wheat through vegetative growth, concurrent vegetative and reproductive growth, and reproductive growth stages, the entire growth period was divided into three main stages: planting-greening, greening-heading, and heading-maturity.

1.2.1 Climate Trend Rate Using a simple linear regression equation y = ax + b, we calculated temporal trends for mean daily temperature (T , °C), mean daily minimum temperature (T , °C), mean daily maximum temperature (T , °C), sunshine hours (S, h), precipitation (P, mm), and duration (d) of each growth period at representative stations, where x represents the year and a×10 represents the climate trend rate. Probability levels of $P<0.05$ and $P<0.01$ indicate significant and highly significant trends, respectively.

1.2.2 Relative Meteorological Yield Winter wheat social yield Y (kg·hm ^{2}) was decomposed into trend yield (kg·hm ^{2}) and meteorological yield Yw (kg·hm ²). The straight sliding average method recommended in meteorological industry standards[14] was employed for simulation, with a sliding step length of 11 years. To reduce the influence of different historical agricultural technology levels and enhance the temporal comparability of meteorological yield series, relative meteorological yield[15] was introduced for further analysis, denoted as a:

[Equation would appear here based on context]

1.2.3 Meteorological Factor Contribution Rate Multiple linear regression was used to fit the relationship between relative meteorological yield and meteorological elements during different growth periods of winter wheat. The sum of regression coefficients for all elements served as the base, and the contribution rate was calculated by dividing the regression coefficients for temperature and sunshine hours in different growth periods by this base. A positive contribution rate indicates a positive effect, while a negative value indicates an adverse effect.

1.3 Crop Model and Scenario Design

The DSSAT CERES-Wheat model with revised parameters was employed for climate change impact simulation. This model has been widely applied in climate change impact studies and proven suitable for China' s main winter wheat production regions[16]. Five representative sites with slightly different cultivar attributes and climatic characteristics—Xinxiang, Xiangcheng, Lushi, Shangqiu, and Zhengyang—were selected in Henan Province for crop model simulation analysis. The model utilized a minimum meteorological dataset comprising daily maximum temperature, minimum temperature, precipitation, and solar radiation, with solar radiation values estimated from sunshine hours using the FAO-recommended method.

Model parameters were calibrated using the GLUE module with observed flowering dates, maturity dates, and actual yield data from 2001-2005 at each station. Validation was performed using data from 1994-2000 and 2006-2010, with model performance evaluated using absolute error (Δ), normalized root mean square error (NRMSE), consistency index (D)[17], and correlation coefficient (R^2) between simulated and observed values . The results demonstrated that the DSSAT CERES-Wheat model achieved relative root mean square errors within 2% for simulating key developmental stages at representative stations, with consistency indices and correlation coefficients approaching 1, and yield simulation errors less than 9%. The model showed good adaptability and met the requirements for climate change research simulations.

Simulation Scenario (I): To understand differential responses of winter wheat to climate change during different growth periods, Scenario A represented changed meteorological conditions during planting-greening while other periods remained constant. Similarly, Scenarios B and C represented changed conditions during greening-heading and heading-maturity periods, respectively. To facilitate simulation analysis and reflect the continuity of climate system changes, for factors showing significant trends, daily meteorological data files for representative stations from 1981-2010 were modified in the crop model database according to their climate trend rates. Meteorological elements were varied in 10-year gradients, with the 30-year new scenarios divided into Phase I, Phase II, and Phase III by decade. For example, if the climate trend rate of daily maximum temperature was n °C • (10a) ^{1}, then daily maximum temperatures in Phases I, II, and III would increase by n °C, 2n °C, and 3n °C, respectively, based on the original values.

Simulation Scenario (II): To further investigate the response magnitude of winter wheat to identical meteorological factor changes during different periods, daily maximum temperature, daily minimum temperature, and sunshine hours were increased or decreased by the same units during the three growth periods, focusing on yield changes and yield variability characteristics. Using Xiangcheng station in the central plain as an example and referencing its climate trend rates, we set up nine treatments: daily maximum temperature (A1, A2, A3) and daily minimum temperature (B1, B2, B3) increased by 0.5 °C, and solar radiation (C1, C2, C3) decreased by 5% during planting-greening, greening-heading, and heading-maturity periods, respectively.

The two scenarios were independent, with results not interfering with each other. The change rate of simulated yield or yield components W was calculated using Equation (2):

[Equation would appear here based on context]

where Ys represents simulated yield or yield components under a given scenario, and YCK represents the average yield or yield components simulated using actual historical meteorological data from the past 30 years.

2. Results and Analysis

2.1 Climate Change Characteristics During Different Winter Wheat Growth Periods

Although regional differences existed among study stations, the trends of climate change during different winter wheat growth periods were generally consistent. The main manifestations were: consistent warming across all periods, particularly significant increases in T with rates higher than those for T , implying reduced diurnal temperature ranges . Compared with other periods, climate trend rates for temperature factors were notably larger during greening-heading, with T increasing at 0.591 °C • (10a) ^{1}. Sunshine hours decreased consistently across all growth periods, especially during planting-greening, which showed a highly significant declining trend with an average climate trend rate of

-40.09 h·(10a) ^{1} across all stations; changes in sunshine hours during other periods were not significant. Therefore, the main characteristics of climate change during different growth stages in the study region were: the largest warming magnitude occurred during greening-heading, with T and T increasing simultaneously at different rates; sunshine hours decreased significantly during planting-greening; and precipitation showed decreasing trends during all developmental periods but did not pass significance tests.

2.2 Effects of Climate Change on Different Winter Wheat Growth Periods

Statistical analysis revealed that under climate change, sowing dates and universal greening dates of winter wheat in Henan Province did not change significantly. Among the 30 study stations, only five showed significant delays in sowing date ($P<0.05$), two showed significant advancement in greening date, and six showed significant postponement. Heading dates advanced significantly at 28 stations, with an average advancement rate of 2.9 d·(10a) ^{1} [Figure 2a: see original paper]; maturity dates advanced significantly at 15 stations, with an average rate of 1.4 d·(10a) ^{1}.

The planting-greening period lasted an average of 124.6 days across stations, with no common pattern in variation. The greening-heading period averaged 61.8 days, with a provincial change rate of -4.3 d·(10a) ^{1} [Figure 2b: see original paper], with 23 stations showing significant shortening trends. The heading-maturity period averaged 41.6 days, extending at a rate of 1.5 d·(10a) ^{1} over the past 34 years, with 22 stations showing significant extension trends; the trend in total growth period days was not obvious across representative stations.

Before greening, winter wheat undergoes vernalization and early panicle differentiation[18], with heading marking the end of panicle differentiation. Pearson correlation analysis revealed that meteorological elements before greening had small correlation coefficients with planting-greening duration but were significantly correlated with subsequent developmental periods , indicating that although climate trend rates for meteorological elements before greening were not the largest, their influence on developmental processes was most pronounced. T and T during the three main growth periods were negatively correlated with inter-stage durations, with T during planting-greening showing the highest negative correlation coefficients with planting-heading and planting-maturity periods. Although precipitation trends were not significant, they were negatively correlated with main growth period lengths. Since increased minimum temperature directly promotes changes in mean temperature, the main manifestation of climate change impacts on winter wheat developmental periods was: panicle differentiation ended earlier with rising minimum temperatures, but the grain-filling period did not shorten significantly with temperature increases. Among Henan' s winter wheat production characteristics of "two long and one short" [19], the "long vernalization period" feature was less affected by climate change, the "long panicle differentiation period" advantage was diminishing, while the “short grain-filling period” disadvantage was improving with climate change.

2.3 Effects of Climate Change on Winter Wheat Yield During Different Periods

As analyzed above, climate change characteristics and magnitudes differed among periods, leading to varied responses of winter wheat to climate change during different growth stages. Here, we comprehensively analyzed these effects using two methods.

2.3.1 Contribution Rates of Meteorological Factors and Spatial Distribution Multiple regression equations between relative meteorological yield and meteorological factors during each growth period at study stations all passed significance tests at P=0.01. [Figure 3: see original paper] and show the contribution rates of all meteorological factors during each growth period, as well as the contribution rates of temperature and sunshine hours individually. Since most wheat fields in Henan have irrigation conditions, which partially mask precipitation effects, precipitation factors had small regression coefficients and are not discussed here.

As shown in [Figure 3: see original paper], except for individual areas in southeastern Henan, meteorological conditions during planting-greening had positive contributions to yield, with contribution rates of 0.1-2.0 across most of the province and an average contribution rate of 0.758. During greening-heading, the average comprehensive contribution rate was -0.105, with relatively large negative contributions in northeastern, eastern, central, and southern Henan. During heading-maturity, the average contribution rate was 0.349, smaller than during planting-greening, but with negative contributions in parts of northeastern, central, and southwestern Henan.

The contribution rate of temperature factors was comparable to that of each growth period, while the average contribution rate of sunshine hours ranged from -0.059 to -0.002, less than one-tenth of the temperature contribution rate, indicating that reduced radiation is not currently the main limiting factor for yield changes in Henan’ s wheat region . Statistical results showed that climate change during greening-heading had clear adverse effects on wheat yield formation, with temperature increase being the main impact factor during this period.

2.3.2 Yield Change Simulation at Representative Stations Under Different Scenarios Simulations were designed to project yield changes caused by further alterations in climatic elements based on current conditions. Average results across stations showed that continuous climate change in all three periods led to yield reductions, but Scenario A (planting-greening) caused relatively small average yield losses of -1.65%, with some stations even showing yield increases. Scenario B (greening-heading) caused the highest average yield reduction rate, consistent with statistical model analysis. In each scenario, Phases I, II, and III represented 阶梯 changes in meteorological elements—when climate change magnitude was relatively small, changes before greening and after heading might increase yields in some regions, with the yield reduction inflection point occurring between Phases I and II.

Combined with the analysis in Section 2.3.1, climate change during planting-greening had the smallest negative impact on winter wheat production. Small climate changes during this period over the past 30 years or in the future may even positively contribute to yield increases, but yields decreased significantly as climate change intensity increased. Under current climate change magnitudes, the negative impact of climate change during greening-heading was more pronounced, but simulation results for intensified Phases II and III revealed that adverse effects of climate change during heading-maturity became prominent.

shows the average change rates of yield components at representative stations. All three scenarios reduced yield components, but climate change during different periods had relatively small effects on 1000-kernel weight, with average changes within 0.1%, mainly causing varying degrees of reduction in kernel density per square meter and kernels per spike. Scenario A had the smallest impact on the three yield components, while Scenario B reduced kernel density and kernel number by 2.74% and 3.94%, respectively—greater reductions than Scenario C—representing the primary reason for yield reduction due to climate change during greening-heading.

2.4 Key Meteorological Factors Affecting Winter Wheat Yield

Since meteorological elements such as temperature and sunshine have synergistic effects on yield, the crop model with specific simulation scenarios can isolate the impact of single-factor changes of identical magnitude. Based on simulation results from Xiangcheng station under Scenario (II), all nine treatments reduced average winter wheat yield compared with the control, with the largest yield reductions occurring in treatments C1, B2, and C2, followed by C3. This indicates that when climate change intensifies, changes in all meteorological factors during heading-maturity have substantial adverse effects on yield, with daily maximum temperature having the greatest negative impact. Treatments A1, A2, and A3 had relatively low yield reduction rates, with only A1 showing a relatively higher reduction, demonstrating that climate change during planting-greening had the smallest negative impact on yield. The key factor affecting yield was daily maximum temperature increase during planting-greening and heading-maturity periods, while daily minimum temperature was critical during greening-heading.

Box plots of yield for each treatment [Figure 4: see original paper] showed that winter wheat not only had reduced average yields but also lower minimum and maximum yield levels. Only the minimum yield under treatment B2 exceeded the control minimum yield level, indicating that increased minimum temperature during greening–heading could raise the minimum wheat yield and reduce yield variability. Changes in maximum and minimum temperatures during each developmental period widened the 25th–75th percentile yield range, suggesting that yield stability is deteriorating.

Discussion and Conclusion

This study analyzed climate change impacts during key winter wheat growth periods in Henan Province and found that climate change characteristics differed among periods, as did their effects. Sunshine hours decreased most significantly during planting–greening but had minimal negative impact on yield. Climate change during planting–greening importantly affected winter wheat developmental processes. The greening–heading period experienced the largest warming magnitude, and climate change during this period had the most adverse effects on yield. Continuous climate change in all periods led to wheat yield reductions, with daily maximum temperature being the key meteorological factor during planting–greening and heading–maturity, while daily minimum temperature was critical during greening–heading.

From sowing and emergence to the overwintering and greening stages, winter wheat undergoes primary vegetative growth. Previous studies have found that sufficient accumulated temperature during the vegetative growth period significantly correlates with tiller survival rate; conversely, pre-greening temperature increases can reduce winter freeze risk and ensure safe overwintering[20-22], which corroborates our findings about the effects of planting-greening climate change on winter wheat yield, though this positive effect is limited to warming within a certain magnitude. Post-greening is a crucial period for wheat spike differentiation, where temperature conditions determine not only the initiation timing but also the progression of differentiation. Both methods in this study confirmed that, compared with other periods, climate change during greening–heading had the most adverse impact on yield, with daily minimum temperature being the key factor. The largest increase in T during this stage implies rapid spring warming, which can accelerate photoperiod response and reduce spikelet and floret numbers[23]. Therefore, when developing climate change adaptation measures for winter wheat, post-greening field management practices should be prioritized to mitigate adverse climate change impacts.

This study identified daily maximum temperature after heading as a key yield-influencing factor, consistent with previous research showing that post-anthesis high temperature adversely affects physiological and biochemical processes such as starch granule formation, enzyme activity, and photosynthate allocation in wheat grains[24-27]. While this paper reveals critical periods and key influencing factors of climate change impacts on yield, the specific mechanisms and physiological processes require further in-depth analysis.

Crop models can reflect yield changes caused solely by meteorological conditions under constant soil and cultivar conditions, offering advantages of quantification, strong comparability, and high credibility that have led to wide application in climate change research[28-30]. However, limitations exist: the simulation scenarios in this study were designed to parallelly analyze potential trends of climate change impacts during different growth periods, which may not fully align with future climate change trends, so the derived yield change magnitudes serve only as research references. Due to data limitations, this study only covered representative stations in Henan' s wheat region. Climate change impacts exhibit both common characteristics and regional differences, which should be addressed by expanding the study area to improve spatial representativeness.

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