



## China could simultaneously increase wheat yield and nitrogen use efficiency under the temperature rise of 1 °C through optimal crop managements

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### ARTICLE INFO

#### Keywords:

Winter wheat  
Nitrogen use efficiency  
Crop model  
Crop management  
Climate change

### ABSTRACT

Climate change has been threatening the sustainable winter wheat production in China under the pressures of food security and economic growth. In particular, with the continued rise in greenhouse gas emissions, the increase in future temperature is expected to negatively impact winter wheat yields. To explore whether optimizing crop managements can improve the yield and nitrogen use efficiency (NUE) of Chinese wheat in the future. To address the challenges of complex interactions between crops and the environment in space and time. we conducted three-year field experiments at a total of 21 different sites across China's main winter producing areas. In the field experiments we compared the effects of traditional crop management practices and optimized crop management practices on winter wheat growth. Additionally, the DSSAT-CERES-Wheat model was used to simulate the experimental results across all winter-wheat producing regions of China, as well as under a future scenario of a 1°C temperature increase, so as to explore the spatiotemporal variations of winter wheat yields under different cropping, management, and climate scenarios. The results showed that crop management optimization could increase national wheat yield by about 5.2% during the experimental years of 2017–2019. Next, the critical time points for climate change were identified when future average temperatures would increase by 1°C in the main winter-wheat producing regions in China. The impacts of optimized crop managements on winter wheat yields were then evaluated under two future climate scenarios of SSP245 and SSP585. Compared with the baseline period of 2017–2019, winter wheat production would increase by about 16% with current farmer management practices in 2021–2047 under SSP585. However, with optimized crop managements, winter wheat yields could additionally increase by about 5% and NUE could be improved by about 33%. The new findings from this study demonstrated that optimized crop management practices could concurrently boost winter wheat yields and NUE across most of winter wheat producing regions in China, which means China could simultaneously achieve sustainable yield increase and enhance resource utilization efficiency in wheat production in the future. Furthermore, the study underscored the spatiotemporal potential of crop management optimization and delivered targeted projections for the diverse winter-wheat cropping systems across different winter-wheat producing regions in China. These insights could help develop more practical management strategies to safeguard food security in China amid future climate change.

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<https://doi.org/10.1016/j.eja.2026.128183>

Received 17 August 2025; Received in revised form 31 March 2026; Accepted 20 May 2026

Available online 27 May 2026

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## 1. Introduction

Wheat is one of the world's top three staple crops, providing the highest amount of calories and proteins to global food supply (FAO, 2023). In light of limited arable land, population growth, and rising demand for food due to economic development, a substantial increase in wheat production is an urgent necessity (Bodirsky et al., 2020; Tilman et al., 2011). As one of the world's most populous countries, China faces critical decisions regarding food security, which will also significantly impact global agriculture and trade (Huang et al., 2017). Against this backdrop, maintaining stable winter wheat productivity in China is of paramount importance both for safeguarding the food supply of its 1.4 billion inhabitants and for advancing global agricultural sustainability. As the world's preeminent wheat-producing nation, China currently accounts for approximately 11% of the global wheat cultivation area and contributes 17% to the total annual output (Gong et al., 2025; NBSC, 2020). However, with the increasing domestic consumption, China's wheat imports have risen from  $3 \times 10^6$  tons in 2014– $12.1 \times 10^6$  tons in 2023 (FAO, 2023). Given the limited potential for planting area expansion, it is crucial for China to boost the wheat yield per unit area so as to achieve its food self-sufficiency (Qin et al., 2015; Qiu et al., 2022).

However, a current urgent challenge is that climate change has increased the instability of global wheat yields. Especially, the changing rainfall patterns and global warming are expected to negatively impact crop production in many regions in the world (Lobell et al., 2013; Wang et al., 2020). Climate change impacts are usually quantified by differences in temporal variations, but especially in view of the local context and the uncertainties of future climate changes. So far, critical time points for climate changes have become key indicators for risk assessment (Hawkins and Sutton, 2012; Jägermeyr et al., 2021). According to the IPCC's Sixth Assessment Report, the global surface temperature has increased by approximately  $1^\circ\text{C}$  from the period 1850–1900–2010–2019 (IPCC, 2021). Additionally, Meteorological records indicated that the annual average temperature in main winter-wheat growing regions rose by about  $1^\circ\text{C}$  (1910–2010), with further increases expected in this century (Zhao et al., 2017). Accordingly, this study defined a  $1^\circ\text{C}$  temperature rise as a critical time point for future climate change in the major winter-wheat growing regions of China. Time of emergence metrics which is the critical time point have been applied to different climatic variables such as temperature and precipitation, indicating that major grain producing regions are increasingly facing climate change in the near future (Kirtman and Power, 2014; Rojas et al., 2019). In this study, a climate-crop modeling framework was utilized to quantify crop yield responses at critical time points of climate changes (Asseng et al., 2013; Han et al., 2024; Jiang et al., 2022; Shoukat et al., 2024).

Crop management optimization is crucial for sustainable intensification of agriculture (Luo et al., 2023; Rizzo et al., 2022). Previous researches showed that different crop management practices could result in synergies and trade-offs between multiple objectives, such as yield and resource use efficiency (Cai et al., 2023; Duan et al., 2019). Kheir et al. (2022) conducted field experiments to optimize wheat management practices in the main wheat-growing areas in Egypt and found that about 80% of the current irrigation volume was sufficient to maintain wheat yields while improving resource use efficiency. Additionally, yield projections under future climate change for the region suggested that optimized management practices could increase wheat yield by about 4.5% and also improve wheat quality (Kheir et al., 2024a). Globally, soil nutrient availability, especially nitrogen (N), is a major constraint to close the wheat yield gaps (Martre et al., 2024; Mueller et al., 2012). Since China has implemented a series of policies aimed at promoting wheat cultivation and fertilizer use, both the yield and quality of winter wheat have seen improvements (Zhang et al., 2018). However, excessive use of N fertilizer could decrease economic benefits and nutrient utilization efficiency, and also could cause severe environmental problems through N leaching or gaseous emissions, which

could threaten human health at local to global scales (Ladha et al., 2016; Quan et al., 2021). Therefore, reducing the harmful impacts of N fertilizer while maintaining food production is an urgent priority for food security and environmental health in China (Lassaletta et al., 2023).

In the past, integrated experiments of soil and cropping managements helped enhance N fertilizer management and boost the yields and nitrogen use efficiency (NUE) of major crops in China (Cui et al., 2011; Lu et al., 2015). Agronomists advised multiple applications of N fertilizer at critical crop growing stages to ensure efficient N uptake and use (Chen et al., 2015; Meng et al., 2016). Chen et al. (2014) suggested reduced N application rates and integrated application of nitrogen, phosphorus, and potassium fertilizers to achieve high crop yields and high NUE through optimal soil-crop system management. Xu et al. (2022) and Wang et al. (2022) considered the spatial and temporal variations of nutrient availability and advocated precise fertilization through site-specific N management and real-time N management. These studies primarily focused on optimizing N fertilization frequency, amount, and methods to minimize the waste and enhance the use efficiency of N fertilizer, highlighting the relationship between N supply and demand as well as timely N availability. However, these studies lack conclusions regarding the synergistic effects between increasing yield and improving NUE. Therefore, this study aims to obtain spatial feasibility results of yield and efficiency improvement for winter wheat in China.

Although field experiments play a crucial role in quantifying the relationships between agricultural management practices and environmental responses, their findings are typically confined to the experimental locales. These studies focused on site-specific scales in China and did not comprehensively consider the combined effects of climate, soil, and crop managements on the yields and NUE of winter wheat production in China. Such constraints stem from the complex, nonlinear interactions governing soil-climate systems at regional scales (Du et al., 2021; He et al., 2023), field experiments alone are inadequate for determining the efficacy of management practices. In the current study, a process-based crop simulation model was utilized to quantify the spatiotemporal impacts of water and nitrogen inputs on winter wheat yield and NUE across diverse management strategies and climatic scenarios. Process-based crop models are capable of capturing agroecosystem dynamics, including crops' nonlinear physiological responses to environmental factors (Bassu et al., 2014). Consequently, crop models have been extensively applied to simulate crop yields and fertilizer application, evaluate environmental impacts (Deng et al., 2019; Yuan et al., 2022), and identify region-specific optimal field management strategies (Gong et al., 2025; Yu et al., 2019). This study was based on the process-based crop models, driven by climatic data derived from the global climate models (GCMs), enable the consideration of the complex and crops' nonlinear physiological responses to climatic and soil conditions (Sun et al., 2018), thereby supporting the development of effective adaptation strategies for climate change.

In this study, we conducted three-year field experiments in the three major winter-wheat growing regions of China. The crop management practices involved in the field experiments were based on local survey and the optimization of multiple-year management trials. The results of site experiments were then scaled up to national level through a crop modeling approach. The effects of optimized crop management practices and traditional management practices were predicted at a  $1^\circ\text{C}$  temperature increase under different future climate scenarios in the main winter-wheat producing regions in China. We utilized nine different global climate models (GCMs) from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) under high end of the radiative forcing setup and medium part of the radiative forcing setup, namely the Shared Socio-Economic Pathways of SSP585 and SSP245 to estimate the yields and NUE of winter wheat at critical time points of climate changes (Meehl et al., 2020; O'Neill et al., 2016).

This study focused on addressing the critical challenge of concurrently enhancing winter wheat productivity and resource utilization

efficiency, a goal pivotal to sustaining winter wheat production sustainability in China. Through the integration of field trials and crop model simulations, the main objectives were as follows: (1) explore the potential to enhance winter wheat yields through crop management optimization under both current and future climatic conditions; (2) examine the spatiotemporal dynamics of the synergies between the yields and NUE of winter wheat in the current producing regions and future warming climates; and (3) propose recommendations for crop management optimization in main winter-wheat planting regions in China.

## 2. Materials and methods

### 2.1. Study area

The primary winter-wheat producing areas in China can be categorized into three main regions (Fig. 1). First, in the Huang-Huai-Hai region (Fig. 1), the wheat-maize rotation system is adopted. The local climate is a temperate continental monsoon climate with an annual average temperature of 9–15°C. Summers in this region are hot and rainy (with average monthly temperatures of 22–28°C), while winters are dry and cold (with average monthly temperatures of –10–+1°C). Due to the circulation patterns and topographical features, the annual precipitation was 440–980 mm, while the precipitation was 150–340 mm (about 200 mm in most areas) during winter wheat growing seasons. The northwest part of this region received less precipitation, while the eastern part received more. The precipitation was temporally unevenly distributed throughout the year, mostly in July and August.

Next, in the Southern region (Fig. 1), the predominant cropping system is rice-wheat rotation. The local climate is warm and humid monsoon climate. This area can be further divided into the middle-and-lower Yangtze River wheat zone and the southwestern wheat zone. The middle-and-lower Yangtze River wheat zone has average annual temperatures of 15–18°C and annual precipitations of 830–1870 mm. The southwestern wheat zone is located in the upper Yangtze River basin,

characterized by numerous hills and limited plains. In this region, the temperature variation across different seasons was relatively small and the large diurnal temperature range favors winter wheat growth. The annual precipitation was about 1100 mm, which was sufficient to meet the water requirements for winter wheat growth. Due to the limitation of arable lands, especially the urbanization development in the North China Plain and southern regions, maintaining the current wheat producing area while increasing the yield per unit area is key to securing the winter wheat production in China (Qiu et al., 2022).

Finally, the Xinjiang region is situated in the northwest part of China at the heart of the Eurasian continent (Fig. 1). This region has cold winters, hot summers, limited precipitations (with only an annual precipitation of 145 mm) and ample solar radiation (Zhao, 2010). Thus, a unique dryland cropping system with drip irrigation had been developed and widely adopted for winter wheat production in this region.

In this study, the entire winter wheat producing areas were divided into 2315 grid cells (0.25°×0.25°) across the three wheat producing regions in China (Fig. 1). The grids were created and identified by overlaying a digital map of wheat crop distribution (SPAM map, with 10 km×10 km resolution) on the national map of China. Since some grids included small wheat planting areas, the grid cells were selected based on the descending order of wheat harvested area until the cumulative harvested area in the selected grids exceeded 90% of the national total harvested area of winter wheat. The winter wheat producing areas generally distributed as follows: about 61% in the Huang-Huai-Hai region, 35% in the Southern region, and 4% in the Xinjiang region. This study simulated the growth and yields of winter wheat within each grid (Fig. 1). To aggregate the simulation results for the three regions and the entire country, the harvested wheat area in each grid was used as a weight. Then, the national average results were calculated using the harvested area in each region as a weight (Eq. 1).

$$Y_{\text{producing area}} = \frac{\sum_{i=1}^q Y_{\text{grid}_i} \times \text{Area}_{\text{grid}_i}}{\sum_{i=1}^q \text{Area}_{\text{grid}_i}} \quad (1)$$

where  $Y_{\text{producing area}}$  is the winter wheat yield for all grids;  $q$  is the number of grids in the winter-wheat planting region; and  $\text{Area}_{\text{grid}_i}$  is the harvested wheat area in grid  $i$ .

### 2.2. Data acquisition and processing

The meteorological data used in the simulation consisted of daily maximum and minimum temperatures, solar radiation and precipitation. Meteorological data for the baseline period (2017–2019) were obtained from the Global Land Data Assimilation System (GLDAS; <https://disc.gsfc.nasa.gov/datasets?keywords=GLDAS>) of the NASA (National Aeronautics and Space Administration) of the USA. Several products, such as AGRMET (Agricultural meteorology modeling system) of AFWA (Air Force Weather Agency), were exploited to improve the quality of SRAD (Solar radiation) data in the GLDAS. This dataset has been verified by actual station observation data and has been widely used in relevant studies on meteorology, hydrology, agriculture, and other fields in China (Araghi et al., 2022; Huang et al., 2021; Qi et al., 2020; Wen et al., 2014; Yang et al., 2017). Future climatic data were derived from nine different global climate models (GCMs; Table S4) of the CMIP6 dataset. The soil properties, despite varying significantly across different regions, remained relatively stable over time. In this study, soil data were mainly sourced from the China Soil Moisture Dataset (Li et al., 2022; Wang et al., 2023a) and the Harmonized World Soil Database (HWSD) (Dai et al., 2013; Wieder et al., 2014). To facilitate regional model simulations in the three main winter-wheat producing regions in China, all of the data were standardized to a spatial grid resolution of 0.25°×0.25°.

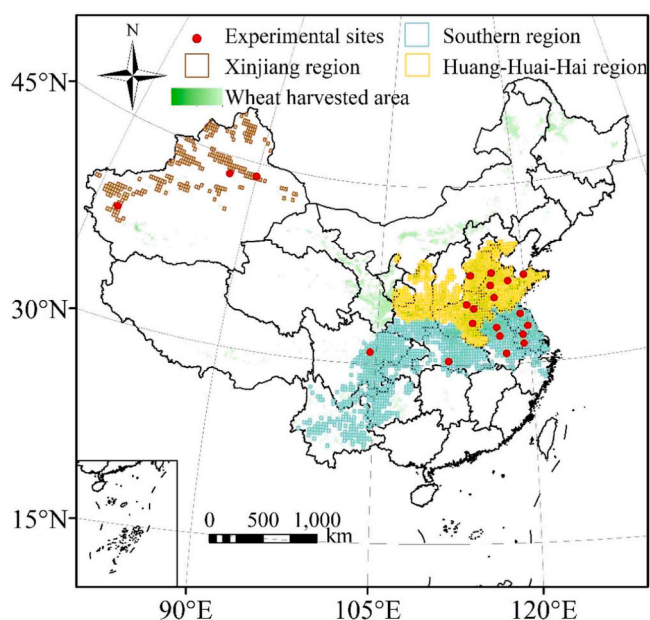


Fig. 1. Experimental sites and selected wheat producing grids in the three main winter-wheat producing regions (Huang-Huai-Hai region, Southern region, and Xinjiang region) in China. The wheat producing grids were selected according to the descending order of the harvested wheat areas in them until the cumulative harvested area in the selected grids exceeded 90% of the national total harvested area of winter wheat.

### 2.3. Field experiments for crop management practice optimization

This research assessed three distinct cropping systems across China's main winter producing regions: Huan-Huai-Hai, Southern, and Xinjiang (Fig. 1). Between 2017 and 2019, field trials were conducted at 21 experimental sites nationwide to optimal crop managements for winter wheat production. The site experiment was conducted under the local climatic conditions. The wheat grew normally and no extreme climatic events occurred during the growing seasons. A key constraint on winter wheat yield and NUE across China is the current crop management (Cui et al., 2018; Duvick, 2005; Gong et al., 2025; Rizzo et al., 2022; Yu et al., 2020). Therefore, the improvement of crop management practices mainly referred to the optimizations of seeding density, N application rates, and irrigation (Fig. S1).

Field experiments incorporated three distinct crop management tiers. The BSF (Basic soil fertility) treatment involved no irrigation or fertilization during the winter wheat growing season, enabling us to quantify NUE across management gradients. The FP (Farmer practice) treatment mirrored local agricultural practices, representing typical regional management. In each county hosting the experimental sites, 2–5 villages were randomly selected. Within each selected village, several farmers were randomly chosen to be interviewed about their crop management practices in winter wheat production. Based on their crop management practices, field experiments were conducted to compare with the experiments with optimized crop management practices. Generally, the experimental results with the surveyed crop management practices could reflect the current actual level of winter wheat production in China. The HEP (High-efficiency practice) referred to an optimized scheme of management practices developed by agronomic experts based on previous multiple-year field experiments, which could simultaneously ensure high winter-wheat yields and improve N use efficiency (Bai et al., 2020; Shen et al., 2013; Wang et al., 2014). These optimized crop management practices included suitable planting density and row spacing, suitable N fertilizer amounts with a reasonable split application strategy, and timely irrigation as needed (Table S1). Based on the winter wheat experiments conducted under the three levels of management practices across 21 various sites in China, this study aimed to scale up the site-specific management practice schemes to spatial grid scale. For this purpose, the management practices adopted at each grid were as the same as those at the nearest experimental site in terms of spatial proximity, and the distance between the experimental site and the coverage grid was calculated (Fig. 1 and Table S2).

### 2.4. Future scenario of 1°C temperature rise

Based on the historical warming trends of the past century for both global surface temperature and major winter-wheat producing regions (PCC, 2021; Zhao et al., 2017), this study defined a 1°C temperature increase as the critical time point for climate change in the main winter-wheat producing regions in China. Thus, we specifically aimed to predict the impacts of a 1°C temperature rise on winter wheat production in the three main regions in China. The years of field experiments (2017–2019) were set as the baseline period. Then, the impacts of 1°C temperature increase on winter wheat production were evaluated through comparisons with the winter wheat productions under the future greenhouse gas emission scenarios of SSP245 and SSP585. Since the rate of temperature increase in winter-wheat producing regions of China differed under different future scenarios, this study first calculated time of emergence metrics at which a 1°C temperature rise under the two future scenarios. Future climate analysis in this study was based on the Coupled Model Intercomparison Project (CMIP6), through incorporating prediction data from the SSP database. Accounting for the increasing trends of atmospheric CO<sub>2</sub> concentration, crop model simulations were conducted under two future scenarios of SSP245 (Eq. 2) and SSP585 (Eq. 3) (Gidden et al., 2019). SSP245 represents a medium-emission and medium-warming intermediate scenario, while

SSP585 represents a high-emission and strongly warming scenario dominated by fossil energy. The increase in temperature in the latter scenario will be significantly higher than that in the former one. Future climate scenarios were derived from nine different global climate models (GCMs; Table S4). The data sources and methods used were well-established and widely recognized in global climate change researches (Shoukat et al., 2024; Stella et al., 2021; Zhang et al., 2023). This is because previous studies have demonstrated discrepancies in the predictions among different global climate models (GCMs) (Jägermeyr et al., 2021; Wang et al., 2020). To ensure the prediction results are not affected by a single GCM and enhance the credibility of the outcomes, we averaged the results obtained by driving the model with each GCM, which serve as the final result for each prediction grid.

$$[\text{CO}_2]_{\text{year}} = 62.044 + \frac{34.002 - 3.8702 \times y}{0.24423 - 1.1542 \times y^{2.4901}} + 0.028057 \times (y - 1900)^2 + 0.00026827 \times (y - 1960)^3 - 9.2751 \times 10^{-7} \times (y - 1910)^4 - 2.2448 \times (y - 2030) \quad (2)$$

$$[\text{CO}_2]_{\text{year}} = 757.44 + \frac{84.938 - 1537 \times y}{0.2011 - 38289 \times y^{-0.45242}} + 2.4712 \times 10^{-4} \times (y + 15)^2 + 1.9299 \times 10^{-5} \times (y - 1937)^3 + 5.1137 \times 10^{-7} \times (y - 1910)^4 \quad (3)$$

### 2.5. Yield and NUE projections under current and future climates

To scale up the results of site experiments both temporally and spatially, crop model simulations were used to extend the site-level findings to the three main winter-wheat producing regions in China. The DSSAT-CERES-wheat model V4.7 (Jones et al., 2003) were used to simulate winter wheat yields at the three levels of crop management practices (i.e., BSF, FP, and HEP). This model has been extensively validated under diverse environmental conditions and was widely employed to simulate crop yields in various wheat planting systems worldwide (Basso et al., 2016; Chen et al., 2020; Paff et al., 2023). Winter wheat yields were first simulated at each level of crop management practices at the experimental sites to enable the comparisons with the actual experimental results.

Wheat varieties exhibited stability in the Huang-Huai-Hai and Xinjiang regions, while variability was unstable in the Southern region. Across all regions, 19 varieties were included: 2 from the Huang-Huai-Hai region and 3 from Xinjiang. In the Southern region, 14 varieties were used in experiments, largely due to year-to-year variety shifts even at the same experimental site. To address this variability, these 14 Southern varieties were grouped into three genetic parameter sets based on their administrative regions. Employing regionally representative wheat varieties in crop model could also ensure simulation accuracy (Chen et al., 2021).

The DSSAT-CERES-wheat model was calibrated using the least square method in R language at each of the experimental sites. The study used Optim () based on R language version 4.3.3 to automatically calibrate and verify variety parameters (He et al., 2024; Jiang et al., 2022). The R language codes for the automatic calibration of winter-wheat variety parameters in the DSSAT-CERES-Wheat model can be found at <https://doi.org/10.5281/zenodo.19183690>. For each wheat variety, experimental data from one randomly selected year at each planting location were used to calibrate the model, and data from the remaining years were used for validation. These two datasets were kept mutually independent. Validation indicators include winter wheat yield and phenology (anthesis and maturity dates) obtained from field experiments. First, the phenological parameters (i.e., P1V, P1D, P5) were calibrated. Then, after the validation of phenological parameters, the yield-related parameters were calibrated and validated. Next, the

standard errors of the simulation results were calculated, so as to quantify the degree of uncertainty in the simulation results (Table S3). Finally, the model performance was evaluated under different regions and crop managements (Figure S2).

The strength of correlation and consistency between simulated and observed values was evaluated using the coefficient of determination ( $R^2$ ; Eq. 4), root mean square error (RMSE; Eq. 5), and Normalized RMSE (NRMSE)—calculated as RMSE relative to the observed mean (Eq. 6).

$$R^2 = \left( \frac{n(\sum xy) - (\sum x)(\sum y)}{\left[ n \sum x^2 - (\sum x)^2 \right] \left[ n \sum y^2 - (\sum y)^2 \right]} \right)^2 \quad (4)$$

$$RMSE = \left[ \left( \sum (x - y)^2 / n \right) \right]^{0.5} \quad (5)$$

$$NRMSE = \left[ \left( \sum (x - y)^2 / n \right) \right]^{0.5} / M_{mean} \times 100\% \quad (6)$$

where  $x$  and  $y$  represent the simulated and observed values, and  $n$  represents the number of paired values.  $R^2$  close to 1 and RMSE and NRMSE close to 0 indicate a good agreement between simulated and observed values. Then, the verified cultivar parameters were used in model simulations at spatial grids. For each given grid, the wheat cultivar parameters were set as same as the cultivar at the closest experimental site.

Nitrogen use efficiency (NUE; kg wheat grain per fertilizer applied; Eq. 7) is a crucial metric to examine the N cycling and inform N management practices (Panel, 2015; Quan et al., 2021). It assesses the efficiency of N utilization in crop production and its potential environmental impacts. In this study, NUE were calculated for the crop management levels of FP (Farmer practice) and HYPE (High-efficiency practice). This study evaluated the NUE in the three main winter-wheat producing regions in China in the baseline period and after a projected 1°C temperature rise, which enabled the comparisons of winter wheat yields and NUE before and after the optimization of crop management practices.

$$NUE = (G_N - G_{Basicsoilfertility}) / F_N \quad (7)$$

where  $G_N$  is the grain yield with applied N fertilizer ( $\text{kg ha}^{-1}$ );  $G_{Basic soil fertility}$  is the crop yield without N application ( $\text{kg ha}^{-1}$ );  $F_N$  is the amount of N fertilizer applied ( $\text{kg ha}^{-1}$ ).

## 2.6. Elasticity coefficient of yield and NUE

In this study, the aim of crop management optimization was to enhance both yield and NUE of winter wheat production in China. Irrigations are necessarily needed in the Huang-Huai-Hai region and Xinjiang to ensure normal growth of winter wheat. Thus, there were no great differences in the irrigation depths in winter wheat productions in these two regions. Meanwhile, winter wheat is rain-fed in the Southern region due to sufficient rainfall. Actually, some previous studies also showed that the differences in the water use efficiency of winter wheat were relatively small under different management practices in China (Gong et al., 2025; Zhang et al., 2017; Zhong and Shangguan, 2014). However, the final grain yields and NUE could be influenced by various factors (Li et al., 2020; Salim and Raza, 2020), leading to varying yield-NUE relationships across China's three main winter-wheat producing areas. Some regions may both have increased yield and NUE, while other regions might only have increased yield but unchanged or even decreased NUE. First, we calculated the relative changes of yields and NUE of winter wheat compared with the crop management level of FP (Farmer practice; Eq. 8), which helped separate the impacts of optimized crop management practices on the yield and NUE of winter wheat across different spatial regions and time periods. Next, the yield NUE elasticity coefficient (YNEC), which was defined as the ratio of the rate of yield change to the rate of NUE change during the winter-wheat

growing seasons after crop management optimization. Based on the changes of YNEC coefficient, the coupling relationship between yield and NUE can be explained. The YNEC value greater than 0 indicates that grain yield and NUE increase together, suggesting that optimized crop management practices could both positively impact the two metrics. Conversely, the YNEC value less than 0 indicates that the trends of yield and NUE are opposite after the crop management optimization. For example, if  $(NUE_{HEPi} - NUE_{FPi}) < 0$ , it means optimized crop management practices could boost the yield, but also lead to a decrease of NUE in winter wheat production.

$$YNEC = \frac{(Y_{HEPi} - Y_{FPi}) / Y_{FPi}}{(NUE_{HEPi} - NUE_{FPi}) / NUE_{FPi}} \quad (8)$$

where  $i$  is the number of grids of wheat producing areas in China (Fig. 1b);  $Y_{HEPi}$  and  $Y_{FPi}$  are winter wheat yields at the crop management levels of HEP (High-efficiency practice) and FP (Farm practice) in grid  $i$ ;  $NUE_{HEPi}$  and  $NUE_{FPi}$  are the NUE at the crop management levels of HEP (High-efficiency practice) and FP (Farm practice) in grid  $i$ . The variation trend of YNEC was analyzed by calculating the trend slope using Sen's slope estimation method, and the existence of a significant variation trend was determined via the Mann-Kendall non-parametric rank correlation test. Specifically, the data analysis and test were implemented using the `mk.test()` and `sens.slope()` functions from the "trend" package in R.

## 3. Results

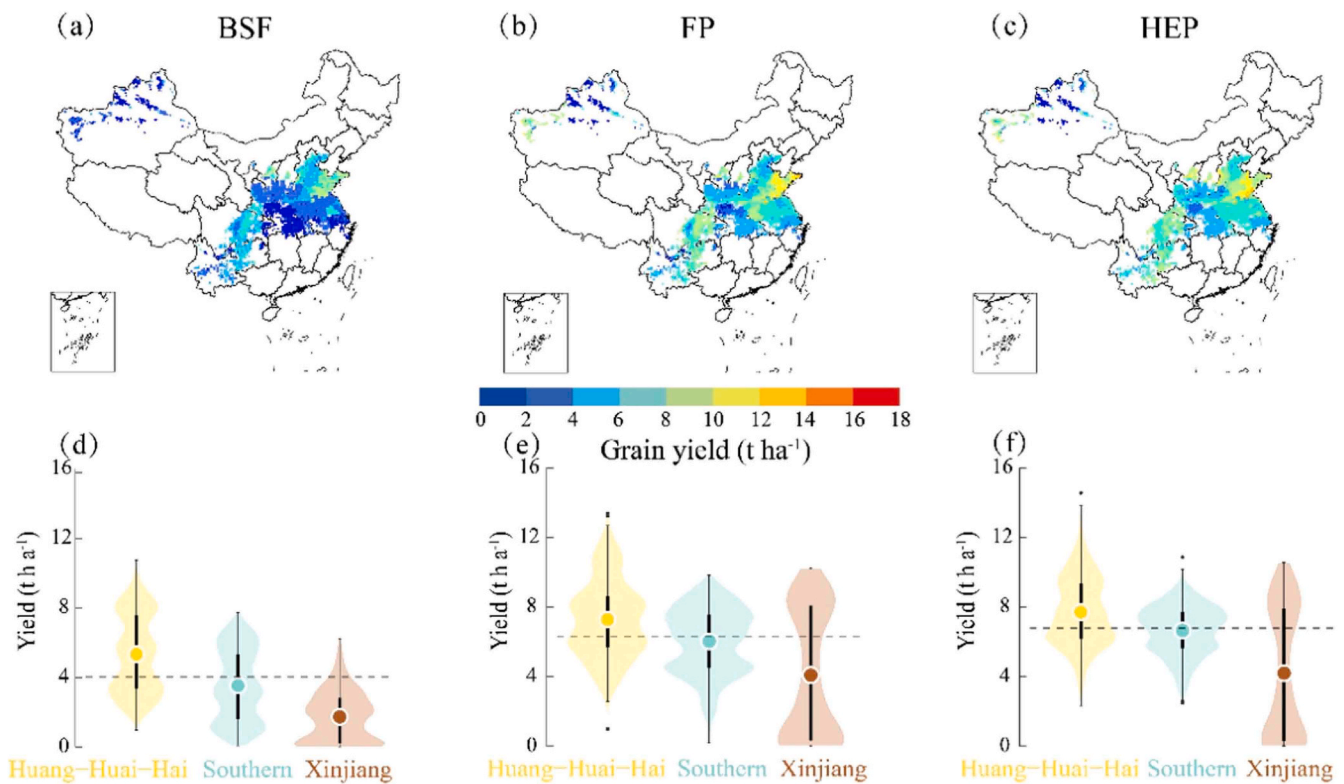
### 3.1. Climate warming trends in main winter-wheat producing regions in China

So far, the main winter-wheat producing areas in China remain concentrated in the Huang-Huai-Hai region (about 60% of national total area; dominated by wheat-corn rotations) and the Southern region (about 36%; characterized by rice-wheat rotations). To investigate how climate warming may affect these key winter-wheat producing areas, we first analyzed the projected shifts in average temperatures by multiple CMIP6 global climate models (GCMs). The changes of annual average temperatures relative to the baseline period of 2017–2019 were explored under different SSPs (Shared socioeconomic pathways) and future periods in the three main winter-wheat producing regions of China (Fig. S3). It was found that the average annual temperature was about 13.5°C during the baseline period. In the future, the average annual temperatures showed increasing trends both under SSP245 and SSP585 scenarios, but the increasing rate under SSP585 was obviously higher than that under SSP245. The time points were determined when future average annual temperatures increased by 1°C compared to the baseline period, which would be the year of 2047 under SSP585 and 2072 SSP245. Thus, the SSP585 scenario would reach this point of 1°C rise about 25 years earlier than the SSP245 scenario.

### 3.2. Spatial distributions of winter wheat yield at different levels of crop management practices in the baseline period

According to the results of field experiments, winter wheat yields varied greatly across different experimental sites and the effects of optimized crop management practices on wheat yield improvement also varied. The experimental results across the whole country showed that the optimized crop management practices could increase winter wheat yields by about 13.2% (Fig. S3). Nonetheless, these results solely reflect conditions specific to the experimental years at the study sites.

To understand the national situation over long future periods, we conducted detailed spatial and temporal model simulations of winter wheat yields across different winter-wheat producing regions in China. First, we conducted spatial simulations of winter wheat yields in the baseline period and studied the spatial distributions of winter wheat



**Fig. 2.** Spatial distributions of winter wheat yields simulated at the crop management levels of BSF (Basic soil fertility; a), FP (Farmer practice; b), and HEP (High-efficiency practice; c) in China in the baseline period of 2017–2019 (a–c) and the comparisons between winter wheat yields at different crop management levels and across China's main winter producing regions of the Huan-Huai-Hai, the Southern, and the Xinjiang (d–f).

yields at different levels of crop management practices (Fig. 2). The results showed spatial variations in winter wheat yields at different levels of crop management practices, with generally higher yields in the North China Plain in the Huang-Huai-Hai region and lower yields in the central and southern areas in China. Especially in the Xinjiang region, there were great disparities and uneven distribution of winter wheat yields across different areas. Under the BSF (Basic soil fertility) conditions, namely without fertilizer input, the North China Plain in the Huang-Huai-Hai region still had relatively higher winter wheat yields. This was because as the largest winter wheat producing area in China, the North China Plain is a traditional winter wheat cultivation region with wheat-corn rotation system (Wu et al., 2006). Thus, long-term high N fertilizer input in this region resulted in high N content in the soil. The well-selected winter wheat varieties and natural conditions in this region also contributed to the relatively higher yields even without N fertilizer input.

The Southern region has higher level of precipitation, thus winter wheat cultivations are mainly rain-fed. The main factors limiting winter wheat yields in this region were the varieties planted, as well as temperature and solar radiation during the winter wheat growing seasons. The Xinjiang region had the lowest winter wheat yields under the BSF (Basic soil fertility) conditions since it is an arid region of China. Although light and temperature resources are abundant, high evapotranspiration (ET) could lead to serious water shortage during winter wheat growing seasons in this region (Li et al., 2011). Additionally, winter wheat yields remained very low without optimized crop management practices.

Through the optimization of crop management practices, the overall national winter wheat yields increased and the spatial yield different approaching in the baseline period (Fig. 2). the gridded winter-wheat yields were then simulated and compared in different winter-wheat producing regions. The results showed that at the three levels of crop

management practices, winter wheat yields were the highest in the Huang-Huai-Hai region, followed by the Southern region, while the lowest in the Xinjiang region. At regional level, the average winter-wheat yields with traditional crop management were about 7.66 t ha<sup>-1</sup> in the Huang-Huai-Hai region, 6.04 t ha<sup>-1</sup> in the Southern region, and 4.14 t ha<sup>-1</sup> in the Xinjiang region in the baseline period.

### 3.3. Spatial distributions of projected winter wheat yield under 1°C temperature rise in the future

The changes of winter wheat yields were then simulated at different levels of crop management practices under 1°C temperature rise in the future. It was found that the annual average temperatures would increase by 1°C in the year of 2047 under SSP585 and in 2072 under SSP245 scenarios in the main winter-wheat producing region in China, respectively (Fig. S4). Through comparing the distribution dispersion of simulated yields under different GCMs, it indicated that the simulation results based on different GCMs were close to each other. Thus, the average of the simulation results based on the nice GCMs would be used as the future prediction result. In this study, the predictions of winter wheat yield also considered the impacts of changes in CO<sub>2</sub> concentration, rainfall, and radiation caused by future climate change. The average winter wheat yields weighted by planting density were obtained in China (Fig. S6). In the baseline period, winter wheat yield per unit area in China decreased year by year in 2017–2019. However, the projection results indicated that winter wheat yields would continue increasing after the year of 2020 at the crop management levels of FP (Farmer practice) and HEP (High-efficiency practice). Under the SSP585 scenario, the national winter wheat yield growth rate exhibited a pronounced acceleration compared to that under SSP245. Furthermore, the rate of winter-wheat yield increase was slightly higher after the optimization of crop managements than that with the farmer management

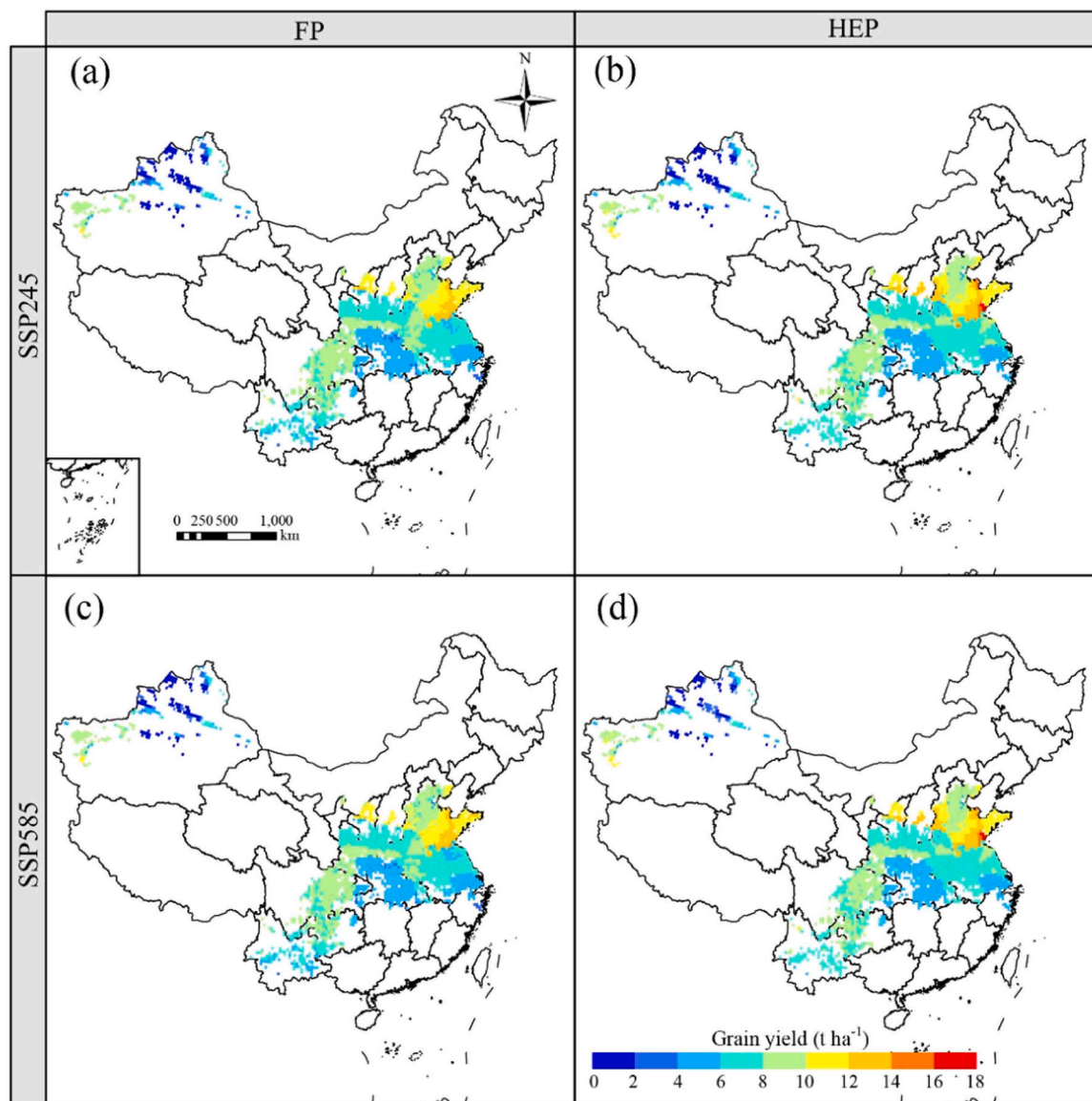
practices at the national level.

The projection results showed that under a future temperature increase of 1°C under both the SSP245 and SSP585 scenarios, national winter wheat yields would increase to about 8.5 t ha<sup>-1</sup> and 8.9 t ha<sup>-1</sup> at the FP (Farmer practice) and HEP (High-efficiency practice) levels, respectively. This represented a 22% yield increase compared to the baseline period. This indicated that a future temperature rise of 1°C would benefit winter wheat yield improvement in the main winter-wheat producing regions in China. Additionally, the spatial distributions of projected winter wheat yields were similar under the two future scenarios of SSP245 and SSP585 (Fig. 3). Projected winter wheat yields after the crop management optimization were obviously higher than those with the traditional farmer crop managements, but the extents of yield increase varied across different regions. Winter wheat productivity in the central-eastern segment of the Huang-Huai-Hai region exceeded 16 t ha<sup>-1</sup>, which traditionally were the areas with the highest winter wheat yields in China. Additionally, some areas in the Xinjiang region had lower winter wheat yields, indicating that the crop management

optimization could not remarkably increase winter wheat yields in these areas since local yields were primarily determined by the environmental factors such as precipitation and temperature.

### 3.4. Winter wheat yield improvement through crop management optimization

We calculated the changes in national winter wheat yields with the optimized crop management practices compared to traditional farmer practices. The yield changes were defined as the yield gap of winter wheat in the given regions. The magnitude of yield gap reflected the effectiveness of crop management optimization in enhancing winter wheat yields. The results of three-year field experiments in this study showed obvious differences in the improvement of winter wheat yields with optimized crop management practices in different main winter-wheat producing regions (Fig. S3). However, these results only reflected the yield gaps for the specific given years and sites of field experiments. To understand national winter wheat yields under future



**Fig. 3.** Projected winter wheat yields during a future temperature increase of 1°C under the SSP245 (2021–2072; a, b) and SSP585 (2021–2047; c, d) scenarios at two crop management levels of FP (Farmer practice; a, c) and HEP (High-efficiency practice; b, d) across three main winter-wheat producing regions (the Huang-Huai-Hai, the Southern, and the Xinjiang region) in China. Data presented are the mean values projected based on the future climatic data derived from the nine selected global climate models (GCMs). All values in the grids are reported on a per-harvest basis and are mapped at the grids.

climate change scenarios, more detailed temporal and spatial projections were conducted. The projection results in the baseline and future periods showed that the effects of optimized crop management practices on winter-wheat yield improvement was generally similar across different main winter-wheat producing regions in China (Fig. 4). Winter wheat yields at the HEP (High-efficiency practice) level reduced particularly in the Shandong Peninsula and central areas. This was because both yield and N use efficiency improvements were considered in the field experiment design. However, it was impossible to simultaneously increase winter wheat yield and improve N use efficiency in some regions. This also reflected the fact that field experiments could not fully capture the actual winter-wheat production simulations in large planting areas, whereas up-scaling simulations of winter wheat yields with crop models could reflect the spatial differences of winter wheat yields at different crop management levels.

In the baseline period of 2017–2019, the HEP (High-efficiency practice) level could increase winter wheat yields, with the highest increase of about 10.4% in the Southern region, followed by 3.1% in the Huang-Huai-Hai region and 2.2% in the Xinjiang region (Fig. 7a). Generally, the national average winter-wheat yields increased by about 5.2% through the optimization of local crop management practices. The projection results of future winter wheat yields indicated that the national winter wheat yields could increase by 5.5% under the future climate warming scenario of SSP245, slightly higher than that under the SSP585 scenario. Among the three different main winter-wheat producing regions, the yield gap in the Southern region was greatly higher than those in the Huang-Huai-Hai and Xinjiang regions. Thus, the Southern region could achieve higher winter wheat yields through crop

management optimization. The average yield gap of winter wheat in the Xinjiang region was the smallest, which indicated that the current crop management practices were not the most important limiting factor for winter wheat yields in this region. The projection results indicated that a future temperature increase of 1°C would generally raise the yield levels of winter wheat. Additionally, crop management optimization would further increase winter wheat yields in most winter wheat producing regions in China.

### 3.5. Relative changes of NUE with optimized crop managements

Overall, the NUE (Nitrogen use efficiency) in winter wheat production after the crop management optimization was obviously higher than that with traditional farmer management practices. The NUE in the central and eastern parts of the Southern region was relatively higher, but was lower in the Huang-Huai-Hai region, southwest part of the Southern region, and Xinjiang region. The results of future projections indicated that the spatial distribution of NUE remained largely unchanged under both climate scenarios (Fig. 5). The average NUE values of different regions showed that both in the baseline and the future periods, the Southern region had the highest NUE, followed by the Xinjiang and the Huang-Huai-Hai regions (Fig. 6). Although the Huang-Huai-Hai region had the highest winter wheat yield, its winter wheat yields without fertilization were also much higher than the other regions, which led to the lowest NUE in this region. The results of future projections indicated that NUE would also increase nationally with the rising temperatures. In the Southern region with optimized crop management practices, the NUE could exceed 23 kg kg<sup>-1</sup>. Notably, the NUE

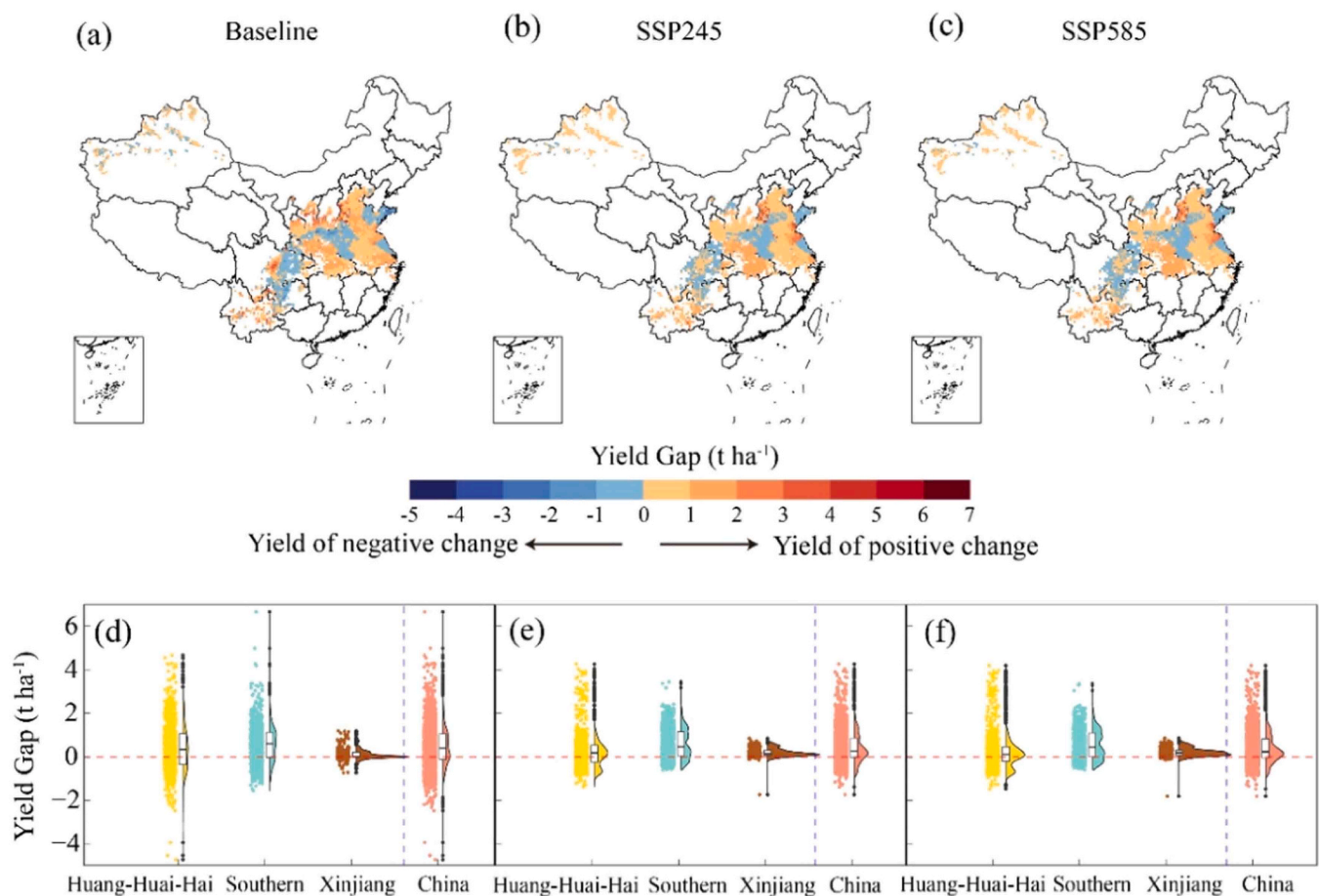


Fig. 4. Spatial distributions of average yield gaps of winter wheat in the baseline period of 2017–2019 (a), under the future scenarios of SSP 245 (b) and SSP585 (c) in China. Average yield gaps of winter wheat were also compared in the three different main winter-wheat producing regions (the Huang-Huai-Hai, Southern, and Xinjiang region) and the whole country of China (d-f).

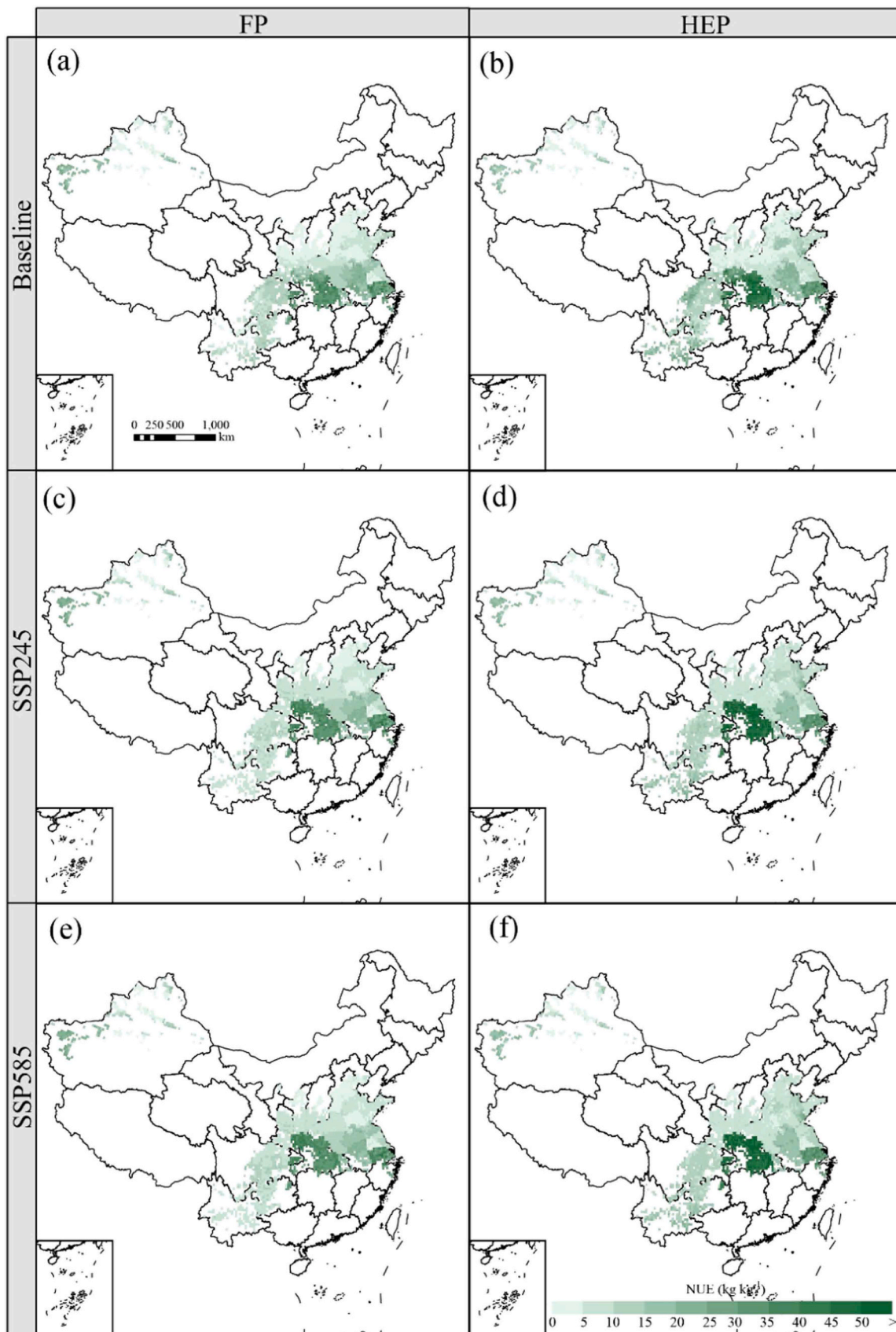
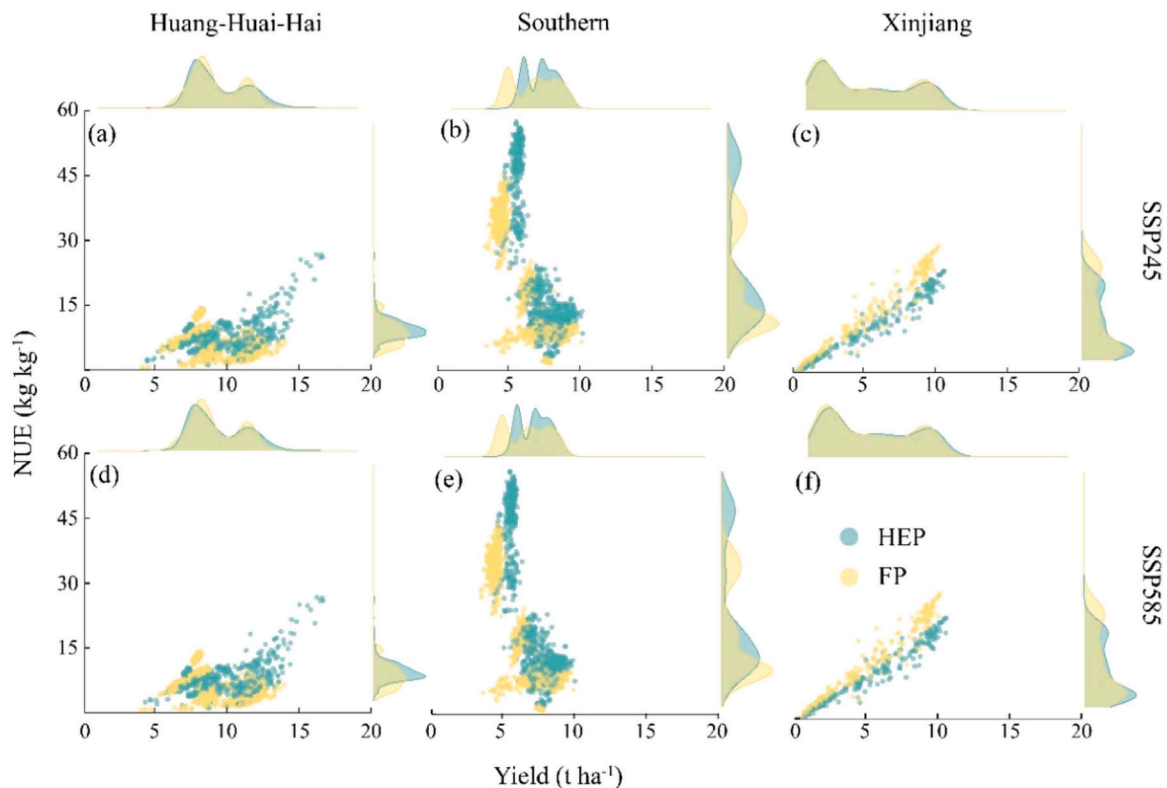


Fig. 5. NUE as absolute values for winter wheat productions at different levels of crop management practices in main winter-wheat producing regions in China in the baseline period of 2017–2019 (a, b), under the scenarios of SSP245 (2021–2072; c, d) and SSP585 (2021–2047; e, f).



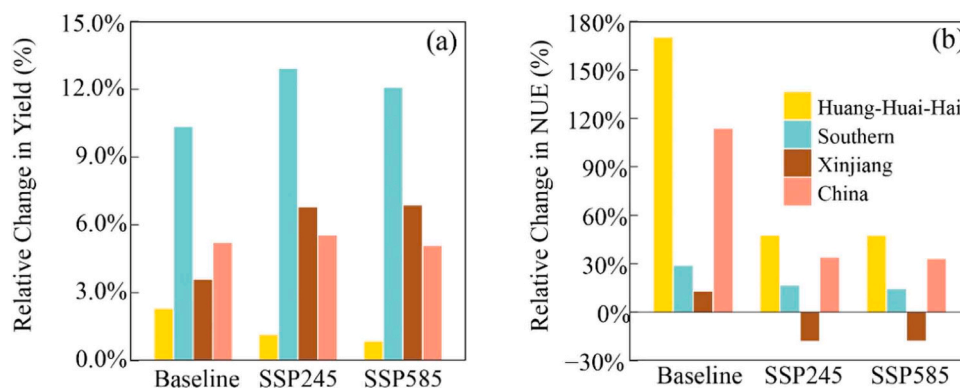
**Fig. 6.** Values of yield and NUE in the grids of main winter-wheat producing regions of the Huang-Huai-Hai (a, d), Southern (b, e), and Xinjiang (c, f) in China at different crop management levels of FP (Farmer practice) and HEP (High-efficiency practice) when temperature would increase by 1°C under the SSP245 (a, b, c) and SSP585 (d, e, f) scenarios in the future. Each value point is the annual average of a given grid.

in the Xinjiang region decreased with increased N fertilizer input, which indicated that increasing N fertilizer could only increase yield in the Xinjiang region. This phenomenon arises because Xinjiang, as an extremely arid region in China, nonetheless benefits from favorable solar radiation, thermal conditions, and soil quality. Consequently, augmenting N fertilizer inputs in this area can narrow yield gaps while reducing NUE.

The distributions of projected NUE and yield values in the grids were compared between traditional farmer practices and the HEP (High-efficiency practice) practices. The results showed that the increase of NUE was remarkably higher than the increase of winter wheat yields in the Huang-Huai-Hai region under both future scenarios (Fig. 6). In the Southern region, crop management optimization could simultaneously increase the yields and NUE in future wheat production. In the Xinjiang

region, the effect of crop management optimization on winter-wheat yield improvement was not obvious, but it could decrease NUE in this region. This was because in this study the optimization of crop management practices in the field experiments more focused on improving water use efficiency (WUE) in Xinjiang since water resource shortage is the most limiting factor for winter wheat production in this region. However, these measures were probably not suitable for the goals of high yield and NUE in winter wheat production in Xinjiang.

Then, the relative changes of NUE were compared before and after the optimization of crop management practices. The relative changes of NUE were unlike the relative changes of winter wheat yields under future climate change scenarios (Fig. 7b). The highest increase of NUE was in the Huang-Huai-Hai region after crop management optimization, followed by the Southern region and the Xinjiang region. Under a



**Fig. 7.** Relative changes in the yields (a) and NUE (nitrogen use efficiency; b) at the crop management levels of FP (Farmer practice) and HEP (High-efficiency practice) during the baseline period (2017–2019) and two future scenarios of SSP245 and SSP585 in three main winter-wheat producing regions (the Huang-Huai-Hai, Southern, and Xinjiang regions) in China.

temperature increase of 1°C in the future, at the crop management levels of FP (Farmer practice) and HEP (High-efficiency practice), the relative change of national average NUE decreased from 114% in the baseline period to 34% under the SSP245 scenario and 33% under the SSP585 scenario. The results of future projections showed a NUE decrease of 18% in the Xinjiang region. The relative change of NUE in the Xinjiang region would be negative after a temperature increase of 1°C (18%), which means that crop management optimization would reduce NUE in the Xinjiang region in the future.

### 3.6. Yield and NUE elasticity coefficient of winter wheat production in China

So far, the main goal of winter wheat production was to simultaneously increase winter wheat yield and improve NUE in China. In this study, the YNEC (Yield NUE elasticity coefficient) coefficient was calculated for winter wheat production after the crop management optimization. The spatial distributions of YNEC coefficients were analyzed in China in the baseline period (2017–2019) and after a temperature increase of 1°C in the future (Fig. 8). The results showed that the YNEC coefficients spatially had both positive and negative values in the main winter-wheat producing regions of China, which indicated that crop management optimization could only increase wheat yield or only improve NUE in many winter-wheat producing areas. In this study, the designed optimization methods of crop management practices in the field experiments could not simultaneously increase winter wheat yields and nutrient use efficiency in many grids. Spatially, the future projections of YNEC under the two scenarios were similar to those in the baseline period. In some southeast and Xinjiang areas, the YNEC coefficients were negative, indicating these areas could only increase yield or NUE through current methods of crop management optimization. However, in most areas of the Huang-Huai-Hai region and the central parts of the Southern region, crop management optimization could obviously increase wheat yield and improve NUE at the same time.

The temporal changes of YNEC coefficients were compared across China's main winter producing areas (Fig. 9). Great interannual fluctuations in YNEC coefficients indicated that the climatic conditions in different years could directly affect the influences of crop managements on the yields and NUE in winter wheat production. In the Xinjiang region, there were remarkable fluctuations in YNEC coefficients (mostly negative) across different years, indicating that climatic conditions in this region could greatly affect the synergistic influences of crop management practices on the yields and NUE in winter wheat production. In the future, the YNEC coefficients in the Huang-Huai-Hai and Southern regions were generally positive and the future fluctuations were relatively small. This indicated that the main winter wheat producing regions in China could simultaneously increase wheat yields and nutrient efficiency through crop management optimization in the future.

Additionally, the future change rate of YNEC coefficients indicated that only the Huang-Huai-Hai region showed an obvious upward trend under the SSP245 scenario (Fig. 9a). However, in other regions and under other climate scenarios, the YNEC coefficients showed a downward trend after crop management optimization in the future. This suggested that future climate change had less influences on the simultaneous improvements of yields and NUE in winter wheat production in China, but inter-annual climate fluctuations had greater impacts.

## 4. Discussion

### 4.1. Contributions of crop management optimization to winter wheat yields in China

As the world's largest wheat-producing nation, China's winter wheat output holds pivotal significance for stabilizing the global wheat supply-demand equilibrium. Key factors influencing crop growth include genotype, environment, and management practices. Among the crop

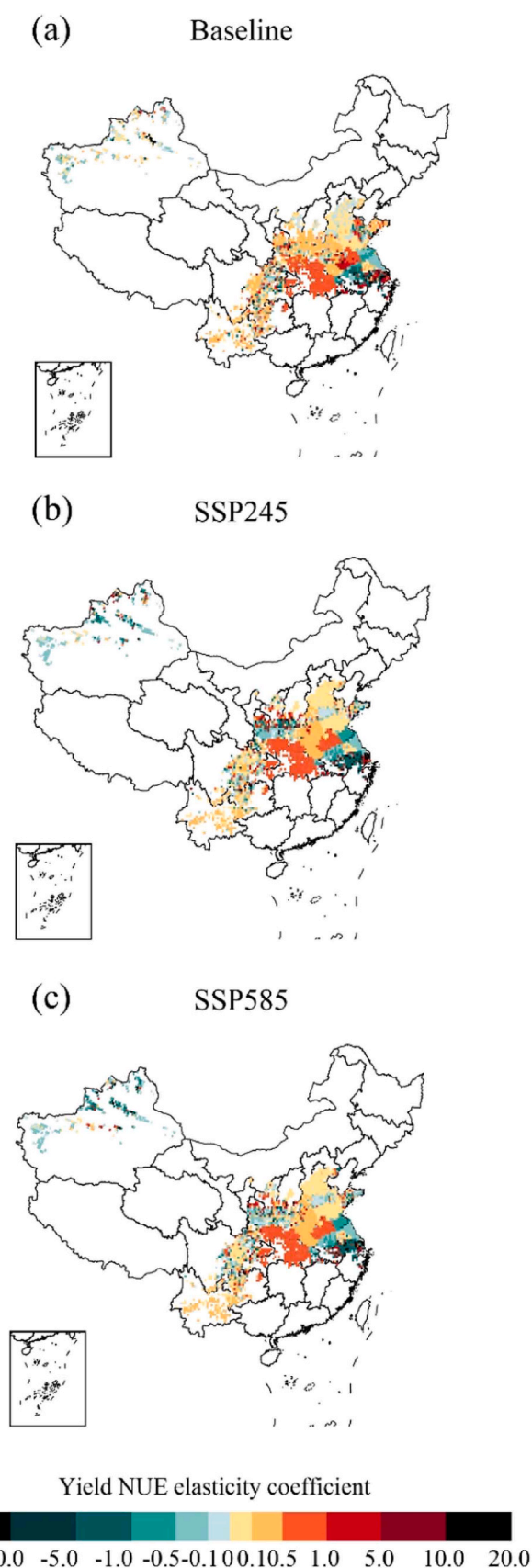
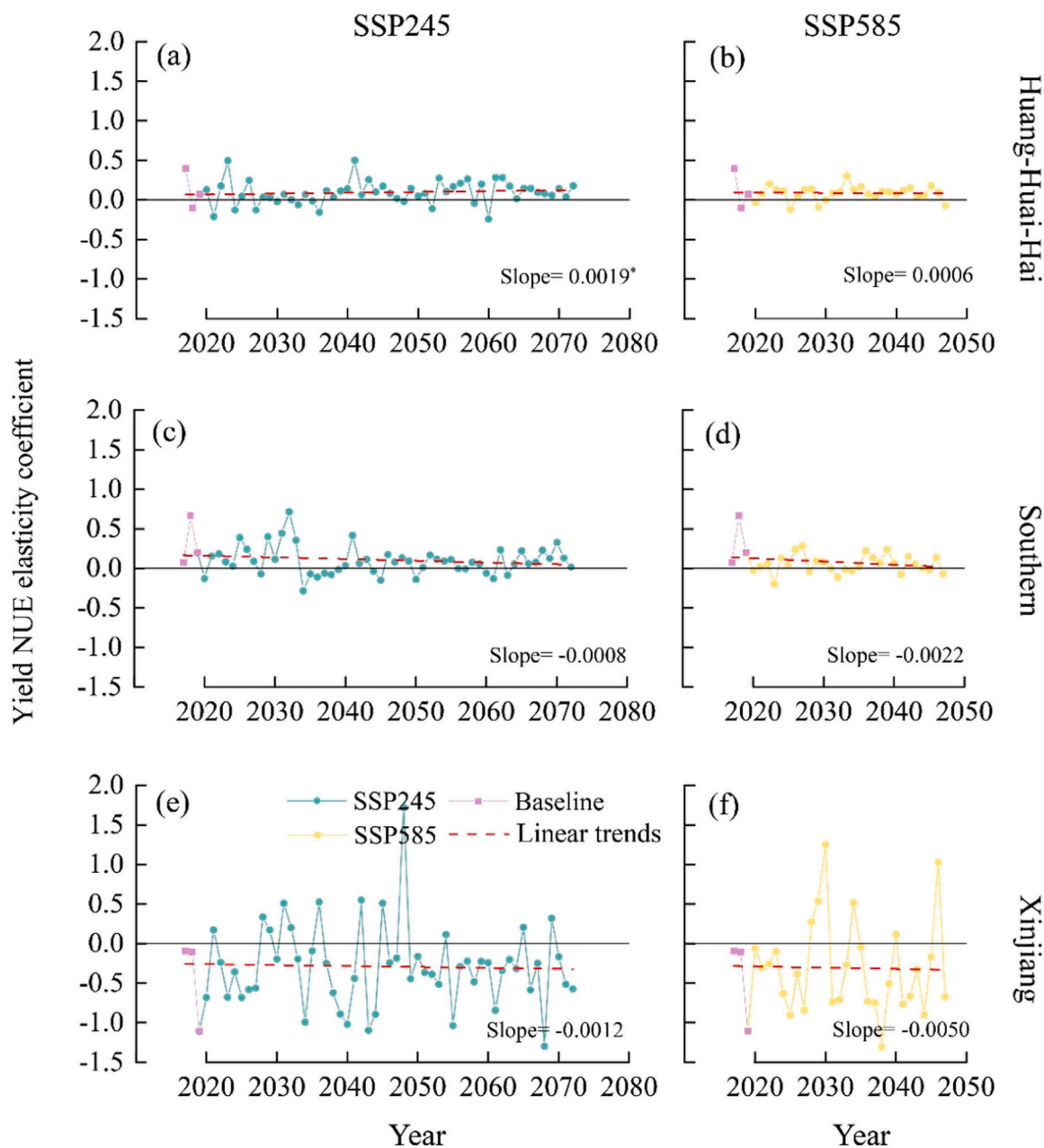


Fig. 8. YNEC (Yield NUE elasticity coefficient) values in the baseline period (a) and under the SSP245 (2021–2072; b) and SSP585 (2021–2047; c) scenarios across China's main winter producing regions in China.



**Fig. 9.** Trends of YNEC (Yield NUE elasticity coefficient) in the baseline period and under the SSP245 (2021–2072; a, c, e) and SSP585 (2021–2047; b, d, f) scenarios at different levels of crop management practices in the three main winter-wheat producing regions of the Huang-Huai-Hai (a, b), Southern (c, d), and Xinjiang (e, f) in China.\* or \*\* are significantly different at  $P < 0.05$  or  $P < 0.01$ , respectively.

managements, planting density, the amount and timing of fertilizer application, and the depth and scheduling of irrigation are particularly crucial and contributed greatly to the past increases in winter wheat yields (Zhang et al., 2016). Hence, understanding and quantifying the impacts of optimization of the current crop managements on winter wheat yields is vital for boosting wheat production and ensuring national food security in China. Through combining field experiments and crop model simulations, this study investigated how the crop management optimization would enhance wheat yields, improve nutrient use efficiency, and help adapt to future climate change for winter wheat production in China.

The results indicated that crop management optimization was highly beneficial to winter wheat production in China both under the current and future climate conditions. Under the current climate conditions, the simulated national average yield of winter wheat was about  $6.94 \text{ t ha}^{-1}$

at the FP (Farmer practice) level, while the average yield rose to about  $7.31 \text{ t ha}^{-1}$  after the crop management optimization. Chinese statistical data showed a national average winter wheat yield of  $5.75 \text{ t ha}^{-1}$  in 2017–2019. This kind of discrepancy was because the farmer management practices in this study were based on the survey in the areas with the highest planting densities across the different winter-wheat growing regions in China. This suggested that the areas with lower planting densities usually had more room for crop management optimization.

The impacts of crop management optimization were closely related to climate and geographical conditions. The results of this study confirmed that the crop management optimization could lead to the highest increases of winter wheat yields in the rice-wheat rotation system in the Southern region of China. This was probably due to the greater emphasis on rice production than on wheat production in this region, since rice was the local staple food and more lucrative (Deng

et al., 2019). The gradual adoption of later-maturing rice varieties delayed winter wheat planting dates and reduced wheat yield (Liu et al., 2022). Therefore, optimizing wheat sowing date could obviously increase winter wheat yields (Zhang et al., 2008). Additionally, some field experiments in this region showed that optimizing water and fertilizer management practices could also dramatically improve winter wheat yields. Meanwhile, it was also found that the distributions of national winter-wheat yield differences after a future temperature rise of 1°C was similar to the baseline period of 2017–2019. Numerous studies showed that the trend of climate warming was beneficial to winter wheat production in China. This was mainly because the warming climate aligned better with the suitable temperature range in winter wheat growing seasons, and increased rainfall and CO<sub>2</sub> levels also favored winter wheat yields (Jägermeyr et al., 2021; Yang et al., 2015). Thus, this study elucidated that due to the G×M×E (gene × management × environment) interactions in winter wheat production in China, the environmental factors could promote winter wheat yields and crop management optimization could further enhance winter wheat yields even if the currently cultivated wheat varieties remained unchanged in the future.

#### 4.2. Contribution of crop management optimization to NUE

The new findings of this study revealed substantial potential for improving NUE in winter wheat production across China, although this potential was unevenly distributed. The crop management optimization in the Huang-Huai-Hai region showed limited potential for yield improvement but the highest potential for NUE enhancement. This was consistent with other previous studies and possibly due to the fertilization effect of increased CO<sub>2</sub> levels (Kimball, 2016). The high basic soil fertility in the Huang-Huai-Hai region made winter wheat yields more susceptible to the increased CO<sub>2</sub> levels. Unlike yields, climate change would likely diminish the positive impacts of crop management optimization on NUE in China, which is consistent with findings from several studies on other crops in this region (Liu et al., 2020). The order of NUE improvement under different scenarios was: baseline period > SSP245 > SSP585. This was probably because higher temperatures and CO<sub>2</sub> concentrations would benefit winter wheat yields, resulting in a decrease in NUE. Additionally, climate change would increase rainfall. When N application coincided with heavy rainfall, surface runoff and leaching would increase N loss and reduce NUE (Liang et al., 2017). Thus, similar to previous studies, improving NUE in the Huang-Huai-Hai region by crop management optimization could help mitigate the negative effects of climate change and promote sustainable agriculture (Cui et al., 2014; Martre et al., 2024; Zhang et al., 2022).

In the Southern region, crop management optimization primarily involved increasing N input (Fig. S3). This region traditionally focused on rice cultivation and invested less in wheat farming. Thus, winter wheat production mainly relied on rain-fed conditions without irrigation. Consequently, increased N input through crop management optimization could lead to obvious yield improvement, but the effect on NUE enhancement was limited. In the Xinjiang region, this study showed that higher N inputs would be necessary to further increase winter wheat yields, even at the expense of reduced NUE. The results indicated a decline in NUE in the Xinjiang region after crop management optimization. The climate in Xinjiang is characterized by high solar radiation and one of the highest evapotranspiration rates in China. As a result, advanced drip irrigation technology was adopted and high irrigation levels were employed in this region to maximize water use efficiency (Heng et al., 2018; Rao et al., 2021). To fully exploit the solar radiation for high crop yields in this region, future strategies of crop management optimization should prioritize wheat yield over resource use efficiency. In general, this study showed that crop management optimization should not solely focus on water or nutrient use efficiency but should also consider other factors including the environmental conditions and traditional crop management practices to obtain the best results.

#### 4.3. Synergistic effects of crop management optimization on wheat yield and NUE

Compared with other countries, the synergistic relationship between the yields and NUE of winter wheat production is unique in China. This study demonstrated that crop management optimization could simultaneously achieve high winter-wheat yields and increase resource use efficiency, which aligned with the results from many field experiments (Cai et al., 2023; Duan et al., 2019). For instance, the Huang-Huai-Hai region, as a major winter-wheat producing region in China, supplied about 50% of the national winter wheat yields. Some field experiments in this region suggested that the total annual N fertilizer application for the wheat-maize rotation system could be reduced from 600 to 330–420 kg ha<sup>-1</sup>, and irrigation level could be reduced by 240–350 mm yr<sup>-1</sup> but without great yield compromise (Wang et al., 2023b). In the Xinjiang region, crop management optimization could simultaneously reduce N fertilizer input and increase winter wheat yield by about 2% (He et al., 2022). However, due to the variations in climate and soil conditions, there were considerable uncertainties in the effectiveness of the crop management optimization across different winter-wheat producing regions in China.

This study analyzed the variations and distributions of the YNEC (Yield NUE elasticity coefficient) coefficients in three different winter-wheat producing systems (wheat-maize rotation, wheat-rice rotation, and drip-irrigated wheat) in China based on the data from field experiments and crop model simulations. The new findings in this study revealed that due to the vast territory, diverse landscape, various environmental conditions in China, there was an interleaving distribution of YNEC coefficients even within the same region. Several previous researches indicated that simply altering N application rate would be insufficient to simultaneously increase the yields and NUE in winter wheat productions. Based on field experiments and gridded model simulations, this study confirmed that crop management optimization could simultaneously enhance the yields and NUE in winter wheat production. This kind of optimization included adjustments of N application rates and fertilization timing, sowing dates, planting densities, and irrigations in the Huang-Huai-Hai region and most areas of the Southern region.

A 1°C temperature increase in the future in main winter-wheat producing regions suggested that crop management optimization in the Huang-Huai-Hai region could help maintain winter wheat yield and reduce nitrogen input. This was because N input levels were almost saturated in this region (Cui et al., 2018). Thus, it could maintain relative high yields and significantly boost NUE in winter wheat production through moderately reducing N input, increasing irrigation level, and lowering planting density. Since this region is a traditional winter-wheat producing region with higher productions than the other regions (Lu and Fan, 2013), high planting densities and fertilizer use could cause water stress and reduced solar radiation use efficiency (Sangoi, 2001). In most areas of the Southern region, where YNEC was greater than 0, future crop management optimization could simultaneously increase winter wheat yields and improve nitrogen use efficiency.

This study underscored the critical importance of crop management optimization for winter wheat production amidst future climate change in China. To effectively implement crop management optimization, tailored strategies were suggested for different winter wheat producing regions. Crop growth simulation models were instrumental in this context, as they integrated the intricate processes and interactions among climate, soil, environment, and crop managements. This study quantified the potential benefits of crop management optimization on winter wheat yields, so as to offer concrete and effective solutions for sustainable agriculture development in China (Cai et al., 2023). Although we could not ascertain whether future climate changes would exactly align with the climatic trends projected in this study, it was found that crop management optimization could both simultaneously improve winter wheat yields or NUE in most regions in a warming

climate under various future climate change scenarios in China. Finally, based on the field experiments and data-driven approaches in this study, it showed that China could sustain high winter wheat yields and ensure efficient resource use under future climatic conditions through optimizing the crop management practices, such as sowing density, irrigation, and N fertilization.

## 5. Conclusions

Due to the influences of climate change on future winter wheat production in China, a temperature increase of 1°C was selected as the critical time point for climate change in the main winter-wheat producing regions of China. This study explored the potential of crop management optimization to promote the sustainable production of winter wheat in China under a 1°C temperature increase, based on a combination of field experiments and crop modeling simulations. The traditional crop management practices were compared with the optimized crop management practices for their influences on winter wheat productions. The results of this study indicated that winter wheat production in China still had substantial potential for yield and efficiency improvements based on the current crop management practices. Most importantly, although future climate change would benefit winter wheat production in China, crop management optimization was probably the most feasible and effective way to reduce fertilizer inputs and achieve higher yields for winter wheat production in China. Particularly in the Huang-Huai-Hai and the Southern regions, which encompass the majority of winter-wheat producing regions in China, crop management optimization could simultaneously increase the yields and improve NUE of winter wheat production.

The limitations of this study mainly include the following aspects. First, although this study achieved localized validation of model parameters based on multi-year site-specific experiments, the simulated yields cannot be completely consistent with the actual yields. This discrepancy could be attributed to the errors in yield measurements, the inherent structure of crop model, and the influential events such as extreme meteorological conditions, plant diseases, and insect pests. In particular, the increased likelihood of extreme climate events in the future could counteract the speed at which management measures were optimized. Therefore, although the research results can reflect the overall future change trends, they are unable to predict the impacts of uncertain events (e.g., extreme climate events) on future wheat production. Second, this study achieved spatial upscale simulation from experimental sites to the regional scale. However, due to factors such as distance, topography, and environmental conditions, simulation errors may vary across different regions. Furthermore, this study performed predictions under the assumption that current varieties remain unchanged; therefore, future variety improvement may further increase yields on the basis of optimized management practices. Based on the findings of this study, future researches are suggested as follows. First, the method of Ensemble Learning should be used for production prediction. Through the "stacking" approach and by assigning weights to the outputs of multiple "weaker" predictors, more accurate production prediction results could be obtained. Next, the accuracy of model simulations can be improved in the future by using higher-resolution data or data assimilation methods, thereby enhancing the reliability of predictions (Kheir et al., 2024b, 2025a, 2025b). Third, methods such as "chance-constrained fuzzy fractional programming" (Sun et al., 2020) can be adopted to analyze and predict the impacts of extreme climate events and variety improvement on crop production. These studies can further elaborate on the role of management practices in winter wheat production in China. Overall, this study provides guidance for future research, based on field experiments and crop model simulations, this study demonstrated that crop management optimization would be an effective strategy for winter wheat production to adapt to future climate change in China.

## CRediT authorship contribution statement

**Xiao Wang:** Data curation. **Yinghua Zhang:** Writing – review & editing, Software, Methodology, Investigation. **Yadong Luo:** Methodology. **Zhihao He:** Supervision, Methodology. **Liangbing Rong:** Data curation. **Xia Li:** Data curation. **Fengying Duan:** Data curation. **Jianqiang He:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Shuoqiu Ding:** Methodology. **Wenbin Zhou:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Kaiyuan Gong:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis. **Qiang Yu:** Supervision, Methodology. **Hao Feng:** Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

This research was partially supported by the National Natural Science Foundation of China (No. 52579046), the National Key Research and Development Program of China (No. 2021YFD1900700), and the National Key Research and Development Program of China (No. 2016YFD0300100).

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128183.

## Data availability

Data will be made available on request.

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