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Strategies to reduce CH_4 and N_2O emissions whilst maintaining crop yield in rice–wheat system under climate change using SPACSYS model

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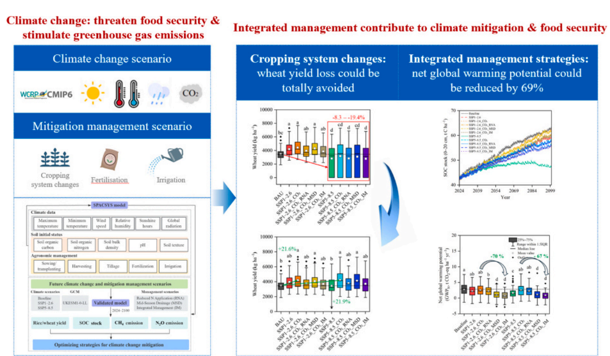
HIGHLIGHTS

- Strategies to mitigate global warming were explored using process-based model.
- Wheat yield may benefit from the climate of SSP1–2.6.
- Rice–winter wheat should be changed to rice–spring wheat in Southwest China under SSP5–8.5.
- Reduced N application rate by 20 % could not decrease crop yield in future.
- Integrated management contribute to climate mitigation and food security.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Climate change is projected to threaten food security and stimulate greenhouse gas emissions. Hence, adaptation measures without sacrificing food production are required.
OBJECTIVE: To assess possible consequences of rice–wheat system under climate change and to propose possible practices for mitigation.
METHODS: The Soil-Plant-Atmosphere Continuum SYStem (SPACSYS) model was tested using datasets from long-term experiment (1991–2019) assessing the impact of different fertilisation on crop production, crop nitrogen (N) content, soil organic carbon (SOC) stock, methane (CH_4) and nitrous oxide (N_2O) emissions in a

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Mitigation
SPACSYS

Cambisol under rice–wheat system. The validated SPACSYS was then used to investigate the possible mitigation strategies from 2024 to 2100 under climate change scenarios (SSP1–2.6 and SSP5–8.5) and the baseline scenario and mitigation management scenarios, i.e., (i) reduced N application rate by 20 % (RNA), (ii) the introduction of mid-season drainage (MSD) and (iii) integrated management combining RNA with MSD (IM).

RESULTS AND CONCLUSIONS: Results showed that SPACSYS performed effectively in simulating yield and N content in grain and straw, SOC stock and CH_4 and N_2O emissions. Scenarios analysis elucidated that RNA would not decrease grain yields for either rice or wheat under the two climate change scenarios. Compared to the baseline scenario, low level of climate change scenario considering the CO_2 fertilisation effects (SSP1–2.6_CO_2) may benefit wheat yield (28 %) and had no effects on rice yield. In contrast, under the SSP5–8.5 scenario, whether CO_2 fertilisation effects are considered or not, both rice and wheat yield could face great loss (i.e., 11.8–29.9 % for rice, 8.3–19.4 % for wheat). The winter wheat would not be suitable for planting in the distant future (2070–2100) due to the incomplete vernalisation caused by warming. The switching from winter wheat to spring wheat from 2070 onward could avoid the yield loss by 8.3–19.4 %. Climate change could decrease SOC sequestration rate. Under future climate change scenarios, IM could significantly decrease CH_4 emissions by 56 % and N_2O emissions by 24 %, as such reducing the net global warming potential by 69 % compared to no adaptation. Our simulations suggest that under climate change, crop switching in rice–wheat system combining integrated mitigation practices is possible to mitigate global warming and maintain crop production.

SIGNIFICANCE: Our results underscore the significance of integrated adaptation of agricultural systems to climate change.

1. Introduction

Rice is a staple food for nearly half of the world's population. Although flooded rice planting systems contributed to a large carbon store resulting from the anaerobic condition (Liu et al., 2021), it accounts for the largest greenhouse gas (GHG) emissions among all the cereal cropping systems due to the high methane (CH_4) emissions (Carlson et al., 2017). Globally, CH_4 and nitrous oxide (N_2O) emissions from paddies have been estimated as 6.3 t CO_2-eq ha^{-1} yr^{-1} (FAO, 2018) and 0.28 t CO_2-eq ha^{-1} yr^{-1} (Carlson et al., 2017), contributes about 18 % and 11 % to the total anthropogenic CH_4 and N_2O emissions (IPCC, 2014; FAO, 2020). Furthermore, climate change, mainly caused by GHG emissions, characterized by increased temperature and atmospheric CO_2 concentration, shifted precipitation patterns, frequent extreme weather events (Shivanna, 2022), is projected to aggravate GHG emissions from agriculture (Liu et al., 2018a; Liu et al., 2020b; Smith et al., 2013) and threaten agricultural productivity (Challinor, 2014; Han et al., 2024). Although many initiatives have been proposed to limit global warming to well below 2 °C, the air temperature is expected to rise about 3.2 °C by 2100 (Raftery et al., 2017). Therefore, it is critical to optimise agricultural managements designed to mitigate global warming without compromising crop production in paddy fields (Bossio et al., 2020; Liao et al., 2021). The single rice–winter wheat rotation system is one of the major cropping systems in China, contributing to 9.5 % of the total grain production. However, the related GHG emissions account for 15 % of the total GHG emissions from rice fields (Gao et al., 2018). As such, it is necessary to explore the potential mitigations for GHG emissions in the rice–wheat system.

Process-based agricultural models, capable of considering the complex interactions between multiple environmental factors and various agronomic practices, are powerful for evaluating the impacts of climate change on agricultural systems and proposing GHG mitigation practices in future climate. A wide range of models have been developed and applied to simulate crop grain yields, SOC stock and GHG emissions in rice cropping systems, including DAYCENT (Guo et al., 2023), DNDC (Guo et al., 2024), WHCNS (Liang et al., 2022), DSSAT (Baishya et al., 2024), CERES (Timsina and Humphreys, 2006), APSIM (Gaydon et al., 2017). Moreover, the potential risk with different management practices and climatic conditions has been assessed with various models. For instance, studies predicted a decreasing trend in SOC content without straw incorporation in paddies in South Korea (Ku et al., 2019), a substantial rice yield loss across China (Liu et al., 2020c) and an enhanced GHG intensity of rice production from global paddies (van Groenigen et al., 2012) under climate change. As such, based on the model approach, adaptive measures and suggestions to improve crop yields and simultaneously mitigating global warming have been recommended. For instance, Wang et al. (2022) highlighted the necessity of increasing C input in enhancing SOC stock under future climatic conditions and Zhou et al. (2023) suggested that the highest crop productivity and lowest CH_4 emissions can be obtained simultaneously by optimising the sowing window for 20 rice field stations across Hubei Province, China. Similarly, Zhao et al. (2020) recommended a reduced N fertiliser application rate combined with moistening irrigation (soil was saturated with water but not covered with a layer of water) for reducing GHG emissions while maintaining grain yields in rice–wheat systems. Although there have been many studies using models to evaluate the response of agricultural systems to field management practices under future climatic conditions, few studies have systematically evaluated the net GHG emissions that combining SOC sequestration with GHG emissions, while considering crop yields.

The Soil-Plant-Atmosphere Continuum SYStem model (shorten as 'SPACSYS') (Wu et al., 2007, 2015) is one of the widely used agricultural models. The model has been proved to be effective in simulating crop growth and development, nitrogen (N) uptake, SOC sequestration, soil water dynamics and GHG emissions (Wang et al., 2019; Liu et al., 2020a). It has been widely used to explore the influence of climate change on agricultural systems under various agricultural management practices including N fertiliser application, organic amendment, irrigation and tillage (Liang et al., 2018; Liu et al., 2018b; Zhang et al., 2018; Hassall et al., 2022; Wu et al., 2022b; Wang et al., 2024a). It has also been used to optimise planting dates and N fertiliser management practices under various soil and climatic conditions (Abalos et al., 2016; Liu et al., 2020a; Wu et al., 2020). The new version of the model (Ver. 6.00) allows to simulate arable systems, bioenergy crops and intensive and extensive grazing systems on grasslands (Wu et al., 2022a; Wang et al., 2024c). Its special features are the biological-based denitrification component that can distinguish different nitrogenous gases emissions (N_2O, NO and N_2) (Wu et al., 2015) and the detailed three-dimensional root growth sub-modules that can simulate water and nutrients uptake by plants accurately (Bingham and Wu, 2011). However, the model lacks processes related to soil microbial mediation of carbon-cycle (e.g. microbial necromass recycling, active and dormant microbial dynamics) (Chandel et al., 2023). In general, SPACSYS is considered as a promising tool for identifying sustainable management practices for climate change adaptation.

In this study, the SPACSYS was calibrated and validated using datasets from an experiment on the rice–wheat system with long-term different fertilisation measures. The validated model was further applied to assess possible consequences under future climate change scenarios (i.e., SSP1–2.6 and SSP5–8.5) for the system and to propose possible agricultural management practices (i.e., chemical N fertilisers and irrigation management) for adaptation and mitigation in Southwest China.

2. Materials and methods

2.1. Study site and experimental design

In the present study, dataset was collected from the long-term experiment (1991–2019) at the National Monitoring Station for Purple Soil Fertility (29°48′N, 106°24′E) in Beibei, Chongqing, China. The area has a subtropical climate with a mean annual temperature of 19.2 °C and mean annual precipitation of 1133 mm between 1991 and 2020 (Fig. 1). The soil is classified as Rhodic Cambisol based on “World Reference Base for soil resources” soil classification and its basic physicochemical characteristics (measured in 1991) were presented in Table 1.

The cropping system is single rice–winter wheat rotation system. Each year, rice is transplanted in mid-May and harvested in late August, whereas winter wheat sown in early November and harvested in early May next year. The changes in crop varieties during the experimental periods are shown in Table S1. Four treatments were considered in this experiment, i.e., no fertiliser application (CK), application of chemical N, P and K fertilisers (NPK), application of manure (M) and a combined application of NPK and M (NPKM). Detailed information about the experiment has been reported previously (Wang et al., 2020a). The N fertiliser was applied in the form of urea in two split doses for both rice and wheat, i.e., 60 % of total application amount for a crop as basal fertiliser (before rice transplanted or wheat sown), and the rest applied at between the 3rd and 4th leaf expansion for wheat and between 2 and 3 weeks after transplantation for rice. The P and K fertilisers were applied as basal fertilisers only. Fresh pig manure was applied at 22.5 t ha^{-1} once a year as basal fertiliser before wheat sown for M and NPKM treatments. From 1996, the M treatment was changed into rice straw return at 7.5 t dry matter ha^{-1} (1996–2013) or 4.5 t ha^{-1} (2014–2017), and then switched back to the application of fresh pig manure from 2018. Table 2 shows the fertiliser application rates used during the experiment for N (urea), P (calcium superphosphate), K (potassium chloride) fertilisers as well as for manure. Wheat was rain-fed and rice was flooded with a waterlogging depth of 5–8 cm till 3 weeks before harvest and then the field was drained. Pesticide and herbicide were applied followed the local conventional practices. Historical (1991–2020) daily weather data were downloaded from the National Meteorological Information Center (http://data.cma.cn/).

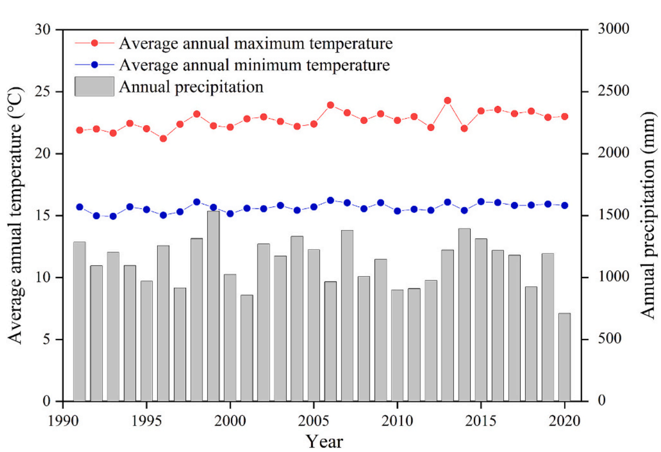

Fig. 1. Average annual temperature and annual precipitation at the experimental site from 1991 to 2020.

2.2. Measurements

Soil samples were collected from the 0–20 cm topsoil (with 4 replicates) after rice harvest. The SOC content was measured with the wet oxidation method (Snyder and Trofymow, 1984) and converted to SOC stock (t C ha^{-1}):

$$SOC = SOC_C \times BD \times 20 \times 0.1 \quad (1)$$

where SOC_C is the soil C content (g kg^{-1}), BD is the soil bulk density, and 0.1 is a conversion coefficient.

The CH_4 and N_2O emission fluxes in CK and NPK treatments were measured (with 3 replicates) every 3–5 days during the rice season and every 7–10 days during the rest of the period from May 2014 to April 2015 using the static closed chamber method (60 cm × 30 cm × 110 cm). Gas samples were collected between 9:00 and 12:00 a.m. at 0, 10, 20 and 30 min after chambers were closed and analysed using a gas chromatograph (GC-2014, Shimadzu, Kyoto, Japan) immediately after collection.

The crop grain and straw were manually collected at harvest and then air-dried and weighed. Crop grain and straw samples were oven-dried at 105 °C for 30 min and then heated at 70 °C to constant weight to determine crop N content with the method of Kjeldahl. The yield stability and sustainability of rice and wheat under different scenarios were evaluated by considering the coefficient of variation (CV) and the sustainable yield index (SYI), respectively (Han et al., 2020), which are calculated as follows:

$$CV = SD / Y_{mean} * 100\ \% \quad (2)$$

$$SYI = (Y_{mean} - SD) / Y_{max} \quad (3)$$

where Y_{mean} and Y_{max} (kg ha^{-1}) are the mean and maximum values of grain yield for a given crop during the study period in each simulation scenario, and SD is the standard deviation of the grain yield for a given crop.

2.3. The SPACSYS model

The SPACSYS model (Ver 6.00) is a field scale, weather-driven, process-based and flexible time step (up to daily) dynamic simulation model (Wu et al., 2007; Wu and Shepherd, 2011; Wu et al., 2015; Wu et al., 2022a). It simulates processes in plant development and growth, soil heat and water transformation, soil C and N dynamics. The actual growth of plant is determined by the potential growth and the limitation of leaf N, P concentration and soil water content in the root zone. The SOM pool is divided into four sub-pools, fresh organic material, humus, dissolved SOM and microbial biomass. The new version of SPACSYS includes a methanogenesis sub-model that considers the anaerobic oxidation of SOM under anaerobic conditions. Dry and wet N deposition was considered by the model.

2.4. Model calibration and validation

The model was initially run with parameters obtained from previous results (Bingham and Wu, 2011; Liu et al., 2020a). Observations from NPK and M treatments were used to calibrate the parameters related to crop and soil processes. The calibrated parameters are shown in Table S2. The calibrated model was validated with the data from CK and NPKM treatments.

2.5. Simulation scenarios

To explore possible practices to mitigate GHG emissions under future climatic conditions in paddy fields, different field management practices with various climate scenarios were investigated. The daily bias-corrected weather data of the two future climate change scenarios

Table 1
The initial soil basic physicochemical characteristics (measured in 1991) at the long-term experimental site.

Soil layer (cm)	Total soil organic matter (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	Total potassium (g kg^{-1})	Available nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})	pH (H_2O)	Soil bulk density (g cm^{-3})
0–20	24.2	1.25	0.67	21.1	93	4.3	88	7.7	1.38
20–40	23.9	1.35	0.52	20.2	95	4.7	85	7.7	–

- No values.

Table 2
Fertiliser application rate for each crop at the experimental site during 1991–2019.

Treatments[1]	Rice (kg ha^{-1})			Wheat (kg ha^{-1})			
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	Manure/ Straw[2]
CK	0	0	0	0	0	0	0
NPK[3]	150 (135)	75 (60)	75 (60)	150	75 (60)	75 (60)	0
M[4]	0	0	0	0	0	0	22,500/ 4500–7500
NPKM	150 (135)	75 (60)	75 (60)	150	75 (60)	75 (60)	22,500

[1] CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications;
[2] The average N, P and K content for manure and straw are 0.56 %, 0.48 %, 1.31 %, and 0.70 %, 0.12 %, 2.59 %, respectively;
[3] Numbers out and in of brackets represent fertiliser application rate in year of 1991–1996 and 1997–2019;
[4] The application of manure changed to straw retention during 1996–2016.

(SSP1–2.6 and SSP5–8.5) for 2024–2100 and the baseline scenario spans the historical time period 1938–2014 with the UKESM1–0-LL model were downloaded from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) (https://esgfnode.llnl.gov/projects/cmip6/). The dataset of the baseline scenario was then cycled to 2100 for model simulation. The UKESM1–0-LL model is developed by the UK Earth System Modelling project, it performs well with the observations in the historical simulation periods (Sellar et al., 2019). Shared Socioeconomic Pathway (SSP) 1–2.6 and 5–8.5 represent two distinct pathways: SSP1–2.6 represents sustainable development with lower GHG emissions and SSP5–8.5 represents energy intensive and fossil-fueled development with higher GHG emissions (O'Neill et al., 2016). The downloaded data was then downscaled to the location based on geographical information with the R 'raster' package. A summary of different weather elements and CO_2 concentrations under each climate change scenario are shown in Table 3.

Local traditional management practices for simulation scenarios refer to the application of chemical N, P and K fertilisers with N application rate at 285 kg N ha^{-1} yr^{-1} (150 and 135 kg N ha^{-1} yr^{-1} for rice and wheat, respectively), and water managements of continuous flooding during rice season and rain-fed irrigation during wheat season in rice–wheat cropping system. We assume that the straw returning rate is 30 %, representing the stubble remaining at harvest. Three mitigation management scenarios were considered: reduced N application rate by 20 % (RNA), the introduction of mid-season drainage (MSD) during the rice growing period and integrated management combining RNA with MSD (IM). Therefore, 11 possible scenarios were generated considering a combination of climate scenarios and mitigation management practices (Table 4). For all the scenarios, we set initial soil properties the same values as the observations. Crop cultivars and the sowing/transplanting dates were assumed to be identical to those of 2018 (Table S1).

Table 4
Designed simulation scenarios combining climate change scenarios with mitigation management scenarios.

Scenarios abbreviation	Climate change scenarios	Mitigation management practices
Baseline	Downloaded historical data	Local traditional management practices*
SSP1–2.6	SSP1–2.6 with a constant CO_2 concentration	Local traditional management practices
SSP1–2.6_CO_2	SSP1–2.6 with CO_2 fertilisation	Local traditional management practices
SSP1–2.6_CO_2_RNA	SSP1–2.6 with CO_2 fertilisation	Reduced N application rate (20 % less N than Baseline)
SSP1–2.6_CO_2_MSD	SSP1–2.6 with CO_2 fertilisation	Mid-Season Drainage (continuous flooding with mid-season drainage in rice growing season)
SSP1–2.6_CO_2_IM	SSP1–2.6 with CO_2 fertilisation	Integrated management (combining RNA with MSD)
SSP5–8.5	SSP5–8.5 with a constant CO_2 concentration	Local traditional management practices
SSP5–8.5_CO_2	SSP5–8.5 with CO_2 fertilisation	Local traditional management practices
SSP5–8.5_CO_2_RNA	SSP5–8.5 with CO_2 fertilisation	Reduced N application rate (20 % less N than Baseline)
SSP5–8.5_CO_2_MSD	SSP5–8.5 with CO_2 fertilisation	Mid-season drainage (continuous flooding with mid-season drainage in rice growing season)
SSP5–8.5_CO_2_IM	SSP5–8.5 with CO_2 fertilisation	Integrated management (combining RNA with MSD)

* Local traditional management practices refer to the application of chemical N, P and K fertilisers with N application rate at 285 kg N ha^{-1} yr^{-1} (150 and 135 kg N ha^{-1} yr^{-1} for rice and wheat, respectively), and water managements of continuous flooding during rice season and rain-fed irrigation during wheat season in rice–wheat cropping system. The straw returning rate is 30 %, representing the stubble remaining at harvest.

Table 3
Characteristics of different meteorological elements for each climate change and baseline scenario.

	Annual mean maximum temperature (°C)		Annual mean minimum temperature (°C)		Annual precipitation (mm)		Annual mean global radiation (MJ m^{-2})		CO_2 concentration range (ppm)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Baseline	21.5	0.6	15.2	0.5	1149.1	207.8	11.4	0.6	400
SSP1–2.6	24.6	0.7	18.1	0.6	1233.2	245.4	12.7	0.7	425.4–476
SSP5–8.5	27.0	2.4	20.4	2.3	1241.6	238.7	12.4	0.7	427.8–1148

Baseline, historical climate (1938–2014, constant CO_2 concentration at 400 ppm); SSP1–2.6, strict limits on GHG emissions; SSP 5–8.5, no limits on GHG emissions. SD, standard deviation.

However, winter wheat requires a period of low temperature in winter for vernalisation, under the intensive climate change scenario, the increasing temperature in winter could hamper winter wheat development (when the development index of winter wheat from model output stops at 2, indicating that the crop cannot enter reproductive growth and the photosynthetic products will continue to accumulate in vegetative organs), we then changed winter wheat to spring wheat, which does not require vernalisation and is more suitable for planting under future climatic conditions.

The annual net global warming potential (GWP_N, kg CO_2-eq ha^{-1} yr^{-1}) is calculated (IPCC, 2021):

$$GWP_N = CH_4 \times 16/12 \times 27 + N_2O \times 44/28 \times 273 – SOC_r \times 44/12 \tag{4}$$

$$SOC_r = SOC_n - SOC_{(n-1)} \tag{5}$$

where CH_4 and N_2O are the annual cumulative CH_4 (kg C ha^{-1} yr^{-1}) and N_2O emissions (kg N ha^{-1} yr^{-1}), respectively, and SOC_r is the annual SOC sequestration rate (kg C ha^{-1} yr^{-1}), SOC_n and $SOC_{(n-1)}$ are the SOC stock in the year n and (n-1), respectively. The values 27 and 273 are the global warming potential of CH_4 and N_2O on a 100-year horizon given by IPCC (2021), 16/12, 44/28 and 44/12 are the conversion factors to get the corresponding CO_2-eq value.

2.6. Statistical analysis

Four statistical metrics were used to assess the model's performance, i.e., the coefficient of determination (R^2, 0 to 1), the normalised root mean square error (NRMSE), modelling efficiency (EF, $-\infty$ to 1) and the index of agreement (d, 0 to 1). R^2 represents the proportion of the variance in measurements explained by the model; NRMSE indicates the percentage deviation from the range of observations; EF compares the modelling efficiency to the efficiency of describing the data as measured averages and d gives the degree to which the deviation toward 0 (Willmott, 1982; Moriasi et al., 2007; Yang et al., 2014; Tesfaye et al., 2021). They are calculated as follows:

$$R^2 = \left(\frac{\left(\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})\right)}{\sqrt{\sum_{i=1}^{n}(Oi - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}} \right)^2 \tag{6}$$

$$NRMSE = \frac{1}{(O_{max} - O_{min})}\sqrt{\frac{\sum_{i=1}^{n}(Si - Oi)^2}{n}} \times 100\% \tag{7}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(Si - Oi)^2}{\sum_{i=1}^{n}(Oi - \overline{O})^2} \tag{8}$$

$$d = 1 - \sum_{i=1}^{n}(S_i - O_i)^2 \Big/ \sum_{i=1}^{n}\left(|(S_i - \overline{O})| + |(O_i - \overline{O})|\right)^2 \tag{9}$$

where S_i and O_i are simulations and observations for the ith sampling point, respectively; $\overline{S}$ and $\overline{O}$ are the averages of all simulations and observations; O_{max} and O_{min} are the maximum and minimum values of the observations; and n is the sample size and "| |" is an absolute calculation.

One-way ANOVA analysis followed by the Duncan's test at the 0.05 level ($P < 0.05$) was used to determine the significant difference of the effects of climate and mitigation management scenarios on crop yields, CH_4 and N_2O emissions and GWP_N. The ANOVA have been performed using SPSS 22.0 (SPSS, Inc., 2017, Chicago, USA).

3. Results

3.1. Model calibration and validation

Statistical indicators for model performance at both the calibration and validation stages are shown in Table 5. The values showed that the SPACSYS model performed relatively well in simulating crop grain and straw yields, crop N uptake, SOC stock, and CH_4 and N_2O emission fluxes in the rice–wheat system. Specifically, simulated crop grain and straw yields along with their N contents matched well with the observed data for each treatment over the whole period (Fig. 2). The simulation performance of wheat was better than that of rice, as shown by lower NRMSE (Table 5). Modelled SOC stock in the top 20 cm of soil was well consistent with the measured data, with modelled and observed average SOC sequestration rates ranged from 57 to 308 kg C ha^{-1} yr^{-1} and 24 to 421 kg C ha^{-1} yr^{-1}, respectively (Fig. 3). The EF ranged between 0.12 and 0.53, the d ranged between 0.68 and 0.79 (Table 5). The model fairly captured the pattern and magnitude of observed daily CH_4 and N_2O fluxes (Fig. 4). The simulated peak for CH_4 flux in summer 2014 (3.49 kg C ha^{-1} day^{-1}) agreed well with the observed (3.30 kg C ha^{-1} day^{-1}), however, the model did not capture the N_2O emission peak in the winter wheat growing season (Fig. 4). The model performance in simulating daily CH_4 and N_2O fluxes were effectively, with EF ranged from 0.14 to 0.63 and d ranged from 0.59 to 0.89 (Table 5).

3.2. Crop grain yields under different climate change and mitigation management scenarios

The influence of climate change scenarios, mitigation management scenarios and their combination on crop yields are shown in Fig. 5a, b (conventional cropping system) and Fig. 5c, d (adaptive cropping system). Under the conventional cropping system (single rice–winter wheat), the climate in the SSP1–2.6 scenario considering the CO_2 fertilisation effects could significantly increase wheat yields by 28 %, while

Table 5
Statistical analysis describing the performance of the SPACSYS model for the simulations of crop yield, crop N content, SOC stock, daily CH_4 and N_2O emissions in the rice–wheat rotation system.

Crop	Variable (kg ha^{-1} for crops)	Calibration					Validation				
		n	R^2	NRMSE	EF	d	n	R^2	NRMSE	EF	d
Wheat	Grain yield	54	0.46**	20 %	0.35	0.75	54	0.58**	18 %	0.48	0.84
	Straw biomass	54	0.38**	21 %	0.29	0.72	54	0.49**	17 %	0.48	0.79
	Nitrogen content in grain at maturity	54	0.54**	20 %	0.48	0.79	54	0.64**	17 %	0.64	0.88
	Nitrogen content in straw at maturity	54	0.43**	18 %	0.34	0.70	54	0.62**	21 %	0.48	0.78
Rice	Grain yield	54	0.38**	20 %	0.32	0.77	54	0.54**	19 %	0.54	0.83
	Straw biomass	54	0.22**	25 %	0.17	0.65	54	0.37**	23 %	0.33	0.72
	Nitrogen content in grain at maturity	54	0.63**	24 %	0.30	0.81	54	0.67**	21 %	0.46	0.85
	Nitrogen content in straw at maturity	54	0.39**	23 %	0.29	0.76	54	0.42**	21 %	0.33	0.78
SOC stock (t C ha^{-1})		30	0.21**	24 %	0.12	0.68	30	0.62**	18 %	0.53	0.79
Daily CH_4 emissions (g C m^{-2} day^{-1})		69	0.64**	16 %	0.63	0.89	69	0.56**	20 %	0.38	0.85
Daily N_2O emissions (g N m^{-2} day^{-1})		69	0.52**	13 %	0.26	0.69	69	0.17*	17 %	0.14	0.59

R^2, the correlation of determination; NRMSE, the normalised root mean square error; EF, the modelling efficiency; d, the index of agreement. ** $P < 0.01$.

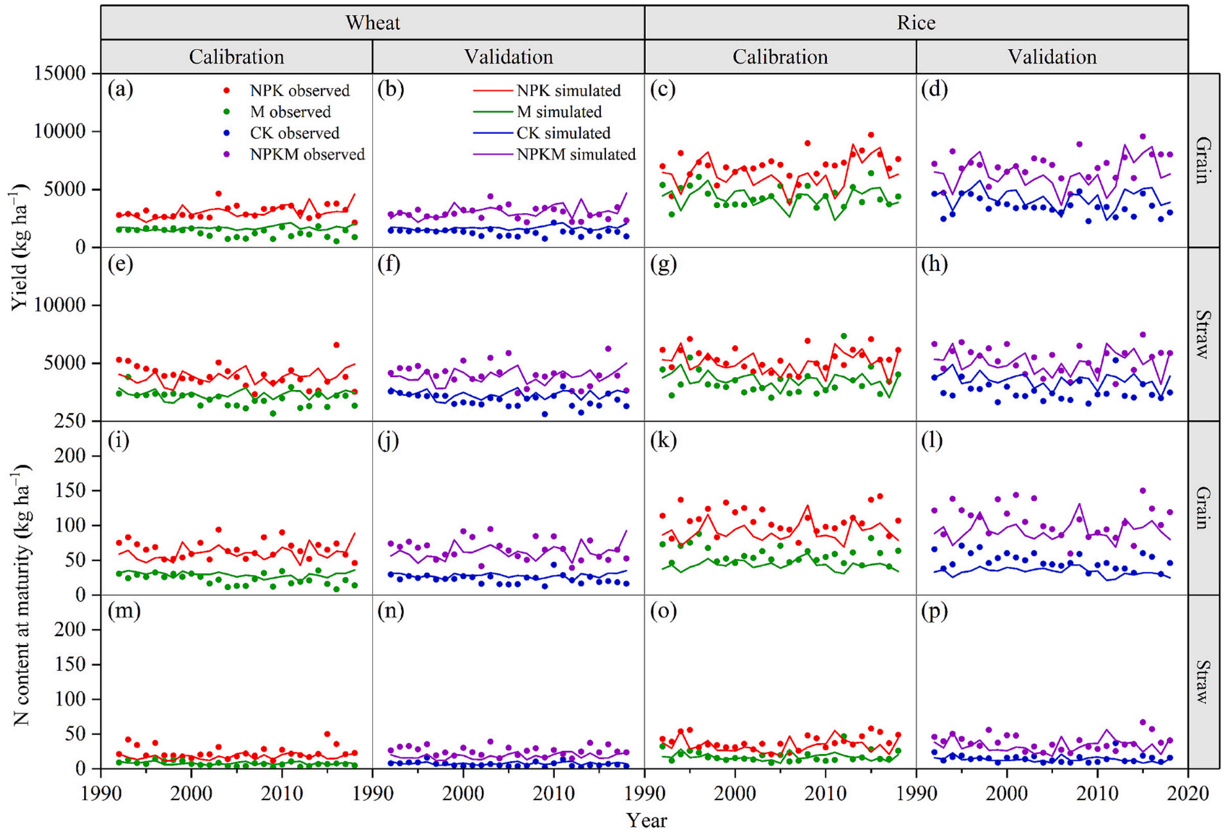

Fig. 2. Observed and simulated crop yield and N content from 1991 to 2019. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications.

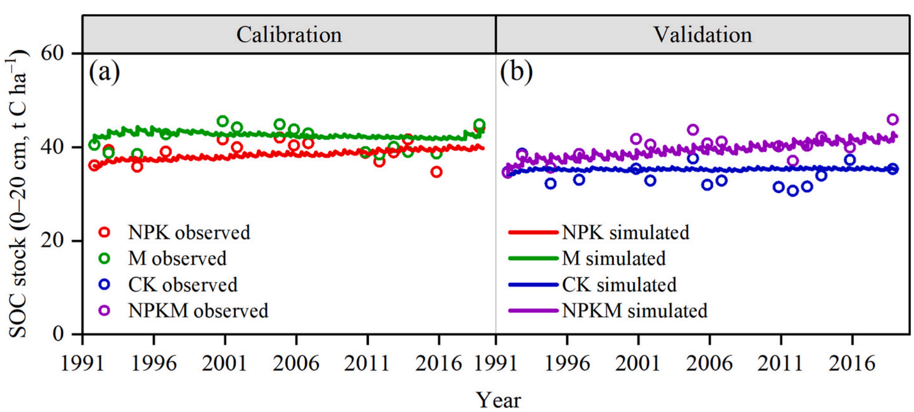

Fig. 3. Observed and simulated SOC stock in the top 20 cm of soil depth in the rice–wheat rotation system from 1991 to 2019. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers; M, manure application; NPKM, a combination of NPK and M applications.

rice yields would not change compared to the baseline scenario ($P < 0.05$) (Fig. 5a, b). However, the climate in the SSP5–8.5 scenario (considering the CO_2 fertilisation effects or considering a constant CO_2 concentration) could significantly decrease rice yields by 11.8–29.9 % and wheat yield by 8.3–19.4 % ($P < 0.05$) (Fig. 5a, b). The decrease in wheat yields is significantly due to the incomplete vernalisation of winter wheat in warmer winter after 2070, suggesting it would be particularly unsuitable for planting winter wheat under the SSP5–8.5 scenario (Fig. S1). Therefore, the winter wheat was replaced by spring wheat from 2070 onward in the rice–wheat cropping system, referred as the adaptive cropping system. The results showed that under the adaptative cropping system, the wheat yield loss caused by warming in the conventional cropping system could be completely avoided (Fig. 5d). On the contrary, wheat yield could increase by up to 21.9 % compared to the baseline scenario (Fig. 5d). A 20 % reduction in N application would not significantly decrease grain yields for either rice or wheat ($P < 0.05$) under the two climate change scenarios (Fig. 5). The yield stability and sustainability of rice and wheat under the SSP5–8.5 climate change scenario could be lower than those under the SSP1–2.6 climate change scenario (Fig. S2). Rice had a higher stability and sustainability than wheat (Fig. S2).

3.3. Soil organic carbon stock under different climate change and mitigation management scenarios

The dynamics of SOC stock in the top 20 cm of soil under various

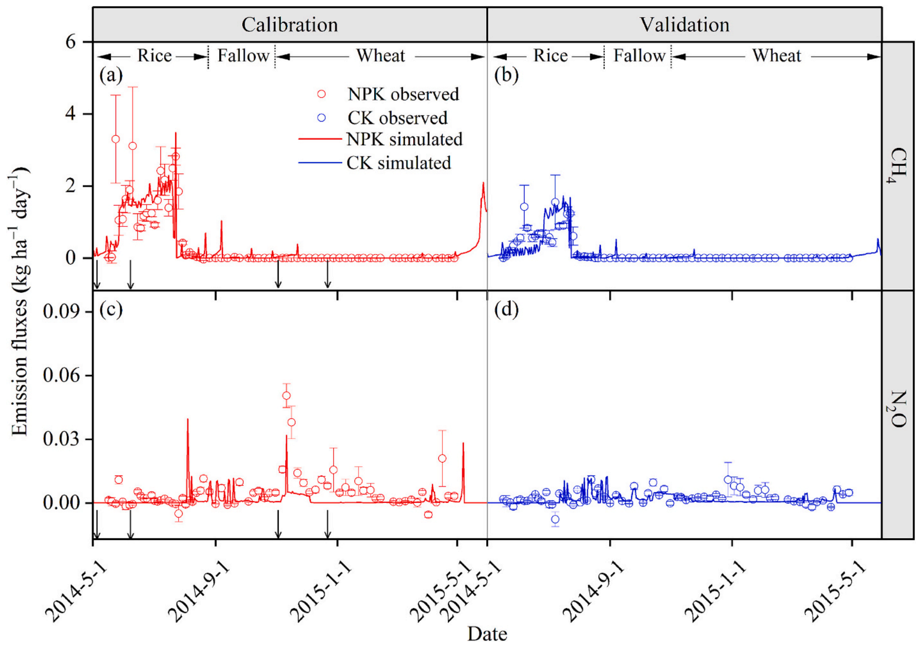

Fig. 4. Observed and simulated CH_4 and N_2O emission fluxes for model calibration and validation at the experimental site in the rice–wheat rotation system between May 1, 2014, and May 31, 2015. Solid downward arrows indicate N fertiliser application events. CK, no fertiliser application; NPK, applications of chemical nitrogen, phosphorus and potassium fertilisers.

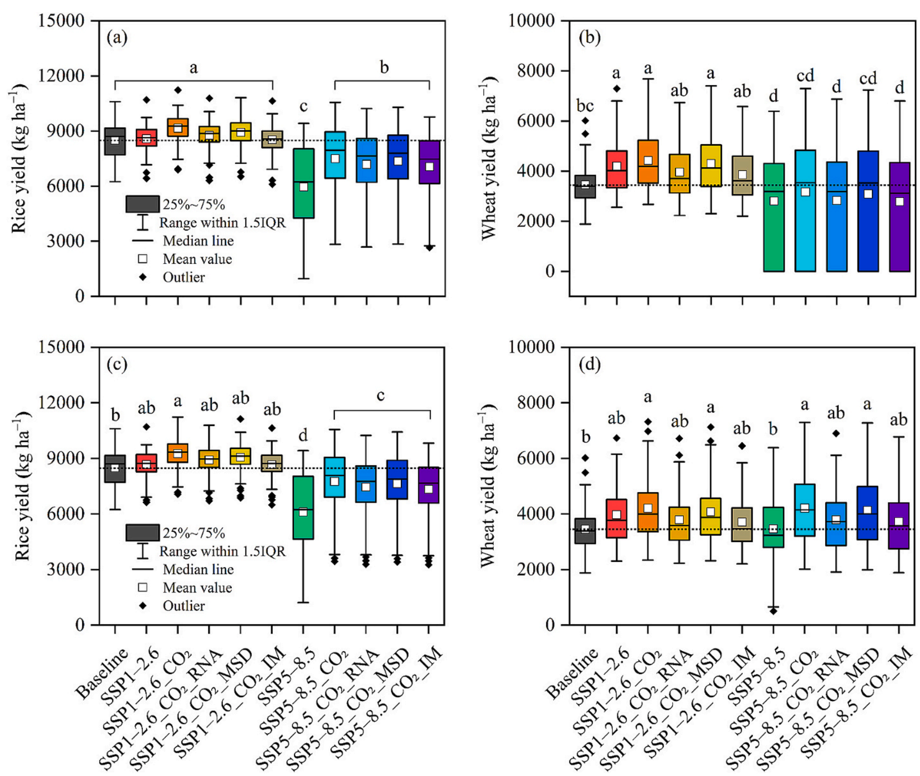

Fig. 5. Rice and wheat yields in conventional cropping system (a, b) and adaptive cropping system (c, d) under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

scenarios is shown in Fig. 6. The SOC stock is projected to increase over the simulation period under all scenarios except for SSP5–8.5 with a constant CO_2 concentration, under which the stock could decline from 2080 onward. However, the average increase rates of SOC stock under both SSP1–2.6 (215–256 kg C ha^{-1} yr^{-1}) and SSP5–8.5 (175–197 kg C ha^{-1} yr^{-1}) are lower than that under the baseline scenario (263 kg C ha^{-1} yr^{-1}), suggesting a negative impacts of climate change on SOC sequestration (Table S3).

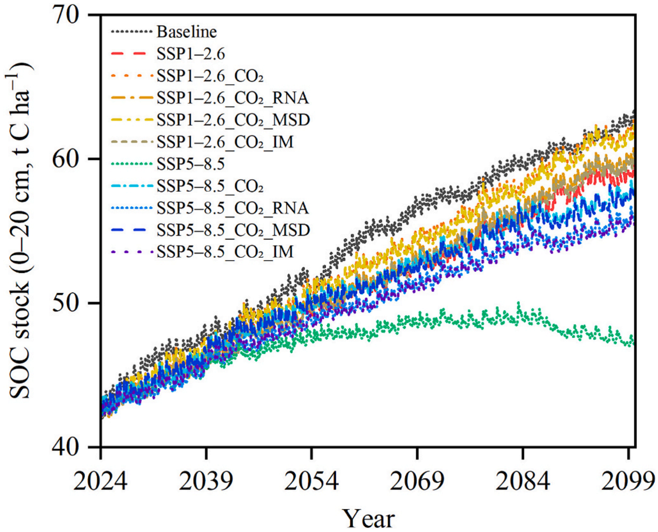

Fig. 6. SOC stock in the top 20 cm of soil depth in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

3.4. *CH_4, N_2O emissions and GWP_N under different climate change and mitigation management scenarios*

The influence of climate change scenarios, mitigation management scenarios and their combination on CH_4, N_2O emissions and net global warming potential (GWP_N) are shown in Fig. 7 and Fig. 8. Switching the irrigation method from continuous flooding to mid-season drainage (MSD) could significantly reduce CH_4 emissions by 45 % under SSP1–2.6 and 47 % ($P < 0.05$) under SSP5–8.5 (Fig. 7a). Additionally, integrated management combining RNA with MSD (IM) could further reduce CH_4 emissions by 55 % under SSP1–2.6 and 57 % ($P < 0.05$) under SSP5–8.5 (Fig. 7a). Reducing N application rate by 20 % (RNA) could significantly lower N_2O emissions by 23 % under SSP1–2.6 and 25 % under SSP5–8.5 ($P < 0.05$) (Fig. 7b). As a result, the GWP_N for the IM scenarios could decrease by 70 % and 67 % under the two climate change scenarios compared with no adaptation (Fig. 8).

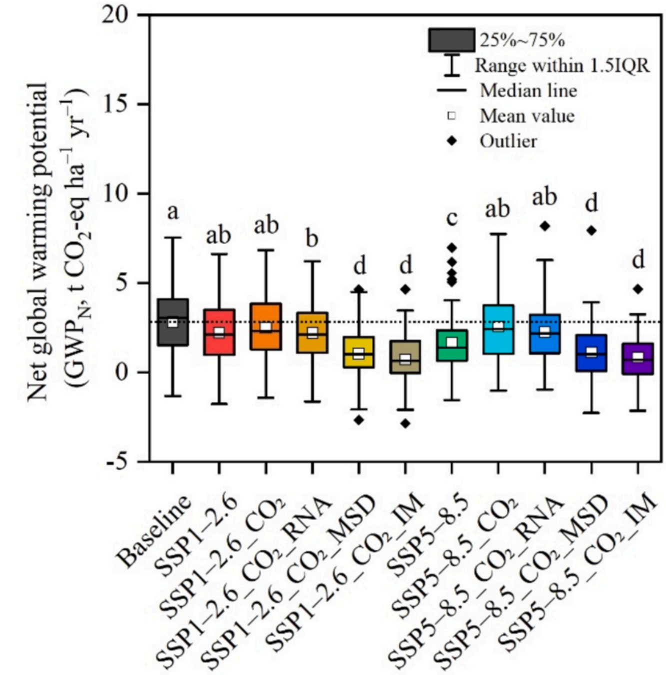

Fig. 8. Net global warming potential (GWP_N) in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

4. Discussion

4.1. *Model performance*

The statistical metrics indicated that the SPACSYS model robustly simulated soil-plant interactions in the rice–wheat system (Table 5). The model performed particularly well in considering the impacts of different fertiliser types on the system. For example, it effectively reproduced the downward trend in SOC dynamics under the M treatment from 1996 to 2017 due to the conversion from manure application to straw retention (Fig. 3). However, the model underestimated rice grain yield and N content in rice grains for both NPK and NPKM

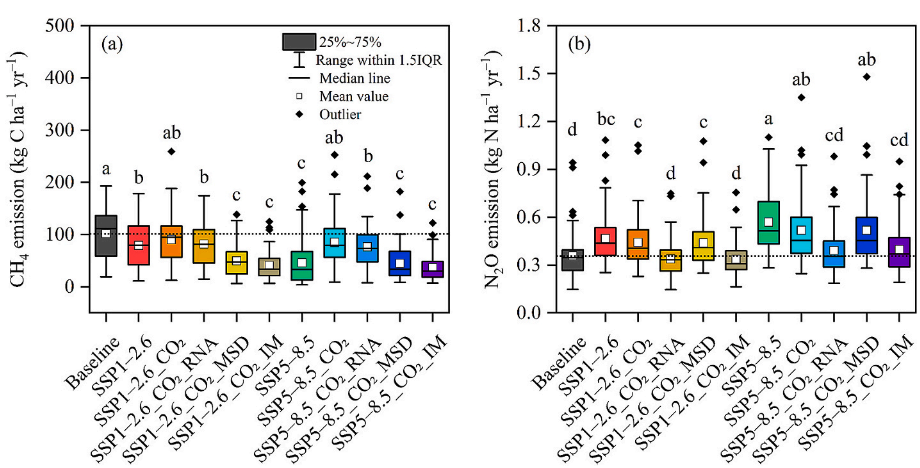

Fig. 7. CH_4 (a) and N_2O emissions (b) in adaptive cropping system under different climate change and mitigation management scenarios from 2024 to 2100. For each boxplot, the central line is the median, the square is the mean value, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the outliers. RNA, reduced N application rate by 20 %; MSD, the introduction of mid-season drainage; IM, integrated management combining RNA with MSD.

treatments, particularly failing to capture high yields in some years (Fig. 2). This discrepancy could be attributed to the model's simplified partitioning of absorbed N in different organs. In the model, the partitioning coefficients are determined by crop development index (obtained from accumulated temperatures from crop sowing/ transplanting), this may not capture the actual dynamic changes during crop growth (Liu et al., 2020a; Wu et al., 2016, 2020). The model failed to capture the N_2O emission peaks during the wheat growing season (Fig. 4c), likely due to 1) the inaccurate simulation of soil water content or soil temperature because the N_2O process is highly dependent on soil moisture and soil temperature (Smith et al., 2008), which was unavailable in this experiment for model validation; 2) other pathways producing N_2O emissions that are not included in the model, e.g. dissimilatory nitrate reduction to ammonium and anaerobic ammonium oxidation (Hu et al., 2015). Additionally, the CH_4 emissions are highly dependent on soil water and temperature conditions (Le Mer and Roger, 2001), the lack of the information in this study could influence the modelling of GHG emissions under future climatic conditions. In future study, the model should be 1) validated with more detailed field measurements to project more reliable results; 2) developed regarding dynamic changes in nutrient partitioning to different organs and other pathways of N_2O production.

4.2. Climate change impacts on crop yields

Climate warming has a huge impact on crop production through shifting phenological development of crops and changing the spatial distribution pattern of crops (Bai and Xiao, 2020; Fatima et al., 2020). Many studies have revealed the potential risk of crop production to climate change (Basche et al., 2016; Wing et al., 2021; Zhu et al., 2022). For example, a recent study showed that under the most severe climate change scenario, yield of globally important staple cereal crops would decrease by 7–23 % (Rezaei et al., 2023). The economic benefit loss of six crops in the United States in 2070 will reach 31 % under RCP 8.5 without adaptation in crop cultivation (Rising and Devineni, 2020). Similarly, our results highlighted the potential risk of both rice and winter wheat yields under the intensive climate change scenario (SSP5–8.5) (Fig. 5 and Fig. S3). The projected rice yield loss would be nearly 30 % without considering CO_2 fertilisation effect (Fig. 5). This aligns with previous result of a 33.8 % loss for late rice (Zhang et al., 2023). Consistent with Wang et al. (2024b), the CO_2 fertilisation effect would not be sufficient to fully compensate for the negative effect of warming on rice yield under the SSP5–8.5 scenario (Fig. 5).

One consequence of global warming is the spatial cropping pattern change in agriculture (Liang et al., 2021; Guo et al., 2024). Rising and Devineni (2020) has indicated that half of the economic benefit losses of crops can be avoided through crop reallocation. In our study, rice production could face serious threat during 2050–2100 under the intensive climate change scenario (SSP5–8.5) (Fig. 5 and Fig. S3). This implies that there might be a possible northward shift for rice cultivation to avoid damaging to crop yields in the future. Previous study has found that the northern limit of Chinese paddies has moved toward higher latitudes due to climate warming from 1984 to 2013 (Liang et al., 2021). Moreover, our results showed that winter wheat might not be suitable for rice–wheat system in Southwest China during 2070–2100 under the intensive climate change scenario (SSP5–8.5) (Fig. S3). This can be mainly explained by the incomplete vernalisation process due to the increasing temperatures during vegetative stage in wheat season. Other researchers have also raised concerns about the vulnerability of winter wheat yields to climate warming (Wang et al., 2015; Wu et al., 2017). Winter wheat requires a period of low temperatures to initiate the transition from vegetative growth to reproductive development (vernalisation), without vernalisation process, crops will continue to grow vegetatively (Chouard, 1960; Deng et al., 2015). Previous studies have demonstrated that the effective maximum temperature for vernalisation of winter wheat is usually below 18 °C depends on different cultivars (Brooking, 1996; Porter and Gawith, 1999). However, in our study, the maximum temperature is basically higher than 20 °C during overwintering period (from early December to mid-February) under the SSP5–8.5 scenario during 2070–2100 (Fig. S4). Therefore, based on our simulations, we recommend converting the cropping pattern from single rice–winter wheat to single rice–spring wheat in the distant future (2070–2100), in order to build agricultural resilience toward global warming across the studied region (Fig. 5 and Fig. S3). Other studies have shown similar results. For example, using CMIP5 models to project optimal crop patterns, Rising and Devineni (2020) reported an upward trend for winter wheat from the south along the Mississippi under RCP 8.5 in the United States. The area for winter wheat suitability could be reduced due to drought risk under a climate with a mean temperature increased by 2 °C in eastern England (Brignall and Rounsevel, 1995). Climate change would reduce the suitable areas for traditional crops in southern Europe due to water shortage and the increase in extreme weather events (Jørgen and Marco, 2002). This implies that agricultural policies toward encouraging the conversion of farming systems is necessary in the future. Overall, our findings highlight the need for the adjustment of cropping patterns and the development of breeding of climate-adapted genotypes to build agricultural resiliency and sustainability in the future.

4.3. GHG emissions mitigation under climate change

Our simulations suggest that comprehensive mitigation management strategies combining reduced N fertiliser with mid-season drainage can significantly reduce CH_4 and N_2O emissions while maintaining crop yield in paddies under climate change. Previous studies have also shown the similar results based on the current climate conditions (Tian et al., 2018; Wang et al., 2020b). It is well recognized that N fertiliser and irrigation regime are two important factors affecting crop yields and GHG emissions in paddies (Meijide et al., 2017; Zou et al., 2005). N fertiliser application is the most important driver of soil N_2O emissions. The application rate of N fertiliser can be reduced to lower N_2O emissions with no or little yield penalty in agriculture (Zhong et al., 2016). Draining the flooded soils of rice paddies can reduce CH_4 emissions substantially. In this study, the magnitude of the CH_4 reduction (45–47 %) (Fig. 7a) is in line with previous result (Liu et al., 2019). However, mitigation measures for CH_4 emissions can lead to an increase of N_2O emissions in paddies due to the changes in water status. Study has indicated that the increase in N_2O emissions caused by mid-season drainage can offset 65 % of the benefits gained by CH_4 reduction (Li et al., 2004). As such, it is crucial to assess the global warming potential of CH_4 and N_2O emissions considering the trade-offs between them. Our results indicated that the integrated mitigation measures could reduce the net global warming potential by 69 % with limited risk for yield reduction under future climate change scenarios (Figs. 5 and 8). Overall, our findings suggest that managing N fertilisation and irrigation regime are crucial for climate mitigation under future climate change.

4.4. Uncertainties and limitations

The uncertainty of the results may come from the methods used and assumptions made. First, we assumed that crop cultivars and crop sowing/transplanting dates remain unchanged under future climate change scenarios. However, studies have shown that improved crop cultivars and shifted sowing/transplanting dates are effective in mitigating the negative influence of climate change on crop production (Rezaei et al., 2018; Ding et al., 2020; Zhang et al., 2023). Second, the climate change scenarios used in this study are derived from single global climate model (GCM), this can only represent a narrow range of uncertainty in projected climate. As such, establishing an ensemble approach that integrating values from multiple GCMs is necessary. Third, process-based model can also introduce some uncertainties in the prediction results due to the specific model structure and parameters

(Chapagain et al., 2022). Martre et al. (2015) has indicated that results from multi-model ensemble have higher accuracy and consistency than that of a single model. Therefore, the potential of improving the predictions through integrating two or more models should be investigated. Fourth, our study lacks measured soil water content and soil temperature for model's calibration and validation, this could introduce significant uncertainty in the results. Soil water content and soil temperature are the two important factors for CH_4 and N_2O emissions (Le Mer and Roger, 2001; Liu and Hayden, 2017). As such, improving the simulation performance of the model with detailed information should be considered in future study.

5. Conclusion

In this study, we tested the SPACSYS model with the observed grain and straw yield, grain and straw N content, SOC stock, CH_4 and N_2O emissions under single rice–winter wheat rotation system from a long-term experimental field in Chongqing city. The validated model was applied to explore GHG mitigation practices without sacrificing crop production from paddy fields. Two climate change scenarios (SSP1–2.6 and SSP5–8.5) in addition to the baseline scenario and three mitigation management scenarios (reduced N application rate by 20 %, the introduction of mid-season drainage and integrated management) were established. Results showed that SPACSYS model effectively simulated the observed variables from the experimental fields. Simulation scenarios indicated that climate change has a positive impact on crop yields under the SSP1–2.6 scenario and a negative impact under the SSP5–8.5 scenario. In this last situation, converting winter wheat to spring wheat in the distant future (2070–2100) could avoid the wheat yield loss. Reduced N application rate by 20 % will not significantly decrease crop yield under the two climate change scenarios, but could decrease N_2O emissions. Mid-season drainage could significantly decrease CH_4 emissions under the two climate change scenarios. Our results suggest that crop switching combining integrated management (e.g. N reduction with mid-season drainage) can significantly mitigate global warming without sacrificing crop production from rice–wheat cropping system under climate change.

CRediT authorship contribution statement

Shuhui Wang: Writing – original draft, Investigation, Formal analysis, Data curation. **Nan Sun:** Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Zhijian Mu:** Data curation. **Fa Wang:** Data curation. **Xiaojun Shi:** Data curation. **Chuang Liu:** Formal analysis. **Shuxiang Zhang:** Formal analysis. **Joost Wellens:** Formal analysis. **Bernard Longdoz:** Writing – review & editing, Formal analysis. **Jeroen Meersmans:** Writing – review & editing, Formal analysis. **Gilles Colinet:** Writing – review & editing, Supervision, Formal analysis. **Minggang Xu:** Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Lianhai Wu:** Writing – review & editing, Validation, Supervision, Software, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104337.

Data availability

Data will be made available on request.

References

Abalos, D., Cardenas, L.M., Wu, L., 2016. Climate change and N_2O emissions from south West England grasslands: a modelling approach. Atmos. Environ. 132, 249–257. https://doi.org/10.1016/j.atmosenv.2016.03.007.

Bai, H., Xiao, D., 2020. Spatiotemporal changes of rice phenology in China during 1981–2010. Theor. Appl. Climatol. 140, 1483–1494. https://doi.org/10.1007/s00704-020-03182-8.

Baishya, A., Mishra, A., Sengupta, S., 2024. Modelling and assessment of climate change impact on Rainfed Rice cultivation in a sub-humid subtropical region. Agric. Res. 13, 85–95. https://doi.org/10.1007/s40003-023-00671-w.

Basche, A.D., Archontoulis, S.V., Kaspar, T.C., Jaynes, D.B., Parkin, T.B., Miguez, F.E., 2016. Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the midwestern United States. Agr Ecosyst Environ 218, 95–106. https://doi.org/10.1016/j.agee.2015.11.011.

Bingham, I.J., Wu, L., 2011. Simulation of wheat growth using the 3D root architecture model SPACSYS: validation and sensitivity analysis. Eur. J. Agron. 34, 181–189. https://doi.org/10.1016/j.eja.2011.01.003.

Bossio, D.A., Cook-Patton, S.C., Ellis, P.W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R.J., von Unger, M., Emmer, I.M., Griscom, B.W., 2020. The role of soil carbon in natural climate solutions. Nat. Sustain. 3, 391–398. https://doi.org/10.1038/s41893-020-0491-z.

Brignall, A.P., Rounsevel, M.D.A., 1995. Land evaluation modelling to assess the effects of climate change on winter wheat potential in England and Wales. J. Agr. Sci. 124, 159–172. https://doi.org/10.1017/s0021859600072841.

Brooking, I.R., 1996. Temperature response of vernalization in wheat: a developmental analysis. Ann. Bot. 78, 507–512. https://doi.org/10.1006/anbo.1996.0148.

Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., Havlik, P., O'Connell, C.S., Johnson, J.A., Saatchi, S., West, P.C., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Change 7, 63–68. https://doi.org/10.1038/NCLIMATE3158.

Challinor, A.J., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287–291. https://doi.org/10.1038/NCLIMATE2153.

Chandel, A.K., Jiang, L.F., Luo, Y.Q., 2023. Microbial models for simulating soil carbon dynamics: a review. JGR Biogeosciences. 128, e2023JG007436. https://doi.org/10.1029/2023JG007436.

Chapagain, R., Remenyi, T.A., Harris, R.M.B., Mohammed, C.L., Huth, N., Wallach, D., Rezaei, E.E., Ojeda, J.J., 2022. Decomposing crop model uncertainty: a systematic review. Field Crop Res 279. https://doi.org/10.1016/j.fcr.2022.108448.

Chouard, P., 1960. Vernalization and its relations to dormancy. Annu. Rev. Plant Physiol. 11, 191–238. https://doi.org/10.1146/annurev.pp.11.060160.001203.

Deng, W., Casao, M.C., Wang, P., Sato, K., Hayes, P.M., Finnegan, E.J., Trevaskis, B., 2015. Direct links between the vernalization response and other key traits of cereal crops. Nat. Commun. 6. https://doi.org/10.1038/ncomms6882.

Ding, Y., Wang, W., Zhuang, Q., Luo, Y., 2020. Adaptation of paddy rice in China to climate change: the effects of shifting sowing date on yield and irrigation water requirement. Agr. Water Manage. 228. https://doi.org/10.1016/j.agwat.2019.105890.

FAO, Food and Agriculture Organization of the United Nations, 2018. Faostat: FAO statistical databases. http://faostat.fao.org/default.aspx.

FAO, Food and Agriculture Organization of the United Nations, 2020. FAOSTAT Emissions shares. http://www.fao.org/faostat/en/#data/EM.

Fatima, Z., Ahmed, M., Hussain, M., Abbas, G., Ul-Allah, S., Ahmad, S., Ahmed, N., Ali, M.A., Sarwar, G., Haque, E.U., Iqbal, P., Hussain, S., 2020. The fingerprints of climate warming on cereal crops phenology and adaptation options. Sci. Rep. 10. https://doi.org/10.1038/s41598-020-74740-3.

Gao, B., Huang, T., Ju, X., Gu, B., Huang, W., Xu, L., Rees, R.M., Powlson, D.S., Smith, P., Cui, S., 2018. Chinese cropping systems are a net source of greenhouse gases despite soil carbon sequestration. Glob. Chang. Biol. 24, 5590–5606. https://doi.org/10.1111/gcb.14425.

Gaydon, D.S., Balwinder, S., Wang, E., Poulton, P.L., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A.K., Chen, C., Choudhury, B.U., Darai, R., Das, A., Hochman, Z., Horan, H., Hosang, E.Y., Kumar, P.V., Khan, A.S.M.M.R., Laing, A.M., Liu, L., Malaviachichi, M.A.P.W.K., Mohapatra, K.P., Muttaleb, M.A., Power, B., Radanielson, A.M., Rai, G.S., Rashid, M.H., Rathanayake, W.M.U.K., Sarker, M.M.R., Sena, D.R., Shamim, M., Subash, N., Suriadi, A., Suriyagoda, L.D.B., Wang, G., Wang, J., Yadav, R.K., Roth, C.H., 2017. Evaluation of the APSIM model in cropping systems of Asia. Field Crop Res 204, 52–75. https://doi.org/10.1016/j.fcr.2016.12.015.

Guo, Y., Zhang, G., Abdalla, M., Kuhnert, M., Bao, H., Xu, H., Ma, J., Begum, K., Smith, P., 2023. Modelling methane emissions and grain yields for a double-rice system in southern China with DAYCENT and DNDC models. Geoderma 431, 116364. https://doi.org/10.1016/j.geoderma.2023.116364.
Guo, E., Li, T., Zhang, Z., Guo, S., Liu, Z., Zhao, J., Zhao, C., Fan, S., Shi, Y., Guan, K., Yang, C., Yang, X., 2024. Potential benefits of cropping pattern change in the climate-sensitive regions of rice production in China. Sci. Total Environ. 934. https://doi.org/10.1016/j.scitotenv.2024.173281.
Han, X., Hu, C., Chen, Y., Qiao, Y., Liu, D., Fan, J., Li, S., Zhang, Z., 2020. Crop yield stability and sustainability in a rice-wheat cropping system based on 34-year field experiment. Eur. J. Agron. 113. https://doi.org/10.1016/j.eja.2019.125965.
Han, X., Roy, A., Moghaddasi, P., Moftakhari, H., Magliocca, N., Mekonnen, M., Moradkhani, H., 2024. Assessment of climate change impact on rainfed corn yield with adaptation measures in deep south, us. Agr Ecosyst Environ 376. https://doi.org/10.1016/j.agee.2024.109230.
Hassall, K.L., Coleman, K., Dixit, P.N., Granger, S.J., Zhang, Y., Sharp, R.T., Wu, L., Whitmore, A.P., Richter, G.M., Collins, A.L., Milne, A.E., 2022. Exploring the effects of land management change on productivity, carbon and nutrient balance: application of an ensemble modelling approach to the upper river taw observatory. UK. Sci. Total Environ. 824. https://doi.org/10.1016/j.scitotenv.2022.153824.
Hu, H.-W., Chen, D., He, J.-Z., 2015. Microbial regulation of terrestrial nitrous oxide formation: understanding the biological pathways for prediction of emission rates. FEMS Microbiol. Rev. 39, 729–749. https://doi.org/10.1093/femsre/fuv021.
IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.a. Meyer (Eds.)]. IPCC, Geneva, Switzerland, p. 151.
IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, *M. Huang*, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1017.
Jørgen, E.O., Marco, B., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239–262. https://doi.org/10.1016/S1161-0301(02)00004-7.
Ku, H.-H., Ryu, J.-H., Bae, H.-S., Jeong, C., Lee, S.-E., 2019. Modeling a long-term effect of rice straw incorporation on SOC content and grain yield in rice field. Arch. Agron. Soil Sci. 65, 1941–1954. https://doi.org/10.1080/03650340.2019.1583330.
Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil Biol. 37, 25–50. https://doi.org/10.1016/S1164-5563(01)01067-6.
Li, C., Mosier, A., Wassmann, R., Cai, Z., Zheng, X., Huang, Y., Tsuruta, H., Boonjawat, J., Lantin, R., 2004. Modeling greenhouse gas emissions from rice-based production systems: sensitivity and upscaling. Global Biogeochem. Cy. 18. https://doi.org/10.1029/2003GB002045.
Liang, S., Li, Y., Zhang, X., Sun, Z., Sun, N., Duan, Y., Xu, M., Wu, L., 2018. Response of crop yield and nitrogen use efficiency for wheat-maize cropping system to future climate change in northern China. Agric. For. Meteorol. 262, 310–321. https://doi.org/10.1016/j.agrformet.2018.07.019.
Liang, S., Wu, W., Sun, J., Li, Z., Sun, X., Chen, H., Chen, S., Fan, L., You, L., Yang, P., 2021. Climate-mediated dynamics of the northern limit of paddy rice in China. Environ. Res. Lett. 16. https://doi.org/10.1088/1748-9326/abfac0.
Liang, H., Xu, J., Hou, H., Qi, Z., Yang, S., Li, Y., Hu, K., 2022. Modeling CH_4 and N_2O emissions for continuous and noncontinuous flooding rice systems. Agr. Syst. 203. https://doi.org/10.1016/j.agsy.2022.103528.
Liao, P., Sun, Y., Zhu, X., Wang, H., Wang, Y., Chen, J., Zhang, J., Zeng, Y., Zeng, Y., Huang, S., 2021. Identifying agronomic practices with higher yield and lower global warming potential in rice paddies: a global meta-analysis. Agr Ecosyst Environ 322. https://doi.org/10.1016/j.agee.2021.107663.
Liu, R., Hayden, L., Suter, H., Hu, H.W., Lam, S.K., He, J.Z., Mele, P., Chen, D.L., 2017. The effect of temperature and moisture on the source of N_2O and contributions from ammonia oxidizers in an agricultural soil. Biol. Fertil. Soils 53, 141–152. https://doi.org/10.1007/s00374-016-1167-8.
Liu, S., Ji, C., Wang, C., Chen, J., Jin, Y., Zou, Z., Li, S., Niu, S., Zou, J., 2018a. Climatic role of terrestrial ecosystem under elevated CO2 : a bottom-up greenhouse gases budget. Ecol. Lett. 21, 1108–1118. doi:https://doi.org/10.1111/ele.13078.
Liu, Y., Li, Y., Harris, P., Cardenas, L.M., Dunn, R.M., Sint, H., Murray, P.J., Lee, M.R.F., Wu, L., 2018b. Modelling field scale spatial variation in water run-off, soil moisture, N_2O emissions and herbage biomass of a grazed pasture using the SPACSYS model. Geoderma 315, 49–58. https://doi.org/10.1016/j.geoderma.2017.11.029.
Liu, X., Zhou, T., Liu, Y., Zhang, X., Li, L., Pan, G., 2019. Effect of mid-season drainage on CH_4 and N_2O emission and grain yield in rice ecosystem: a meta-analysis. Agr. Water Manage. 213, 1028–1035. https://doi.org/10.1016/j.agwat.2018.12.025.
Liu, C., Wang, L., Cocq, K.L., Chang, C., Li, Z., Chen, F., Liu, Y., Wu, L., 2020a. Climate change and environmental impacts on and adaptation strategies for production in wheat-rice rotations in southern China. Agric. For. Meteorol. 292-293, 108136. https://doi.org/10.1016/j.agrformet.2020.108136.
Liu, S., Zheng, Y., Ma, R., Yu, K., Han, Z., Xiao, S., Li, Z., Wu, S., Li, S., Wang, J., Luo, Y., Zou, J., 2020b. Increased soil release of greenhouse gases shrinks terrestrial carbon uptake enhancement under warming. Glob. Chang. Biol. 00, 1–13. https://doi.org/10.1111/gcb.15156.
Liu, Y., Tang, L., Qiu, X., Liu, B., Chang, X., Liu, L., Zhang, X., Cao, W., Zhu, Y., 2020c. Impacts of 1.5 and 2.0°C global warming on rice production across China. Agric. For. Meteorol. 284, 107900. https://doi.org/10.1016/j.agrformet.2020.107900.
Liu, Y., Ge, T., van Groenigen, K.J., Yang, Y., Wang, P., Cheng, K., Zhu, Z., Wang, J., Li, Y., Guggenberger, G., Sardans, J., Penuelas, J., Wu, J., Kuzyakov, Y., 2021. Rice paddy soils are a quantitatively important carbon store according to a global synthesis. Commun. Earth Environ. 2. https://doi.org/10.1038/s43247-021-00229-0.
Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J.W., Rötter, R.P., Boote, K.J., Ruane, A.C., Thorburn, P.J., Cammarano, D., Hatfield, J.L., Rosenzweig, C., Aggarwal, P.K., Angulo, C., Basso, B., Bertuzzi, P., Biernath, C., Brisson, N., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R.F., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Müller, C., Kumar, S.N., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C.O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., White, J.W., Wolf, J., 2015. Multimodel ensembles of wheat growth: many models are better than one. Glob. Chang. Biol. 21, 911–925. https://doi.org/10.1111/gcb.12768.
Meijide, B.A., Gruening, C., Goded, I., Seufert, G., Cescatti, A., 2017. Water management reduces greenhouse gas emissions in a Mediterranean rice paddy field. Agr Ecosyst Environ 238, 168–178. https://doi.org/10.1016/j.agee.2016.08.017.
Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153.
O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9, 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016.
Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. Eur. J. Agron. 10, 23–36. https://doi.org/10.1016/S1161-0301(98)00047-1.
Raftery, A.E., Zimmer, A., Frierson, D.M.W., Startz, R., Liu, P., 2017. Less than 2°C warming by 2100 unlikely. Nat. Clim. Change 7, 637–641. https://doi.org/10.1038/nclimate3352.
Rezaei, E.E., Siebert, S., Hüging, H., Ewert, F., 2018. Climate change effect on wheat phenology depends on cultivar change. Sci. Rep. 8. https://doi.org/10.1038/s41598-018-23101-2.
Rezaei, E.E., Webber, H., Asseng, S., Boote, K., Durand, J.L., Ewert, F., Martre, P., MacCarthy, D.S., 2023. Climate change impacts on crop yields. Nat. Rev. Earth Env. 4, 831–846. https://doi.org/10.1038/s43017-023-00491-0.
Rising, J., Devineni, N., 2020. Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5. Nat. Commun. 11. https://doi.org/10.1038/s41467-020-18725-w.
Sellar, A.A., Jones, C.G., Mulcahy, J.P., Tang, Y., Yool, A., Wiltshire, A., O'Connor, F.M., Stringer, M., Hill, R., Palmieri, J., Woodward, S., de Mora, L., Kuhlbrodt, T., Rumbold, S.T., Kelley, D.I., Ellis, R., Johnson, C.E., Walton, J., Abraham, N.L., Andrews, M.B., Andrews, T., Archibald, A.T., Berthou, S., Burke, E., Blockley, E., Carslaw, K., Dalvi, M., Edwards, J., Folberth, G.A., Gedney, N., Griffiths, P.T., Harper, A.B., Hendry, M.A., Hewitt, A.J., Johnson, B., Jones, A., Jones, C.D., Keeble, J., Liddicoat, S., Morgenstern, O., Parker, R.J., Predoi, V., Robertson, E., Siahaan, A., Smith, R.S., Swaminathan, R., Woodhouse, M.T., Zeng, G., Zerroukat, M., 2019. UKESM1: description and evaluation of the U.K. earth system model. J. Adv. Model. Earth Sy. 11, 4513–4558. https://doi.org/10.1029/2019MS001739.
Shivanna, K.R., 2022. Climate change and its impact on biodiversity and human welfare. P. Indian Natl. Sci. Ac. 88, 160–171. https://doi.org/10.1007/s43538-022-00073-6.
Smith, W.N., Grant, B.B., Desjardins, R.L., Rochette, P., Drury, C.F., Li, C., 2008. Evaluation of two process-based models to estimate soil N_2O emissions in eastern Canada. Can. J. Soil Sci. 88, 251–260. https://doi.org/10.4141/CJSS06030.
Smith, W.N., Grant, B.B., Desjardins, R.L., Kroebel, R., Li, C., Qian, B., Worth, D.E., McConkey, B.G., Drury, C.F., 2013. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agr Ecosyst Environ 179, 139–150. https://doi.org/10.1016/j.agee.2013.08.015.
Tesfaye, K., Takele, R., Sapkota, B., Khatri-Chhetri, A., Solomon, D., Stirling, C., Albanito, F., 2021. Model comparison and quantification of nitrous oxide emission and mitigation potential from maize and wheat fields at a global scale. Sci. Total Environ. 782, 146696. https://doi.org/10.1016/j.scitotenv.2021.146696.
Tian, Z., Niu, Y., Fan, D., Sun, L., Ficsher, G., Zhong, H., Deng, J., Tubiello, F.N., 2018. Maintaining rice production while mitigating methane and nitrous oxide emissions from paddy fields in China: evaluating tradeoffs by using coupled agricultural systems models. Agr. Syst. 159, 175–186. https://doi.org/10.1016/j.agsy.2017.04.006.
Timsina, J., Humphreys, E., 2006. Performance of CERES-Rice and CERES-wheat models in rice–Wheat systems: a review. Agr. Syst. 90, 5–31. https://doi.org/10.1016/j.agsy.2005.11.007.
van Groenigen, K.J., van Kessel, C., Hungate, B.A., 2012. Increased greenhouse-gas intensity of rice production under future atmospheric conditions. Nat. Clim. Chang. 3, 288–291. https://doi.org/10.1038/nclimate1712.
Wang, B., Liu, D.L., Asseng, S., Macadam, I., Yu, Q., 2015. Impact of climate change on wheat flowering time in eastern Australia. Agric. For. Meteorol. 209–210, 11–21. https://doi.org/10.1016/j.agrformet.2015.04.028.
Wang, L., Yuan, X., Liu, C., Li, Z., Chen, F., Li, S., Wu, L., Liu, Y., 2019. Soil C and N dynamics and hydrological processes in a maize-wheat rotation field subjected to different tillage and straw management practices. Agric. Ecosyst. Environ. 285, 106616. https://doi.org/10.1016/j.agee.2019.106616.
Wang, F., Mu, Z., Guo, T., Huang, A., Lin, X., Shi, X., Ni, J., 2020a. Effect of long-term differentiated fertilisation regimes on greenhouse gas emissions from a subtropical

rice-wheat cropping system. Plant Soil Environ. 66, 167–174. https://doi.org/10.17221/693/2019-PSE.
Wang, H., Zhang, Y., Zhang, Y., McDaniel, M.D., Sun, L., Su, W., Fan, X., Liu, S., Xiao, X., 2020b. Water-saving irrigation is a 'win-win' management strategy in rice paddies – with both reduced greenhouse gas emissions and enhanced water use efficiency. Agr. Water Manage. 228. https://doi.org/10.1016/j.agwat.2019.105889.
Wang, Y., Tao, F., Chen, Y., Yin, L., 2022. Interactive impacts of climate change and agricultural management on soil organic carbon sequestration potential of cropland in China over the coming decades. Sci. Total Environ. 817. https://doi.org/10.1016/j.scitotenv.2022.153018.
Wang, S., Sun, N., Zhang, X., Hu, C., Wang, Y., Xiong, W., Zhang, S., Colinet, G., Xu, M., Wu, L., 2024a. Assessing the impacts of climate change on crop yields, soil organic carbon sequestration and N_2O emissions in wheat–maize rotation systems. Soil Till. Res. 240. https://doi.org/10.1016/j.still.2024.106088.
Wang, X., Wang, L., Chen, Y., Hu, Y., Guan, R., Li, M., Wang, L., Zhang, Y., 2024b. Mitigating the negative effect of warming on crop yield: assessing the carbon fertilization and organic amendment application effect. Field Crop Res 311. https://doi.org/10.1016/j.fcr.2024.109370.
Wang, Y., Wang, Z., Wu, L., Li, H., Li, J., Zhu, A., Jin, Y., Han, G., 2024c. Effects of grazing and climate change on aboveground standing biomass and sheep live weight changes in the desert steppe in Inner Mongolia. China. Agr. Syst. 217. https://doi.org/10.1016/j.agsy.2024.103916.
Willmott, C.J., 1982. Some comments on the evaluation of model performance. B. Am. Meteorol. Soc. 63, 1309–1313. https://doi.org/10.1175/1520-0477(1982)063<1309:SCOTEO>2.0.CO;2.
Wing, I.S., De Cian, E., Mistry, M.N., 2021. Global vulnerability of crop yields to climate change. J. Environ. Econ. Manag. 109. https://doi.org/10.1016/j.jeem.2021.102462.
Wu, L., Shepherd, A., 2011. Special features of the SPACSYS modeling package and procedures for parameterization and validation. In: Ahuja, L.R., Ma, L. (Eds.), Advances in Agricultural Systems Modeling. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, pp. 117–154. https://doi.org/10.2134/advagricsystmodel2.c4.
Wu, L., McGechan, M.B., McRoberts, N., Baddeley, J.A., Watson, C.A., 2007. SPACSYS: integration of a 3D root architecture component to carbon, nitrogen and water cycling—model description. Ecol. Model. 200, 343–359. https://doi.org/10.1016/j.ecolmodel.2006.08.010.
Wu, L., Rees, R.M., Tarsitano, D., Zhang, X., Jones, S.K., Whitmore, A.P., 2015. Simulation of nitrous oxide emissions at field scale using the SPACSYS model. Sci. Total Environ. 530–531, 76–86. https://doi.org/10.1016/j.scitotenv.2015.05.064.
Wu, L., Zhang, X., Griffith, B.A., Misselbrook, T.H., 2016. Sustainable grassland systems: a modelling perspective based on the north Wyke farm platform. Eur. J. Soil Sci. 67, 397–408. https://doi.org/10.1111/ejss.12304.
Wu, X., Liu, H., Li, X., Tian, Y., Mahecha, M.D., 2017. Responses of winter wheat yields to warming-mediated vernalization variations across temperate Europe. Front. Ecol. Evol. 5. https://doi.org/10.3389/fevo.2017.00126.
Wu, L., Misselbrook, T.H., Feng, L., Wu, L., 2020. Assessment of nitrogen uptake and biological nitrogen fixation responses of soybean to nitrogen fertiliser with SPACSYS. Sustainability 12. https://doi.org/10.3390/su12155921.
Wu, L., Harris, P., Misselbrook, T.H., Lee, M.R.F., 2022a. Simulating grazing beef and sheep systems. Agr. Syst. 195, 103307. https://doi.org/10.1016/j.agsy.2021.103307.
Wu, L., Wu, L., Bingham, I.J., Misselbrook, T.H., 2022b. Projected climate effects on soil workability and trafficability determine the feasibility of converting permanent grassland to arable land. Agr. Syst. 203. https://doi.org/10.1016/j.agsy.2022.103500.
Yang, J.M., Yang, J.Y., Liu, S., Hoogenboom, G., 2014. An evaluation of the statistical methods for testing the performance of crop models with observed data. Agr. Syst. 127, 81–89. https://doi.org/10.1016/j.agsy.2014.01.008.
Zhang, X., Sun, Z., Liu, J., Ouyang, Z., Wu, L., 2018. Simulating greenhouse gas emissions and stocks of carbon and nitrogen in soil from a long-term no-till system in the North China Plain. Soil Till. Res. 178, 32–40. https://doi.org/10.1016/j.still.2017.12.013.
Zhang, Z., Li, Y., Chen, X., Wang, Y., Niu, B., Liu, D.L., He, J., Pulatov, B., Hassan, I., Meng, Q., 2023. Impact of climate change and planting date shifts on growth and yields of double cropping rice in southeastern China in future. Agr. Syst. 205. https://doi.org/10.1016/j.agsy.2022.103581.
Zhao, Z., Cao, L., Deng, J., Sha, Z., Chu, C., Zhou, D., Wu, S., Lv, W., 2020. Modeling CH_4 and N_2O emission patterns and mitigation potential from paddy fields in Shanghai, China with the DNDC model. Agr. Syst. 178, 102743. https://doi.org/10.1016/j.agsy.2019.102743.
Zhong, Y., Wang, X., Yang, J., Zhao, X., Ye, X., 2016. Exploring a suitable nitrogen fertilizer rate to reduce greenhouse gas emissions and ensure rice yields in paddy fields. Sci. Total Environ. 565, 420–426. https://doi.org/10.1016/j.scitotenv.2016.04.167.
Zhou, Z., Jin, J., Liu, J., Si, Y., 2023. Optimizing the sowing window for direct-seeded rice (Oryza sativa L.) considering high yield and methane emissions in Central China. Agr. Syst. 205. https://doi.org/10.1016/j.agsy.2022.103594.
Zhu, P., Burney, J., Chang, J., Jin, Z., Mueller, N.D., Xin, Q., Xu, J., Yu, L., Makowski, D., Ciais, P., 2022. Warming reduces global agricultural production by decreasing cropping frequency and yields. Nat. Clim. Change 12, 1016–1023. https://doi.org/10.1038/s41558-022-01492-5.
Zou, J., Huang, Y., Jiang, J., Zheng, X., Sass, R.L., 2005. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Global Biogeochem. Cy. 19. https://doi.org/10.1029/2004GB002401.