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Impacts of climate change on crop production and soil carbon stock in a continuous wheat cropping system in southeast England

Shuo Liang [a,b], Nan Sun [a,*], Jeroen Meersmans [b], Bernard Longdoz [b], Gilles Colinet [b], Minggang Xu [a,c,**], Lianhai Wu [d]

[a] State Key Laboratory of Efficient Utilization of Arid and Semi-arid Arable Land in Northern China, Key Laboratory of Arable Land Quality Monitoring and Evaluation, Ministry of Agriculture and Rural Affairs/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[b] TERRA Teaching and Research Centre, Gembloux Agro-Bio Tech, University of Liège, Gembloux 5030, Belgium
[c] Institute of Eco-Environment and Industrial Technology, Shanxi Agricultural University, Taiyuan 030031, China
[d] Net Zero and Resilient Farming, Rothamsted Research, North Wyke, Okehampton EX20 2SB, UK

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ABSTRACT

Understanding dynamics of soil organic carbon (SOC) stock in agroecosystems under climate change is imperative for maintaining soil productivity and offsetting greenhouse gas emissions. Simulations with the SPACSYS model were conducted to assess the effects of future climate scenarios (RCP2.6, RCP4.5 and RCP8.5) and fertilisation practices on crop yield and SOC stock by 2100 for a continuous winter wheat cropping system in southeast England. Weather data between 1921 and 2000 was considered as the baseline. SPACSYS was first calibrated and validated with the data of the Broadbalk continuous winter wheat experiment for over a century. Six treatments were used: no fertiliser, a combination of chemical nitrogen, phosphorus and potassium with three nitrogen application rates (N1PK, N3PK and N5PK), manure only (FYM, close N application rate to N5PK) and a combination of manure and chemical nitrogen application (FYMN, the same chemical N application rate as N3PK). Compared with the observations, SPACSYS was able to simulate grain yields and dynamics of SOC and TN stocks. Our predications showed that wheat yield would increase by 5.8–13.5% for all the fertiliser application treatments under future climate scenarios compared to that under the baseline because of a gradual increase in atmospheric CO_2 concentration. Meanwhile, the SOC stock can increase for the practices under the scenarios except the NPK fertiliser practices under RCP2.6. Increased C input through "CO_2-fertilisation effects" can compensate C losses by soil respiration under the RCP scenarios. We concluded that manure application practices can be considered as a sustainable strategy for enhancing wheat yield and soil C sequestration under the future climate scenarios.

1. Introduction

Sequestrating more organic carbon (C) in agricultural soils plays a critical role in mitigating climate change (Sykes et al., 2020). It has been reported that about 90% of the total mitigation potential in agriculture could be achieved by soil organic C (SOC) sequestration (Begum et al., 2017). SOC changes can be manipulated by agronomic management practices, especially fertilisation. It has been shown that types and rates of applied fertiliser have various effects on the SOC stock under different climatic conditions (Ma et al., 2022; Wan et al., 2011; Wiesmeier et al., 2016). For example, SOC stocks in cropland surface soils in North China were predicted to decrease by 6.6–17.8% by the 2080 s compared with the 1980 s without additional organic materials added to the soils (Wan et al., 2011). However, if appropriate amounts of manure and stubble were applied, surface soils of more than 90% of North China's cropland could be a net C sink, and the average SOC stocks would increase by 58% by the 2060 s (Wang et al., 2014). The crop stubble conservation practise would increase the SOC storage in Ohio's cropland in the USA at a rate of

* Corresponding author.
** Corresponding author at: State Key Laboratory of Efficient Utilization of Arid and Semi-arid Arable Land in Northern China, Key Laboratory of Arable Land Quality Monitoring and Evaluation, Ministry of Agriculture and Rural Affairs/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China.
E-mail addresses: sunnan@caas.cn (N. Sun), xuminggang@caas.cn (M. Xu).

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42.0 kg C ha^{-1} yr^{-1} by 2100 whist the practise without crop straw input be at a rate of 24.6 kg C ha^{-1} yr^{-1} (Evrendilek and Wali, 2004). Furthermore, changes in SOC stock are very slow, and a steady-state soil C content would be realized over 50–100 years, depending on fertiliser application practices as well as soil type specific settings (Johnston et al., 2009; Rasmussen et al., 1998). Therefore, long-term experiments based on regional specific common soil and crop types as well as fertiliser practice conditions (Smith et al., 1997), may be the best choice to estimate whether a given fertiliser practice can sustain crop productivity and improve soil health under climate change on the long-term.

Winter wheat is currently the most extensively grown arable crop in the UK with approximately 40% of the arable aera (Cho et al., 2012; Harkness et al., 2020). Future climate projections suggested a hotter and drier summer and warmer and wetter winter across the UK (Harkness et al., 2020). CO_2 concentration would even increase to more than 900 ppm by 2100 under the worst scenario (Meinshausen et al., 2011). Because of uncertainty in climate change in the future and a slow response of SOC to the change, it would be difficult to observe the consequences with field or controlled experiments timely.

Modelling is a powerful option for predicting SOC changes under different climate and fertilisation scenarios (Begum et al., 2017). Previous predictions showed that climate change would increase winter wheat yield by ca. 5–33% in most regions of the UK (Cho et al., 2012; Ghaffari et al., 2002; Semenov and Shewry, 2011; William et al., 2018) and also increase SOC stock by 2.5–10 t C ha^{-1} in the following decades (Lugato et al., 2014; Smith, 2005; Yigini and Panagos, 2016). However, those positive responses were mainly derived from uncoupled crop growth models and soil C models that consider an altered C-input value using estimates of net primary productivity (NPP). They didn't take into consideration the interaction of C and N among soil, plant and atmosphere. Thus, models that are able to simulate the interactions between crop, soil nutrients cycling, management practices and other environmental variables are needed to conduct a more realistic and comprehensive assessment about crop yield, and the C sequestration capacity considering various fertiliser management practices and/or different climate scenarios. Process-based models could be used as decision support tools in order to assess the impacts of climate change and agronomic management practices on agroecosystems, as they allow an integration of various sources of data and knowledge on crop and/or environmental variables to evaluate hypotheses (Arulnathan et al., 2020).

The SPACSYS model has been proven with a strong ability to accurately simulate plant growth, N uptake, SOC and TN stocks, and CO_2, CH_4 and N_2O emissions of cropland and grassland across Europe and China (Liu et al., 2018, 2020; Perego et al., 2016; Wu et al., 2015; Zhang et al., 2016a, 2016b). Compared with other popular process-based models, it considers more processes in C, N and P cycling (Table S1). The Broadbalk continuous wheat winter experiment at Rothamsted Research in England is the longest continuous experiment (>170 years) in the world and has well-documented records about crop and field managements (Johnston and Poulton, 2018). If simulations by SPACSYS can be verified by the data from the experiment, then the prediction on crop yield and the dynamics of SOC under future climate scenarios would be much more credible. Although the same dataset has been used for model validation with CENTURY/DailyDayCent (Falloon and Smith, 2000; Begum et al., 2017), Roth-CNP (Muhammed et al., 2018), C-TOOL (Taghizadeh-Toosi et al., 2014) and Roth-C (Falloon and Smith, 2000), the impacts of future climate change on the yield of winter wheat and SOC stock have not been explored simultaneously. This is important because a question needs to be answered whether continuous FYM amendment over 170 years would impede the goal of C neutrality under future climate scenarios as a low SOC sequestration rate is expected when approaching SOC saturation (Stewart et al., 2007).

In this study, we tried to identify the response of crop yield and SOC stock to future climate change in the winter wheat continuous system in southeast England and recommend a sustainable strategy for both soil productivity and carbon sequestration. To achieve this, firstly we calibrated and validated the SPACSYS model using the data collected from the Broadbalk continuous winter wheat experiment over a century on the wheat yield, and SOC and TN stocks, then quantified the yield response of winter wheat to future climate change scenarios with different fertiliser practices, and finally assessed the dynamics of SOC stock and C balance with the continuous winter wheat cropping system and various fertiliser application practices under future climate scenarios.

2. Materials and methods

2.1. Site description and experiment treatments

The data from the Broadbalk continuous winter wheat experiment (http://www.era.rothamsted.ac.uk/experiment/rbk1) which started from 1843 at Rothamsted Research, Harpenden, UK (0°22′30″ W, 51°48′36″ N, 128 m a.s.l.) are used for model calibration and validation in this study. The soil type corresponds to a Chromic Luvisol when considering FAO soil classification. The site has a cool temperate climate with an average temperature of 10.2℃ and an average total annual precipitation amount of 793 mm (according to 1991–2017 period). Its original purpose was to test the response of crop yields on various combinations of fertilisers. The experiment remains its long-term integrity but has been modified to address current agriculture challenges (Johnston and Poulton, 2018). The original plots were sub-divided twice, occurred in 1926 and 1968, respectively. There are 10 sections since the last subdivision. The grain and straw yields and soil data, as used in this study, were from Section 1 of Broadbalk. Because of availability of historic daily weather data, only the data from 1914 onwards were used in this study.

The treatments that were basically established in 1852 were kept largely unaltered until 1968. Some of the fertiliser treatments were updated to better reflect modern agriculture after 1968. There are 20 treatments in total. In our study, six treatments were chosen: no fertiliser application (CK), a combination of chemical N, phosphorus (P) and potassium (K) fertilisers with three N application rates (thereafter, N1PK, N3PK and N5PK), and farmyard manure (FYM) application only or with N chemical fertiliser (thereafter, FYM and FYMN). All details about fertiliser applications for the selected treatments are summarized in Table 1.

Winter wheat was generally sown between September and October

Table 1
Nitrogen fertiliser and manure application rates for different treatments of the Broadbalk continuous winter wheat experiment.

Treatment	N[†] (kg N $ha^{-1}yr^{-1}$)	Manure[‡] (t $ha^{-1}yr^{-1}$)	form
CK	-	-	before 1967: ammonium sulphate and ammonium chloride (1:1); 1968 −1985: calcium ammonium nitrate; After 1985: ammonium nitrate; Farmyard manure (cow)
N1PK	48	-	
N3PK	144	-	
N5PK	96 (1852–1967)/ 144 (1968–1984)/ 240 (from 1985)	-	
FYM	-	35 (from 1843)	
FYMN[#]	96 (from 1968)/ 144 (from 2005)	35 (from 1885)	

[†] Before 1968, a fixed rate of 24 kg N ha^{-1} chemical N fertiliser was applied in the autumn and the remainder in spring each growing season, and then all applied in spring.
[‡] It was estimated 224 kg N ha^{-1} yr^{-1}.
[#] The treatment started from 1885.

and harvested between late July and early September the following year. Cultivars varied over time, and short-strawed cultivars were introduced after 1967 (Table S2). Herbicides and insecticides have been used as routine applications since 1964 and 1979, respectively. The plots were cultivated before sowing each year with a ploughing depth of 23 cm. Grain yield and straw yield at 85% dry matter were recorded each year. Soil samples taken within the 0–23 cm depth increment were taken and analysed periodically.

2.2. Data

Historic daily weather data for the site, agronomic management records, grain yield, straw yield, SOC and TN contents were downloaded from e-RA (http://www.era.rothamsted.ac.uk). Management includes cultivation (ploughing depth and date), crop management (date and rate of seeding and harvesting date) and fertiliser application (date, amount and fertiliser type) for each treatment.

2.3. Model description

The SPACSYS model is a multi-dimensional, field-scale, weather-driven, flexible time step (from minute up to daily), and process-based model that quantifies the biogeochemical processes of C, N, and P cycling, and the water and heat budgets in soil, plant and ruminant animal. As the details of the model have been described elsewhere (Wu et al., 2007, 2015, 2019, 2022), here we briefly described it in terms of organic pools and simulated processes. Carbon and N are held in a number of above-ground and below-ground pools, including the fresh litter pool, the microbial pool, the humus pool, the dissolved organic matter pool, the fresh OM pool (if manure was applied), the ammonium pool and the nitrate pool. Main plant growth processes are plant development, assimilation, respiration, and partitioning of photosynthate and nutrients from uptake estimated with various mechanisms implemented in the model, plus N fixation for legume plants, and root growth and development that is described either in 3D or 1D root system. Nitrogen cycling coupled with C cycling covers the transformation processes for OM and inorganic N. The main processes and transformations causing size changes to soluble N pools are mineralization, nitrification, denitrification and plant N uptake. Most of these are dependent on soil water content and temperature. Nitrate is transported through the soil profile and into field drains or deep groundwater with water movement. A biological-based component for the denitrification process has been implemented that can estimate nitrogen gaseous emissions. Fluxes between the pools occur in a particular way according to physical and biological conditions in the source and destination pools. The fresh litter, dissolved OM and humus pools receive contributions from above ground litter fall and below ground root litter. Decomposed OM from litter, dissolved OM and humus are partitioned to different pools. Meanwhile, CO_2 is released from soils with the decomposition process and microbial respiration. The Richards equation for water potential and Fourier's equation for temperature are used to simulate water and heat fluxes, which are inherited from the SOIL model.

2.4. Model input and parameterization

The SPACSYS model was operated with a daily time-step in our study. Daily meteorological data (max temperature, min temperature, precipitation, wind speed, humidity and solar radiation) were provided as model input. Because photosynthesis was calculated on an hourly basis, hourly temperatures and solar radiation were interpolated based on the date and site location in a simulation. Soil physical properties shown in Table 2 were estimated by pedotransfer functions

Table 2
Soil texture and pH, and estimated soil properties in different soil layers for different treatments of the Broadbalk continuous winter wheat experiment.

Treatment	Upper depth (m)	Lower depth (m)	SOC† (t/ha)	Clay‡ (%)	Sand‡ (%)	Silt‡ (%)	Saturated water content (%)	Field capacity (%)	Saturated total conductivity (mm/day)	pH‡
CK	0	0.2	21.78	24	8	68	50.23	41.75	105.55	7.60
	0.2	0.51	25.16	57	3	40	55.39	55.03	88.50	7.20
	0.51	0.96	40.07	71	9	20	56.17	59.87	109.33	7.00
	0.96	1.42	25.87	70	8	22	56.16	59.66	105.55	6.80
N1PK	0	0.23	29.08	19	16	65	48.36	39.83	139.91	7.60
	0.23	0.41	16.11	25	10	65	50.31	41.70	113.25	7.50
	0.41	0.66	22.35	39	3	58	53.28	47.21	88.50	7.30
	0.66	0.94	25.03	40	5	55	53.28	47.50	94.96	7.30
	0.94	1.17	13.72	36	10	54	52.33	45.26	113.25	7.40
N3PK	0	0.23	32.83	19	16	65	48.36	39.83	139.91	7.60
	0.23	0.41	17.14	25	10	65	50.31	41.70	113.25	7.50
	0.41	0.66	24.24	39	3	58	53.28	47.21	88.50	7.30
	0.66	0.94	27.15	40	5	55	53.28	47.50	94.96	7.30
	0.94	1.17	15.52	36	10	54	52.33	45.26	113.25	7.40
N5PK	0	0.23	30.53	19	16	65	48.36	39.83	139.91	7.60
	0.23	0.41	16.91	25	10	65	50.31	41.70	113.25	7.50
	0.41	0.66	23.47	39	3	58	53.28	47.21	88.50	7.30
	0.66	0.94	26.29	40	5	55	53.28	47.50	94.96	7.30
	0.94	1.17	14.41	36	10	54	52.33	45.26	113.25	7.40
FYM	0	0.18	49.33	25	18	57	49.73	40.18	150.12	7.30
	0.18	0.48	80.99	37	12	51	52.34	45.32	121.52	7.00
	0.48	0.71	34.47	50	29	21	52.78	46.03	221.18	7.00
	0.71	1.02	46.45	43	27	30	52.09	43.88	206.13	7.00
	1.02	1.52	34.73	35	30	35	50.73	39.94	229.11	6.90
FYMN	0	0.18	38.67	25	18	57	49.73	40.18	150.12	7.30
	0.18	0.48	40.85	37	12	51	52.34	45.32	121.52	7.00
	0.48	0.71	15.36	50	29	21	52.78	46.03	221.18	7.00
	0.71	1.02	20.70	43	27	30	52.09	43.88	206.13	7.00
	1.02	1.52	15.46	35	30	35	50.73	39.94	229.11	6.90

† Soil organic carbon (SOC) content was only measured in the 0–23 and 23–46 cm depths in 1914 and estimated in different soil layers based on the ratio of each layer fraction to total SOC stock of the measured soil profile in 1969.
‡ measured data.

implemented in the model based on soil texture and soil organic matter content prior to simulations. Initial SOC content of each treatment used the average value of three consecutive measurements around 1914 to avoid measurement errors. The atmospheric CO_2 concentration was set to 296 ppm in 1914 and 380 ppm in 2017 (IPCC, 2021) with a linear increase over the period. Parameters about C and N cycling, soil water redistribution and heat transformation were adopted from previous studies (Bingham and Wu, 2011; Wu et al., 2015). Those for plant photosynthesis and development were based on the previous study (Liu et al., 2020). The built-in Multi-Objective Shuffled Complex Evolution Metropolis algorithm (MOSCEM-UA) (Vrugt et al., 2003) was applied for parameter optimization. The calibrated parameters with optimisation on wheat winter, and soil C and N cycling are listed in Tables S3 and S4, respectively.

Because wheat cultivars varied over time and some of them only planted for a short period (Table S2), especially the short-strawed wheat cultivars, which are not enough to parameterise them. Thus, we assumed that the performance of cultivars grown during the 1914–1967 (tall-strawed varieties), the 1968–1995 (short-strawed varieties), and the 1996–2017 (short-strawed varieties) periods is similar and chose cultivars Red Standard, Cappelle Desprez, and Hereward as the dominant cultivar for each period, respectively. During each period, the grain and straw yields for the chosen dominant cultivars were for calibration, whereas the yields data of rest cultivars were used for validation. The parameters related to soil C and N cycling, water redistribution and heat transformation were kept constant through the entire period. SOC and TN stocks in the plough layer (i.e. 0–23 cm) were calculated after using the C contents and soil bulk density measurements. The SOC and TN stocks data from the three NPK treatments were used to calibrate and those from the rest of the treatments for model validation. Fig. 1 presents the methodological flowchart of the model calibration and validation.

2.5. Prediction

In order to investigate the impacts of future climate change on wheat yield, SOC stock, and C balance with different fertiliser practices, the daily bias-corrected weather data for three future climate scenarios (2021–2100) and the baseline climate (1921–2000) based on the well-cited HadGEM2-ES model with a spatial resolution of 0.5° × 0.5° (Collins et al., 2011; Jones et al., 2011) were downloaded from the Inter-Sectoral Impact Model Intercomparison Project (www.isimip.org, Arneth et al., 2017). The future scenarios were Representative Concentration Pathway (RCP) 2.6, 4.5 and 8.5 (Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011). The average annual precipitation, maximum and minimum temperatures (°C) for the baseline and RCP climate scenarios are shown in Table 3. Their dynamic changes are shown in Fig. S1. Climate projections showed warmer and dryer future conditions in the study region.

Current cultivar "Crusoe" was used for the future crop variety. To simplify the impact of climate change on crop phenology and yield, the sowing date was fixed on 15th October each year in this study, and the harvest date is determined by simulated physiological maturity. To study the response of existing fertilisation practices to future climate change, field management and fertiliser practices are the same as the experimental treatments.

2.6. Statistical analysis

We used three statistical criteria to evaluate model performance: (1) the coefficient of determination (R^2) that describes the degree of fitness between simulation and observation; (2) the root mean squared error (RMSE), a measure of the average deviation of the estimates from the observed values; and (3) the relative error (RE) that reflects the overall difference between simulated and observed data.

For the predications, two-way ANOVA and Tukey ($P < 0.05$) were used in order to compare the effects of fertiliser treatments and climate scenarios on grain yield, SOC stock, NPP (gross primary productivity minus plant respiration), soil respiration and C balance. Coefficient variation (CV, %) was used to represent stability of grain yield. A low CV value means high yield stability (Berzsenyi et al., 2000). Statistical analysis was performed with SPSS 24.0 (SPSS, Inc., 2017, Chicago, USA).

3. Results

3.1. Model calibration and validation

Overall, the SPACSYS model was able to simulate wheat yields for different treatments in the Broadbalk continuous wheat cropping system under more than a century of fertilisations (Table 4; Fig. 2, Fig. S2). However, model performance for the modern short-strawed varieties was better than the tall varieties. For the tall varieties, the main discrepancy between simulation and observation occurred for cv. Red Standard with all the treatments during the period 1918–1925.

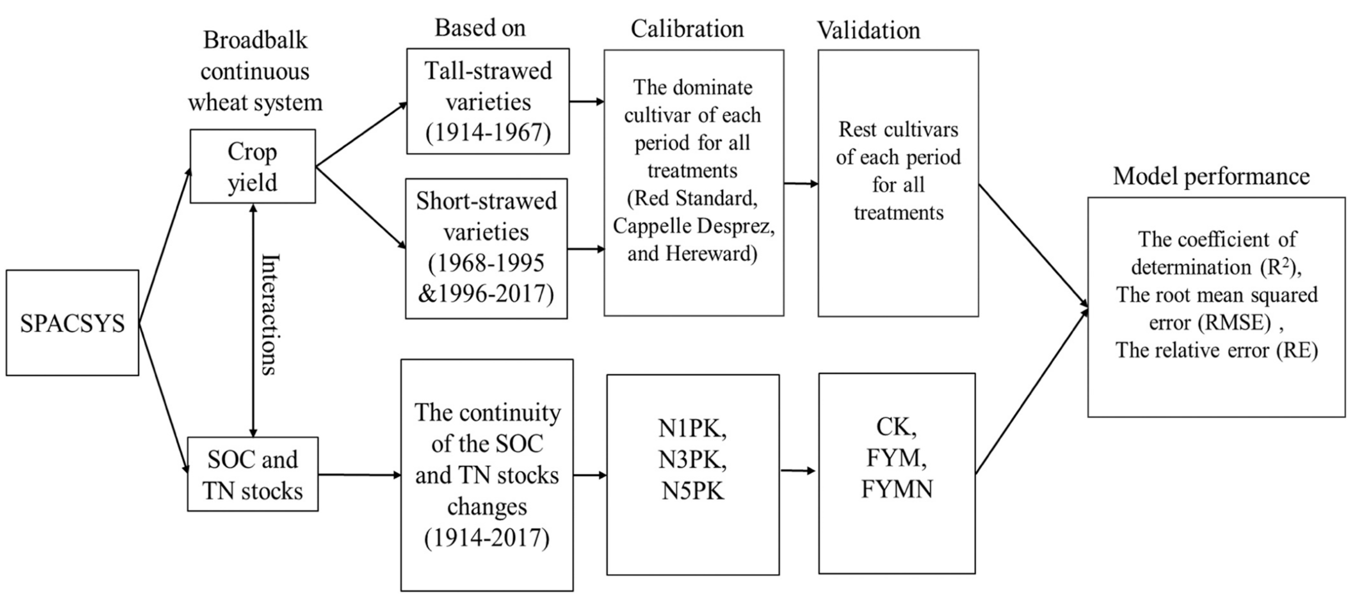

Fig. 1. A methodological flowchart of model calibration and validation.

Table 3
Average annual maximum and minimum temperatures, precipitation and CO_2 concentration under the future climate scenarios (2021–2100) and the baseline (1921–2000) at the experimental site.

Scenarios	Maximum (°C)	Minimum (°C)	Precipitation (mm)	Precipitation events (times)	Frequency daily precipitation >10 mm (times)	CO_2 concentration† (ppm)
Baseline	13.3 (±0.7)	7.7 (±0.6)	829 (±149)	17171	1642	380
RCP2.6	16.0 (±0.8)	8.0 (±0.6)	730 (±135)	16127	1438	424
RCP4.5	16.7 (±0.9)	8.6 (±0.8)	688 (±112)	15249	1300	536
RCP8.5	17.8 (±1.6)	9.5 (±1.3)	656 (±112)	14669	1306	934

† CO_2 concentration in 2100 for different future climate scenarios.

Table 4
The statistical criteria about model performance for wheat grain yield, straw dry matter and SOC and TN stocks at Broadbalk.

Index	Calibration	Validation	Calibration	Validation
	Grain yield		Straw dry matter	
Tell-strawed varieties (1915–1967)				
R^2	0.24**	0.30**	0.53**	0.41**
RMSE (%)	52	34	37	32
RE (%)	-31	-10	-41	-16
n	119	131	119	131
Short-strawed varieties (1968–1995)				
R^2	0.71**	0.67**	0.55**	0.41**
RMSE (%)	26	26	37	47
RE (%)	-16	-11	4	-15
n	60	108	60	106†
Short-strawed varieties (1996–2017)				
R^2	0.70**	0.65**	0.63**	0.58**
RMSE (%)	26	32	38	36
RE (%)	-16	-20	-26	-26
n	101	30	101	30
	SOC stock		TN stock	
R^2	0.40**	0.98**	0.69**	0.98**
RMSE (%)	5.8	9.8	3.4	9.4
RE (%)	-4.6	-3.5	-0.5	3.5
n	9	48	9	48

† data missing for CK and N3PK in 1987.
** means $P < 0.01$.

Discrepancies also existed for short-strawed cultivars between 1978 and 1995, however, the model underestimated grain and straw yields only for FYMN, with approximately 11% and 35%, respectively. In addition, the SPACSYS model satisfactorily simulated the dynamics of SOC and TN stocks in the ploughing layer under different fertiliser application practices for over a century (Fig. 3) as being sown by supportive statistical indicator values (Table 4). About 16% underestimation in TN with FYMN after 1992 was found (Fig. S3).

3.2. Climate change effect on wheat yield under long-term fertilisations

Compared with the baseline, future climates had a positive effect on grain yield (5.81–13.51%) with all N input treatments and negative without N input (−9.12 to −4.26%) with a rank of: RCP8.5 ≥ RCP4.5 ≥ RCP2.6 ($P < 0.05$) (Fig. 4 and S4; Table 5). Grain yields were higher (5366–10976 kg ha^{-1}) with a higher N application rate (N5PK and FYMN) than those (2207–9663 kg ha^{-1}) with other N application rates ($P < 0.05$) (Fig. 4 and S4). Grain yields with N5PK and FYMN did not show significant differences among the three RCP scenarios ($P > 0.05$) (Fig. 4). In an individual treatment, grain yields under the RCP scenarios were in general more stable with lower CV values (8.80–11.80%) than those under the baseline (10.19–14.13%) except CK and N1PK (Table 5).

3.3. Climate change effect on SOC stock under long-term fertilisations

The SOC stock with FYM or FYMN had positive responses to all three RCP scenarios with an average relative increase (0.84–2.34%) to that under the baseline (Fig. 5; Table 5). Meanwhile, the field with FYM had the highest C sequestration rate over the simulation period (i.e. 107–142 kg C ha^{-1} yr^{-1}) among all the fertiliser practices for both baseline and RCP scenarios (Table 6). In addition, when considering SOC stock under future climate scenarios with CK and NPK fertiliser practices, these SOC stocks had positive responses to the RCP4.5 and RCP8.5 scenarios during 2021–2100 with average relative increases of 0.19–3.99% (Fig. 5; Table 5). However, the SOC stocks with CK and NPK fertiliser practices showed a negative response with average decreases of 0.27–1.08% to the RCP2.6 (Fig. 5; Table 5).

3.4. Climate change effect on C balance under long-term fertilisations

The analysis of average annual inputs and outputs of C with different fertiliser practices under the climate scenarios indicated that all the fertiliser treatments resulted in a C sink under each climate scenario within a range of 62–166 kg C ha^{-1} yr^{-1} for CK, 242–881 kg C ha^{-1} yr^{-1} for NPK fertiliser practices and 543–855 kg C ha^{-1} yr^{-1} for FYM and FYMN (Fig. 6; Table 5). Hence, future climate changes seem to result in a net C sink (i.e. 112–881 kg C ha^{-1} yr^{-1}) and a relative increase of 50–424 kg C ha^{-1} yr^{-1} as compared with the baseline (i.e. 62–593 kg C ha^{-1} yr^{-1}). This was especially the case under the RCP8.5 climate scenario with an average increase of 104–424 kg C ha^{-1} yr^{-1}. There was no significant difference for C sink levels among N5PK, FYM and FYMN under the RCP scenarios.

4. Discussion

4.1. Model performance

The SPACSYS model is able to simulate winter wheat grain yields (R^2 of 0.24–0.71 and RMSE of 26–52%) and SOC and TN stocks (R^2 of 0.40–0.98 and RMSE of 3–10%), respectively, for both calibration and validation ($P < 0.05$) (Table 4). The values of R^2 and RMSE for the yield were close to or slightly better than of those from DayCent (R^2: 0.06–0.64 and RMSE: 32–83%; Begum et al., 2017) and Roth-CNP (R^2: 0.20–0.76 and RMSE: 52–70%; Muhammed et al., 2018) when using the same dataset, indicating that SPACSYS is a competitive tool for predicting wheat yield. Moreover, SPACSYS has also a good performance for modelling SOC and TN stocks, which was comparable to the performance of DayCent, C-TOOL and Roth-C with R^2 of 0.23–0.85 and RMSE of 7–9% (Begum et al., 2017; Falloon and Smith, 2000; Taghizadeh-Toosi et al., 2014), but was better than the performance of CENTURY and Roth-CNP with R^2 of 0.18–0.86 and RMSE of 6–17% (Falloon and Smith, 2000; Muhammed et al., 2018; Taghizadeh-Toosi et al., 2014).

Although the simulations turned up to be better performance, the discrepancies between simulated and observed values still existed over a century period, especially for some specific growing seasons. The reasons may be due to model simplification on the interactions between plant growth and driving variables, and sampling errors. The model was assumed that plant growth is not affected by either weeds, diseases or insects (Liang et al., 2018; Zhang et al., 2016b), which would be impossible for long-term field experiments especially before herbicides and insecticides were introduced. In reality, any adverse events happened in a growing season, the model would overestimate crop

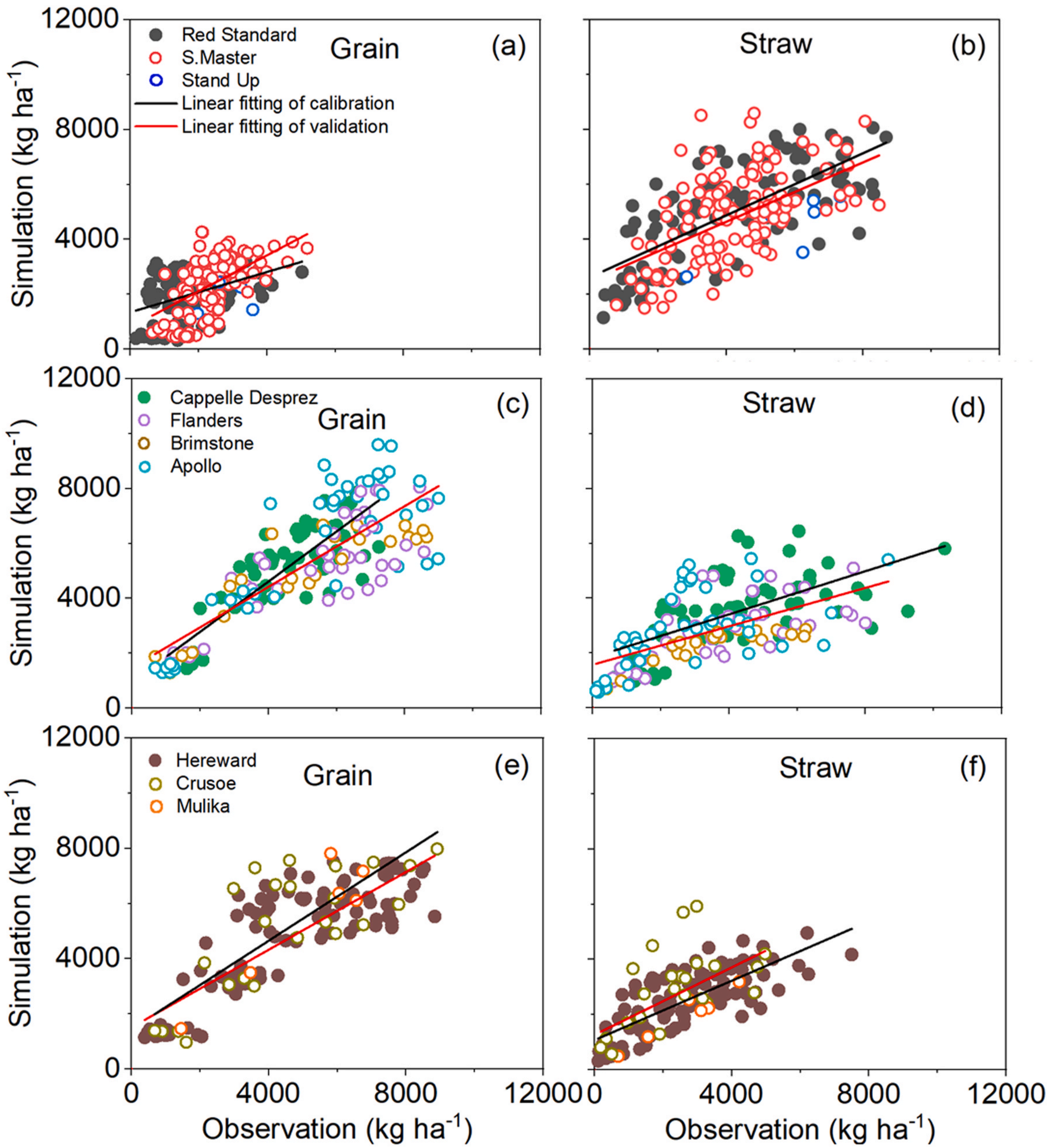

Fig. 2. Relationship between simulated and observed grain and straw yields of winter wheat from different treatments over the 1914–1967 (a and b), 1968–1995 (c and d) and 1996–2017 (e and f) periods for calibration and validation. The cultivars with solid circle were used for model calibration, and others with open circle were used for model validation.

growth and grain yield. For example, an overestimation of 41% of grain yield and 69% of straw yield for cv. Red Standard during 1918–1925, which is in accordance with the record that "a decline set in during the first World War, when labour for hand weeding became scarce and weeds got out of control, and fallowing the field one year in five was adopted to control weeds after 1925" (Jenkinson, 1991). Furthermore, extreme weather events occurred much more frequently recently. Heavy and persistent precipitation in the spring and/or summer of 1979, 2007 and 2012, a prolonged drought in 1989 and 2011, and a cold winter in 1991 and 2013 were recorded in the studied region (Addy et al., 2020; Harkness et al., 2020). The influence of the events, especially waterlogging, on crop growth and development has not been given enough attention in the model, which should be improved in the future.

4.2. Climate change and fertiliser impacts on wheat yield

Our prediction showed that future climate change had positive effects on the wheat yields for all the N application practices. It was reported that the grain yield of winter wheat decreased by approximately 10% in South-East England if only precipitation or temperature changes relative to the baseline without considering the CO_2-enrichment effect (Cho et al., 2012). Apparently, an increasing CO_2 concentration plays a critical role in crop growth. Our results confirmed no significant difference in grain yield under the baseline and the RCP scenarios (N1PK, N3PK except RCP8.5) or a significantly decreased yield under the RCP scenarios (CK, N5PK, FYM and FYMN) when the CO_2 concentration was kept unchanged (Fig. S5). The contribution of the concentration to the grain yield was in the order of RCP8.5 > RCP4.5 > RCP2.6 (Table S6). Controlled experiments on winter wheat in the studied region showed that the photosynthetic rate can increase by 10% at a doubled CO_2

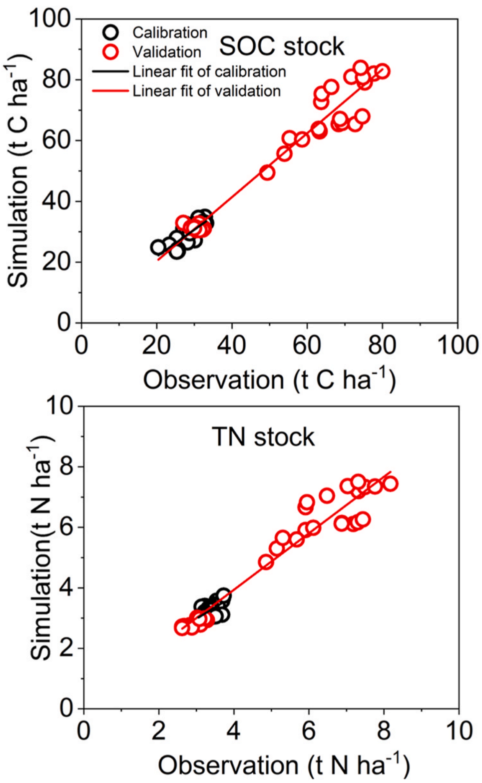

Fig. 3. Relationship between simulated and observed soil organic carbon and total nitrogen stocks in the plough layer (0–23 cm) for calibration and validation.

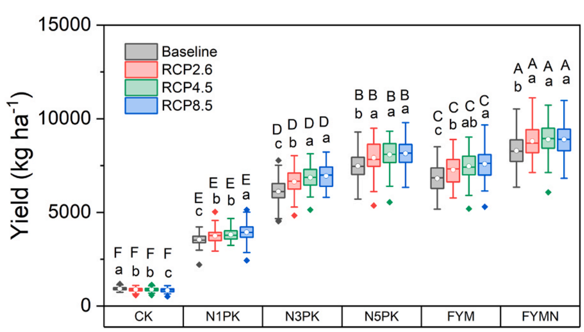

Fig. 4. Wheat grain yield with different fertiliser practices under future climate scenarios. The lines and circles within the boxes are the median and mean values. The spots are outliers. Columns with different lowercase letters indicate significant differences among climate scenario with an individual treatment ($P < 0.05$). Columns with different capital letters indicate significant differences among different treatments under the same climate scenario ($P < 0.05$). The effects of fertilization treatments and climate scenarios on wheat yields between 2021 and 2100 were shown in Table S5.

concentration (i.e. 700 µmol mol^{-1}) compared to that at the ambient concentration (Delgado et al., 1994), and a doubled CO_2 concentration (i.e. 684 µmol mol^{-1}) also increased the partitioning of assimilates to grain by 8.0 mg DM ear^{-1} d^{-1} as compared with that under 380 µmol mol^{-1} CO_2 (Wheeler et al., 1996). Furthermore, it was reported by a summary of both field and laboratory results that the wheat yield would keep increasing until the CO_2 elevated to around 900 ppm (Amthor, 2001), which is very close to the CO_2 concentration around 2090 s under the RCP8.5. Meanwhile, we found that grain yields under all the fertiliser practices could increase more under the high-emissions scenario (RCP 8.5) compared with those under the low- or medium-emissions scenario (Tables 3 and 5, Fig. 4), which is in agreement with the previous reports for the studied region (Cho et al., 2012; Semenov and Shewry, 2011; William et al., 2018).

For the impact of the N application practices on the yield, there was no significant difference among three RCP scenarios in grain yields with N5PK or FYMN, and the highest yield was achieved with the FYMN practice (Fig. 4; Table 5). Those indicated that high N supplication might favour crop growth under the future climate change. Further, combined inorganic N and manure application could effectively increase soil organic matter and quantity of the soil microbial community that release nutrients persistently (Yang et al., 2020). As a consequent, those are much favourable for wheat growth and final grain yield (Dhaliwal et al., 2020). Annual N application amounts between N5PK and FYM were very close (Table 1). However, the relative increase of the yield for FYM was higher than that for N5PK under the RCP scenarios (Table 5). Thus, with the similar application rate, manure application should be more beneficial to keep or increase the yield under climate change than that with chemical fertilisers applied only.

4.3. Climate change and fertilisation impacts on SOC stock and C balance

The response of SOC stock to future climate change varied among the RCP scenarios and fertiliser practices. Although wheat yields for each NPK fertiliser treatment increased under the future climate change scenarios (Table 5; Fig. 4), a significant decrease of the SOC stock was found under the RCP2.6 compared with the baseline (Table 5; Fig. 5). The remarkable decrease in the fresh litter pool (Table S7), transferred from above-ground residues and dead roots, could explain the SOC stock decrease. More precisely, the shortened grow period under the RCP scenarios resulted in a lower accumulation of dead materials (Fig. S6), despite a significant increase in crop biomass. For example, significant decreases in transferring plant biomass to the fresh litter pool for N5PK and FYMN under the climate scenarios compared to that under the baseline (Table S8). Increasing temperature under the RCP scenarios would shorten the growing season of wheat in study region, which could provide less time to accumulate dead leaf, stem and root to above- and below-ground litter under future climate change (Balkovič et al., 2014; Senapati et al., 2019), especially during the reproductive stage in our study (Fig. S6). This has also been clarified by other modelling studies in the UK (Harkness et al., 2020; Richter and Semenov, 2005). In addition, our predictions proved that the enhanced biomass under the RCP scenarios increased the dissolved organic matter (DOM) pool (Table S7) that mainly originates from fresh organic material, fresh litter and root exudates in the simulations. This principally results in the SOC stock increase under higher atmospheric CO_2 concentration and intensified climate change situations (i.e., RCP4.5 and RCP8.5) in our study. C3 crops, like wheat, tend to produce more exudation under higher CO_2 concentrations (Drigo et al., 2008; Phillips et al., 2006). Further, an experiment with labelled ^{14}C wheat showed that increases in CO_2 concentration quantitatively increased rhizosphere soluble C by 60% because of the significantly increased substrate input to the rhizosphere due to both increased root biomass and root activities per unit of roots under the elevated atmospheric CO_2 (Cheng and Johnson, 1998).

Furthermore, C balance analyses showed that climate change resulted in a net C sink and an average increase of 50–424 kg C ha^{-1} yr^{-1} as compared with the baseline (Table 5). An increase in NPP under the RCP scenarios supports the hypothesis that continuous wheat cropping in south-east England could result in a larger C sink (i.e. 112–881 kg C ha^{-1} yr^{-1}) in the future as compared with the baseline (i.e. 62–593 kg C ha^{-1} yr^{-1}) (Fig. 6 and S7; Table 5). The increase in NPP due to CO_2-fertilisation could be a dominant factor in determining whether SOC stocks continue to act as a sink of C in the future (Wieder et al., 2015). Studies have indicated that the rising CO_2 concentration could ease climatic constraints to plant growth by decreasing stomata conductance and hence reducing transpiration, which could improve water use efficiency and inhibit drought stress, resulting in global NPP increases throughout the next few decades (Pan et al., 2014; Wieder et al., 2015).

Table 5
The coefficient variation (CV) of grain yield, average SOC stock and C budget for different fertiliser application treatments under all the climate scenarios over the simulation period. Numbers with different lowercase letters indicate significant differences among climate scenarios for a treatment ($P < 0.05$) and those with different capital letters indicate significant differences among different treatments under a climate scenario ($P < 0.05$).

Treatments	Climate scenarios	Grain		SOC		C budget (kg C ha^{-1} yr^{-1})
		Relative changes (%)	CV (%)	Stocks (t C ha^{-1})	Relative changes (%)	
CK	Baseline	-	9.53	24.85 bF	-	62 cD
	RCP2.6	-4.76	11.88	24.66 cF	-0.74	112 bcC
	RCP4.5	-4.26	10.68	24.89 bF	0.19	132 abC
	RCP8.5	-9.12	12.86	25.07 aF	0.92	166 aB
N1PK	Baseline	-	8.62	33.92 cE	-	242 cC
	RCP2.6	5.92	9.66	33.77 dE	-0.43	374 bcB
	RCP4.5	7.88	8.86	34.49 bE	1.70	467 abB
	RCP8.5	11.41	12.15	35.26 aE	3.99	650 aA
N3PK	Baseline	-	11.06	36.11 cD	-	443 cB
	RCP2.6	8.53	8.80	36.00 dD	-0.27	610 bcA
	RCP4.5	12.14	8.88	36.80 bD	1.93	683 abA
	RCP8.5	13.51	9.00	37.36 aD	3.49	867 aA
N5PK	Baseline	-	10.19	36.53 cC	-	504 bA
	RCP2.6	5.81	9.88	36.13 dC	-1.08	642 abA
	RCP4.5	8.10	8.85	36.72 bC	0.54	687 abA
	RCP8.5	8.88	9.89	37.36 aC	2.28	881 aA
FYM	Baseline	-	14.13	92.82 dA	-	543 bA
	RCP2.6	9.71	10.16	93.60 cA	1.56	673 abA
	RCP4.5	12.10	10.24	93.91 bA	1.63	780 abA
	RCP8.5	13.39	11.63	94.42 aA	2.34	855 aA
FYMN	Baseline	-	13.39	84.66 dB	-	593 bA
	RCP2.6	8.64	11.02	85.38 cB	0.84	694 abA
	RCP4.5	10.61	9.42	85.44 bB	0.92	701 abA
	RCP8.5	9.56	11.80	85.81 aB	1.36	774 aA

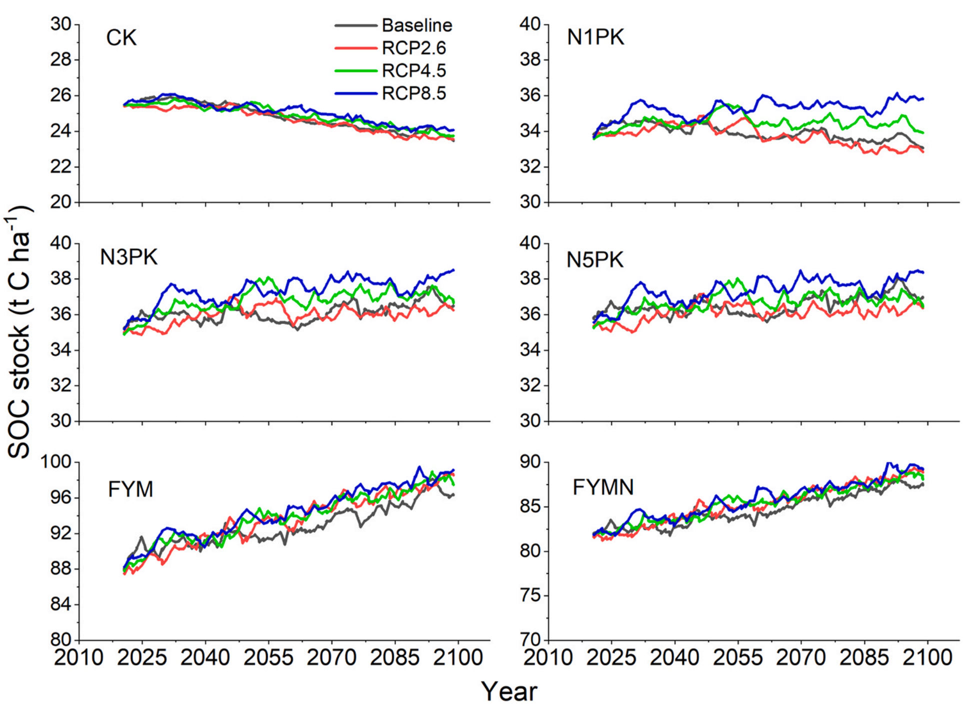

Fig. 5. Soil organic carbon stock dynamics in the plough layer (0–23 cm) with different fertiliser practices under future climate scenarios from 2021 to 2100.

Our simulations indicated there was an average increase of 524, 690 and 841 kg C ha^{-1} yr^{-1} for NPP under RCP2.6, RCP4.5 and RCP8.5 (Fig. 6), respectively, which is close to previous study reporting increases in the range of 0–500 kg C ha^{-1} yr^{-1} under a low emission scenario, and 500–1000 kg C ha^{-1} yr^{-1} under a high emission scenario for the South-East of England (Pan et al., 2014). In addition, our predictions also showed significantly high soil respiration rates, especially from the microbial pool, under all the RCP scenarios compared with the baseline (Fig. S7; Table S9). This is corroborated by the previous simulation reports that warming future climates in Europe would accelerate microbial respiration predicted by CENTURY (Lugato et al., 2018) and Roth-C (Gutierrez et al., 2023; Wiesmeier et al., 2016) both of which have the similar respiration-temperature relationship as SPACSYS. Therefore, increased C input through the CO_2 concentration effect can compensate C losses caused by the increased temperatures under the climate scenarios in the region.

Table 6
The average annual change rate of soil organic carbon stock (kg C ha^{-1} yr^{-1}) during 2021–2100 with various fertiliser management practices under different climate scenarios.

Treatments	Baseline	RCP2.6	RCP4.5	RCP8.5
CK	-26.64	-23.62	-22.56	-18.28
N1PK	-10.37	-11.08	4.26	22.27
N3PK	15.26	15.68	22.08	41.94
N5PK	13.81	12.74	14.51	35.88
FYM	106.72	142.16	124.56	139.25
FYMN	70.97	93.80	81.98	95.22

4.4. Adaptation strategies to future climate change

Our simulations suggested that the practice of manure application only (FYM) or combined chemical N fertiliser and manure application (FYMN) can realise higher grain yields of winter wheat and SOC sequestration rates among the investigated practices under the future climate scenarios. Despite of higher soil respiration rates under the two practices (Fig. S7), the SOC sequestration rates are higher than those for N3PK and N5PK (Table 6). Thus, manure application practices seem to be sustainable for the continuous winter wheat cropping system in southeastern England to adapt to climate change.

However, in our prediction, the N application rates keep unchanged under future climate change. It has been reported that increasing the N application rate enhanced both crop yield and plant residues that was incorporated in the soil (Johnston et al., 2009). Furthermore, the contribution of "CO_2-fertilisation effects" to vegetation photosynthesis has been declined at the global scale, owing to nutrient supply limitations (Wang et al., 2021). Thus, further investigation should be made to explore an appropriate N applied rate to enhance both crop yield and C sequestration in the study region under future climate change.

5. Conclusion

Verified by the Broadbalk continuous wheat experiment over a period of more than 100 years, the SPACSYS model was able to simulate grain yield of different tall and modern short-strawed varieties of winter wheat, and the dynamics of SOC and TN stocks in the plough layer (i.e. 0–23 cm). Future climate change in the studied region had positive impacts on wheat grain yield for both chemical and manure applied practices because of a gradual CO_2 concentration increase. However, the effects of future climate change on the SOC stock varied among the RCP scenarios and fertiliser practices. Compared to the baseline, the medium- and high- emissions scenarios would cause significantly increase the SOC stock for all the N treatments by 2100 whist the very stringent pathway (RCP2.6) resulted in reduction of the SOC stock for the practices of chemical fertiliser application only because of the least residue return among the scenarios. Further, manure application practices are effective to sustain the winter wheat production and promote soil C sequestration under future climate change in southeastern England. In conclusion, our results provide in-depth insights into the response of wheat yield and cropland SOC dynamics under long-term fertilisation as well as future climate change conditions, especially for the regions with long history of fertilisations or approaching the SOC equilibrium level.

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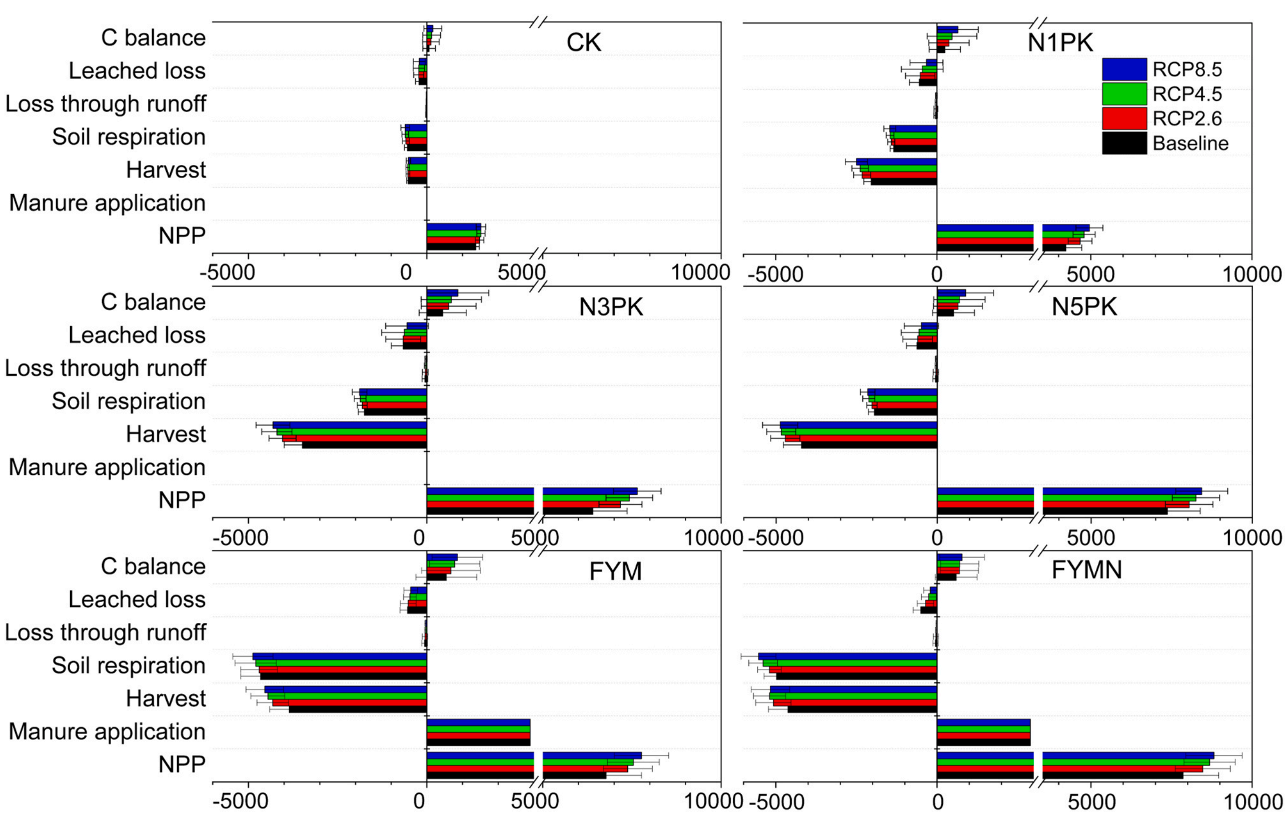

Fig. 6. Simulated average annual carbon inputs and outputs (kg C ha^{-1} yr^{-1}) with different fertiliser practices under the baseline and RCP climate scenarios. The bar is the standard deviation of annual values from 2021 to 2100.

CRediT authorship contribution statement

Liang Shuo: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Sun Nan:** Supervision, Software, Conceptualization. **Meersmans Jeroen:** Writing – review & editing, Methodology. **Longdoz Bernard:** Supervision, Methodology. **Colinet Gilles:** Supervision, Methodology. **XU Minggang:** Supervision, Funding acquisition, Conceptualization. **Wu Lianhai:** Writing – review & editing, Software, Methodology, Funding acquisition.

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

The authors do not have permission to share data.

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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.agee.2024.108909.

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