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Crop yield increments will enhance soil carbon sequestration in coastal arable lands by 2100

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ABSTRACT

Coastal lands are crucial arable land reserves that play a vital role in ensuring future global food security. In arable coastal lands, low soil quality often results in limited crop yield and soil organic carbon (SOC), making them promising sites for enhancing both soil carbon sequestration and agricultural production. However, a scarcity of long-term site experiments has led to a research gap regarding SOC sequestration in coastal arable lands, leaving potential uncertainties due to variations in planting systems, crop yields, and the influence of climate change. In this study, we focused on the Yellow River Delta (YRD) in China, which is a typical coastal agricultural area. We verified the adaptability of the Denitrifcation-Decomposition (DNDC) model in coastal farmlands based on an 11-year long-term observation experiment and continuous sampling survey data. We further explored the spatiotemporal changes of regional SOC stocks under two Shared Socio-Economic Pathways (SSPs) scenarios based on five Global Climate Models (GCMs) derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6), along with three yield increase scenarios from 2020 to 2100. The results indicated that promoting single-cotton cultivation in coastal saline–alkali lands would result in at least 88.2% of farmland being converted into carbon sinks. In contrast, promoting the cultivation of a wheat–maize rotation system can promote regional SOC sequestration as a whole, with a maximum increase of 31.90 Mg C ha^{-1}. By 2100, the SOC stocks decreased in cotton and wheat–maize rotation farmland by 3.9% and 11.6%, respectively, in the SSP585 scenario compared with that in the SSP126 scenario. Except for farmlands with wheat-maize rotation cropping system under the SSP126 scenario, the SOC stocks in all other scenarios are projected to reach their theoretical maximum values before 2050. Additionally, when reaching the North China Plain (S1) and national (S2) high-yield levels of farmland, the SOC stocks in cotton farmland by 2100 increased by 16.7% and 21.6%, respectively, whereas the SOC stocks in wheat-maize farmland increased by 1.8% and 4.8%, respectively. Our study revealed the mutually beneficial relationship between yield increment and SOC sequestration in coastal farmlands under climate change, as well as the potential for future SOC sequestration. We provided scientific support for land management and climate change mitigation strategic decision-making in coastal saline–alkali farmlands.

1. Introduction

Coastal areas are crucial food production centers, supporting food security for approximately two–thirds of the global population through agricultural production (Sarkar, 1996). These areas often face unfavorable conditions such as soil salinization and water scarcity, resulting in relatively low grain yields compared to areas with better natural resources and production conditions (Loc et al., 2021). To address the increasing pressure of population growth on grain production, improved development and utilization of medium- and low-yield areas, especially coastal farmlands, are important (Lipper et al., 2014).

Soil organic carbon (SOC) is a crucial factor in promoting agricultural productivity and ecological services in coastal lands. SOC can improve soil physical structure, buffering soil water and salt transport,

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and can decompose to release more available nitrogen for crops, thus enhancing agricultural productivity (Haj-Amor et al., 2022; Stockmann et al., 2013). Additionally, SOC is an essential component of agricultural ecosystems, playing a significant role in mitigating regional and global greenhouse gas emissions, thereby contributing to climate change mitigation (Friedlingstein et al., 2022; Lal, 2016; Trenberth and Guillemot, 1994). Many previous studies have focused on assessing SOC stocks and their reactivity to agricultural practices (such as conservation tillage and organic amendments) in high-yield croplands of typical agricultural production regions (Han et al., 2018; Ul Islam et al., 2022). Both crop yields and SOC in coastal farmlands frequently fall below their theoretical maximum values, indicating substantial untapped potential. Consequently, even minor interventions can lead to significant improvements in crop yield and the accumulation of SOC stocks in these environments (Li et al., 2016). This underscores the potential of coastal farmlands as ideal candidates for carbon sequestration, a promising avenue that has received limited attention. Nevertheless, a knowledge gap persists owing to the limited availability of observed field data and the prevailing focus on high-yield farmlands. This knowledge deficit pertains to our understanding of the present state of SOC stocks in low-yield farmlands, as well as the precise SOC sequestration potential under anticipated climate change scenarios. Understanding the SOC sequestration in coastal areas is crucial for enhancing the adaptability of coastal farmlands to climate change and achieving sustainable development while preserving natural resources and the carbon sink functions of agricultural ecosystems (Harrison et al., 2021).

Typically, there is often a synergistic relationship between SOC sequestration and yield increments in agricultural ecosystems. Increased crop yield results in higher carbon input from above- and below-ground residues, promoting SOC sequestration (Campbell et al., 2000). Additionally, higher SOC levels can enhance the mineralization of soil organic matter (SOM), leading to increased nutrient availability for crops and improved nutrient cycling through positive impacts on soil biological communities (Schmidt et al., 2011; Watts and Dexter, 1997). Nonetheless, some studies revealed that SOC is utilized in the formation of crop biomass, thereby enhancing crop yields but concurrently diminishing SOC stocks (Moinet et al., 2023). Furthermore, elevated SOC may induce nutrient competition, notably for nitrogen, between the soil and plants, potentially exerting an adverse influence on crop yields (Terrer et al., 2021). Limited crop yields in coastal farmlands stem primarily from soil salinity. Elevated soil salinity can impede the osmotic potential of soil water, thereby constraining the uptake of water and nutrients essential for crop growth (Yu et al., 2020). Furthermore, the accumulation of salt in specific plant tissues disrupts their normal physiological processes, and crops may engage in competitive uptake of soil salts, potentially resulting in a deficiency of vital nutrients necessary to sustain crop development (Tyagi, 1996). Since the 1980s, China has endeavored to address the escalating food demand by harnessing and cultivating coastal arable land, with the Yellow River Delta (YRD) exemplifying this approach. Through the implementation of enhanced irrigation techniques, such as brackish water irrigation, improving soil by modifying microbial content and other refinements in agricultural practices, substantial reductions in soil salinity and crop yield increase have been achieved (Ouyang et al., 2020). Although crop yields have experienced substantial growth, it remains unclear whether there has been a corresponding increase in SOC stocks over recent decades owing to various anthropogenic activities in coastal farmlands. This lack of clarity regarding the relationship between yield increments and SOC sequestration poses a significant barrier to the further advancement of coastal farmlands. Notably, a considerable gap persists between current crop yield levels in the YRD and those in high-yield farmlands. Therefore, determining whether augmenting policy investments to achieve higher agricultural productivity may lead to SOC losses is pivotal and requires elucidation prior to the formulation of current and future agricultural policies. This will be a critical determinant for forecasting the SOC sequestration potential within coastal farmlands, thereby facilitating the pursuit of synchronized development between agricultural production and SOC sequestration in coastal ecosystems.

The impact of coastal farmlands development and utilization on SOC sequestration potential under long-term cultivation, remains uncertain (Zavattaro et al., 2017; Zhu et al., 2020). Uncertainty arises from environmental variations, including disparities in soil properties, farmland management and climatic conditions (Chenu et al., 2019; Lessmann et al., 2022). In coastal farmlands, crop carbon input is the main pathway for SOC sequestration. However, predicting SOC sequestration is more difficult than on conventional farmland because of the inhibitory effects of salt stress and complex water and salt transport processes on plant growth and soil microbial activity, which reduce crop carbon input and SOC sequestration efficiency (Lozupone and Knight, 2007; She et al., 2021). The diversity of planting systems, including crop rotations, is an additional source of uncertainty in assessing regional SOC sequestration potential. In coastal areas, there is often a trade-off between cash crops (e.g., cotton) and food crops (e.g., maize or wheat) due to economic considerations. Previous research has shown that crop rotation can increase or decrease SOC stocks compared to monoculture (Song et al., 2021; Zhang et al., 2021). Additionally, the SOC stocks of an agricultural ecosystem will also change with future climate changes (Sitch et al., 2008). Climate change can directly or indirectly affect SOC sequestration in farmland through changes in water and thermal conditions. For instance, in coastal farmlands, a temperature rise may increase the activity of soil microorganisms that are inhibited by salt, resulting in improved SOC sequestration through increased utilization of available carbon by microorganisms. However, it may also reduce SOC by promoting the decomposition rate (Shiferaw et al., 2021). The effects of climate conditions on SOC stocks are often uncertain and can vary spatiotemporally (Stockmann et al., 2013). These uncertainty factors pose challenges in predicting the SOC sequestration potential of coastal farmlands. Therefore, it is crucial to clarify the evolving SOC status during long-term cultivation. The response of SOC stocks in farmlands with different cropping systems in coastal arable lands is essential for understanding the SOC stock dynamics in these environments.

Currently, empirical models based solely on on-site experiments are insufficient for agricultural decision-making and production at a larger scale. Instead, biological process models, such as the Denitrification–Decomposition (DNDC), Rothamsted C (Roth C) models, are widely used to accurately reflect the detailed biological and chemical processes in the soil, providing scientific support for the optimization of farmland management practices in the context of climate change at regional or point scales (Feng et al., 2019; Gilhespy et al., 2014; Wang et al., 2022b). However, there is often a lack of long-term field experiments (over 10 years) and sufficient validation datasets to verify the adaptability of these models in coastal farmlands, which has a relatively short cultivation time (Setia et al., 2013). This is important as SOC turnover is a long-term process, and short-term changes may not fully capture the potential of SOC sequestration. Additionally, while many C dynamic models have been validated for conventional high-yield farmland (Chen et al., 2018; Wang et al., 2022a), few studies have evaluated their ability to predict long-term SOC stocks in coastal farmlands. Through long-term field experiments and biological process models, we can enhance our understanding of how crop growth, environmental influences, and human activities affect SOC stocks. This allows for a precise prediction of the SOC sequestration potential in coastal farmlands. Therefore, it is crucial to verify the adaptability of the biological process models in coastal farmlands to assess whether current management practices can achieve a win-win situation of increased production and SOC sequestration in the context of climate change.

In this study, we chose the Yellow River Delta (YRD) in China as the study area and established a long-term (11 years) farmland site experiment to verify the adaptability of the DNDC model under the two typical cropping systems, wheat–maize rotation and single cotton. We then predicted the impact of climate change on regional SOC sequestration based on Shared Socio-Economic Pathways (SSPs) produced by five

Global Climate Models (GCMs) of the Coupled Model Intercomparison Project 6 (CMIP6). We explored the potential for SOC sequestration in coastal farmlands, considering the potential yield increment in the future. We hypothesized that i) enhancing coastal farmland yields can bolster future SOC in the region and ii) wheat-maize crop rotation outperforms single cotton farmland in promoting SOC under climate change.

2. Materials and methods

2.1. Study area description

The study area was located in the YRD (36.42°–38.27°N, 117.52°–120.30°E) in China. The YRD is an alluvial plain formed by the sediment carried by the Yellow River into the sea. We selected 11 counties and districts along the Bohai Sea in Shandong Province as the study area (Fig. 1). The YRD is characterized by coastal agriculture, with medium-to low-yield coastal farmlands due to the influence of saltwater intrusion from the sea. Over the past decade, the mean annual precipitation was 582.6 mm, the temperature was 13.7 °C, and evapotranspiration was approximately 1800 mm. The dominant cropping system in the YRD is wheat–maize rotation, which accounts for 43% of the planting system, with cotton being the most important monoculture system.

2.2. Experimental design

To obtain long-term historical data for DNDC model validation, a total of 12 long-term farmland experiments in Kenli District, Shandong Province (37.42°–37.74°N, 118.27°–118.86°E) within the YRD were evaluated from 2007 to 2017. Among these experiments, six farmlands were under wheat–maize planting system and six were under single cotton planting systems. The initial soil physicochemical properties are presented in Table 1, with SOC ranging from 4.48 to 6.76 g kg^{-1}, soil pH ranging from 7.6 to 8.1, and bulk density ranging from 1.42 to 1.54 g cm^{-3}.

Cotton was planted in early May and harvested in late October each year. Irrigation of 50–100 mm and base fertilizer applications of 154.1 kg P_2O_5 ha^{-1} and 253.8 kg N ha^{-1} were carried out in early May. In wheat–maize rotation farmlands, summer maize was planted in mid-June and harvested in late September each year. Irrigation of 100–150 mm was applied in mid-June. Base fertilizer was applied in mid-June and topdressing during the bell-mouth growth stage in late July, with a total of 175.7 kg P_2O_5 ha^{-1} and 266.7 kg N ha^{-1}. The winter wheat was planted in early October and harvested in early June of the following year. Irrigation of 200–250 mm was applied during the regreen growth stage in early March, and base fertilizer of 189.67 kg P_2O_5 ha^{-1} and 288.5 kg N ha^{-1} was applied in early October.

2.3. Data collection and analysis

2.3.1. Soil data

For the long-term field experiments, soil samples of 0–20 cm were collected every October when the crops reached maturity from 2007 to 2017. For regional sampling, a total of 84 soil samples of 0–20 cm were collected in October 2020 to obtain baseline information on soil properties in the study area (Fig. 1). SOM was measured using the potassium dichromate volumetric external heating method, with a correction index of 1.1 applied to account for incomplete oxidation of carbon in SOM. The Bemmelen index of 0.58 was used to convert SOM to SOC. The SOC stock (0–20 cm) was calculated according to Equation (1):

$$SOC\ stock = \frac{1}{10} \times SOC \times \rho \times D \quad (1)$$

where *SOC stock* is the soil organic carbon stock (Mg C ha^{-1}), *SOC* is the SOC content (g kg^{-1}), ρ is the soil bulk density (g cm^{-3}), and D is the thickness of the soil layer (cm). The soil layer thickness was taken as 20 cm in this study.

To investigate the changes in SOC over a longer time period, we obtained data on SOC stocks in 1980 in Kenli County from the 2nd National Soil Survey (NSS). This data provided us with a reference point for understanding the SOC dynamics over the past 40 years.

2.3.2. Climate data

The historical meteorological data (2007–2017) was extracted from the Daily Station Observation of the China Meteorological Elements dataset, which was provided by the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn).

Fig. 1. Location of the study area and the distribution of the 84 sampling sites.

Table 1
Soil physicochemical properties of study sites in the Yellow River Delta.

Site	Cropping system	Soil texture	SOC (g kg^{-1})	pH	BD (g cm^{-3})	Available P (mg kg^{-1})	Available K (mg kg^{-1})
1	Cotton	Loam	4.64	7.6	1.54	8.33	103
2	Cotton	Loam	5.38	7.7	1.54	3.50	115
3	Cotton	Loam	6.23	8.1	1.53	8.40	155
4	Cotton	Sandy Loam	5.96	7.9	1.43	8.76	115
5	Cotton	Sandy Loam	5.33	7.9	1.42	4.50	195
6	Cotton	Loam	6.76	7.8	1.53	4.98	165
7	Wheat–maize	Loam	5.22	7.8	1.53	9.50	138
8	Wheat–maize	Loam	5.91	7.8	1.53	21.60	298
9	Wheat–maize	Loam	6.49	7.7	1.53	6.75	210
10	Wheat–maize	Loam	4.48	7.7	1.52	3.72	108
11	Wheat–maize	Loam	6.43	7.6	1.52	27.43	176
12	Wheat–maize	Loam	5.38	7.7	1.53	28.22	95

BD = soil bulk density; SOC = soil organic carbon.

Future climate data was obtained from the CMIP6 (https://esgf–node.llnl.gov/search/cmip6/). To reduce uncertainties in predicting future climate scenarios, we used five GCMs to obtain future climate data (average temperature and precipitation) from January 2015 to December 2099. The basic information of each GCM model is summarized in Table 2. We considered two representative Shared Socio-Economic Pathways (SSP126 and SSP585) which encompass comprehensive future climate change scenarios. These scenarios account for radiation forcing targets and social development trajectories, blending sustainable development, resource optimization, and reduced fossil fuel demand (SSP126), as well as high-speed development with a primary focus on traditional fossil fuels (SSP585) (O'Neill et al., 2016). These pathways have been widely applied in the study of farmland ecosystem responses to climate change (De Vos et al., 2023; Li et al., 2022). Due to the varying resolutions of the GCMs, a bilinear interpolation method was applied to interpolate the data to a common grid of 0.5°. Subsequently, the temporal and spatial downscaling analysis was performed to obtain the future climate in daily steps for the study area (Feng et al., 2019; Liu and Zuo, 2012).

2.4. DNDC model

2.4.1. Model description

The DNDC model is an important biogeochemistry model used for simulating the carbon and nitrogen cycles in soil ecosystems. It was initially developed by Li et al. (1992) to simulate the response of N_2O, CO_2 and N_2 emissions in farmland soils to rainfall events in America (Gilhespy et al., 2014). The DNDC model comprises two main components: soil condition simulation and trace gas simulation modules, encompassing six sub-models: soil climate, crop growth, decomposition, fermentation, nitrification, and denitrification. The DNDC operates on daily or hourly time steps, offering a detailed portrayal of SOC dynamics in farmland ecosystems over simulation periods ranging from several years to decades. Currently, the DNDC model is extensive utilized to simulate SOC dynamics within agricultural ecosystems (Jiang et al., 2023; Liu et al., 2022).

Table 2
Basic information of the five GCMs in CMIP6 used in this study.

Name of GCM	Institute	Country
ACCESS-CM2	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology	Australia
BCC-CSM2-MR	Beijing Climate Center	China
CMCC-ESM2	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	Italy
CNRM-CM6−1-HR	Centre National de Researchers Meteorologiques, Meteo-France	France
MPI-ESM1-2-LR	Max-Planck-Institut für Meteorologie	Germany

2.4.2. Model calibration and validation

Considering the discrepancies in regions and crop varieties, which can affect the physiological parameters of crops, it was imperative to first calibrate the crop parameters in the DNDC model. We considered salinity as an indirect factor affecting crop growth simulations. This primarily involves the adjustments of crop physiological parameters (such as max biomass, grain C fraction) during the parameter calibration process to account for the negative impact of salinity. We collected the measured SOC stocks from the long-term farmland experiments for 11 years and adopted a multi-point validation approach to minimize result bias. The model was first calibrated using 2007–2009 measurements of SOC stocks. The calibrated crop parameters for the improved DNDC model are presented in Table 3. The 2010–2017 measured data was then compared with the simulated data generated by the DNDC model to validate the model performance in coastal farmlands. To quantify the difference between observed and simulated values, we calculated three statistical indices: R^2, root mean square error (RMSE), and mean absolute error (MAE). The equations for these three statistical indices are as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(P_i - \overline{P_i})(O_i - \overline{O_i})}{\sqrt{\sum_{i=1}^{n}(P_i - \overline{P_i})^2 \sum_{i=1}^{n}(O_i - \overline{O_i})^2}}\right]^2 \tag{2}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{3}$$

$$\text{MPE} = \frac{\sum_{i=1}^{n}(|P_i - O_i|)}{n} \tag{4}$$

where P_i and O_i are predicted and observed SOC stock, respectively, $\overline{P_i}$ and $\overline{O_i}$ are the average values of predicted and observed SOC stock, respectively, and n is the number of observations.

Table 3
Calibration of DNDC crop parameters in the study area.

Parameters	Maize	Wheat	Cotton
max_biomass	3600	2398	983
grain_fraction	0.4	0.41	0.32
leaf_fracation	0.22	0.21	0.26
stem_fraction	0.22	0.21	0.26
root_fraction	0.16	0.17	0.16
GrainCN	50	40	10
LeafCN	80	95	45
SteamCN	80	95	45
RootCN	80	95	75
TDD	2550	1300	2500
WaterDemand	150	200	400

2.4.3. Scenario simulations

In this study, our objective was to comprehensively investigate the SOC dynamics in coastal farmlands by considering various yield increments and climate change scenarios. We conducted simulations using the verified DNDC model in two parts: regional and point simulation.

In the regional simulation, we ran the DNDC model on 84 regional sampling points, utilizing soil background information from regional sampling as reference values. We ran a total of 336 simulation files under the two climate change scenarios (SSP126 and SSP585) and the two crop scenarios (wheat–maize and single cotton), assuming all farmland in the YRD will be planted with these crops by 2100. We generated an annual change of SOC stocks from 2020 to 2100 using the DNDC model. We extracted agricultural land within the study area according to the land use classification in 2020, and then generated the spatial maps of SOC stock changes for the subsequent 80-year period using the Kriging interpolation method implemented in ArcGIS 10.2 (ESRI).

In the point simulation, we aimed to assess the contribution of increasing crop yields to SOC sequestration potential in coastal farmlands. We considered three yield increment scenarios: the current yield level (CK), the high-yield level of farmland in the North China Plain (NCP) (S1), and the national high-yield level (S2). Based on the yield levels in the YRD, the NCP, and China over the past 10 years, we determined the relative maximum biomass for each yield increment scenario, as shown in Table 4. We then ran the DNDC model under six combined scenarios of climate change and yield increment and obtained SOC stocks for the two cropping systems from 2020 to 2100.

2.5. Statistical analysis

One-way analysis of variance and descriptive analysis (mean values and standard deviations) were used to describe the SOC stocks over the past 40 years. Linear regression analysis was used to determine the trends in SOC stocks over the years. Statistical significance was determined at a 95% confidence level ($p < 0.05$). SPSS software (version 25.0; SPSS Inc., Chicago, IL, USA) was used for data analysis.

3. Result

3.1. SOC stock and crop yield changes over past 40 years

Compared with the SOC stocks in coastal farmlands in 1980 (13.38 Mg C ha^{-1}), the SOC stocks in wheat–maize and single cotton farmland showed significant increase of 8.26 and 6.48 Mg C ha^{-1}, respectively (Fig. 2a). Since 2007, the SOC stocks in coastal farmlands have significantly increased ($p < 0.05$), with the SOC stocks of wheat–maize farmland being significantly higher than those of single cotton farmland (19.99 and 18.74 Mg C ha^{-1}, respectively). In single cotton farmland, the SOC stock in 2017 was significantly higher than that in 2007 (19.86 and 17.13 Mg C ha^{-1}, respectively), with an average annual increasing rate of 0.25 Mg C ha^{-1} yr^{-1} over 11 years. In wheat–maize farmland, the SOC stock increased from 17.27 to 21.06 Mg C ha^{-1} in 2007–2017, with an average annual increasing rate of 0.40 Mg C ha^{-1} yr^{-1}.

Over the last four decades, crop yields in the YRD have significantly improved. Specifically, the wheat yield per unit area increased from 3399 kg ha^{-1} in 1983 to 6182 kg ha^{-1} in 2020, reflecting an average annual growth rate of 163.7 kg ha^{-1} yr^{-1}. Similarly, maize yield per unit area increased from 3312 to 4779 kg ha^{-1} over the same period, with an average annual growth rate of 68.6 kg ha^{-1} yr^{-1}. The cotton yield per unit area also increased from 817.5 kg ha^{-1} in 1983 to 1351.5 kg ha^{-1} in 2020 at an average annual growth rate of 31.4 kg ha^{-1} yr^{-1}.

Table 4
Relative maximum biomass of maize, wheat, and cotton in the three yield increment scenarios.

Scenario	Maize	Wheat	Cotton
CK	1.00	1.00	1.00
S1	1.10	1.10	1.45
S2	1.20	1.20	1.70

3.2. Performance of the DNDC model

We compared the simulation results with the measured results in 2009–2017 to validate the improved DNDC model. The results indicated that DNDC model had good applicability in coastal farmlands (Fig. 3). There was a highly significant ($p < 0.001$) regression fitting relationship between the simulated SOC stock and the measured values. Overall, the statistical indicators R^2, RMSE and MAE in cotton farmland (Fig. 3a) were 0.78, 1.09 and 0.96, respectively, which were better than those in wheat–maize farmland (Fig. 3b), with 0.72, 1.35, and 0.91, respectively. DNDC slightly overestimated the SOC stocks of coastal farmlands, which was more obvious in wheat–maize farmland (the linear fitting slope was 0.91).

3.3. Regional SOC stock simulations under climate change

Based on the 84 sampling sites in the YRD and using the DNDC model, spatial distribution maps of future SOC stock changes were obtained (Fig. 4). Overall, if all farmland in the study area were to be converted to single cotton planting system (Fig. 4a and b) in the next 80 years, 88.2% and 91.0% of farmland under the SSP126 and SSP585 scenarios, respectively, would be transformed into carbon sources. This would result in a loss of SOC stocks, with a maximum loss of 15.31 Mg C ha^{-1}. However, some areas along the Yellow River showed a potential for SOC sequestration, with the highest increase at 4.77 Mg C ha^{-1}. In contrast, if all farmland in the study area were converted to a wheat–maize rotation system (Fig. 4c and d) in the next 80 years, only a very small area of the eastern part of the YRD (0.86%) would become carbon sources under the SSP585, with the highest loss of 8.23 Mg C ha^{-1}. The other areas in this simulation would become carbon sinks, with the highest increase at 31.90 Mg C ha^{-1}. Under SSP126 scenario, the entire study area showed potential for carbon sequestration, with increases ranging from 4.38 to 26.60 Mg C ha^{-1}.

The dynamic distribution of SOC stock was significantly influenced by the proximity of farmland sites to the Yellow River and Bohai Sea. In the same simulation scenario within the study area, regions where the Yellow River flows exhibited relatively higher SOC sequestration than other regions. Additionally, farmland near the Bohai Sea showed higher SOC sequestration than regions further inland. For example, considering farmland planted with single cotton under the SSP126 scenario (Fig. 4a), areas with increased SOC stocks (ranging from 0 to 6 Mg C ha^{-1}) were mainly distributed within 65 km of the Yellow River, whereas areas with the most significant SOC stock losses (ranging from −15 to −7 Mg C ha^{-1}) were mainly distributed in farmland 50 km away from the Bohai Sea.

3.4. SOC sequestration potential under yield increment scenarios

The predicted changes in SOC stocks in coastal saline–alkali farmland under different scenarios of climate change and yield increment were assessed from 2020 to 2100 (Fig. 5). The findings revealed that climate change had a significant impact on SOC stocks, with lower SOC stocks under the SSP585 compared to the SSP126 scenario. Specifically, SOC stocks in single cotton farmland and wheat–maize rotation farmland in 2100 under the SSP585 scenario were estimated to be 0.68–0.92 Mg C ha^{-1} and 3.55–3.76 Mg C ha^{-1} lower than those under the SSP126 scenario, respectively. Furthermore, we found that higher yields were associated with higher SOC stocks when compared to those under the current yield level (CK).

The future SOC dynamics in wheat–maize farmland were divided into two stages: rapid SOC increase and carbon saturation stages. Under

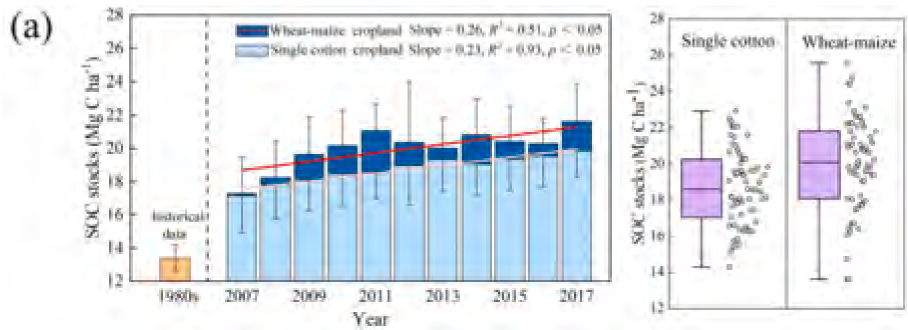

Fig. 2. Changes in (a) soil organic carbon (SOC) stocks and in YRD over 40 years under two cropping systems. Data in the column plot are presented as mean values ± standard deviation.

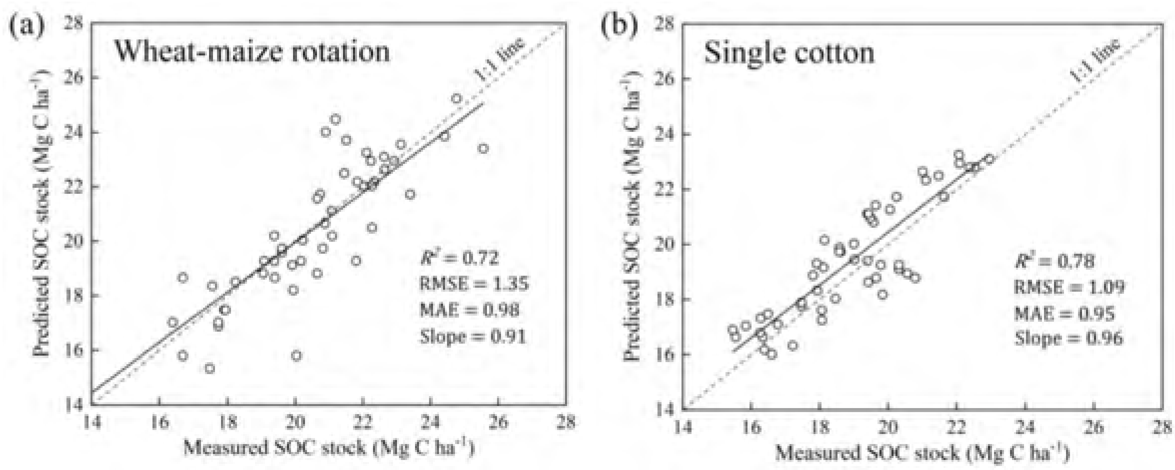

Fig. 3. Comparison of soil organic carbon (SOC) stocks between measured and simulated values using the DNDC model in (a) single cotton and (b) wheat–maize rotation farmland. Slope is the linear fitting slope.

the SSP126 scenario, the period before 2030 was a rapid SOC increase stage, and the average annual increase rate of the three yield increment scenarios was 0.35 Mg C ha^{-1} yr^{-1}. From 2030 to 2100, the SOC increase rates of CK, S1, and S2 slightly decreased by 0.08, 0.085 and 0.094 Mg C ha^{-1} yr^{-1}, respectively. Finally, the SOC stocks of CK, S1, and S2 increased to 30.69, 31.24 and 32.16 Mg C ha^{-1} in 2100, respectively. Under the SSP585 scenario, the period before 2050 was a rapid SOC increase stage, and the average SOC increase rate of the three yield increment scenarios was 0.19 Mg C ha^{-1} yr^{-1}. The SOC stocks in the following 50 years remained unchanged, and the SOC stocks under the CK, S1, and S2 scenarios were 27.32, 27.93, and 28.53 Mg C ha^{-1}, respectively.

The future SOC dynamics in single cotton farmland (Fig. 5c and d) were also clearly divided into two phases: the rapid SOC increase (2020–2035) and the carbon saturation (2035–2100) stages. During the rapid SOC increase stage, all scenarios showed a rapid increase in SOC stocks. Under the two climate change scenarios, the increase rates of SOC stocks in CK, S1, and S2 were 0.061, 0.15, and 0.18 Mg C ha^{-1} yr^{-1}, respectively. In the carbon saturation stage, the results differed under the SSP126 scenario and SSP585. In the SSP126 scenario, SOC in the CK yield scenario declined linearly, from 19.71 Mg C ha^{-1} in 2035 to 18.42 Mg C ha^{-1} in 2100. In contrast, the SOC increase rate dropped sharply in the S1 situation and increased slowly in S2. Following the same decline, the SOC stocks remained almost unchanged over the 70 years in the S1 scenario, reaching the carbon saturation value of 21.42 Mg C ha^{-1}. In the S2 scenarios, SOC stocks increased from 22.11 Mg C ha^{-1} in 2035 to 23.07 Mg C ha^{-1} in 2100, and the increase rate decreased by 91.8% compared with that in the previous stage. Under the SSP585 scenario, the SOC stocks all decreased in the CK, S1, and S2 yield increment scenarios, and the carbon loss rates in 70 years were 0.032, 0.01 and 0.01 Mg C ha^{-1} yr^{-1}, respectively.

4. Discussion

4.1. *Climate change and location of water body significantly affect SOC stocks in coastal farmlands*

The results showed that it is feasible to accurately simulate the SOC dynamics in coastal farmlands by calibrating the crop parameters of the DNDC model. By adding modules, the existing optimization of process models under saline–alkali stress mainly aims to explain the impact of soil salinity on soil microbial decomposition rate and crop input information, quantifying the indirect impact of soil salinity on SOC stock (Setia et al., 2012). This study achieved the validation of the DNDC model in coastal farmlands by calibrating crop physiological parameters and changing crop input information.

The distances from farmland to the Yellow River and Bohai Sea significantly affected the SOC sequestration in coastal saline–alkali farmland. Specifically, the proximity to the Yellow River and the sea promoted SOC sequestration. The possible reason for this is that freshwater resources are limited in coastal areas, and farmland near the Yellow River often ensures sufficient irrigation, thereby improving soil physical structure and promoting crop growth, increasing external crop carbon input into the soil (Trost et al., 2013). Moreover, the sediment accumulated from the upstream scouring of the Yellow River often contains a large amount of organic matter, which will improve the soil

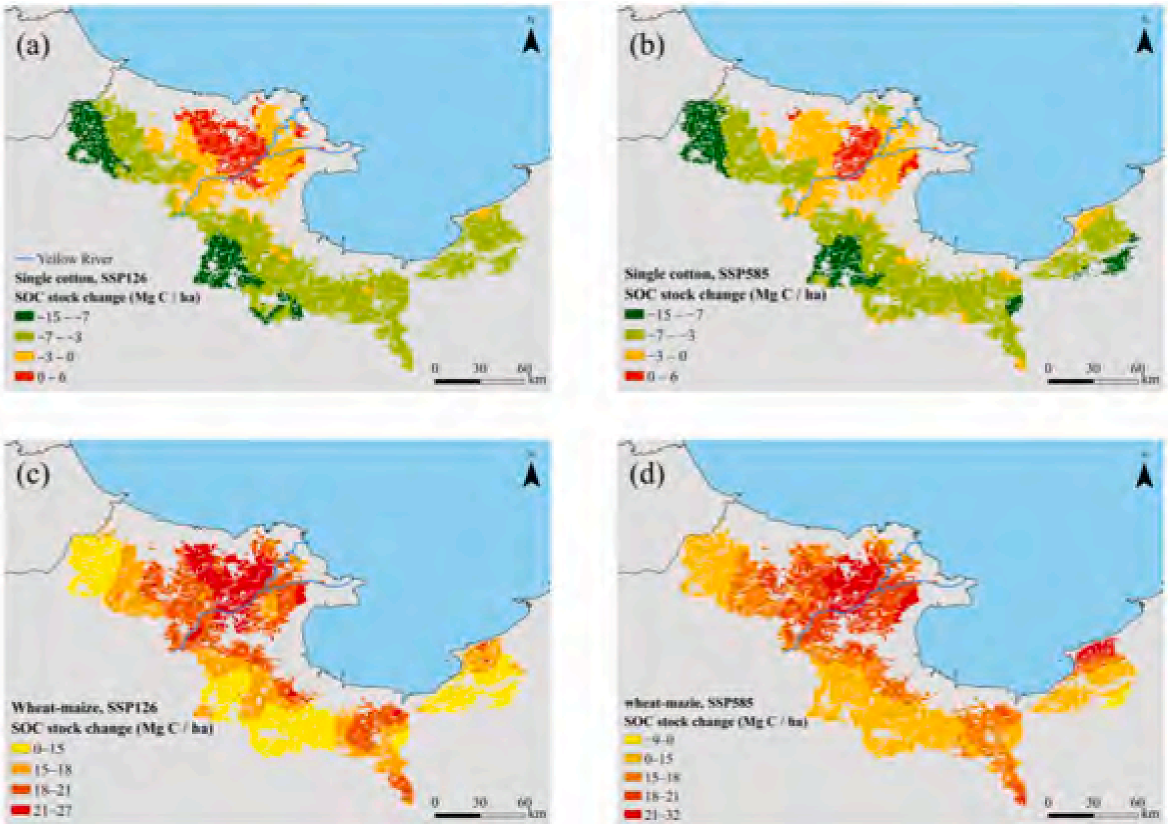

Fig. 4. Predicted soil organic carbon (SOC) stock changes across the Yellow River Delta (YRD) in different cropping systems and climate change scenarios. (a) Single cotton and SSP126, (b) single cotton and SSP585, (c) wheat–maize and SSP126, and (d) wheat–maize and SSP585 during 2020–2100. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

nutrients and structure of farmland adjacent to the river, thereby promoting the growth of crops and increasing carbon input (Loucks, 2019). Farmland close to the ocean is more susceptible to the influence of seawater salinity; the soil close to the sea often has a higher soil salinity. High salinity increases the osmotic potential of soil solutions, causing ion-specific toxicity and inhibiting soil microbial activity, thereby delaying the decomposition of SOC and promoting SOC sequestration (She et al., 2021; Yu et al., 2020). We found that the current agricultural management in cotton farmland is unscientific and unsustainable. If existing agricultural measures and yield levels remain unchanged, coastal farmlands cultivated with single cotton will be converted to carbon sources in the future. This finding proves the necessity and urgency of exploring scientific carbon management measures for coastal farmlands.

Compared with the SSP126 scenario, simulations showed that SSP585 scenario will lead to an average decrease of 3.9% and 11.6% in SOC stocks in cotton farmland and wheat–maize rotation farmland, respectively, by 2100. This indicates that future climate warming will further reduce the SOC stocks in coastal saline–alkali farmland. In the context of current global warming, the increase in atmospheric CO_2 concentration and the global average temperature has a strong impact on farmland soil carbon pools by affecting soil microorganisms and crop productivity (Feng et al., 2022; Melillo et al., 2017). The increase in temperature promotes the active decomposition rate of microbial decomposition reactions in farmland soil, thereby reducing the SOC content (Davidson and Janssens, 2006). This may be because warming can change the structure of soil microbial communities and provide the optimal temperature for enzymatically catalyzed reactions (Bradford, 2013). Additionally, changes in atmospheric CO_2 concentration can affect photosynthesis, thereby altering the input of crop residues and root exudates as carbon sources into farmland (Casali et al., 2021). While the soil carbon stocks in coastal cotton farmland have better resistance to climate warming, their general SOC level is lower than that of wheat–maize farmland. If necessary measures are not taken to reduce future atmospheric CO_2 emissions, increase SOC sequestration and alleviate global warming, this warming trend will further cause negative feedback on SOC sequestration in coastal farmlands, forming a vicious cycle.

4.2. Enhancing crop yield is an adaptive strategy for SOC sequestration

Since 1980, China has undertaken agricultural technology initiatives, such as the Huang-Huai-Hai Agricultural Campaign (1980–2000), to transform coastal farmlands and reduce soil salinity (Shi et al., 2013). This initiative has substantially improved soil fertility, boosted crop water and fertilizer absorption efficiency and reduced nitrogen loss (Zhao et al., 2018). Wheat yield per unit area increased by 64.7% over the past 40 years in the YRD (SBS, 2023). However, the growth rate of wheat yield over the last decade has only been 39% of that observed in high-yield farmlands within the NCP (SBS, 2023). This discrepancy suggests considerable untapped potential for further yield enhancement rooted in the scientific basis of soil fertility improvement in coastal farmlands. This study further confirmed that increasing yield is an effective strategy for increasing SOC sequestration in coastal farmlands. Both SSP126 and yield increment scenarios simulated the transformation of cotton farmland from carbon sources into carbon sinks. Taking measures to increase the yield of low-and medium-yield coastal farmlands to the level of the adjacent North China Plain (S1) and the optimal level (S2) will promote the increase of soil carbon stocks by 16.7% and 21.6% in single cotton farmland and by 1.8% and 4.8% in wheat–maize farmland, respectively. The main reason for this difference is that the yield of cotton farmland in the YRD has more room to increase

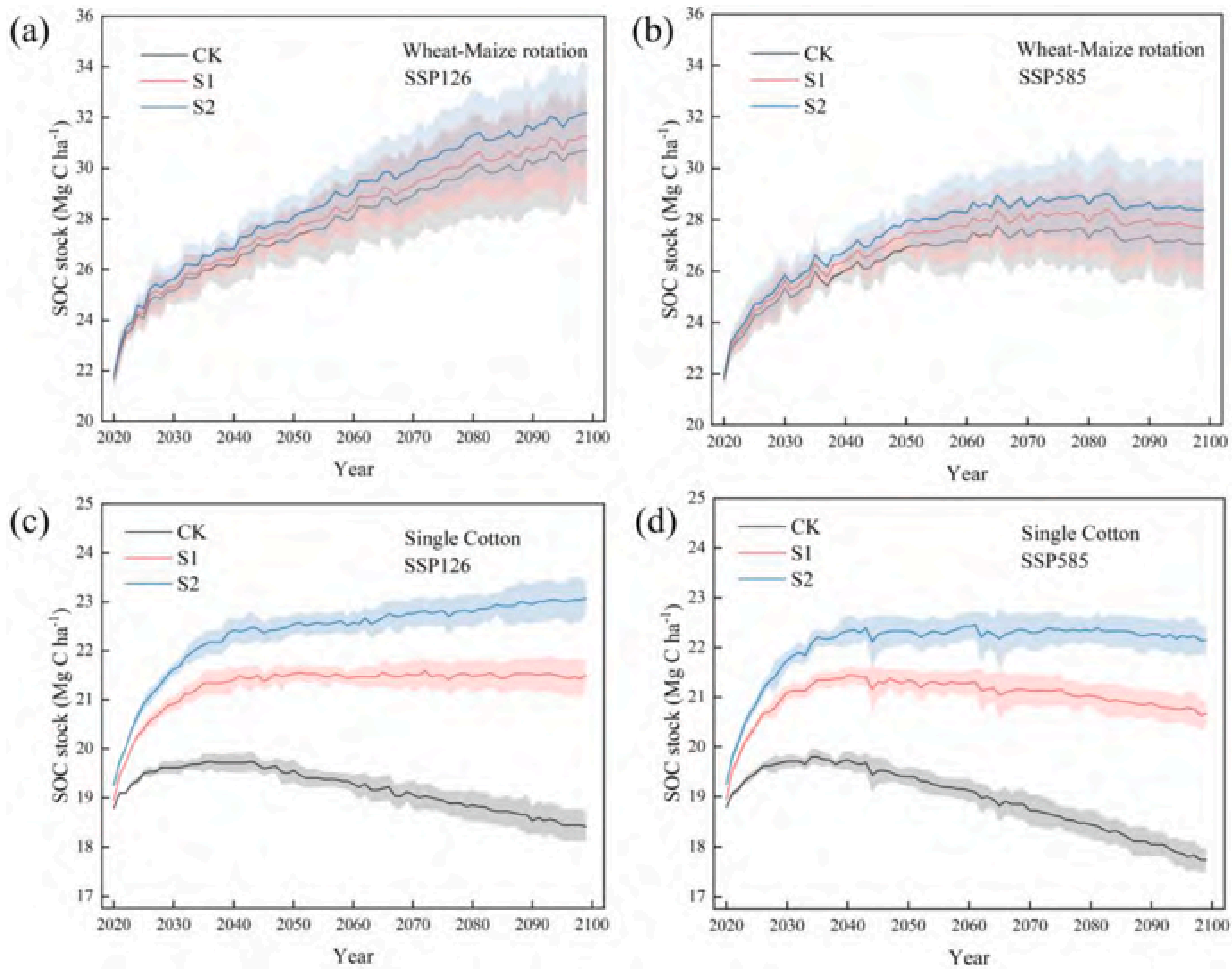

Fig. 5. Changes of soil organic carbon (SOC) stocks in two croplands of the Yellow River Delta (YRD) under different climate and yield increment scenarios. (a) Wheat–maize and SSP126, (b) wheat–maize and SSP585, (c) single cotton and SSP126, and (d) single cotton and SSP585 during 2020–2100. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for achieving a high yield and bringing more exogenous carbon input to the soil. In summary, the current management measures and yield levels of coastal farmlands are not optimal. In the future, coastal farmlands has great potential for SOC sequestration, and transforming medium-to low-yield farmland to increase crop yield may effectively achieve SOC sequestration on coastal farmlands.

Previous studies have revealed the absence of a direct causal relationship between yield increase and SOC sequestration, as agricultural practices that promote yield enhancement frequently lead to concurrent SOC sequestration (Jeffery et al., 2017; Thapa et al., 2018). For instance, actions such as cover cropping and straw incorporation can bolster soil nutrient availability and crop yields, while increasing carbon input to promote SOC sequestration (Lin et al., 2023). Furthermore, the interplay between these two factors is often controversial due to the influence of soil and climatic conditions (Janzen, 2006). However, our findings since 1980 have confirmed that augmenting yields in coastal farmlands can indeed stimulate SOC sequestration. We identified a synergistic relationship among salt reduction, increased yield, and SOC sequestration in coastal farmlands. The next phase in developing the potential for SOC sequestration in coastal farmlands should involve the integration of optimized agricultural management practices. These practices include strategies for salt reduction, yield improvement, and SOC sequestration. This could include the rational allocation of regional crop layouts and reducing single cotton cultivation in favor of main grain crops, with a focus on economic and sustainable requirements to increase grain yield and straw return rates to promote SOC sequestration. It is imperative to conduct comprehensive agricultural soil background assessments such as SOC content and salt levels to guide decisions regarding crop variety selection, planting density, irrigation, and other agricultural approaches.

Soil carbon saturation indicates that organic carbon in soil has the maximum storage capacity. The saturation point of SOC is due to the limited surface that soil minerals can combine with, and the physical and chemical processes in soils are limited by the environment (Six et al., 2002; Smith, 2012). Previous studies have demonstrated that achieving maximum SOC stocks is primarily influenced by environmental factors, in addition to the inherent constraints of soil properties (McNally et al., 2017; Poulton et al., 2018). With the existing farmland management measures unchanged, SOC stocks in a single cotton farmland were simulated to reach maximum values by 2030, whereas the maximum SOC stock of wheat–maize rotation farmland were reached by 2050 in the SSP585 scenario, whereas they were not reached by 2100 in the SSP126 scenario. The reason for this difference may be the continuous carbon input to the soil by straw incorporation in wheat–maize farmland, which also demonstrates the importance of exploring efficient reuse technologies for cotton residues (Zhang et al., 2022). Our research further demonstrates that, even if the natural environment is similar, differences in farmland management (fertilization, planting systems and irrigation) can lead to significant differences in the SOC dynamics of the farmland environment. Based on our results, it is estimated that under the ideal yield increment state in the future, the coastal mid- and low-yield agricultural areas in China (with an area of approximately 2.12×10^6 ha) will contribute 54.82 Tg C and 68.18 Tg C to China's dual carbon targets by 2030 and 2050, respectively (Tian et al., 2006; Wu et al., 2003).

4.3. Uncertainties and limitations

In the present study, there was uncertainty in predicting SOC sequestration in coastal farmlands. Although our research relies on simulation predictions using multiple GCMs, SSPs scenarios, and the DNDC model, we acknowledge that incorporating more integrated biophysical models and diverse climate change scenarios could enhance the assessment of future SOC dynamics. The uncertainties in model simulation may also arise from measurement errors in the input data. To account for spatial heterogeneity of specific sites, conducting comprehensive regional samplings and measuring key sensitive parameters, such as initial SOC content, soil bulk density (Qin et al., 2016), could improve the accuracy of the regional simulation.

Furthermore, given the scarcity of available irrigation water resources in coastal farmland agriculture, the planting area for rice in the YRD has declined by 74.9% over the past decade and is anticipated to decrease further (SBS, 2023). Our study exclusively considered dry-field crops such as maize, wheat, and cotton, excluding paddy crops. It is worth noting that we did not consider the specific impact of agricultural measures taken to achieve yield increases on SOC sequestration in farmland. However, with the development of conservation tillage and sustainable agriculture, more and more farmland management practices have been proven to achieve a win–win situation for both increasing yield and SOC sequestration (Lessmann et al., 2022; Minasny et al., 2017). This sustained effort could facilitate the promotion of crop yield and SOC sequestration. This study serves as essential scientific and technological support for the sustainable development of coastal farmlands.

5. Conclusion

This study identified the spatiotemporal dynamics of soil organic carbon (SOC) stocks in typical single cotton and wheat–maize farmland in the Yellow River Delta (YRD) under climate change and yield increment scenarios in 1980–2100. The improved Denitrifcation-Decomposition (DNDC) model was accurate for simulating SOC stock dynamics in coastal farmlands. Keeping the current yield levels unchanged until 2100, the conversion of all agricultural systems to single cotton farmland in the YRD was simulated to cause at least 88.2% of farmland to become a carbon source, whereas the conversion to wheat–maize rotation farmland promoted regional SOC sequestration. Increasing the yields was simulated to promote an increase in SOC stocks by a maximum of 21.6% in coastal farmlands. Compared with the SSP126 scenario, SSP585 resulted in a decrease in SOC stocks in cotton farmlands by 2100. The evidence suggests that informed policy decisions are needed to increase crop yields and fully utilize the carbon sequestration potential of coastal farmlands under future climate change conditions. It underscores the significance of continued government and policymaker investments in coastal farmland to enhance agricultural productivity and SOC sequestration.

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Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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CRediT authorship contribution statement

Jing Li: Conceptualization, Methodology, Supervision, Funding acquisition, Resources, Writing – review & editing. **Deyao Liu:** Conceptualization, Methodology, Software, Visualization, Data curation, Writing – original draft. **Huarui Gong:** Conceptualization, Methodology, Writing – review & editing. **Zhen Liu:** Methodology. **Yitao Zhang:** Methodology.

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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