

# Assessing the impacts of climate change on crop yields, soil organic carbon sequestration and N<sub>2</sub>O emissions in wheat–maize rotation systems

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## ABSTRACT

Straw retention has been widely implemented to increase soil organic carbon (SOC) sequestration and greenhouse gas (GHG) mitigation for global agriculture. However, the combined effects of long-term straw retention on crop production, SOC sequestration and GHG emissions response to climate change remain unknown. Two nearby wheat–maize rotation field experiments in the North China Plain, combined with local weather, soil and agronomic measurements, were used to evaluate the applicability of the SPACSYS model. The model was then applied to assess the response of crop yield, SOC storage and nitrous oxide (N<sub>2</sub>O) emissions to three nitrogen fertilizer application levels (100, 200, 400 kg N ha<sup>-1</sup>) and three representative concentration pathway scenarios (RCP2.6, RCP4.5 and RCP8.5) under straw retention for the wheat–maize rotation systems during 2021–2100. In general, the model was reasonably accurate with  $R^2$  and model efficiency ( $EF$ ) ranging from 0.25 to 0.96 and 0.32–0.94, respectively. Climate change decreased wheat yield by 4–39%, while maize showed a slight increase (3%) under RCP2.6 and a decrease of 1–15% under RCP4.5 and RCP8.5. The SOC storage in the 0–20 cm soil increased at a rate of 73–195 kg C ha<sup>-1</sup> yr<sup>-1</sup> but decreased within the upper 1 m soil at 280–390 kg C ha<sup>-1</sup> yr<sup>-1</sup>. Climate change reduced the positive effect of SOC sequestration except in RCP2.6 and stimulated substantial N<sub>2</sub>O emissions ranging from 1–7.5 to 2.9–23.2 kg N ha<sup>-1</sup> yr<sup>-1</sup>, consequently, the global warming potential increased from –79–2555 to 548–9357 kg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> under various N fertilizer application levels. This study reveals that the negative feedback under climate change with modelling approach, and extensive efforts are needed to make adaptations to ensure food production and reduce GHG emissions in the future.

## 1. Introduction

Mineral nitrogen (N) fertilizer is widely applied in farmland to increase crop grain production (Vitousek et al., 2009). During 2001–2015, China and India together consumed more than half of the increase in N

fertilizer used worldwide (FAO, 2018). The excessive and improper use of mineral fertilizer has resulted in large environmental risks, including nutrient losses (Liu et al., 2019), greenhouse gas (GHG) emissions (Winiwarter et al., 2018) and soil acidification (Schroder et al., 2011). As food production is expected to increase by 60%–110% by 2050

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(compared to 2005) to meet human demand (Tilman et al., 2011), extensive efforts should be dedicated to ensuring global food security and to achieve sustainable and environmentally friendly agriculture.

The North China Plain (NCP) is a major crop production area in China, that produced 67% and 28% of China's wheat and maize in 2014, respectively (NBSC, 2015). The wheat–maize rotation system is the dominant planting system in this area. Since the early 1980s, mineral N fertilizer consumption has dramatically increased (Fang et al., 2006). The over-reliance on mineral fertilizer has resulted in tremendous environmental costs. Ju et al. (2009) reported that annual N fertilizer application at 550–600 kg ha<sup>-1</sup> did not improve crop production but caused approximately twice the N losses compared with optimum N fertilizer application. In another study, when the annual N fertilizer application levels increased from 270 kg N ha<sup>-1</sup> to 430 kg N ha<sup>-1</sup> and 850 kg N ha<sup>-1</sup>, the cumulative nitrous oxide (N<sub>2</sub>O) emissions increased by 35%–115%, while the crop grain yields increased by only 3%–15% in a wheat–maize rotation system (Liu et al., 2012). As a key strategy to mitigate environmental risks, the Ministry of Agriculture and Rural Affairs of the People's Republic of China released the “zero growth in mineral fertilizer” target in 2015 (Liu et al., 2016).

Agricultural intensification in the NCP, which is characterized by high levels of mineral fertilizer application (Ju et al., 2004) and irrigation (Kong et al., 2016), has led to the production of a large amount of straw residue every year. These straw residues are widely burned in the field, leading to air contamination and resource waste (Lu et al., 2010). Consequently, China has proposed straw retention to replace a portion of mineral fertilizers to effectively enhance the soil organic carbon (SOC) stock. Han et al. (2018) reported that straw retention increased crop production by 13.4% and improved SOC sequestration in the 0–20 cm soil layer at the rate of 350 kg C ha<sup>-1</sup> yr<sup>-1</sup> compared with straw removal in China but did not consider the impacts of straw retention on SOC storage changes in the deep soil. Some studies have demonstrated that straw retention can stimulate N<sub>2</sub>O emissions (Hu et al., 2013; Ho et al., 2017), whereas others have reported reduced N<sub>2</sub>O emissions under straw retention (Yao et al., 2017). As soil N<sub>2</sub>O emissions are an important indicator of global warming, quantifying and mitigating soil N<sub>2</sub>O emissions from cropland are critical for the realization of China's carbon neutrality goal by 2060. Although numerous studies have clarified the effects of straw retention on crop yields, SOC storage and N<sub>2</sub>O emissions in the NCP (Wang et al., 2015a; Xu et al., 2017), the trade-offs between these outcomes under long-term fertilization combined with straw retention remain poorly understood. As the positive benefits of C sequestration through the optimization of agricultural management may be offset by the stimulation of N<sub>2</sub>O emissions, it is necessary to obtain a comprehensive perspective (Liu and Greaver, 2009).

Climate change coupled with agronomic practices will affect agricultural production and nutrient cycling dramatically. The interactions between the components in agricultural systems are complex, making it difficult to use field or laboratory experiments to observe these interactions (Shen et al., 2009). Instead, agroecosystem models, due to their power to evaluate how systems respond to climate change and management practices, have been increasingly used (Lu and Tian, 2013). As such, it is important to evaluate the impacts of farming practices on crop yields, SOC storage and N<sub>2</sub>O emissions in the NCP of China under climate change in order to optimize potential adaptation measures for climate change mitigation. Different agroecosystem models are characterized by different objectives and varying levels of complexity (Turkeltaub et al., 2022). Shepherd et al. (2011) reviewed over 30 agricultural models for assessing the diffuse pollution response to farmer adaptations and mitigation methods under climate change and concluded that SPACSYS together with DayCent and APSIM were the most suitable models. SPACSYS is a model with a proven track record in simulating various cropping systems, rotations or intercropping, interactions between plant and environment (Wu and Shepherd, 2011). It has been widely applied to simulate crop growth and production (Wu et al., 2009; Bingham and Wu., 2011; Liang et al., 2018), SOC and soil N

storage (Wu and Shepherd, 2011; Zhang et al., 2016a), the dynamics of soil water content (Wu et al., 2016; Liu et al., 2023) and N<sub>2</sub>O emissions (Wu et al., 2015; Zhang et al., 2016a) under different soils and climate conditions. Furthermore, the implementation of a biological-based denitrification component in SPACSYS enables it to estimate different nitrogenous gases emissions (N<sub>2</sub>O, NO and N<sub>2</sub>) (Wu et al., 2015; Liu et al., 2020). However, APSIM considers only the denitrification of NO<sub>3</sub><sup>-</sup>, the intermediate products NO<sub>2</sub> and NO are neglected (Del Grosso et al., 2020). Moreover, SPACSYS is capable of simulating N and water uptake by plants, as well as input of carbon and nutrients to soil more precisely with a detailed three-dimensional root growth sub-model, while most other models simplify the root system by using root length density (Wu et al., 2007). A comparison in structure and processes about C and N cycling among several popular models was presented in Table S1.

This study aimed to 1) evaluate the performance of the SPACSYS model for the wheat–maize planting system; and 2) use the validated model to predict the crop production, SOC sequestration and N<sub>2</sub>O emissions in the system response to climate change in the NCP. To do so, the model was calibrated and validated with data collected from two nearby field experiments on straw retention and mineral N fertilization with the wheat–maize rotation in the NCP. This study then quantified the impacts of various climate scenarios and three fertilizer application rates on the grain yields of the crops, SOC storage in the soil profile and N<sub>2</sub>O emissions in the future.

## 2. Materials and methods

### 2.1. Site description and experimental design

The data used for model evaluation were obtained from two experiments at the Luancheng Agroecosystem Experimental Station (37°53'N, 114°41'E, elevation 50.1 m) of Chinese Academy of Sciences (Fig. 1). The area represents a semi-arid and semi-humid climate with a mean annual temperature of 12.5°C and mean annual precipitation of 480 mm (Fig. 2). The soil type is predominantly calcareous Fluvo-Aquic soil (Argic, Rusty Ustic Cambisols). The main soil characteristics are shown in Table 1. The dominant planting system is the wheat–maize rotation system. Maize and wheat are sown in mid-June and early October, respectively, and harvested in late September and early June of the next year, respectively.

Both experiments were established in 1998. One experiment was focused on straw retention and aimed to identify the influence of long-term straw retention on the net SOC budget under the wheat–maize rotation system. The other experiment was focused on different urea N application levels, aiming to explore the long-term N fertilization impacts on the GHG emissions from the wheat–maize rotation system. The detailed information about the experiments have been reported previously (Wang and Hu, 2011; Wang et al., 2015c), measurements from the experiments are briefly described in the following subsection. In each experimental year, straw (chopped by an automated machine to lengths of 5 cm) was returned to the field at harvest. After maize was harvested in October of each year, the fields were ploughed (0–15 cm). Details on the fertilizer application rates under different treatments in the two experiments are shown in Table 2 and Table S2. Both crops were flood irrigated (Table S3).

### 2.2. Measurements

#### 2.2.1. Experiment I

The crop yield, SOC content, soil temperature, soil moisture, soil respiration (SR) and the net ecosystem exchange of CO<sub>2</sub> between the biosphere and the atmosphere (NEE) were measured (Wang et al., 2015c). Ten soil samples from the field were randomly collected at a depth of 0–20 cm after crop harvest and before any fertilizer input for the determination of SOC content using the wet oxidation method (Snyder and Trofymow, 1984). The SOC content was then converted to

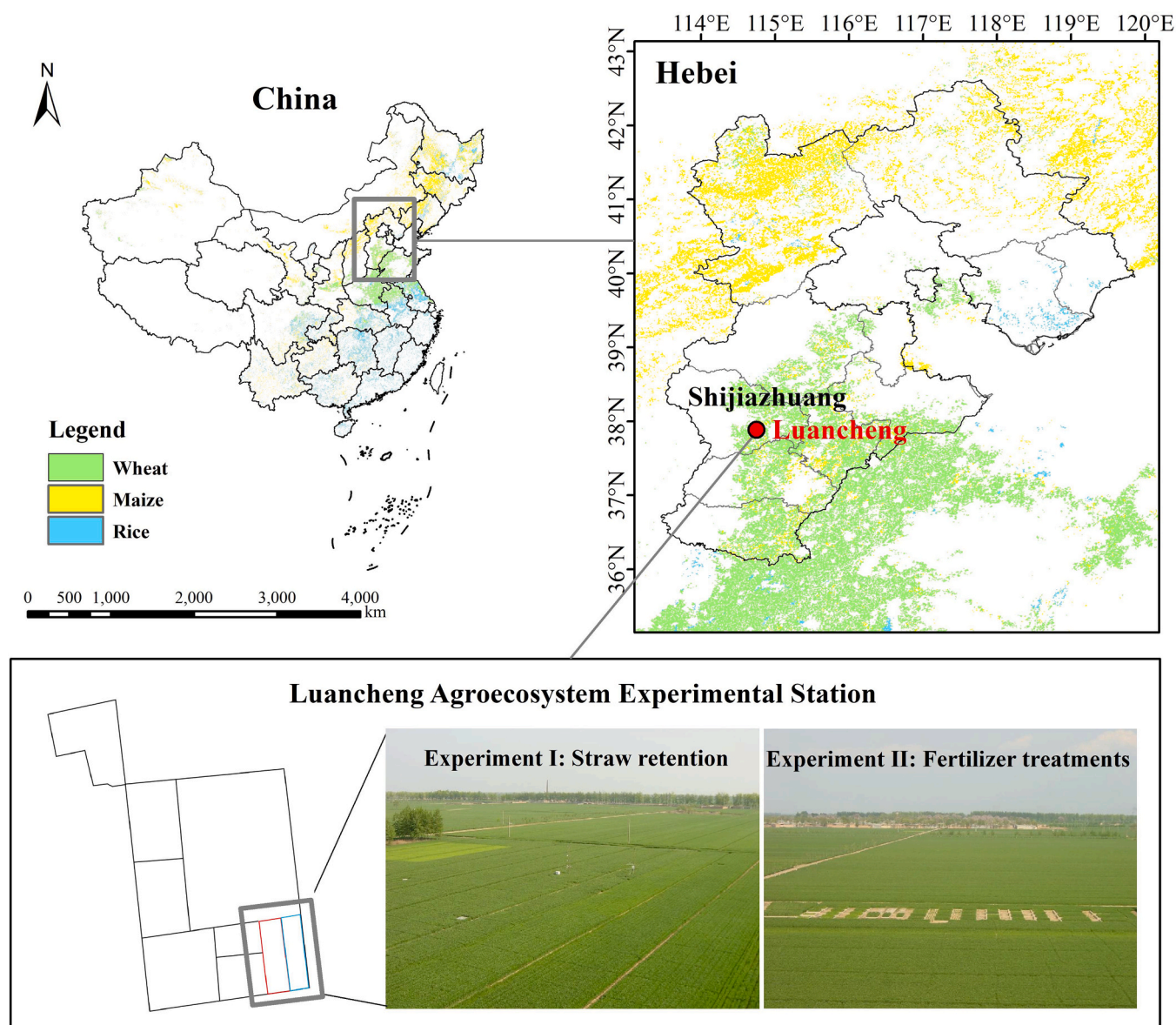


Fig. 1. The location of the study area and the two experiments in Luancheng Agroecosystem Experimental Station. The 1 km-grid crop harvesting area for three main crops (i.e., wheat, maize and rice) of China in 2015 was obtained from Luo et al., (2020).

SOC storage ( $\text{t C ha}^{-1}$ ) using the soil bulk density. The SR was measured directly between the rows of crops from October 2007 to October 2008 using an automated soil  $\text{CO}_2$  flux system (LI-COR 8100, LI-COR Inc., Lincoln, NE, USA) equipped with a portable chamber (Model 8100–103). Gas samples were collected between 9:00 and 11:00 a.m. local time once per week during the study period so that fluxes could be estimated over a period corresponding closely to the daily average temperature (Li et al., 1998). The NEE was measured with an open-path eddy covariance (EC) system during October 2007 to October 2008. At the same time, the soil temperature and moisture at different soil depths were measured every 30 min near the EC station.

The total SOC storage ( $\text{t C ha}^{-1}$ ) in the top 20 cm soil is estimated as follows:

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

where  $SOC_C$  is the soil C content ( $\text{g kg}^{-1}$ ),  $BD$  is the soil bulk density ( $\text{g cm}^{-3}$ ),  $H$  is the thickness (cm), and 0.1 is a conversion coefficient.

The NEE ( $\text{kg C ha}^{-1} \text{ day}^{-1}$ ) is calculated as follows:

$$NEE = GPP - TER \quad (2)$$

where  $GPP$  is the gross primary production ( $\text{kg C ha}^{-1} \text{ day}^{-1}$ ), and  $TER$  is the total ecosystem respiration ( $\text{kg C ha}^{-1} \text{ day}^{-1}$ ).

#### 2.2.2. Experiment II

The soil  $\text{CO}_2$  and  $\text{N}_2\text{O}$  emissions were determined using the static chamber/gas chromatography technique with three replicates per plot (Wang and Hu, 2011). Polypropylene chamber bases ( $60 \text{ cm} \times 20 \text{ cm} \times 40 \text{ cm}$ ) were inserted to a soil depth of 20 cm after crop sowing and removed before crop harvest. Emission measurements were made once a week in general from July 2008 to June 2010. Gas samples were collected with polypropylene syringes (60 ml) between 9:00 and 11:00 a.m. at 0, 10 and 20 min after the chambers were installed. The samples were analyzed using a gas chromatograph (Agilent 6820, Agilent Technologies Inc. Santa Clara, CA, USA) immediately after collection.

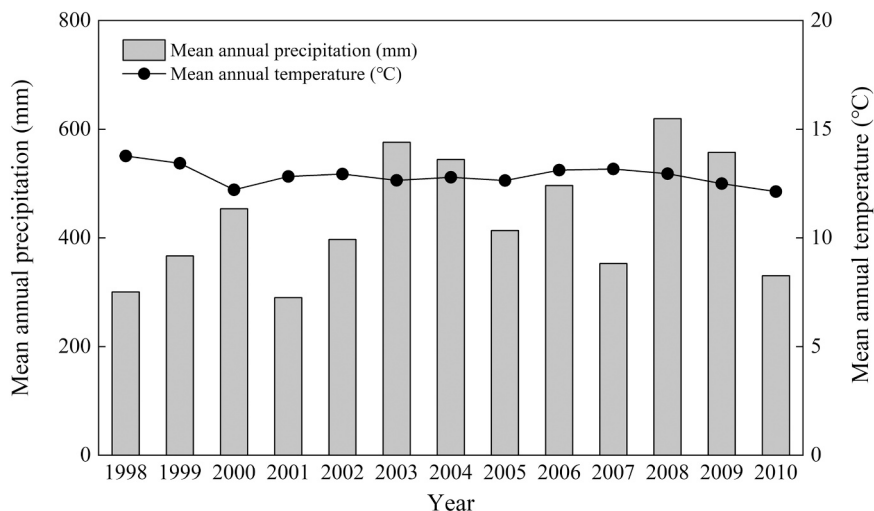


Fig. 2. Mean annual temperature and mean annual precipitation at the experimental site during 1998–2010.

Table 1

The initial soil physical and chemical properties at the long-term experimental site.

Depth (cm)	Total soil organic carbon (g kg <sup>-1</sup> )	Total nitrogen (g kg <sup>-1</sup> )	Total phosphorus (g kg <sup>-1</sup> )	Total potassium (g kg <sup>-1</sup> )	Clay (%)	Dry bulk density (g cm <sup>-3</sup> )
0–10	10.9	1.13	0.76	16.6	12.2	1.41
10–20	6.7	0.82	0.62	16.7	13.3	1.60
20–40	3.8	0.53	0.41	17.0	13.7	1.58
40–60	3.2	0.45	0.35	16.9	15.4	1.44
60–100	4.9	0.60	0.37	16.7	16.0	1.44

Table 2

Fertilizer application rate for each crop in the two experiments between 1998 and 2008.

Experiments	Treatments <sup>a</sup>	Supplementary N (kg ha <sup>-1</sup> )	
		Wheat (in October)	Maize (in July)
I: Straw retention <sup>b</sup>	SN	140	276
II: Fertilizer treatments	N0	0	0
	N200	50	100
	N400	100	200
	N600	150	300

<sup>a</sup> : SN denotes the treatment that received straw retention and synthetic urea (N); N0, N200, N400 and N600 denote the treatments that received synthetic urea (N) at the rate of 0, 200, 400 and 600 kg ha<sup>-1</sup>, respectively;

<sup>b</sup> : The fertilizer application rate varies from year to year, see details in Table S2.

### 2.3. The SPACSYS model

The SPACSYS model (Ver 5.23) is a weather-driven, field-scale and daily-time-step process-based model that simulates C and N cycling and water and heat transformation in a soil–plant–atmosphere continuum (Wu and Shepherd, 2011). The model was published in 2007 (Wu et al., 2007). Since then, it has been gradually improved. A user-defined soil profile contains numbers of soil layers with different thicknesses. As the SPACSYS model has been described elsewhere in detail (Bingham and Wu, 2011; Wu et al., 2015; Zhang et al., 2016a), this work only summarizes the main processes considered. The processes mainly include

plant development, assimilation, respiration, N and water uptake, the partitioning of photosynthate and absorbed N, soil organic matter (SOM) decomposition, mineralization/immobilization, nitrification/denitrification and N loss pathways. The Richards equation and Fourier's equation are utilized to describe soil water and heat transfers, respectively (Johnsson and Jansson, 1991). A sensitivity analysis of the model with respect to changes in 61 input parameters and their influence on 27 output variables was conducted (Shan et al., 2021), in which the relative importance of model parameters to their influence on the simulated outputs were described.

### 2.4. Model calibration and validation

The model was first run with observed and default input parameters, as well as those adopted from previous studies (Bingham and Wu, 2011; Zhang et al., 2016b). The data in experiment I and the data from the N400 treatment in experiment II were used to calibrate the parameters involved in crop growth and development, soil temperature and water distribution, and soil C and N cycling, while the data from other treatments (N0, N200 and N600) in experiment II were used for validation. The optimized parameters with calibration in this study are shown in Table S4.

### 2.5. Model evaluation

A combination of three statistical indicators was used to evaluate the accuracy of the model: (1) coefficient of determination ( $R^2$ ), which evaluated the percentage of variation in measurements explained by the simulations; (2) model efficiency ( $EF$ ), which provided a comparison between the efficiency of the model and the efficiency of describing the data as the mean of the measurements; and (3) mean absolute error ( $MAE$ ), which quantified the difference between simulations and measurements (Smith et al., 1997). The model was considered to be perfect when  $EF = 1$ , good when  $0.5 < EF \leq 1$ , fair when  $0 < EF \leq 0.5$  and poor when  $EF < 0$  (Moriasi et al., 2007). Each indicator reflects a specific aspect of a model's performance, and the comprehensive evaluation of different indicators can reflect the overall model performance.  $R^2$ ,  $EF$  and  $MAE$  are calculated as follows:

$$R^2 = \frac{\sum_{i=1}^n (S_i - \sigma)^2}{\sum_{i=1}^n (M_i - \sigma)^2} \quad (3)$$

$$EF = 1 - \frac{\sum_{i=1}^n (S_i - M_i)^2}{\sum_{i=1}^n (M_i - \sigma)^2} \quad (4)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |S_i - M_i| \quad (5)$$

where  $S_i$  and  $M_i$  are simulations and measurements, respectively;  $\sigma$  is the mean value of the measurements;  $n$  is the sample size and “ $||$ ” is an absolute calculation.

## 2.6. Model predictions

Three mineral N fertilizer application rates (100, 200 and 400 kg N ha<sup>-1</sup> yr<sup>-1</sup>, 1/4 applied at wheat sowing, 1/4 at wheat jointing, and 1/2 at maize tasselling) combined with straw retention (90% of straw was returned to the field for the two crops) were investigated to predict crop production, SOC storage and N<sub>2</sub>O emissions in response to climate change from the system with various agronomic practices. The N application rate of 100 kg N ha<sup>-1</sup> yr<sup>-1</sup> was used to explore the impacts of N reduction on the system and the N application rate of 600 kg N ha<sup>-1</sup> yr<sup>-1</sup> was excluded because it would be regarded as excessive usage in this area (Ju et al., 2009). Simulations were run with the same field management practices under the climatic datasets between 2021 and 2100 with three representative concentration pathway (RCP) scenarios: 2.6, 4.5 and 8.5 (Van Vuuren et al., 2011) for the study site plus a baseline with the rotation of daily weather data between 1980 and 2012. The numerical values of the RCPs (2.6, 4.5 and 8.5) represented the possible range of radiative forcing values in 2100 (2.6, 4.5 and 8.5 W/m<sup>2</sup>, respectively) (Moss et al., 2008). The future climate datasets were extracted from the HadCM model (Collins et al., 2011). The average values and variations of the main weather elements over the period for each climate scenario (2021–2100) and the baseline (1980–2012) are shown in Table S5. The initial atmospheric CO<sub>2</sub> concentration was set to 380 ppm and gradually increased to 443, 538 and 927 ppm in 2100 for RCP2.6, RCP4.5 and RCP8.5, respectively, whereas it was set to 350 ppm in baseline. All other agronomic practices and irrigation schedules were the same as those in the experiments.

## 2.7. Indices

To comprehensively investigate the relationship between SOC sequestration and N<sub>2</sub>O emissions under different climate scenarios, the annual global warming potential (GWP, kg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>) is estimated following the IPCC method (IPCC, 2014):

$$GWP = N_2O \times 44/28 \times 265 - SOC_r \times 44/12 \quad (6)$$

where  $N_2O$  denotes the annual cumulative N<sub>2</sub>O emissions (kg N ha<sup>-1</sup> yr<sup>-1</sup>), and  $SOC_r$  denotes the annual SOC sequestration rate (kg C ha<sup>-1</sup> yr<sup>-1</sup>), which is the slope of the simple linear regression that describes the changes of SOC storage over time. The values 44/28 and 44/12 are the conversion factors, and 265 is the global warming potential of N<sub>2</sub>O on a 100-year horizon given by IPCC (2014). Since the upland is a CH<sub>4</sub> sink, it was not taken into consideration.

**Table 3**  
Statistical analysis for model calibration and validation.

Criteria	Calibration								Validation		
	Wheat yield	Maize yield	SOC storage	Soil temperature	Soil moisture	NEE	SR	Soil CO <sub>2</sub>	Soil N <sub>2</sub> O	Soil CO <sub>2</sub>	Soil N <sub>2</sub> O
R <sup>2</sup>	0.64**	0.62**	0.68**	0.96**	0.63**	0.47**	0.74**	0.77**	0.25**	0.64**	0.36**
EF	0.81	0.64	0.50	0.94	0.59	0.49	0.70	0.42	0.37	0.53	0.32
MAE	0.55	0.63	3.28	2.00	6.23	23.54	9.7	-5.9	-0.006	5.39	0.005
n	8	8	11	329	329	333	33	42	42	126	126

R<sup>2</sup>, coefficient of determination; EF, model efficiency; MAE, mean absolute error; n, sample size. NEE and SR denote net ecosystem exchange of CO<sub>2</sub> and soil respiration. \*\* P<0.01.

## 3. Results

### 3.1. Model calibration and validation

Statistical indicators for model calibration and validation were shown in Table 3. Simulated and observed crop yields, SOC storage, soil temperature, soil moisture, SR, NEE, and daily soil CO<sub>2</sub> and N<sub>2</sub>O emissions during the experimental period for the two experiments were shown in Figs. 3–6. The model showed a good fit between the simulated and observed crop yields (R<sup>2</sup>: 0.62–0.64; EF: 0.64–0.81), although the model overestimated the wheat and maize yields by 29% and 21%, respectively, in 2006 (Table 3 and Fig. 3). The simulated SOC storage (0–20 cm) followed the observations well (R<sup>2</sup>: 0.68; EF: 0.5), and the simulated annual SOC sequestration rate (0.553 t C ha<sup>-1</sup> yr<sup>-1</sup>) was close to the observed rate (0.577 t C ha<sup>-1</sup> yr<sup>-1</sup>) during the compared years (Table 3 and Fig. 4). The model captured the peaks and troughs in soil temperature very well, with R<sup>2</sup> > 0.9 and EF > 0.9 (Table 3 and Fig. 5a). The simulated soil moisture followed the observed fluctuations reasonably well, with R<sup>2</sup> > 0.6 and EF > 0.5 (Table 3 and Fig. 5a). The model basically captured the trends and patterns of SR and NEE fluxes during the whole growth period (R<sup>2</sup>: 0.47–0.74; EF: 0.49–0.7). However, the SR fluxes appeared to be underestimated during the wheat season (Table 3 and Fig. 5b).

The model reasonably simulated the pattern and magnitude of the daily soil CO<sub>2</sub> and N<sub>2</sub>O emissions for each treatment and successfully highlighted the differences between treatments, especially for soil N<sub>2</sub>O emissions (Fig. 6 and Table 3). Although the peaks of daily soil CO<sub>2</sub> emissions appeared to be underestimated for N600, a moderate association was found between the observations and simulations with R<sup>2</sup> > 0.6 and EF > 0.4 (Fig. 6d and Table 3). The model captured the peaks of daily soil N<sub>2</sub>O emissions that appeared following fertilizer application, precipitation or irrigation events (Fig. 6e–h). However, some peaks of daily N<sub>2</sub>O emissions for N400 and N600 were overestimated, which probably led to the lower values of R<sup>2</sup> (0.25–0.36) and EF (0.32–0.37) between the simulations and observations (Fig. 6g, h and Table 3).

### 3.2. Simulated grain yields

In general, a decline trend was found in the average wheat and maize grain yields during the simulation years in the three RCP scenarios with different N fertilization rates compared with the baseline for the same level of fertilizer application (Fig. 7), and the lowest average grain yields were 3.7 t ha<sup>-1</sup> for wheat under RCP8.5 and 5.8 t ha<sup>-1</sup> for maize under RCP4.5 at an N application rate of 100 kg ha<sup>-1</sup>. The simulation results suggested that the C3 crop (wheat) was more sensitive to climate change than the C4 crop (maize) (Table S6).

### 3.3. Simulated SOC storage

The simulated dynamics of SOC storage in the topsoil (0–20 cm) and 1 m soil are shown in Fig. 8. The topsoil SOC storage increased over time under all conditions, with a mean annual SOC storage change rate of 73–195 kg C ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 8 and Table 4). However, the trend of SOC

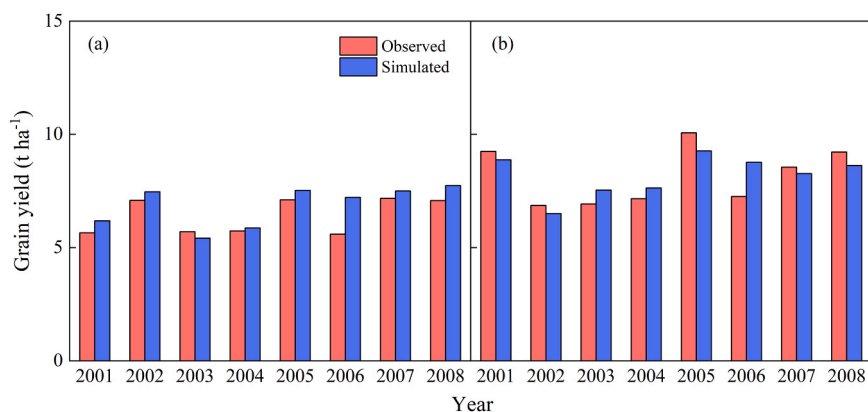


Fig. 3. Observed and simulated winter wheat yield (a) and summer maize yield (b) from 2001 to 2008.

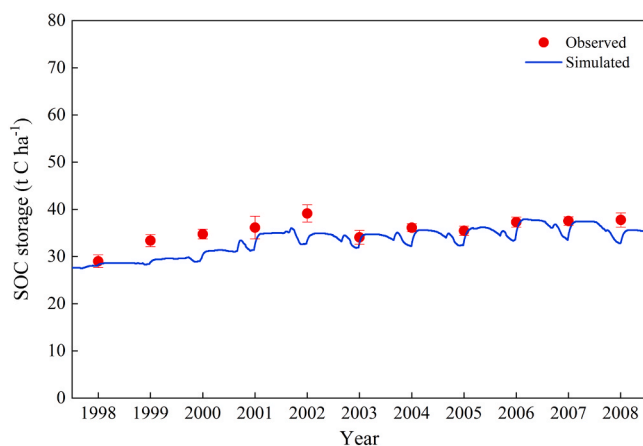


Fig. 4. Observed and simulated SOC storage in the top 20 cm soil depth from 1998 to 2008. The bar over a solid circle (mean) is the standard deviation of samples ( $n=5$ ).

storage within 1 m soil depth was opposite to that in the topsoil (Fig. 8) and declined at the rate of 280–390 t C ha<sup>-1</sup> yr<sup>-1</sup> (Table S7).

### 3.4. Simulated N<sub>2</sub>O emissions

The N<sub>2</sub>O emissions varied significantly under different N levels, and the cumulative N<sub>2</sub>O emissions ranged from 82 kg N ha<sup>-1</sup> (N100) under the baseline to 1831 kg N ha<sup>-1</sup> (N400) under RCP8.5 at the end of the simulations (Fig. 9 and Fig. S1). The model demonstrated that N<sub>2</sub>O emissions were strongly affected by climate change and there was little difference between the three RCP scenarios for each individual fertilization treatment (Fig. 9 and Table 4).

### 3.5. Simulated GWP

The N<sub>2</sub>O emissions played a critical role in the GWP, which led to an increase in the mean annual GWP from -79 kg CO<sub>2</sub>-eq ha<sup>-1</sup> (N100) under the baseline to 9357 kg CO<sub>2</sub>-eq ha<sup>-1</sup> (N400) under RCP8.5 (Table 4). When straw retention was combined with an N application rate of 100 kg N ha<sup>-1</sup>, the wheat–maize rotation system acted as a small carbon sink under the baseline, however, the system changed to a carbon source under climate change at the end of the simulations (Fig. S2 and Table 4).

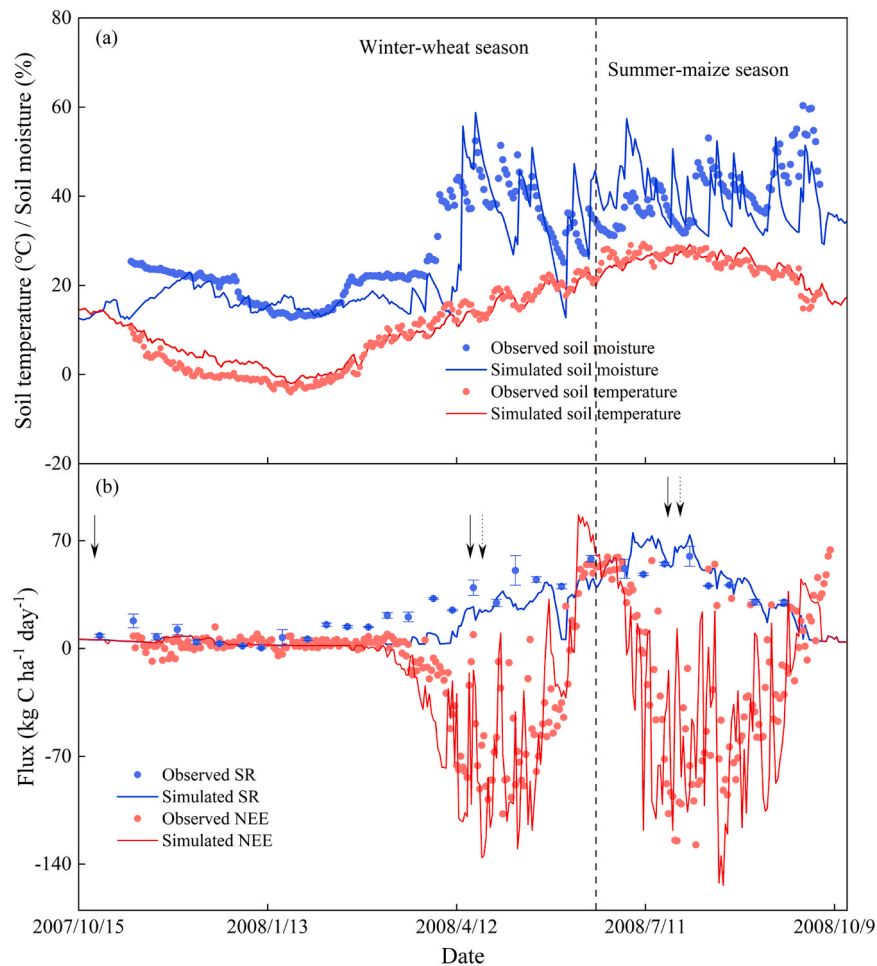
## 4. Discussion

### 4.1. Model performance

The statistical indicators used for model calibration and validation indicated that the SPACSYS model effectively reproduced observed crop yields, SOC storage, and various variables related to soil C and N cycling under different agronomic measures in the wheat–maize rotation system in the NCP. However, there were discrepancies in the simulations compared to the observations because the model did not include the impacts of pests and diseases on crop growth and yield. For example, the model overestimated the wheat and maize yields by 29% and 21% in 2006, respectively (Fig. 3), because gibberellic and midge diseases occurred during the wheat season and weeds occurred during the maize season in 2006. The high overestimation in the N<sub>2</sub>O emission peak on 8/31/2009 corresponded with a high daily rainfall event (94 mm) on 8/26/2009. Uncertainties in input information also attribute the discrepancies. For example, the model requires detailed soil physical properties, including the pore size distribution index and saturated water conductivity as input. However, these properties were not directly measured in the experiments. To fill the gap, pedotransfer functions implemented in the model were used to estimate them, potentially resulting in values that differ from the actual measurements. It has reported that the uncertainty in soil inputs may have led to the uncertainty in the estimated N<sub>2</sub>O emissions (Nol et al., 2010). Moreover, identifying SOM pools and determining transformation rates among the pools are critical in soil C and N cycles, as they influence numerous parameters within the component and other relevant components (Wu and Shepherd, 2011). Despite the model categorizing SOM into several pools, these divisions are arbitrary and are distinguished based on their resistance to microbial action rather than their chemical characteristics. The manner in which SOM is divided in the model could potentially account for the discrepancies between simulations and measurements. Therefore, obtaining more accurate input information is critical for generating precise simulations.

### 4.2. Grain yield change under climate change

The predicted average grain yields were decreased by 4%–39% for wheat under three climate change scenarios and decreased by 1%–15% for maize under RCP4.5 and RCP8.5 compared to those under baseline for each individual N fertilization treatment over the simulation years (Table S6). This was consistent with Xiong et al. (2009), who estimated that cereal production will decline by up to 40% in all cases without adaptation measures compared with the baseline scenario. Similarly, Luo et al. (2005) indicated that wheat yields could decrease by 13.5%–32% in future climate scenarios in south Australia. Climate warming is thought to accelerate wheat growth, shorten its growth period (Xiao



**Fig. 5.** Observed and simulated soil temperature and soil moisture at 10 cm soil depth (a), soil respiration (SR) and daily net ecosystem exchange of CO<sub>2</sub> (NEE) (b) in the growing seasons of winter wheat and summer maize in 2007–2008. Solid and dot downward arrows indicate N fertilizer application and irrigation events, respectively.

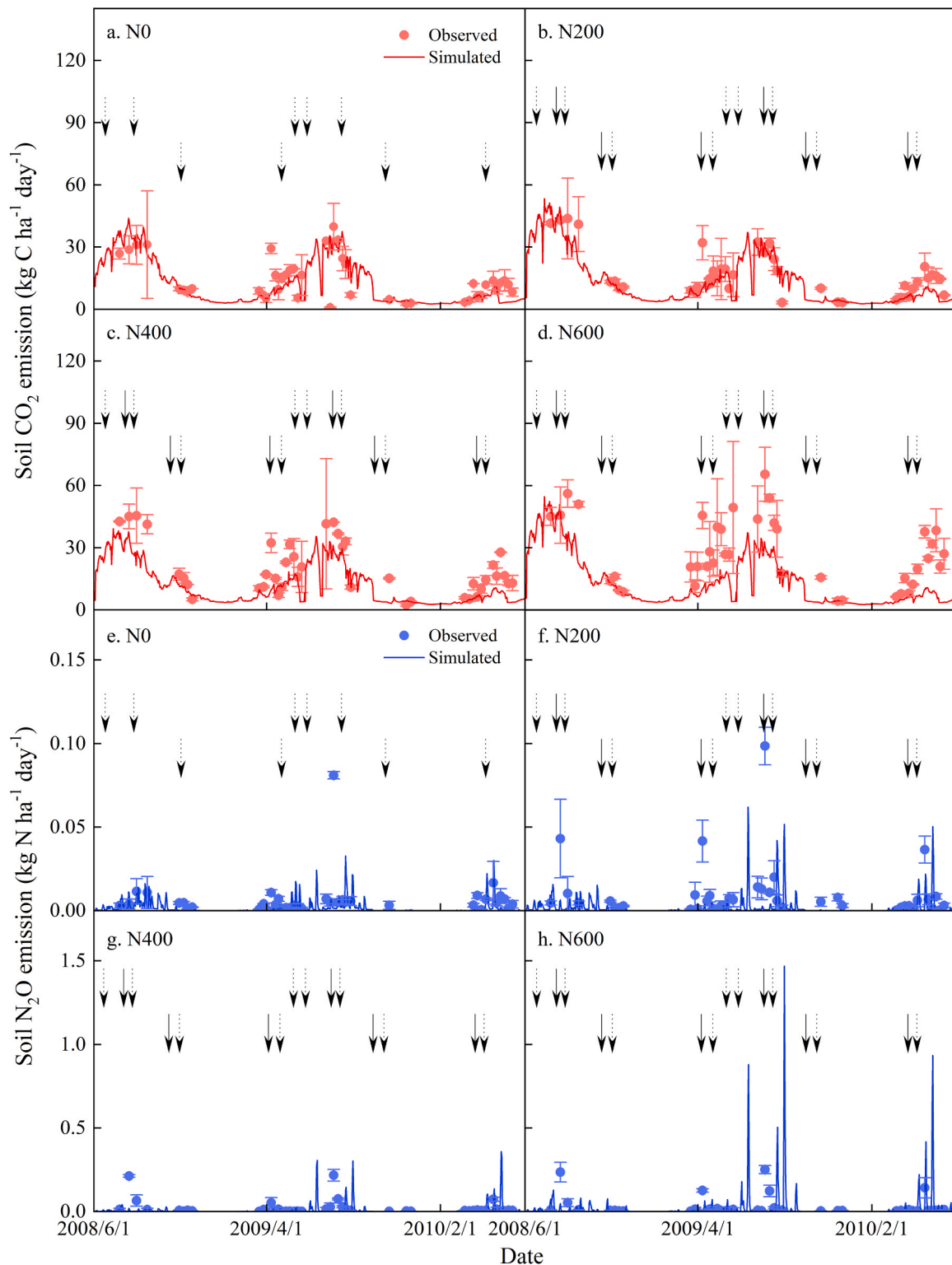
et al., 2013) and reduce the time for photosynthesis and biomass accumulation (Porter and Gawith, 1999), thus leading to the decrease of wheat production in the NCP. The projected maize yield was increased by 3% compared with the baseline under RCP2.6, indicating that the minor increase in temperature does not exceed the optimal temperature for maize growth (Sanchez et al., 2014). Many studies based on long-term field observations of yield data associated with historic meteorological data have found that grain yields increase with elevated CO<sub>2</sub> concentrations but decrease with increased temperature (Challinor et al., 2014; Bai et al., 2016). Adaptation measures such as the development of new cultivars and shifts in sowing dates can help overcome the adverse effects of climate warming and have made significant contributions to crop production over the last few decades in China (Zhang et al., 2013). Therefore, efforts should be dedicated to cultivar improvement to better adapt to warmer climate conditions in the future.

#### 4.3. SOC storage change under climate change

The modelling results indicated that SOC storage in the topsoil (0–20 cm) increased at a rate of 73–195 kg C ha<sup>-1</sup> yr<sup>-1</sup> under all the conditions with straw retention across the treatments from 2021 to 2100 in the NCP (Fig. 8 and Table 4). These rates were much lower than those reported in a study conducted in northern China, where the SOC sequestration rate ranged from 170 to 2310 kg C ha<sup>-1</sup> yr<sup>-1</sup> in agroecosystems (Gu et al., 2017). The difference between the previous research and the present study was probably due to the experimental

duration of straw retention, which agreed with the general conclusion of previous research (Gao et al., 2018; Berhane et al., 2020). For example, researches have confirmed that straw retention is one of the most effective measures for sequestering SOC within the first 10 years for upland crops (Shang et al., 2021) or within the first 10–20 years across the major agricultural regions of China (Wang et al., 2015b), while the increase rate declines over longer periods of time (Han et al., 2018). The driving factors for SOC sequestration through straw retention may include C input rates, initial SOC content levels, soil clay content and climate conditions (Liu et al., 2014; Zhu et al., 2023). According to the soil C saturation hypothesis (Stewart et al., 2007), it is suggested that the longer the practice endures, the closer the soil approaches its saturation level, resulting in a lower rate of SOC sequestration. However, limited studies have investigated straw retention in uplands spanning periods longer than three decades (Berhane et al., 2020). Therefore, the importance of the long-term impacts of straw retention on SOC sequestration in farmland should be stressed in the future.

Although SOC storage in the topsoil increased over time, the model showed that the SOC storage at 0–1 m declined at the rate of 280–390 kg C ha<sup>-1</sup> yr<sup>-1</sup> over time under all the conditions in various treatments (Fig. 8 and Table S7), which revealed that the C gain in topsoil after straw retention could not compensate for the C loss in subsoil. These findings are in line with SOC storage changes in subsoil reported previously (Grant et al., 2007; Hiel et al., 2018). As Lyu et al. (2021) reported, the subsoil SOC may not be as difficult to decompose as previously thought. In fact, the subsoil SOC would be more sensitive to

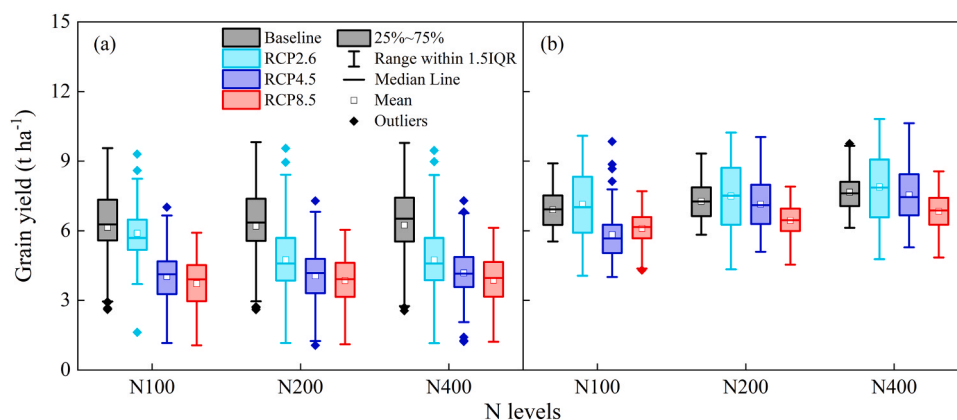


**Fig. 6.** Observed and simulated soil  $\text{CO}_2$  (a–d) and  $\text{N}_2\text{O}$  emissions (e–h) under different N application rates in the growing seasons of winter wheat and summer maize in 2008–2010. Solid and dot downward arrows indicate N fertilizer application and irrigation events, respectively. N0, N200, N400 and N600 denote the treatments that received synthetic urea (N) at the rate of 0, 200, 400 and 600  $\text{kg ha}^{-1}$ , respectively. The bar over a solid circle (mean) is the standard deviation of samples ( $n=3$ ). Notes that the scale of the coordinate is different.

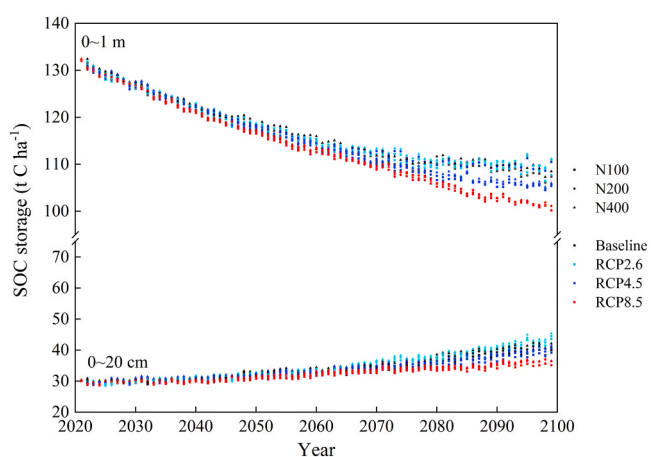
environmental or anthropogenic changes than the topsoil SOC. This may be attributed to the lower C input from crop residues in the subsoil and the lower stability of SOM at deep soil depths due to microbial N mining (Chen et al., 2014).

In agroecosystems, the amount of SOC stored within the soil profile is

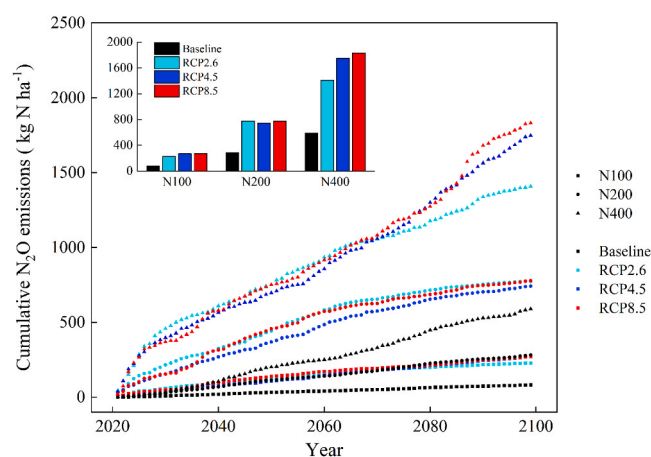
the ultimate result of the balance between carbon input, mainly from manure amendment, crop litter incorporation or rhizosphere deposition, and carbon losses through the decomposition of SOM by microorganisms or erosion (Álvarez-Fuentes et al., 2012). Many factors affect the SOC decomposition, such as the temperature, precipitation, clay content



**Fig. 7.** Simulated wheat (a) and maize (b) yield at various N fertilizer application rates under different climate change scenarios between 2021 and 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. IQR: interquartile range. N100, N200 and N400 denote the treatments that received synthetic urea (N) at the rate of 100, 200 and 400 kg ha<sup>-1</sup>, respectively.



**Fig. 8.** Simulated dynamics of SOC storage in the top 20 cm and 1 m soil depth at various N fertilizer application rates in winter wheat–summer maize rotation system under different climate change scenarios from 2021 to 2100. N100, N200 and N400 denote the treatments that received synthetic urea (N) at the rate of 100, 200 and 400 kg ha<sup>-1</sup>, respectively.



**Fig. 9.** Simulated cumulative N<sub>2</sub>O emissions at various N fertilizer application rates in winter wheat–summer maize rotation system under different climate change scenarios from 2021 to 2100. N100, N200 and N400 denote the treatments that received synthetic urea (N) at the rate of 100, 200 and 400 kg ha<sup>-1</sup>, respectively.

**Table 4**

Simulated mean annual SOC storage change rate (SOC<sub>r</sub>), N<sub>2</sub>O emissions and global warming potential (GWP) at various N application rates in the winter wheat–summer maize rotation system under different climate scenarios between 2021 and 2100.

Treatments <sup>a</sup>	Climatic condition	SOC <sub>r</sub> (kg C ha <sup>-1</sup> yr <sup>-1</sup> )	N <sub>2</sub> O emissions (kg N ha <sup>-1</sup> yr <sup>-1</sup> )	GWP (kg CO <sub>2</sub> -eq ha <sup>-1</sup> yr <sup>-1</sup> )
N100	Baseline	135	1.0	-79
	RCP2.6	180	2.9	548
	RCP4.5	131	3.4	936
	RCP8.5	73	3.4	1148
N200	Baseline	145	3.6	967
	RCP2.6	188	9.8	3392
	RCP4.5	138	9.4	3408
	RCP8.5	86	9.8	3766
N400	Baseline	155	7.5	2555
	RCP2.6	195	17.8	6697
	RCP4.5	144	22.1	8675
	RCP8.5	83	23.2	9357

<sup>a</sup> : N100, N200 and N400 denote the treatments that received synthetic urea (N) at the rate of 100, 200 and 400 kg ha<sup>-1</sup>, respectively.

and agronomic practices (cropping systems and tillage) (Wan et al., 2011). The results of the present study indicated that positive feedback of SOC storage in topsoil occurred under minor warming (RCP2.6) and negative feedback occurred under moderate and high warming (RCP4.5 and RCP8.5, respectively) (Fig. 8 and Table 4). The increase in SOC storage in the topsoil under RCP2.6 may be because of the higher C input into soil under the greater net primary production of maize compared with the baseline (Table S6). In contrast, the C loss under RCP4.5 and RCP8.5 may be related to the lower C input into soil under the lower net primary production of both wheat and maize combined with the faster SOC decomposition and turnover rate under higher temperature and precipitation compared with the baseline (Table S5 and Table S6). Previous experimental studies have reported that increased SOC decomposition occurred in association with the increased microbial activity at higher temperatures, resulting in increased SOC loss from soils (Trumbore et al., 1996; Lin and Zhang, 2012). It was reported that the upland soils would lose SOC storage (0–30 cm) by 7.8 t C ha<sup>-1</sup> by the year 2080 without organic material amendment under the B2 climate scenario (HadCM3, beneficial to social and environmental development) in China (Wan et al., 2011). Furthermore, the present study revealed that the SOC storage at the 0–1 m soil depth will continue to decline under all climate conditions in the wheat–maize rotation system in the NCP even though straw residue has been returned to the soil since 2021,

indicating that continuous straw retention and N fertilization are not sufficient to sustain the SOC storage in the 0–1 m soil depth in the uplands of the NCP regardless of the degree of climate change. Therefore, additional protective management strategies (manure amendment or conservation tillage) must be adopted to increase the C storage in this area.

#### 4.4. Trade-offs between grain yields, SOC sequestration and N<sub>2</sub>O emissions

Consistent with previous studies, increased N fertilizer application greatly increased the N<sub>2</sub>O emissions although it was beneficial to atmospheric CO<sub>2</sub> sequestration in farmland and tended to increase grain yields, leading to an increase in the mean annual GWP in the simulation years (Table 4). The N<sub>2</sub>O emissions were strongly stimulated by climate change, especially at the N fertilization rate of 400 kg ha<sup>-1</sup> under RCP8.5. The high N<sub>2</sub>O emissions may be the ultimate result of the influence of rich substrates, higher temperature and favourable soil moisture content. First, the accelerated SOM decomposition under higher temperature will provide abundant energy and substrates for the nitrification/denitrification processes, thus resulting in higher N<sub>2</sub>O emissions (Rustad et al., 2001). Second, the enhanced soil moisture in combination with the increased soil temperature under climate change creates an ideal soil environment for N<sub>2</sub>O production (Marushchak et al., 2011). Numerous studies have revealed that the positive feedback of N<sub>2</sub>O emissions in response to climate warming (Griffis et al., 2017; Li et al., 2019). Therefore, maintaining or enhancing crop yield, increasing SOC storage and mitigating GHG emissions need to be balanced when fertilization and field management practices are introduced under future climate change.

Studies have demonstrated that there are trade-offs between crop production, SOC sequestration and GHG emissions affected by fertilization or organic amendments (Wang et al., 2018; Guenet et al., 2020). It has been reported that optimized N application rates can increase wheat yields while reducing soil N<sub>2</sub>O emissions compared with the current situation in Australia (Luo et al., 2017). Similarly, Chen et al. (2016) found that crop benefits and GHG reduction could be simultaneously obtained through optimized N fertilization based on a double-rice cropping system in Hunan Province, China. However, another study suggested that the increases in grain yield or SOC storage caused by N fertilization could be totally offset by the accompanied N<sub>2</sub>O emissions (Gao et al., 2018). The present study showed that the N fertilization level of 200 kg N ha<sup>-1</sup> yr<sup>-1</sup> obtained a relatively high grain yield (sum of wheat and maize, 13470 kg ha<sup>-1</sup>) and low N<sub>2</sub>O emissions (3.6 kg N ha<sup>-1</sup>) when excluding the impacts of climate change, with a mean annual GWP of 967 kg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup>. However, the grain yield (sum of wheat and maize) would decrease by 9%–23% and the N<sub>2</sub>O emissions increase by 5.8–6.2 kg N ha<sup>-1</sup> yr<sup>-1</sup> under three climate change scenarios compared with the baseline, with the mean annual GWP reaching to 3392–3766 kg CO<sub>2</sub>-eq ha<sup>-1</sup> yr<sup>-1</sup> (Table S6 and Table 4). Moreover, the increasing GWP caused by N fertilization came with a small improvement in the SOC sequestration rate but at the great cost of soil N<sub>2</sub>O emissions during 2021–2100. For example, the increase in N fertilization from 100 to 400 kg N ha<sup>-1</sup> contributed to an increase in the mean annual SOC sequestration rate of 20 kg C ha<sup>-1</sup> yr<sup>-1</sup>, but simultaneously caused a substantial increase in mean annual N<sub>2</sub>O emissions from 1 to 7.5 kg N ha<sup>-1</sup> yr<sup>-1</sup> under the baseline (Table 4). The results showed that N<sub>2</sub>O emissions were 0.8–31.8 times the SOC sequestration in terms of CO<sub>2</sub> equivalent among all N fertilization treatments under all the conditions, indicating that much attention should be paid to mitigating non-CO<sub>2</sub> GHG emissions for the realization of global carbon neutrality.

## 5. Conclusion

The SPACSYS model reasonably simulated the crop yield, SOC

storage, soil temperature, soil moisture, soil respiration, daily net ecosystem exchange of CO<sub>2</sub> and soil CO<sub>2</sub> and N<sub>2</sub>O emissions at various N fertilization rates with straw retention under the wheat–maize rotation system in the NCP and highlighted the differences between treatments. The simulation results showed that climate change led to the decline of wheat yield by 4%–39%, while a slight increase in maize yield by 3% was found under RCP2.6 and decrease of 1%–15% were projected under RCP4.5 and RCP8.5. The SOC storage (0–20 cm) increased at the rate of 73–195 kg C ha<sup>-1</sup> yr<sup>-1</sup> but decreased within the upper 1 m soil depth at the rate of 280–390 kg C ha<sup>-1</sup> yr<sup>-1</sup> at various N fertilizer application levels under different climate scenarios over the 2021–2100 period. In addition, the annual N<sub>2</sub>O emissions were substantially aggravated by climate change, leading the annual GWP to increase from –79–2555 under baseline to 548–9357 kg CO<sub>2</sub>-eq ha<sup>-1</sup> under different climate scenarios in various N fertilizer application levels. This study highlights how modelling approaches can help to strengthen the understanding of the impacts of climate warming on crop production, SOC sequestration and N<sub>2</sub>O emissions and contribute to assessing agronomic strategies aimed at improving the resiliency of the system in the NCP.

## CRedit authorship contribution statement

**Shuhui Wang:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. **Nan Sun:** Data curation, Funding acquisition, Project administration, Resources, Supervision, Conceptualization, Investigation. **Xubo Zhang:** Formal analysis, Validation. **Chunsheng Hu:** Data curation, Funding acquisition, Project administration. **Yuying Wang:** Data curation, Investigation. **Wei Xiong:** Data curation. **Shuxiang Zhang:** Formal analysis. **Gilles Colinet:** Formal analysis, Writing – review & editing. **Minggang Xu:** Conceptualization, Funding acquisition, Project administration, Supervision, Data curation, Methodology. **Lianhai Wu:** Conceptualization, Project administration, Software, Supervision, Validation, Writing – review & editing.

## Declaration of Competing Interest

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

## Data availability

Data will be made available on request.

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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.still.2024.106088](https://doi.org/10.1016/j.still.2024.106088).

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