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Optimizing stubble returning rate in mulched farmland to balance trade-offs between greenhouse gas emission and maize yield under climate change

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ABSTRACT

Context: Plastic film mulching (PM) is a widely adopted technique for enhancing crop yield in arid and semiarid regions. However, the improved soil hydrothermal conditions under PM may accelerate the mineralization of soil organic carbon (SOC) and increase greenhouse gas (GHG) emissions. Concurrently, crop stubble return, while widely recognized for its benefits in improving soil properties and mitigating GHG emissions, has demonstrated inconsistent effects on crop yield. Given the individual advantages of these practices, their combined application may offer a sustainable agricultural approach to achieving high yields and low GHG emissions. It is important to investigate the long-term combined effects of stubble return and PM on SOC dynamics, crop productivity, and GHG emissions under future climate change scenarios.
Objective: We aim to investigate the novel synergy of PM combined with stubble return as a strategy to achieve high yield and environmental sustainability under future climate change.
Methods: The SPACSYS model was calibrated using seven years of field trial data to evaluate its precision in simulating yield, SOC dynamics, and GHG emissions in Yangling, northwest China. Our simulations utilized an ensemble of 27 global climate models across two emission scenarios (SSP245 and SSP585) from Coupled Model Intercomparison Project Phase 6 to drive the model. We explored multiple agronomic strategies, including 11 stubble return levels (from 0 % to 100 % in 10 % increments) and two mulching practices (no mulching and PM), to identify the optimal management practice under future climate change.
Results: The yields of the reference management (CK, without mulching and stubble return) are projected to decline by 20.3 % and 60.0 % under SSP245 and SSP585, respectively, during the 2080 s (2061–2100), compared to the baseline period (1981–2020). Additionally, SOC under the CK is expected to decrease by 23.6–29.7 % in the 2040 s and by 43.0–58.1 % in the 2080 s. An optimal scenario involving 100 % stubble return with PM (PM_R100) increases yields in the 2040 s and mitigates yield losses in the 2080 s under SSP585, compared to CK during the baseline. Furthermore, PM_R100 leads to an increase of 11.1–23.6 % in SOC during the 2040 s and

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alleviates SOC decomposition in the 2080 s under SSP585. PM_R100 also reduces global warming potential (GWP) compared to CK, transforming the dryland maize system into a carbon sink in the 2040 s.
Conclusions: PM combined with 100 % stubble return is the optimal practice to increase yield and SOC stock while reducing GWP. This approach effectively ensures high yields and promotes sustainable agriculture under climate change.
Significance: Our study underscores the significance of adopting stubble return practices in dryland rainfed areas where PM is applied. Our results are anticipated to assist farmers and policymakers in formulating effective mitigation and adaptation strategies to promote low-carbon sustainable agricultural development in dryland maize-growing regions under climate change.

1. Introduction

Climate change has garnered widespread concern due to its potential long-term impacts on environmental quality and agricultural productivity (Dhaliwal et al., 2022; Wang et al., 2022). The primary driver of climate change is emissions of greenhouse gas (GHG), with agriculture contributing around 20 % of the global total. From 2010–2019, global GHG emissions grew by 1.10 %, with roughly one-third of these emissions attributed to the food system (Crippa et al., 2021). Achieving equilibrium between enhancing productivity and preserving environmental sustainability poses a dual challenge for agricultural ecosystems (United Nations, 2019). It is thus crucial to identify effective solutions to enhance crop production and mitigate GHG emissions (Fan et al., 2024).

Plastic film mulching (PM) is now a commonly used technique to boost crop yield by regulating soil temperature and improving soil water storage in arid and semiarid regions (Zhang et al., 2023). However, enhanced soil hydrothermal conditions under PM could potentially hasten the mineralization of soil organic carbon (SOC) and elevate GHG emissions (He et al., 2018; Steinmetz et al., 2016). For example, Huo et al. (2017) conducted a four-year maize cultivation experiment under PM conditions and observed a 6.8 % reduction in SOC content within the top 40 cm of the soil profile. Lee et al. (2022) reported PM notably raised total CH_4 and N_2O emissions by 140–600 % and 4–61 %, respectively, compared to no mulching. There is no doubt that this management practice enhances yield; however, this improvement comes at the cost of soil health and environmental quality. On the other hand, numerous studies have demonstrated that stubble returning facilitates sustainable carbon sequestration, increasing SOC content and mitigating the adverse effects of GHG emissions (Bai et al., 2021; Xia et al., 2018; Zhang et al., 2022). For example, a study by Zhang et al. (2017) revealed that the combination of stubble incorporation and PM led to a 2.3 % increase in SOC stock based on multiple years of field trials, outperforming the impacts of using either PM or stubble incorporation independently. Zhang et al. (2022) observed stubble returning under PM significantly enhanced maize yield, SOC content, and water use efficiency. However, few studies have explored the development of a comprehensive approach that fully leverages the benefits of stubble retention and PM to investigate the effects of combined strategies on soil carbon sequestration, GHG emissions, and maize yield under future climate change scenarios.

Process-based biogeochemical models have the capability to simulate the response of carbon and nitrogen dynamics to agricultural management practices under climate change (Zhang et al., 2018). The SPACSYS (Soil–Plant–Atmosphere Continuum System) model, developed as a process-oriented and weather-driven agricultural tool, operates with multiple time steps, including daily intervals (Wu et al., 2019). This model offers comprehensive representations of the growth of plants along with the cycles of carbon and nitrogen (Wu et al., 2015). Additionally, it effectively quantifies the storage of SOC and the emissions of greenhouse gases, including CO_2, N_2O, and CH_4 (Liang et al., 2018; Wang et al., 2024b). Our earlier research demonstrated the model's effectiveness in simulating maize growth under mulching practices and its application in assessing the impact of climate change on maize production with plastic mulch (Quan et al., 2022).

This model is particularly well-suited for the present study for two key reasons. First, it features a plastic film mulching module, which has been proven to effectively simulate the growth and development of maize in arid regions (Quan et al., 2022). Second, the model incorporates detailed plant growth, carbon and nitrogen cycle processes, enabling precise simulations of SOC dynamics and GHG emissions (Wang et al., 2024b). In this research, we first calibrated the SPACSYS model using data collected from seven years of field experiments to simulate yield, SOC dynamics, and GHG emissions under plastic mulching and stubble return practices in Yangling, northwest China. We subsequently utilized future climate data, which was downscaled from a collection of 27 Global Climate Models (GCMs) based on two emission scenarios (SSP245 and SSP585), to evaluate the effects of climate change on maize yield, SOC stock, and global warming potential with integrated mulching and stubble return strategies. The primary objective was to identify the optimal stubble incorporation rates under PM, with the aim of balancing the trade-offs between GHG emissions and maize yield in the context of climate change. We expect that these results will contribute to the development of sustainable, low-carbon agricultural practices in a changing climate.

2. Materials and methods

2.1. Study site, soil, and climate data

The research was conducted at the China Institute of Water Conservation in Dry Areas, located within Northwest A&F University in Yangling District, Shaanxi Province, China. The study site is situated at geographic coordinates 108°24' E, 34°20' N with an elevation of 521 m (Fig. 1). The region experiences a subhumid climate prone to drought, with an average annual temperature of 12.5°C, mean annual evaporation of 1500 mm, and average annual precipitation of 593 mm

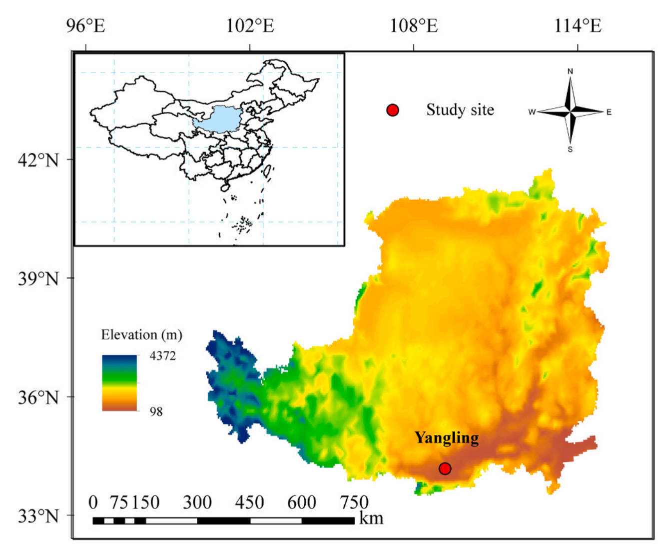

Fig. 1. Location map of the study site on the Loess Plateau in northwest China, highlighted with blue shading in the inset image.

(1992–2021). The groundwater level is approximately 60 m below the surface, making upward moisture supply negligible. Soil properties data for the 0–100 cm soil layer is presented in Table S1.

Historical weather data from 1981 to 2020, including daily maximum and minimum temperatures, sunshine duration, and precipitation, were obtained from an automatic weather station situated approximately 1 km from the experimental site. Daily solar radiation (MJ $m^{-2}d^{-1}$) was determined using the Ångström equation, which is based on sunshine hours (Wang et al., 2015). Monthly climate projections for the period 1981–2100 were obtained from 27 Global Climate Models (GCMs) within the Coupled Model Intercomparison Project Phase 6 (CMIP6) dataset (Chen et al., 2022) (Table S2). Future daily climate data for the study site were generated using the NWAI-WG statistical downscaling technique (Liu and Zuo, 2012). Climate projections from 27 GCMs were analyzed under two distinct Shared Socioeconomic Pathways (SSPs) to evaluate the varying impacts of climate scenarios on crop yields, soil carbon dynamics, and greenhouse gas emissions. The first scenario, SSP245, depicts a moderate-emission future scenario with a radiative forcing of 4.5 W m^{-2} and a projected atmospheric CO_2 concentration of 603 ppm by 2100. The second scenario, SSP585, depicts a high-emission pathway driven by extensive fossil fuel consumption, leading to stronger radiative forcing of 8.5 W m^{-2} and projected CO_2 concentrations of 1135 ppm by the year 2100 (Meinshausen et al., 2020).

Annual CO_2 concentrations were utilized to drive the model spanning the years 1981–2100. Empirical equations formulated through nonlinear least-squares regression analysis were used to estimate annual atmospheric CO_2 concentrations for the SSP245 and SSP585 scenarios. The following are the empirically derived equations used to calculate CO_2 concentrations for the SSP245 and SSP585 scenarios (Wang et al., 2024a).

$$[\mathrm{CO_2}]_{SSP245} = 62.044 + \frac{34.002 - 3.8702y}{0.24423 - 1.1542y^{2.4901}} + 0.028057(y-1900)^2 + 0.00026827(y-1960)^3 - 9.2751\times10^{-7}(y-1910)^4 - 2.2448(y-2030) \quad (1)$$

$$[\mathrm{CO_2}]_{SSP585} = 757.44 + \frac{84.938 - 1.537y}{2.2011 - 3.8289y^{-0.45242}} + 2.4712\times10^{-4}(y+15)^2 + 1.9299\times10^{-5}(y-1937)^3 + 5.1137\times10^{-7}(y-1910)^4 \quad (2)$$

where the variable y represents the calendar year from 1900 to 2100, i.e., y = 1900, 1901, …, and 2100.

2.2. Field management and experimental design

The experiment utilized a fully randomized design that included three types of mulching treatments: plastic film mulching (PM), stubble mulching (SM), and no mulching (CK, control treatment). The polyethylene plastic film employed had an albedo value of 11 %, measured 70 cm in width, and possessed a thickness of 0.01 mm. Each treatment consisted of three replicates, resulting in a total of nine plots arranged with a spacing of 1 m. At sowing, 225 kg N ha^{-1} (urea: N, 46 %) and 40 kg P ha^{-1} (calcium superphosphate: P, 7 %) were applied. After sowing, plastic film and stubble (4000 kg ha^{-1} wheat stubble) was laid on the soil layer. Table S3 provides comprehensive field management information, including the dates for sowing and harvesting, planting depth, and the types and application rates of fertilizers used each growing season. Weed and pest management followed local farming practices.

2.3. Field data collection

SOC content was assessed annually at both planting and harvesting times. Three soil samples were collected from the 0–20 cm soil layer in each plot using a soil drill and then merged to form a composite sample. Following the removal of roots and apparent contaminants, the sample was sieved through a 2 mm mesh. The soil organic carbon content was then quantified using the external heating potassium dichromate method (Bao, 2000). The yield of maize was assessed annually by collecting ears from the two central rows within each plot, which were then sun-dried for a duration of five days, threshed, and weighed (Quan et al., 2022).

SOC stock (kg ha^{-1}) was determined using the following formula (Lin et al., 2022):

$$SOC\ stock = SOC \times BD \times H \times 10^{-1} \quad (3)$$

where SOC represents SOC content (g kg^{-1}), BD stands for soil bulk density (g cm^{-3}), H denotes the thickness of the soil layer (0.2 m), and 10^{-1} is a constant used for unit conversion.

The static chamber/gas chromatography method was used to measure soil CO_2, CH_4, and N_2O emissions, with three samples taken from each plot (Wang and Hu, 2011). Polypropylene chamber bases (50 cm × 50 cm × 20 cm) were embedded 20 cm deep in the soil post-sowing and removed prior to harvesting. Emissions were recorded every 7–10 days. The sampling frequency was adjusted in response to precipitation events. Specifically, following a heavy precipitation event, gas sampling was increased to daily intervals for one week. Gas samples were drawn using 60 ml polypropylene syringes at 0, 10, 20, and 30-minute intervals after the chamber was installed, between 9:00 and 11:00 a.m. The samples were then promptly analyzed using a gas chromatograph (Agilent Technologies Inc., Santa Clara, CA, USA).

2.4. SPACSYS model overview and calibration

The SPACSYS model features detailed components that simulate key plant physiological processes, including phenological development, respiration, assimilation, water and nitrogen uptake, nitrogen partitioning, and root system dynamics. These components facilitate accurate predictions of crop growth and development. Additionally, the model effectively predicts SOC dynamics and GHG emissions by incorporating detailed simulations of organic matter decomposition, mineralization, nitrification, and denitrification processes integral to carbon and nitrogen cycling. Moreover, the model proficiently simulates the impacts of diverse agricultural management practices, including film mulching and stubble incorporation, on crop performance (Quan et al., 2024; Wang et al., 2024b). We used grain yields, SOC, and GHG emissions from our long-term field experiment data to calibrate and validate the SPACSYS model.

2.5. Model settings

Stubble return was combined with or without plastic mulching (PM and NM) to explore SOC dynamics, GHG emissions, and yield change. We established 11 levels of stubble return, represented as fractions ranging from 0 % to 100 % in 10 % increments (R0 to R100) of the maize plant, excluding the economic organ. It should be noted that the "NM_R0" treatment corresponds to the control (CK) treatment in future scenarios. Other management practices were maintained in accordance with our field experiment.

The validated SPACSYS model was used to perform 1188 simulation experiments, comprising 2 climate scenarios, 27 GCMs, and 22 treatments, with each simulation spanning the years 1981–2100. We examined variations in maize productivity, SOC stock in the top 20 cm of soil, and GHG emissions over the baseline period (1981–2020) and two future intervals (2040 s: 2021–2060, 2080 s: 2061–2100) to evaluate the enduring impacts of climate change and diverse management strategies.

2.6. Global warming potential

The Global Warming Potential (GWP) represents the total CO_2 equivalent emissions from CO_2, CH_4, and N_2O. Positive GWP values signify emissions of soil carbon, while negative values denote carbon sequestration in the soil.

$$GWP = -SOCr \times 44/12 + N_2O \times 44/28 \times 265 + CH_4 \times 16/12 \times 28 \quad (4)$$

where N_2O represents the total seasonal emissions of N_2O (kg N ha^{-1} yr^{-1}), CH_4 refers to the total seasonal emissions of CH_4 (kg C ha^{-1} yr^{-1}), and SOCr denotes the annual SOC sequestration rate (kg C ha^{-1} yr^{-1}), which is determined by the slope of a linear regression that illustrates changes in SOC stock over time. The conversion factors used are 44/28, 16/12, and 44/12. Additionally, 265 and 28 are the GWP values for N_2O and CH_4, respectively, relative to CO_2 over a 100-year period (IPCC, 2014).

2.7. Simulated yield, SOC stock, and GWP variations across various scenarios

The percentage changes in simulated maize yield (ΔY_{GCM}, %), SOC stock (ΔSOC_{GCM}, %), and GWP (ΔGWP_{GCM}, %) under the SSP245 or SSP585 scenario, relative to the baseline, were computed as follows:

$$\Delta Y_{GCM}\left(\%\right) = \frac{(Y_{GCM\_Future} - Y_{OB\_BL})}{Y_{OB\_BL}} \times 100 \quad (5)$$

$$\Delta SOC_{GCM}\left(\%\right) = \frac{(SOC_{GCM\_Future} - SOC_{OB\_BL})}{SOC_{OB\_BL}} \times 100 \quad (6)$$

$$\Delta GWP_{GCM}\left(\%\right) = \frac{(GWP_{GCM\_Future} - GWP_{OB\_BL})}{GWP_{OB\_BL}} \times 100 \quad (7)$$

where Y_{GCM_Future}, SOC_{GCM_Future}, and GWP_{GCM_Future} were the simulated yield (kg ha^{-1}), SOC stock (kg ha^{-1}), and GWP (kg CO_2 eq ha^{-1}), respectively, for different treatments under future climate projections from GCMs. Y_{OB_BL}, SOC_{OB_BL}, and GWP_{OB_BL} were the simulated yield, SOC stock, and GWP, respectively, for the reference treatment (CK, no mulching and stubble return) during the baseline period (1981–2020).

2.8. Model evaluation and data analysis

We employed the coefficient of determination (R^2), the normalized root mean squared error (nRMSE), and the Willmott index of agreement (d) to assess the model's performance. The equations for calculating these two statistical indices are detailed below:

$$R^2 = 1 - \frac{SSR}{SST} \quad (8)$$

$$nRMSE\left(\%\right) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \times \frac{100}{\overline{O}} \quad (9)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i - \overline{O}| + |O_i - \overline{O}|)^2} \quad (10)$$

where *SSR*, the sum of squares for regression, comprises the sum of squared differences between the actual observations and the values predicted by the linear model; *SST*, the total sum of squares, represents the overall variance within the dependent variable. O_i and S_i denote the actual and modeled values, respectively, and $\overline{O}$ represents the average of the observed data. n is the number of years.

All statistical analyses were conducted using R software, utilizing various packages, with a significance level of $P < 0.05$. Figures were created with Origin 9.1 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Model evaluation for simulating yield, SOC, and GHG emissions

The observed and simulated maize yields ranged from 5561 to 9717 kg ha^{-1} and 5767–10006 kg ha^{-1}, respectively, with $R^2 = 0.89$, nRMSE = 9.2 %, and d = 0.97 (Fig. 2a). For N_2O, CH_4, and CO_2 emissions, the R^2 values were 0.83, 0.74, and 0.68, respectively, while the nRMSE values were 9.8 %, 14 %, and 18 %, and the d values were 0.94, 0.92, and 0.90, respectively. The discrepancies between simulated and observed SOC stock were minimal, with observed SOC stock ranging from 17,300 to 26,000 kg ha^{-1}, closely aligning with simulated SOC stock of 18560–25130 kg ha^{-1} ($R^2 = 0.70$, nRMSE = 16 %, and d = 0.89, Fig. 2e). Therefore, the SPACSYS model accurately simulated yield, SOC stock, and GHG emissions across various mulching treatments at the research site.

Maize yields varied among the CK, SM, and PM treatments, ranging from 5180 to 7284 kg ha^{-1}under the baseline climate scenario. The PM treatment resulted in the highest yields, whereas the CK treatment had the lowest yields (Fig. 3a). In terms of SOC stock, the simulated average at a depth of 0–20 cm also differed across these treatments, with values ranging from 18,261 to 24,789 kg ha^{-1}. The SM treatment exhibited the highest SOC stock, whereas the PM treatment had the lowest (Fig. 3b). Furthermore, the GWP was negative across all treatments, indicating that the maize cultivation system functioned as a net carbon sink. The SM treatment showed the lowest GWP values, suggesting greater carbon sequestration, while the PM treatment displayed the highest values (Fig. 3c).

3.2. Future air temperature, precipitation, and radiation change

Ensemble means from multiple climate models suggested that, relative to the baseline, the annual mean maximum temperature was projected to rise by 2.2–3.7°C under SSP245 and 2.7–5.9°C under SSP585 (Fig. 4a). Correspondingly, the minimum temperature was expected to rise by 1.5–2.6°C under SSP245 and 1.9–4.5°C under SSP585 (Fig. 4b). Moreover, the average radiation from the multi-GCM ensemble was anticipated to rise by 3.6–9.6 % under SSP245 and 4.6–9.4 % under SSP585 (Fig. 4c). In contrast, ensemble mean projections for precipitation indicated a slight decrease of 2.3–1.0 % under SSP245, a decrease of 2.7 % in the 2040 s under SSP585, followed by an increase of 5.4 % in the 2080 s under the same scenario.

3.3. Projected yield under different management options

The projected yields under NM_R0 (CK in the future period) were expected to increase by 20.9 % under SSP245 and by 5.8 % under SSP585 during the 2040 s (2021–2060), compared to the baseline period (1981–2020). Conversely, yields were projected to decrease by 20.3 % under SSP245 and by 60.0 % under SSP585 during the 2080 s (2061–2100). PM combined with an increased stubble return rate significantly enhanced yields in the 2040 s and helped offset or mitigate the negative impacts of future climate change in the 2080 s under SSP245 and SSP585 scenarios (Fig. 5). The combination of a 100 % stubble return rate with PM (PM_R100) proved to be an optimal adaptation strategy, leading to yield increases of 50.7 % under SSP245 and 31.6 % under SSP585 in the 2040 s, when compared to the CK treatment from the baseline period. In the 2080 s, the yield losses caused by

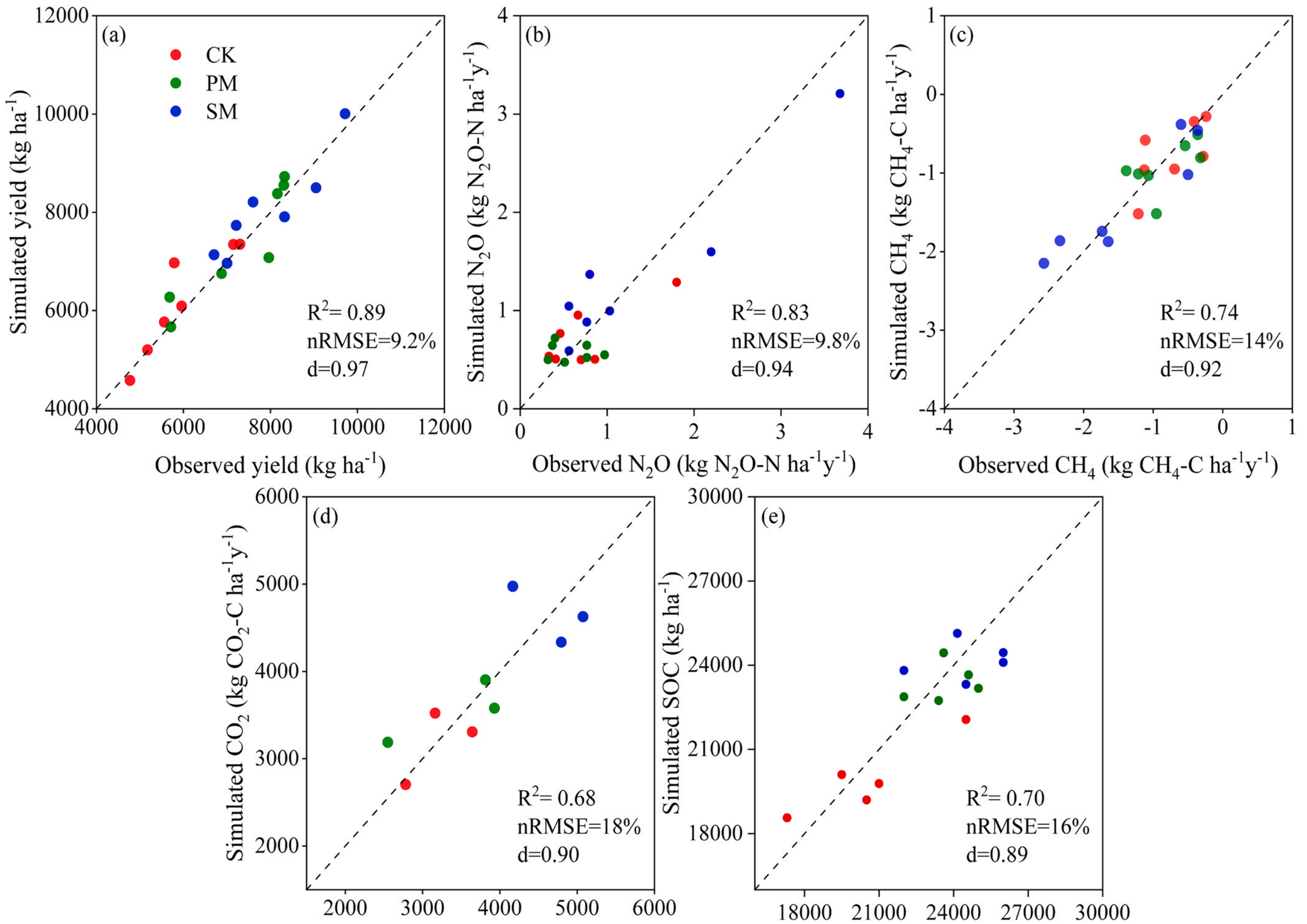

Fig. 2. Observed and simulated maize yield (a), N_2O (b), CH_4 (c), CO_2 emissions (d), and SOC stock at 0–20 cm soil depth (e) under various agricultural measures. All statistical indices include: coefficient of determination (R^2), Willmott index of agreement (d), and normalized root mean square error (nRMSE). CK, PM, and SM represent no mulching, plastic film mulching, and stubble mulching treatments, respectively.

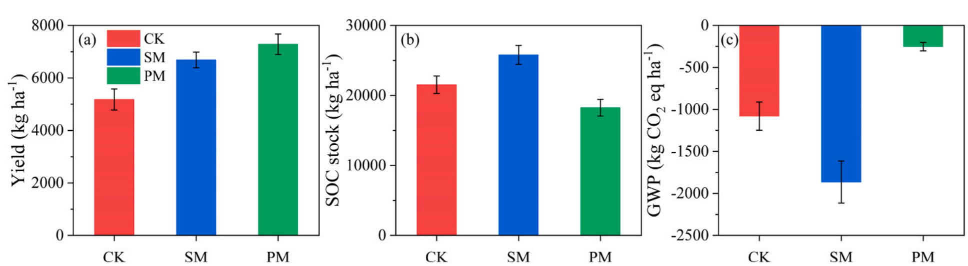

Fig. 3. Simulated annual mean Yield (a), SOC stock (b), and GWP (c) during 1981–2020 under different management measures. Negative GWP indicate carbon sequestration in the soil. CK, PM, and SM represent no mulching, plastic film mulching, and stubble mulching treatment, respectively. The error bars show the standard deviation of the multi-year average.

climate change under the SSP245 were completely countered, resulting in a 2.5 % increase relative to the CK treatment during the baseline. In contrast, under SSP585, while the optimal treatment mitigated yield losses, it still resulted in a 34.3 % decrease compared to the CK treatment from the baseline period.

3.4. Projected SOC under different management options

The projected SOC for NM_R0 was expected to decrease by 23.6–29.7 % in the 2040 s and by 43.0–58.1 % in the 2080 s (Fig. 6). Under various stubble return treatments in future periods, SOC stock exhibited a decreasing trend over time. However, SOC stock increased as the stubble return rate rose. The projected SOC loss was completely offset by increasing the stubble return rate (except in the 2080 s under SSP585), with the optimal return rate identified as 100 % stubble return under both NM and PM conditions. In the SSP245 scenario, a 100 % stubble return under PM and NM conditions increased SOC stock by 23.6 % and 89.9 %, respectively, in the 2040 s, and by 16.2 % and 43.2 % in the 2080 s relative to the CK treatment during the baseline period. Similarly, in the SSP585 scenario, a 100 % stubble return under PM and NM conditions resulted in increases of 11.1 % and 32.3 % in SOC stock in the 2040 s and an increase of 7.8 % in NM conditions, but a 35.9 % decrease in PM conditions in the 2080 s, relative to the CK treatment in the baseline. Notably, PM led to a lower SOC stock

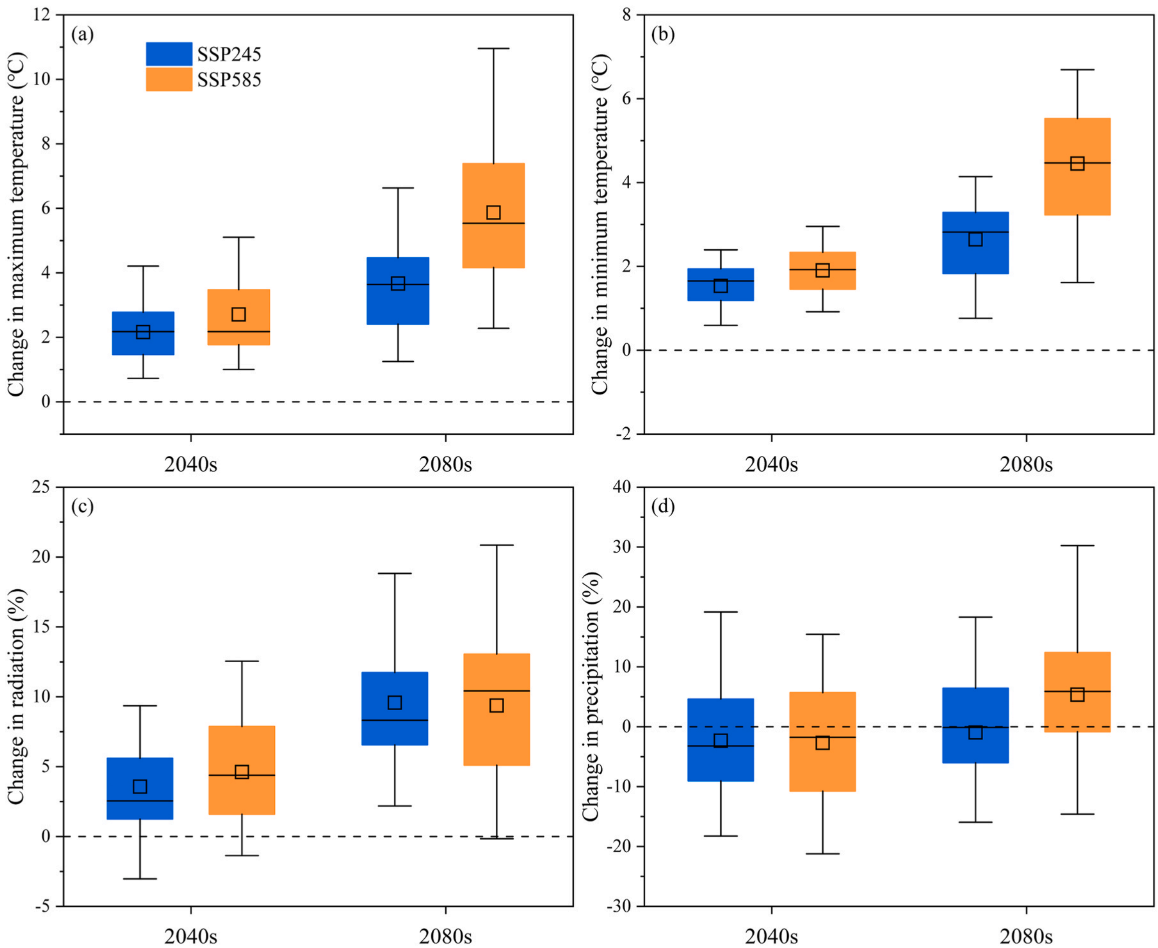

Fig. 4. Multi-GCM ensemble changes in annual average (a) maximum temperature, (b) minimum temperature, (c) radiation, and (d) total precipitation during the maize growing season (June to September) under SSP245 and SSP585 scenarios at the study site. The changes are calculated for two future periods (2040 s: 2021–2060 and 2080 s: 2061–2100) relative to the baseline period (1981–2020). Each box summarizes values from 27 GCMs. Box boundaries represent the 25th and 75th percentiles, while whiskers below and above the box represent the 10th and 90th percentiles. Lines and boxes within each box represent the median and mean, respectively.

compared to NM at the same stubble return rate.

3.5. Projected GWP under different management options

The projected GWP for NM_R0 was expected to increase, yet it exhibited a generally decreasing trend over time (Fig. 7). Specifically, GWP was projected to rise by 306.2–316.8 % in the 2040 s and by 160.2–234.1 % in the 2080 s. However, as the rate of stubble return increased, GWP gradually declined across both the SSP245 and SSP585 scenarios. For instance, under the SSP245 scenario, a 100 % stubble return under PM and NM conditions resulted in GWP increases of 101.0 % and 12.6 %, respectively, in the 2040 s, and 131.0 % and 93.6 % in the 2080 s, compared to the CK treatment during the baseline period. A stubble return rate exceeding 60 % under NM conditions and 90 % under PM conditions in the 2040 s led GWP to turn negative, indicating a transformation into a carbon sink (Fig. S1a). However, in the 2080 s, only rates exceeding 90 % under NM conditions were effective in turning GWP negative. Under the SSP585 scenario, a 100 % stubble return under both PM and NM conditions increased GWP by 165.0 % and 80.1 %, respectively, in the 2040 s, and by 183.0 % and 115.8 % in the 2080 s, relative to the CK treatment during the baseline period. Similarly, a stubble return rate exceeding 80 % under NM conditions led GWP to turn negative in the 2040 s. Conversely, in the 2080 s, GWP remained positive under SSP585, maintaining a carbon source status (Fig. S1d).

3.6. Projected yield, SOC, and GWP dynamics under optimal treatment

From the perspective of maximizing output, we selected the PM_R100 treatment as the optimal treatment. The yield dynamics under the optimal treatment exhibited a declining trend as time progressed (Fig. 8a). Projections indicate that the yield from the optimal treatment will decrease by 45.4 % under the SSP245 scenario and by 81.0 % under the SSP585 scenario by the end of the 21st century, relative to initial conditions in 2021. The simulated dynamics of SOC at the optimal treatment initially increased, followed by a decreasing trend over time under both SSP245 and SSP585 scenarios (Fig. 8b). Projections indicate that SOC stock from the optimal treatment will decrease by 2.5 % under the SSP245 scenario and by 68.2 % under the SSP585 scenario by the end of the 21st century, relative to initial conditions in 2021. Yield and SOC under SSP245 consistently surpassed those under SSP585, and the disparity in yield and SOC between the two emission scenarios increased over time. Furthermore, the dynamics of GWP at the optimal treatment initially increased and then decreased under both SSP245 and SSP585 scenarios (Fig. 8c). Projections indicate that GWP from the optimal treatment will decrease by 144.9 % under the SSP245 scenario and by 23.8 % under the SSP585 scenario by the end of the 21st century, relative to initial conditions in 2021. GWP values under SSP245 were lower than those under SSP585.

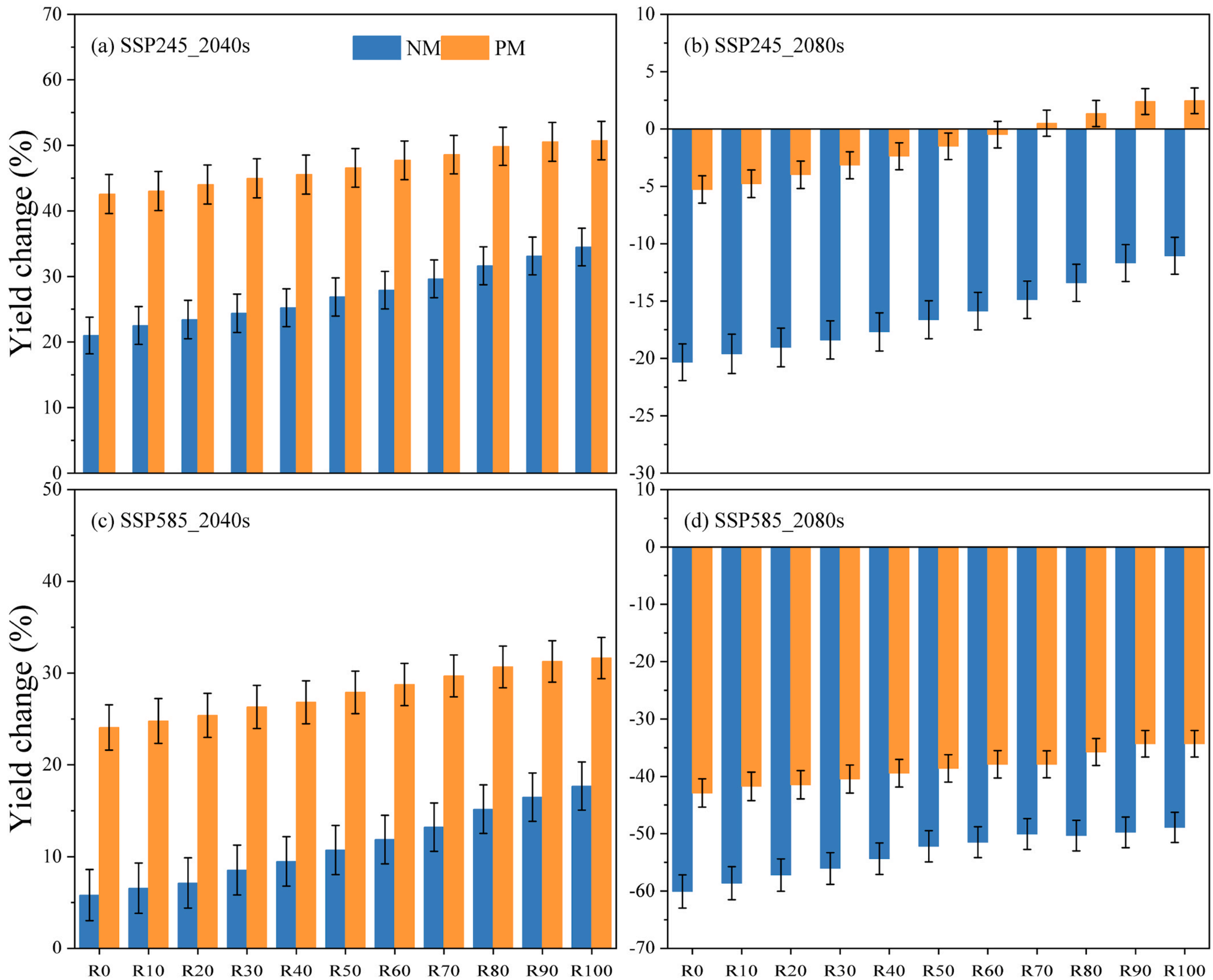

Fig. 5. Maize yield changes across 22 combinations of stubble return levels (R0–R100) and mulching levels (NM and PM) in the 2040 s (2021–2060) and 2080 s (2061–2100) under two emission scenarios (SSP245 and SSP585) based on the 27 GCMs relative to the reference treatment (CK, no mulching and stubble return) during the baseline period (1981–2020). The x-axis represents stubble return levels: 0 % (R0), 10 % (R10), 20 % (R20), 30 % (R30), 40 % (R40), 50 % (R50), 60 % (R60), 70 % (R70), 80 % (R80), 90 % (R90), and 100 % (R100). NM: no plastic mulching, PM: plastic mulching.

4. Discussion

Previous studies have highlighted the SPACSYS model's robust performance in the simulation of crop yields under varying agronomic measures (Liang et al., 2019; Wang et al., 2024b). For example, Zhang et al. (2016) applied the SPACSYS model to simulate maize yields in northern China, achieving a good fit between simulated and observed values, with a correlation coefficient of 0.81 and a RMSE of 4.13 % under different fertilizer practices. Our results are consistent with these results, indicating strong model performance for maize yield simulations with an R^2 of 0.89 and a nRMSE of 9.2 %. Furthermore, the model effectively captures variations in SOC stock and GHGs emissions (CO_2, N_2O, and CH_4) across various mulching treatments, evidenced by R^2 values ranging from 0.68 to 0.83 and nRMSE between 9.8 % and 18 % (Fig. 2). Further corroborations come from Wang et al. (2024b) and Quan et al. (2024), who reported accurate simulations of soil CO_2 and N_2O emissions and SOC under stubble incorporation and PM conditions, respectively. Such good performance is mainly due to the detailed incorporation of a biologically-based denitrification component in SPACSYS, which allows for the estimation of various nitrogenous gas emissions (N_2O, NO, and N_2) (Liu et al., 2020), as well as the detailed root growth module that simulates carbon and nutrient interactions between plants and soil (Wu et al., 2007).

Under the future climate scenarios of the 2080 s (SSP245 and SSP585), we found a predominant decline in maize yields without adaptation (no mulching and stubble return) (Figs. 5b and 5d). Such decrease is primarily attributed to heightened temperatures, which may shorten the reproductive growth stages, accelerate crop senescence, and diminish photosynthetic activity, ultimately resulting in reduced grain yields (Xiao et al., 2021). Similar projections have been made for maize-growing regions in northwest China, where Liu et al. (2022) and Xu et al. (2021) also anticipate yield declines due to a warming climate. Contrastingly, the PM system displayed higher crop yields compared to the NM system, attributed to the improved soil water environment (Zhang et al., 2024).

Additionally, the SPACSYS model effectively captures the response of crop yields to stubble incorporation, demonstrating a positive correlation between the stubble incorporation rate and yield increments (Fig. 5). Such benefit is mainly due to increased soil nutrient content from the returned stubble, particularly carbon and nitrogen levels, which creates a nutrient-rich environment conducive to high grain yields (Chen et al., 2019). By enhancing soil water retention and

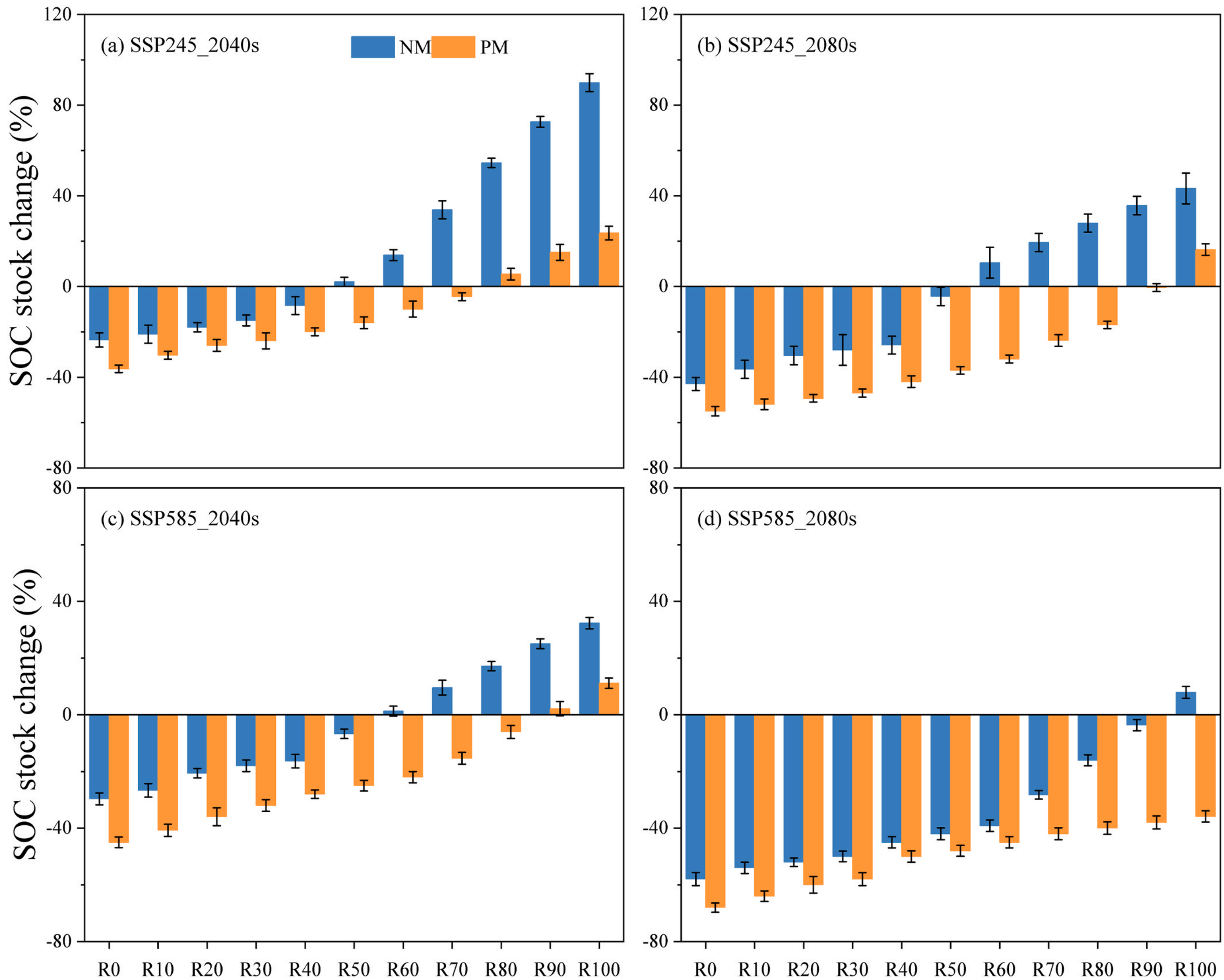

Fig. 6. Soil organic carbon (SOC) stock changes under 22 combinations of stubble return levels (R0–R100) and mulching levels (NM and PM) in the 2040 s (2021–2060) and 2080 s (2061–2100) under two emission scenarios (SSP245 and SSP585) based on the 27 GCMs relative to the reference treatment (CK, no mulching and stubble return) during the baseline period (1981–2020). The x-axis represents stubble return levels: 0 % (R0), 10 % (R10), 20 % (R20), 30 % (R30), 40 % (R40), 50 % (R50), 60 % (R60), 70 % (R70), 80 % (R80), 90 % (R90), and 100 % (R100). NM: no plastic mulching, PM: plastic mulching.

nutrient availability, PM combined with stubble return measures enhances crops' capacity to absorb water and nutrients, thereby promoting yield formation (Zhang et al., 2022). Our results specifically highlighted that the PM_R100 treatment yielded the highest maize outputs among all treatments in future periods, significantly increasing yields in the 2040 s compared to the CK treatment during the baseline period. Notably, this treatment completely counteracted the projected production declines under the SSP245 scenario for the 2080 s. However, it did not fully compensate for the anticipated declines under the SSP585 scenario during the same timeframe. This discrepancy is likely due to the more severe temperature increases that are expected (Figs. 4a and 4b), which could particularly affect yields during critical growth phases such as anthesis and grain filling, leading to infertility and premature maturation (Muleke et al., 2022).

There was a predominant decline in SOC stock under the non-adaptation scenario (NM_R0) in future projections (Fig. 6). The primary reason for this reduction is the rise in temperatures, which leads to increased CO_2 emissions by enhancing soil respiration and accelerating the biogeochemical cycling of carbon (Kuzyakov et al., 2019). Additionally, previous experimental studies have indicated that higher temperatures lead to increased microbial activity and subsequent SOC decomposition, resulting in greater SOC loss from soils (Lin and Zhang, 2012). In contrast, the PM treatment exhibited a lower SOC stock than the NM due to two primary factors. Firstly, the improvement of soil hydrothermal conditions under PM promotes carbon mineralization, exacerbating the release of carbon into the atmosphere (Zhang et al., 2022). Secondly, the use of mulching film prevents litter from being incorporated into the soil during crop growth, thereby hindering the replenishment of soil carbon (Quan et al., 2024). All these processes are effectively represented in the SPACSYS model to differentiate the impacts of various coverage methods on the SOC (Quan et al., 2022; Wu et al., 2007).

Our findings indicate that returning stubble to the field is advantageous for enhancing SOC reserves in the coming decades (Fig. 6). Stubble return directly introduces new carbon sources into agroecosystems and indirectly enhances photosynthetic product inputs by improving plant growth conditions (Fig. 5). These combined effects increase the total carbon inputs in agroecosystems, aligning with prior research that highlights the benefits of residue management in enhancing and stabilizing SOC stock within the upper soil layers (Bai et al., 2021; Zhang et al., 2022). Additionally, the optimal treatment (PM_R100) is projected to increase SOC stock by 11.1–23.6 % in the

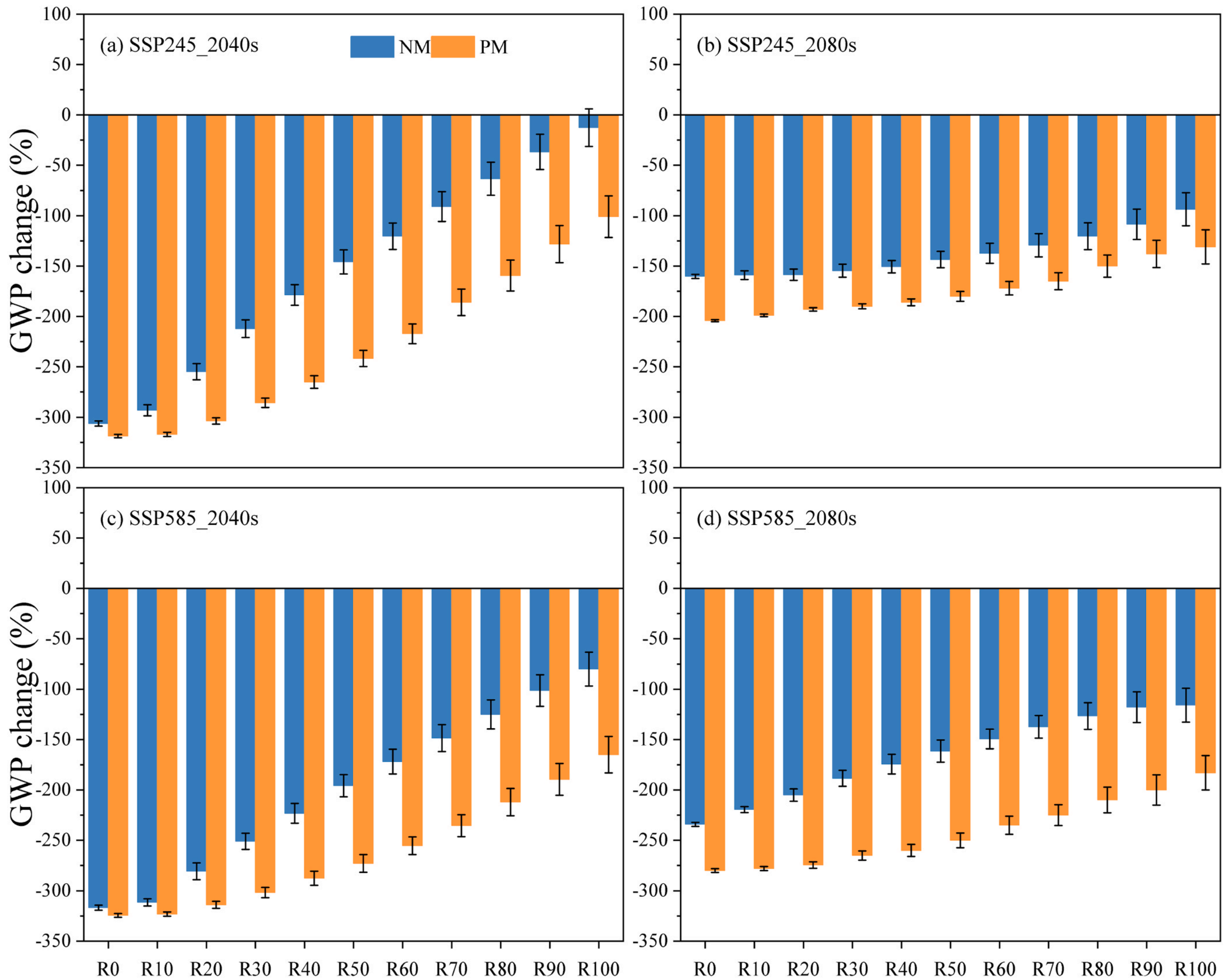

Fig. 7. Changes in global warming potential (GWP) under 22 combinations of stubble return levels (R0–R100) and mulching levels (NM and PM) in the 2040 s (2021–2060) and 2080 s (2061–2100) under two emission scenarios (SSP245 and SSP585) based on the 27 GCMs compared to the reference treatment (CK, no mulching and stubble return) during the baseline period (1981–2020). The x-axis represents stubble return levels: 0 % (R0), 10 % (R10), 20 % (R20), 30 % (R30), 40 % (R40), 50 % (R50), 60 % (R60), 70 % (R70), 80 % (R80), 90 % (R90), and 100 % (R100). NM: no plastic mulching, PM: plastic mulching.

future, except during the 2080 s under the SSP585 scenario, compared to the CK treatment during the baseline period. However, PM_R100 did not fully offset the anticipated declines in SOC during the 2080 s under the SSP585 scenario. This can be attributed to several factors: Firstly, elevated temperatures may stress plants, impairing their growth and productivity, which in turn reduces the incorporation of plant stubble into the soil, thereby decreasing organic carbon inputs (Wang et al., 2024b). Secondly, increased temperatures and precipitation may accelerate the mineralization process, leading to a faster SOC decomposition (Wang et al., 2019).

There was an increase of more than 150 % in GWP emissions under the non-adaptation scenario (NM_R0) in the future (Fig. 7), indicating that the reference treatment acted as a carbon source. Interestingly, our data from the 2040 s indicate that as stubble return increases, GWP gradually decreases, eventually shifting from a carbon source to a carbon sink (Fig. 7 and Fig. S1). However, by the 2080 s, even 100 % stubble return (PM_R100) is insufficient to transition the maize growing system under PM conditions from a carbon source to a carbon sink, as indicated by persistently positive GWP values (Fig. 8c). This aligns with the results of Wang et al. (2024b), who found that under future climate conditions, the maize growing system remains a carbon source, exhibiting an average annual GWP of 967 kg CO_2-eq ha^{-1} yr^{-1} under conditions of optimal straw retention. We also noted that in the 2040 s and 2080 s, GWP under PM conditions was higher than under NM conditions, aligning with Zhang et al. (2024)'s findings, which indicated increased GWP under PM compared to the control across various climate models and emission scenarios. This phenomenon is primarily attributed to increased temperature and soil moisture in the PM system, which enhances soil respiration, alters the carbon-to-nitrogen ratio, and subsequently increases carbon loss and N_2O emissions (Scheer et al., 2014). Additionally, further analysis indicates that GWP under the optimal treatment remained positive under the SSP585 scenario in the 2080 s and was higher than that under other scenarios, primarily due to the substantial decline in SOC (Fig. 6), consistent with the findings of Yang et al. (2015). This indicates that plastic mulched farmland systems still act as sources of carbon emissions under the high-emission scenario of the 2080 s, although stubble return can reduce GWP. To counteract this, we must adopt additional protective management strategies, such as manure amendment (Liang et al., 2018), conservation tillage (Maia et al., 2022), and the breeding of heat-resistant cultivars (Zhang and Zhao, 2017), to enhance carbon sequestration in the region. Only through these measures will it become feasible to gradually transform

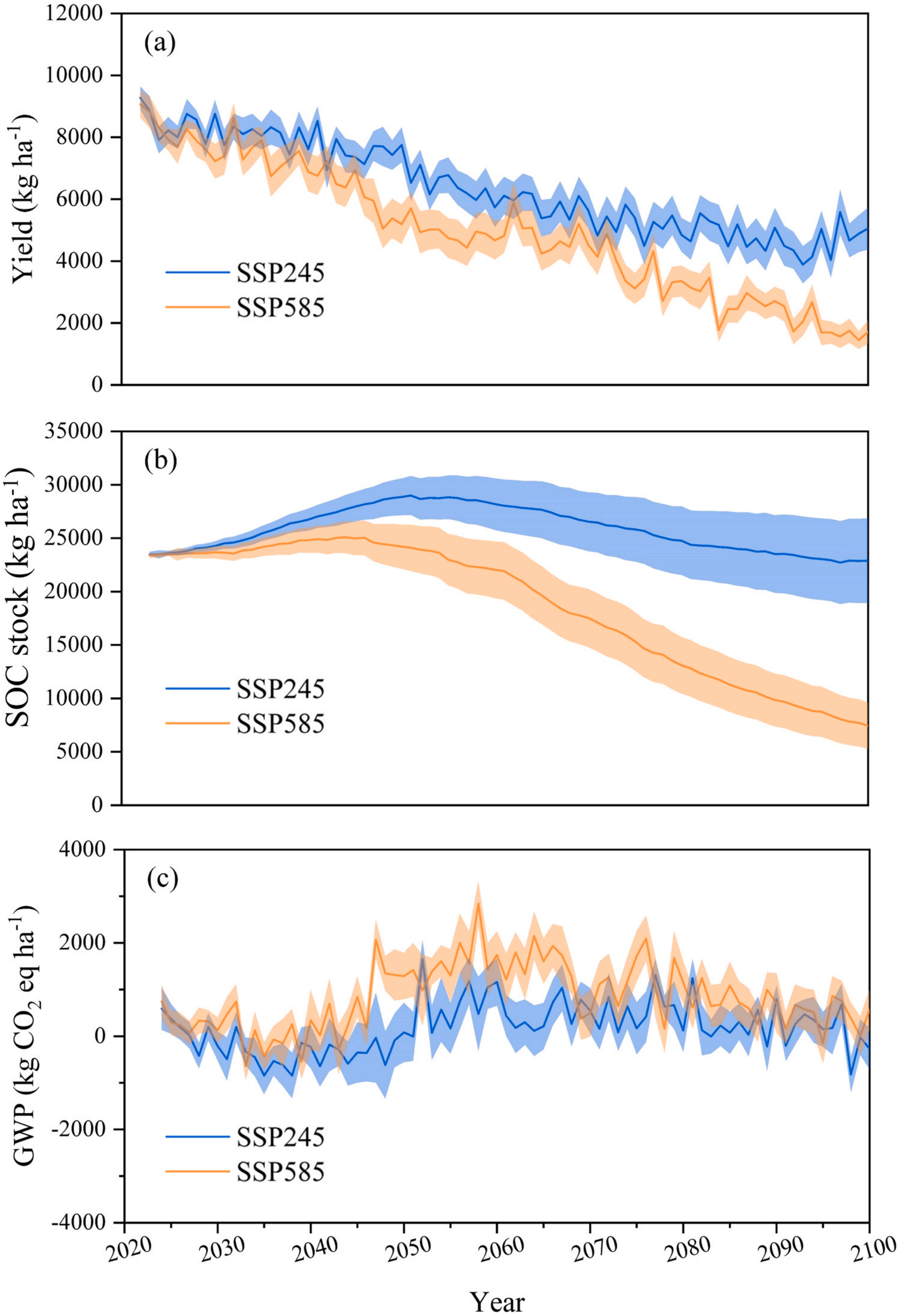

Fig. 8. Simulated dynamics of maize yield (a), SOC stock (b), and GWP (c) under the optimal treatment (100 % stubble return with plastic mulching) across SSP245 and SSP585 scenarios for the period 2021–2100.

maize growing system from carbon sources into carbon sinks under a high-emission scenario in the future.

The combination of 100 % crop stubble return with plastic film mulching has been identified as an effective approach to enhance crop yield while maintaining low-carbon sustainable agriculture in the arid regions of Northwest China under climate change conditions. However, large-scale implementation of these practices encounters significant challenges, particularly regarding labor and economic costs. In response to these challenges, China has developed integrated mechanization technologies coupled with government subsidies for conservation agriculture, enabling cost-effective implementation at scale. The technological framework specifically comprises the following components: First, advanced rotary tillers that simultaneously pulverize crop residues and incorporate them into soil, achieving dual objectives of tillage and residue return in a single operation. Second, combined plastic-film-laying-and-seeding machinery that minimizes manual installation costs while ensuring precision. Empirical evidence demonstrates the effectiveness of these integrated systems in reducing operational costs and labor requirements. Studies by Wu et al. (2024) highlight the necessity of developing integrated, time-saving, and labor-efficient technological systems suitable for regional application. Furthermore, research by Luo et al. (2023), Thidar et al. (2020), and

Zheng et al. (2022) consistently indicate that while mulching involves associated costs, the yield benefits derived from reduced evaporation and maintained soil moisture outweigh these investments, ensuring stable yields and food security. With ongoing government support and the anticipated development of carbon credit markets, these findings significantly contribute to the advancement of a low-carbon, efficient agricultural economy in arid regions.

Our analysis focused on the maize yield and environmental effects of management practices under climate change. Despite the insights gained, there are several limitations that warrant further exploration in future studies. Firstly, our research employed only one crop model, SPACSYS, to simulate yield, GHG emissions, and SOC stock. As a result, all outcomes are inherently dependent on the SPACSYS model. It is widely recognized that agricultural simulation models are subject to uncertainty due to limitations in model structure, simplifications of integrated biophysical systems, and approximations of physiological processes. These limitations prevent the models from fully replicating real-world agricultural production (Liu et al., 2017). Moreover, the outputs of different models often exhibit significant variability, which introduces further uncertainty into optimization and prediction efforts. Several studies have demonstrated that simulation analyses using multiple well-calibrated models can provide a range of results, improve prediction reliability, and reduce uncertainty (Holzkämper et al., 2015; Jiang et al., 2023; Wang et al., 2020). Such approaches are critical for informing climate change adaptation strategies for cropping systems. Additionally, we utilized daily climate data from 27 GCMs under two Shared Socioeconomic Pathways (SSPs) to drive the SPACSYS model, enabling us to evaluate the agricultural system's response to different weather scenarios and reduce uncertainty in our assessments. However, these GCMs are subject to several sources of uncertainty, including unknown GHG emissions, inadequate representations of the climate system, intrinsic climate variability, and downscaling process (Woldemeskel et al., 2014). Consequently, the development of more accurate and reliable GCM data tailored to specific study regions will remain a critical focus in future climate research. To more effectively assess the impact of climate change on agricultural productivity, we will employ a variety of crop models under different GCMs to generate more robust and accurate predictions. Secondly, due to limitations in the experimental sampling data, the analysis of soil organic carbon dynamics is confined to the 20 cm soil layer, which is particularly sensitive to climate factors such as temperature and precipitation. In the future, we will further collect deeper soil organic carbon data for model calibration and simulation, with the goal of providing a more comprehensive understanding of how climate change affects soil carbon sequestration. Furthermore, our analysis did not consider the impact of variety substitution. The development of heat-resistant crop varieties could play a significant role in enhancing crop adaptation to climate change. This approach can be combined with additional management strategies, such as biochar application and the use of green manure, to balance yield enhancement and environmental protection under changing climate conditions (Koide et al., 2015; Lee et al., 2021). Such advancements are essential for providing robust insights and formulating effective recommendations to ensure high crop yields and sustainable agricultural practices in the Loess plateau.

5. Conclusions

We utilized calibrated SPACSYS model to assess the effects of various stubble return rates combined with PM on maize yield, GWP, and SOC stock changes on the Loess Plateau in northwest China. Key findings include:

(1) Yield under the CK treatment was projected to decrease by 20.3–60.0 % in the 2080 s. The optimized adaptation measure, PM_R100, was expected to mitigate these yield losses in the 2080 s under the SSP585 scenario and increase yields by 2.5–50.7 % in other future scenarios.
(2) Future climate change adversely affected SOC stock under CK treatment. However, adopting PM_R100 slowed the decrease in SOC in the 2080 s under the SSP585 and resulted in an SOC stock increase of 11.1–23.6 % in other future scenarios.
(3) The GWP of CK treatment was expected to increase in the future. However, PM_R100 could reduce GWP, potentially transforming the maize growing system from a carbon source into a carbon sink by the 2040 s. Moreover, it would still reduce GWP in the 2080 s, even though the maize farm is projected to become a carbon source during this period.

These findings highlight the importance of adopting stubble return practices in dryland rainfed areas where plastic film mulching is used. The results from our work are expected to support farmers and policymakers in devising mitigation and adaptation strategies to promote low-carbon sustainable agricultural development in northwest China under future climate conditions.

CRediT authorship contribution statement

Liu De Li: Writing – review & editing, Supervision, Methodology, Conceptualization. **Quan Hao:** Software, Methodology, Investigation, Conceptualization. **Chen Fangzheng:** Validation, Software, Investigation. **Feng Hao:** Writing – review & editing, Supervision, Software, Funding acquisition, Conceptualization. **Yu Qiang:** Methodology, Investigation, Conceptualization. **Wu Lianhai:** Validation, Software, Resources. **Wu Lihong:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Wang Bin:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.109964.

Data availability

Data will be made available on request.

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