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Continuous crop rotation increases soil organic carbon stocks in river deltas: A 40-year field evidence

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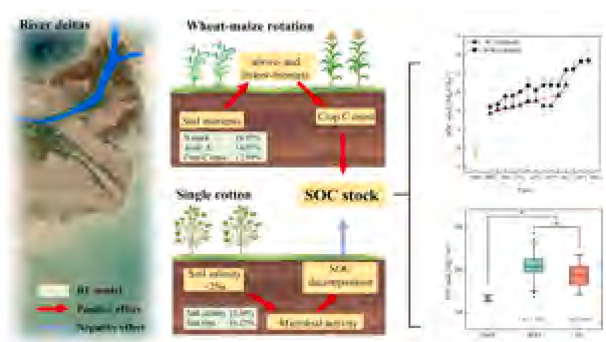
HIGHLIGHTS

- The SOC increasing rate in delta croplands was 57% of that in North China Plain in the past 40 years.
- Wheat-maize rotation croplands sequestered more carbon than single cotton croplands.
- A 1.5–2.0‰ increase in soil salinity caused a 17.5% loss in SOC stocks in single cotton croplands.
- Soil nutrients and salinity were two pivotal factors impacting SOC sequestration in delta croplands.

GRAPHICAL ABSTRACT



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ABSTRACT

River deltas, as important food production centers, support 66 % of the world's population, together with other coastal areas. However, agriculture in river deltas is negatively affected by soil salinization and agricultural intensification. Improving the soil carbon pool is a mutually beneficial solution for maximizing crop production and improving climate resilience to secure food production. In this study, long-term croplands in the Yellow River Delta (YRD), with a wheat-maize (WM) rotation system and a single cotton (SC) cropping system, were selected to explore the changes in soil organic carbon (SOC) stocks and the driving mechanisms at 0–20 cm depth from 1980 to 2020. We found that, over the past 40 years, the SOC stocks in WM and SC croplands had increased by 10.05 Mg C ha^{-1} and 7.44 Mg C ha^{-1}, respectively. The Random forest model revealed that in the WM croplands, soil N stock and available K were the most important driving factors of SOC stocks, while in SC

Abbreviations: SOC, soil organic carbon; SC, single cotton; WM, wheat–maize; SOM, soil organic matter; YRD, Yellow River Delta; YR, Yellow River; LCI, low carbon input; MCI, medium carbon input; HCI, high carbon input.

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croplands, soil type and salinity were the most important driving factors of SOC stock dynamics. An increase in soil salinity to 2.0 ‰ caused a 17.5 % loss in SOC stocks in SC croplands. Our results show that, in the long run, croplands with a WM rotation system have stronger carbon sequestration potential. Depending on the planting system, promoting crop carbon input under high soil nutrients and affecting SOC decomposition by soil salinity are two different pathways of SOC sequestration in delta croplands. We propose that nutrient management and organic fertilizer application are crucial for increasing SOC stocks in the WM and SC croplands, respectively. This study confirms that it is of practical significance to take measures to promote soil carbon sequestration at the farmland scale and to provide scientific guidance for the sustainable development of river delta agriculture.

1. Introduction

The growing global population requires a 60 % increase in food production by 2050 to ensure food security (Lipper et al., 2014). River deltas are widely distributed in 54 river estuaries worldwide, together with other coastal areas, and support almost 66 % of the world's population (Besset et al., 2019; Sarkar, 1996). They are also important food production centers that can help cope with climate change and ensure food security (Loucks, 2019; Minkman et al., 2022). However, in recent years, large-scale urbanization, intensive anthropogenic activities, and climate change have exacerbated soil degradation and seawater intrusion, considerably restricting agricultural production in river deltas (Loc et al., 2021; Syvitski, 2008). Affected by climate change and continuous farming, the intensive long-term development of agriculture in river deltas is expected to cause adverse effects such as carbon release, nitrogen pollution, and loss of ecological service functions from estuarine wetlands (Wolters and Kuenzer, 2015; Zhu et al., 2020). The increase in the soil carbon pool of croplands is not only related to the increase in agricultural production efficiency but also to the improvement of ecological services, such as carbon sequestration, greenhouse gas emission reduction, and climate adaptation (Chenu et al., 2019). Therefore, to achieve sustainable agriculture in river deltas, we should not only further increase crop production capacity but also evaluate its ecological benefits.

Soil carbon sequestration is an important component of terrestrial ecosystem services and is important for reducing regional and global greenhouse gas emissions and mitigating climate change (Lal, 2016). Specific attention should be paid to the carbon sequestration potential of croplands because an increase in soil organic carbon (SOC) stocks in agroecosystems can upgrade soil fertility, improve the stability of the soil's physical structure, and build resilience to climate impacts (Schmidt et al., 2011). Further development of the carbon sequestration potential in croplands is a mutually beneficial solution for achieving both carbon neutrality and food security (Lehmann et al., 2021). The soil carbon pool in croplands depends on the dynamics of the input and output of organic carbon, which are mainly influenced by environmental (climate conditions, land use, soil clay content, biodiversity, etc.) and anthropogenic factors (agricultural management, including fertilizer application, straw incorporation, and organic amendments) (Stockmann et al., 2013). However, the responses of soil carbon pools to these driving factors are not consistent because of varied agricultural activities (cropping systems and tillage management) (Gao et al., 2022; Smith et al., 2008). Hence, soil carbon management is the basis for the sustainable development of croplands, and it is vital to identify the driving factors of a specific agroecosystem.

The river deltas are formed by sediment accumulation from the upstream, and the abundant nutrients are favorable conditions for agricultural prosperity in local croplands. However, the excessive anthropogenic pressure on agriculture, and the sophisticated salt and water transport process caused by land–river–sea interactions have resulted in soil salinization (Xie et al., 2011). This then leads to uncertainty in the driving mechanisms of SOC stocks and their specific effects on the SOC in river deltas (Haywood et al., 2020). First, an increase in soil salinity increases the osmotic potential of the soil solution, causing ion-specific toxicity and inhibiting soil microbial activities, thereby delaying the decomposition of SOC and promoting SOC sequestration (She et al., 2021; Shiferaw et al., 2021; Yu et al., 2020). However, when microorganisms are exposed to a high-salinity soil conditions for a long time and gradually adapt, they continue to accelerate the mineralization of soil organic matter (SOM) (Wong et al., 2010). Soil salt will then limit the growth of crops and reduce plant productivity, resulting in decreased carbon inputs to the soil, and consequently inhibiting soil carbon sequestration (Bhardwaj et al., 2019). Third, the frequent alternation between drying and wetting conditions caused by the frequent vertical changes in the groundwater level will lead to pulses in the activity of the local soil microbial community (Banks et al., 1999). In this way, the decomposition of SOC will be accelerated and will also affect soil carbon cycle via salt accumulation in the soil surface through evaporation (Zhao et al., 2020). Increasing the SOC stocks in saline croplands can mitigate or reverse soil degradation and promote its sustainable development. Therefore, clarifying the effect of land–river–sea interactions on soil carbon pools under long-term agricultural development is key to understanding and managing soil carbon in the croplands of river deltas.

The Yellow River Delta (YRD) is the most recently formed and largest coastal wetland ecosystem in the warm temperate zone of China. It is also the last river delta without large-scale urbanization development in China and the world (Bai, 2020; Kong et al., 2015). Since the 1980s, many government-led agricultural projects have been carried out in the YRD to reclaim the medium- and low-yield fields. The YRD is a typical representative of the river deltas that are in the transition from intensive farming to sustainable agriculture (Liu et al., 2018; Zeng et al., 2021). In recent years, cash crops (such as cotton) have gradually been replaced with large-scale intensive food crops (such as maize and wheat) for economic benefits and to meet food increment goals, and this trend is particularly evident in the YRD (Ouyang et al., 2020). Previous studies have found that rotation can improve SOC stocks when compared with monoculture cropland, mainly because crop rotation improves root and aboveground biomass, thereby providing a relatively more abundant carbon source for the soil (K.L. Zhang et al., 2021). However, some studies have found completely opposed views, which state that rotation causes more carbon loss (Iost et al., 2007; Song et al., 2021). Furthermore, the selection of cropping systems contributes to the enhancement of crop diversity within YRD agricultural ecosystems, ultimately enriching the ecosystem biodiversity of protected river delta regions. This increase in biodiversity extends to various aspects, including soil microbial activity, as differences in the biochemical composition of plant tissues and diverse agricultural management practices foster the development of distinct microbial communities (Garland et al., 2021). This microbial biodiversity in the soil plays a pivotal role in the process of SOC sequestration, thereby influencing the overall ecosystem quality of river deltas (Tiemann et al., 2015). In this study, we selected wheat-maize (WM) rotation system and single cotton (SC) system, which are two representative cropping systems in estuarine agriculture, to identify the differences in carbon sequestration.

The objectives of this study were to i) explore the dynamics of SOC stocks in croplands with two main cropping systems in the YRD over the past 40 years; ii) identify the response of SOC stocks to soil nutrients, environmental characteristics, and anthropogenic activities in river delta croplands; and iii) clarify the driving mechanism of SOC stocks in river delta croplands and propose a future scenario-oriented soil carbon management scheme for croplands in river deltas. We hypothesized that: i) The wheat-maize rotation in delta croplands achieves greater SOC sequestration abilities than single cotton cropping system. ii) Soil salinity is an important factor affecting the SOC stock dynamics in river deltas.

2. Materials and methods

2.1. Study area

The study area, located in the YRD (37.42–37.74° N, 118.27–118.86° E) of China, is an alluvial plain formed by the deposition of sediment carried by the Yellow River; it is also the most recently formed delta in the world. The YRD is a typical coastal and agricultural estuary, and its soil is characterized by high salinity, low fertility, poor permeability, and compaction. The YRD has a temperate monsoon climate, with an average annual temperature of 13.7 °C, an annual precipitation of 582.6 mm, and an annual evaporation of >1800 mm for last 10 years. The evaporation is far greater than the annual rainfall, resulting in the accumulation of soil salt on the surface, which further aggravates soil salinization. In 2020, the total cropping areas was 2.71×10^5 ha in YRD, with WM rotation accounts for approximately 43 % of the cropping systems in the YRD, while SC is the typical monoculture cropping system in the region.

2.2. Data collection and calculation

2.2.1. The 2nd National Soil Survey (NSS) data of the 1980s

County-level soil information was collected based on the 2nd NSS of the 1980s, which included 22,487 soil property data points. Our study focused on soil properties within the 0–20 cm depth range, and we calculated the average values of several key soil properties, including SOM (g kg^{-1}), total nitrogen (TN) (g kg^{-1}), available phosphorus (Avail. P) and potassium (Avail. K) (ppm), and soil bulk density (g cm^{-3}). Moreover, we used historical sampling data from croplands as a baseline to explore these changes over the past 40 years.

2.2.2. Sampling and laboratory analysis

Twenty long-term cropland experiments were conducted in the study area between 2007 and 2020 (Fig. 1). These were composed of 11 sites with a WM cropping system and nine sites with an SC cropping system. Annual farming measures, including irrigation, planting time, and specific amounts of fertilizer, were recorded in detail. The groundwater level was measured using onsite sensor monitoring. The amount of fertilizer applied was then converted into N, P, and K inputs (kg ha^{-1}).

Soil and plant samples were collected after the crops had matured each year (June and October). For the WM croplands, the growth period of maize was from June to October of each year, whereas that of wheat was from October to June of the following year. Cotton was planted in May each year and harvested in October, and the field was allowed to fallow for the remainder of the time. Starting in 2017, the local government undertook initiatives to expand the cultivation of staple crops such as wheat and maize. Consequently, the nine experimental sites in cotton cropping were discontinued after 2017, and the sampling data in SC was from 2007 to 2017. Soil samples (0–20 cm) were air dried after removing roots and stones. One portion was passed through a 2 mm sieve for pH, Avail. P and Avail. K analyses. The other portion, passed through a 0.15 mm sieve, was used to determine SOM and TN (Gao et al., 2021). Extracting method was used to determine the soil salinity (Bao,

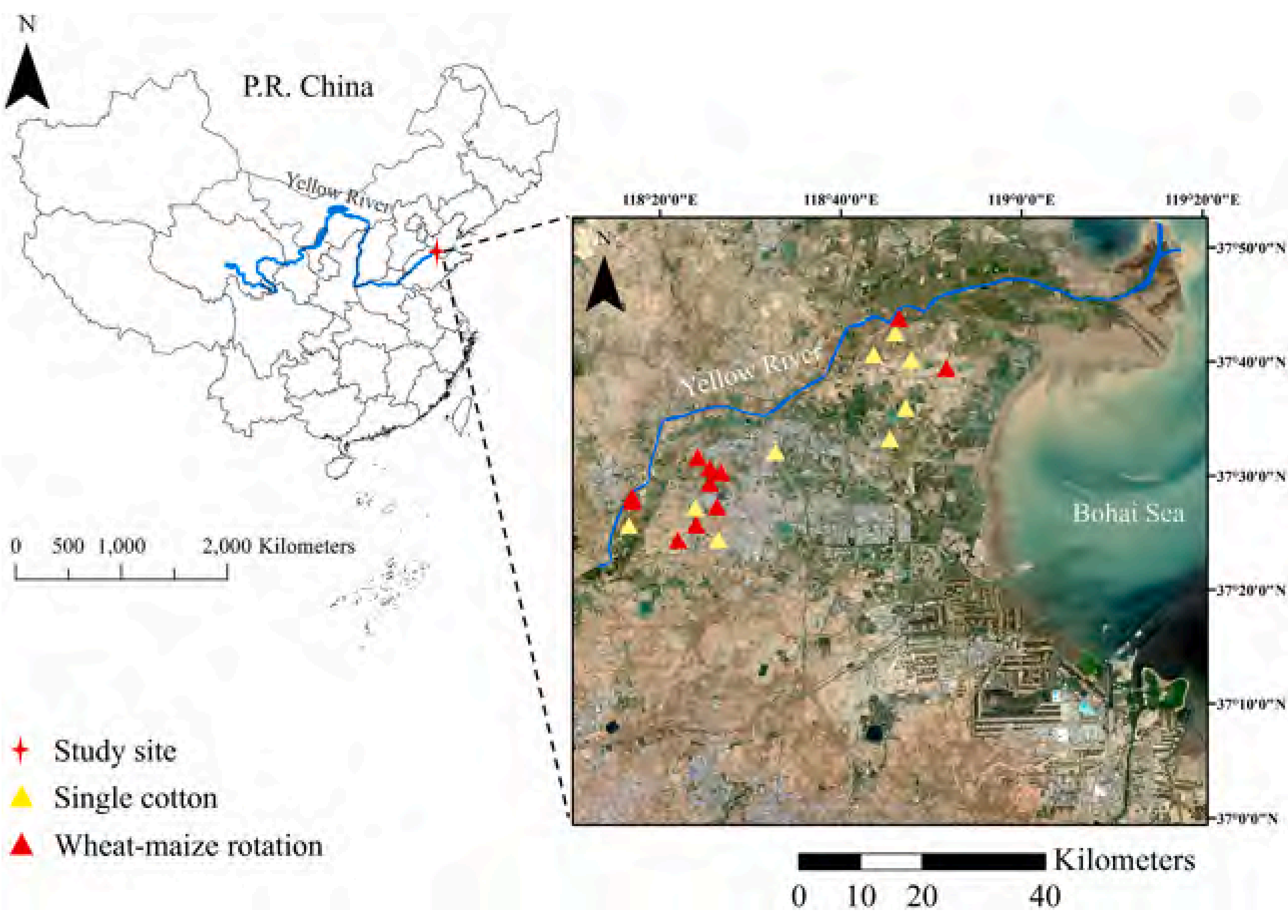

Fig. 1. Location of 20 long-term field sites in the Yellow River Delta, China.

2000). The SOM was determined by the wet oxidation method (Lu, 1999). An index of 1.1 was used to correct for the incomplete oxidation of carbon in SOM (Han et al., 2016). The SOC was converted using the Bemmelen index (0.58), and the SOC stock (Mg C ha^{-1}) and soil TN stock (SNS) (Mg N ha^{-1}) were calculated using Eq. (1). Basic information for each site is presented in Table S1.

$$SOC\ stock = \frac{1}{10} \times SOC \times \rho \times D \tag{1}$$

where SOC is the SOC concentration (g kg^{-1}); ρ is the soil bulk density (g cm^{-3}); and D is the thickness of each soil horizon (cm), which was taken as 20. The same method was used to calculate the SNS.

After the plant samples were collected, we measured both the yield (kg ha^{-1}) and crop aboveground biomass (kg ha^{-1}). Since 2007, the average yields for wheat, maize and cotton have been recorded as 6,925.5 kg ha^{-1}, 7,858.5 kg ha^{-1}, and 5,055 kg ha^{-1}, respectively. Moreover, the average aboveground biomass for these three crops has been measured as 7,309.5 kg ha^{-1}, 16,057.5 kg ha^{-1}, and 5,881.5 kg ha^{-1}, respectively. The annual crop C input (kg C ha^{-1}) at each site was calculated according to the sum of shoot C and root C using Eq. (2).

$$\begin{aligned} Crop\ C\ input &= Shoot\ C + Root\ C \\ &= \sum \left[\left(k_{1,i} + k_{2,i}\right) \times G_i k_{3,i} \right] \end{aligned} \tag{2}$$

where i is the i^{th} crop in a year, $i = 1, 2$ in WM croplands and $i = 1$ in SC croplands; G_i is the aboveground biomass of the i^{th} crop (kg ha^{-1}); and $k_{1,i}$ is the straw incorporation rate of the i^{th} crop (%). The value was taken as 1 for WM croplands and 0 for SC croplands, according to local agricultural practices. Moreover, $k_{2,i}$ is the ratio of (root + rhizosphere) biomass to the aboveground biomass of the i^{th} crop (%). The values, which were derived from Dong et al. (2008) and Johnson et al. (2006), are taken as 0.6 for maize and wheat and 0.33 for cotton. Additionally, $k_{3,i}$ is the C content of the straw and roots of the i^{th} crop (%), where the value taken from Yan et al. (2007), is 0.4 for wheat, maize, and cotton.

2.2.3. Topographic and meteorological factors

To study the impact of topographic and meteorological factors on the SOC stocks of croplands in river deltas, we used ArcGIS v10.2 software (ESRI Inc., Redlands, CA) to extract the digital elevation model (DEM), mean annual precipitation (MAP), and mean annual temperature (MAT) of each site, and the slope and topographic wetness index (TWI) were further calculated using Eq. (3). We recorded the vertical distance from each experimental site to the Yellow River (YR) and Bohai Sea, denoting it as "distance from YR" and "distance from the ocean". The soil type (*Fluvisols*, *Salic Fluvisols*, *Solonchak*, and *Anthrosols*) of each site was recorded according to the Food and Agriculture Organization of the United Nations (FAO) Soil Classification System. The data sources were the China DEM spatial dataset (resolution = 90 m) and the China Meteorological Elements spatial interpolation dataset (resolution = 1 km) provided by the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn).

$$TWI = ln\left(\frac{SCA}{tan\alpha}\right) \tag{3}$$

where SCA is the specific contributing area and α is the slope.

2.3. Random Forest model

Random forest (RF) is a machine learning method used for classification and regression, with numerous trees within the bagging algorithm to provide a single prediction (Breiman, 2001; Mahmoudzadeh et al., 2020). The advantages of this model over other models in driving factor identification are that it is insensitive to noise features, has a low bias, and is robust against overfitting (Diaz-Uriarte and de Andres, 2006).

In this study, the RF model was used to identify the relative importance of the potential driving factors behind SOC stock dynamics in the two cropping systems in river delta farmlands over 14 years using the R package *randomForest* (Liaw and Wiener, 2002). First, to address the complex interplay among soil, anthropogenic, and natural factors, SPSS (version 25.0; SPSS Inc., USA) was used to perform a collinearity diagnosis. After screening, 20 factors were selected, including soil properties (SNS, Avail. P, Avail. K, soil salinity, soil type, and soil pH), anthropogenic activities (N, P, and K input, irrigation, and crop C input), and natural factors (TWI, slope, DEM, groundwater table, MAT, MAP, distance from the YR, distance from the ocean, and year). These selected factors were subsequently utilized as influencing variables in the RF model for the driving factor analysis. To build the forest, 500 trees were established with three available decisions at each node, and the minimum number of data points in each terminal node was five. An iterative approach was used to determine the best *mtry* (number of randomly selected predictor variables at each node) according to the smallest out-of-bag (OOB) mean square error (MSE). The relative importance of the variables was assessed using the percentage increases in MSE (MSE increase%). The root mean square error of prediction (RMSEP), mean percentage error (MPE), and R^2 were used to evaluate the performance of the RF model. The calculations are as follows:

$$MSE = \frac{\sum_{i=1}^{n} \left(y_i - y_i^{\bar{O}OB}\right)^2}{n} \tag{4}$$

$$\mathrm{RMSEP} = \sqrt{\sum_{i=1}^{n} \frac{\left(P_i - O_i\right)^2}{n}} \tag{5}$$

$$\mathrm{MPE} = \frac{\sum_{i=1}^{n} \left(P_i - O_i\right)}{n} \tag{6}$$

$$R^2 = \left[\sum_{i=1}^{n} (P_i - \frac{\bar{P}_i)(O_i - \bar{O}_i)}{\sqrt{\sum_{i=1}^{n} \left(P_i - \bar{P}_i\right)^2 \sum_{i=1}^{n} \left(O_i - \bar{O}_i\right)^2}} \right]^2 \tag{7}$$

where $y_i^{\bar{O}OB}$ in Eq. (4) is the average of all OOB predictions. In Eqs. (5)–(7), P_i and O_i are the predicted and observed SOC stock values, respectively; $\bar{P}_i$ and $\bar{O}_i$ are the averages of the predicted and observed values, respectively; and n is the number of available observations.

2.4. Statistical analysis

One-way analysis of variance and descriptive analysis (mean values and standard deviations) were used to describe changes in SOC stocks and soil nutrients in river delta croplands over the past 40 years. They were also used to analyze the effects of environmental factors (year, distance from the YR, distance from the ocean, slope, TWI, soil type, and soil salinity) on SOC stocks, and regression analysis was used to analyze the correlation between soil nutrients (SNS, Avail. P, and Avail. K) and SOC stocks. Statistical significance was determined at a 95 % confidence level ($p < 0.05$). The SPSS software (version 25.0; SPSS Inc., USA) was used for data analysis.

3. Results

3.1. SOC stock changes over the past 40 years

We identified variations in the SOC stocks of the croplands in the WM and SC systems between 1980 and 2020 (Fig. 2). Compared with the average SOC stocks in 1980 (13.38 Mg C ha^{-1}), the SOC stocks in WM and SC systems increased by 10.05 Mg C ha^{-1} and 7.44 Mg C ha^{-1}, respectively, with an average rate of increase of 0.25 Mg C ha^{-1} yr^{-1} and 0.20 Mg C ha^{-1} yr^{-1}, respectively. The average rate of increase of SOC stocks in the WM and SC cropping systems was 0.38 Mg C ha^{-1} yr^{-1}, and

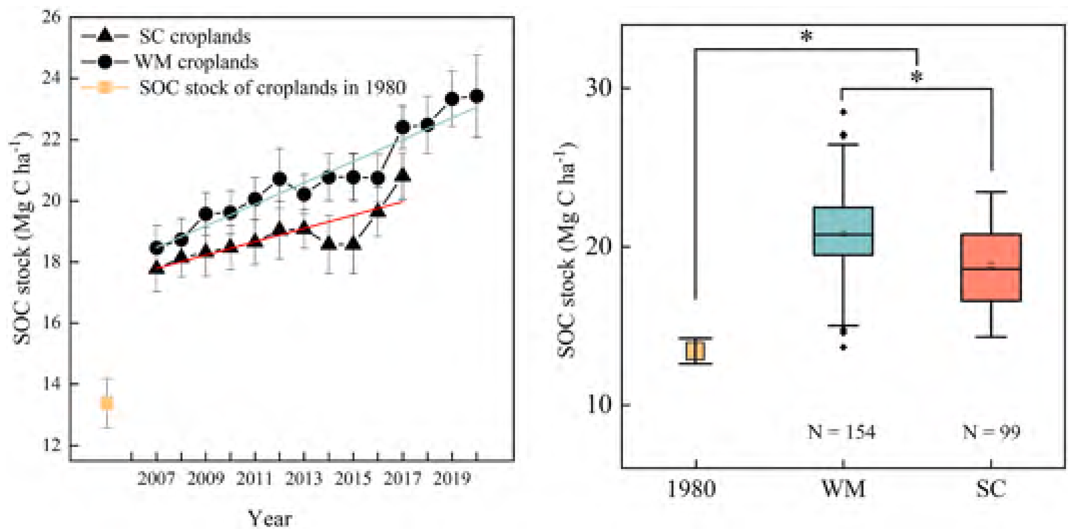

Fig. 2. Changes in soil organic carbon (SOC) stocks in river delta croplands over 40 years under two cropping systems; SC and WM refer to single cotton and wheat-maize rotation, respectively. The box plot demonstrates the SOC stocks of croplands in 1980 and two cropping systems from 2007 to 2020. The two lines in the left subfigure represent linear fitting of the SOC stock changes under two cropping systems. N is the number of data.

0.28 Mg C ha^{-1} yr^{-1}, respectively, and the rate of increase in the WM system was 1.36 times that of the SC system.

3.2. SOC stock changes under different environmental factors

Soil salinity and soil type significantly affected SOC stocks in the river delta croplands (Fig. 3a, b). In WM croplands, the SOC stock of *Anthrosols* was 17.83 Mg C ha^{-1}, which was significantly lower than that of *Solonchak* (21.44 Mg C ha^{-1}) and *Salic Fluvisols* (20.36 Mg C ha^{-1}). In SC croplands, the SOC stock of *Fluvisols* was 20.95 Mg C ha^{-1}, which was significantly higher than that of *Anthrosols* (18.22 Mg C ha^{-1}) and *Solonchak* (16.34 Mg C ha^{-1}). The two cropping systems showed different responses to soil salinity. In the SC croplands, SOC stocks decreased with increasing salinity. The SOC stock was 22.07 Mg C ha^{-1} when soil salinity was 0.5–1.0 ‰, and it decreased to 19.19 Mg C ha^{-1} and 18.20 Mg C ha^{-1} when soil salinity increased to 1.0–1.5 ‰ and 1.5–2.0 ‰, respectively. However, in WM croplands, the SOC stock increased first with the increase in salinity, reaching the maximum value of 22.33 Mg C ha^{-1} when the salinity was 1.5–2.0 ‰, and then decreased significantly with salinity >2.0 ‰.

We explored the effects of distance from the YR and ocean on the SOC stocks (Fig. 3c, d). In SC croplands, when the YR is far away from the croplands (7–15 km), the SOC stock was 17.72 Mg C ha^{-1}, which was significantly lower than that of the croplands near the YR (0–7 km) (19.71 Mg C ha^{-1}). Moreover, when SC croplands were close to the ocean (5–15 km), the SOC stock was significantly higher than that of croplands far from the ocean (30–50 km), at 20.10 Mg C ha^{-1}, 18.13 Mg C ha^{-1}, respectively. However, the SOC stocks increased from 19.07 Mg C ha^{-1} to 20.44 Mg C ha^{-1} when the distance to ocean increased. The distance from YR had no significant effect on SOC stocks in the WM croplands. Regarding topographical factors, the SOC stocks in both cropping systems increased with increasing TWI (Fig. 3e), and both decreased with a high slope (Fig. 3f).

In terms of crop C input (Fig. 3g), the SOC stock of SC croplands was 18.03 Mg C ha^{-1} under high C input (HCI), which was significantly lower than that under low C input (LCI) (19.74 Mg C ha^{-1}). However, the relationship between SOC stocks and crop C input in WM croplands followed the order of medium C input (MCI) (21.89) > HCI (19.63) > LCI (18.50). The year (Fig. 3h) qualitatively reflected the effects of agricultural policies on SOC stocks over a specific period (detailed descriptions are provided in Table S2). These policies and technological initiatives enhance carbon input through improved agronomic measurements and sustained investments (Chen et al., 2006; Zhao et al., 2018). In WM croplands, the SOC stocks increased significantly from 19.09 Mg C ha^{-1} in the first stage (2005–2010, Soil Testing and Formulated Fertilization) to 20.81 Mg C ha^{-1} (2010–2015, Bohai Granary Project). In SC croplands, SOC stocks increased significantly during the latest period (2015–2020, Fertilizer Zero-Growth Action), reaching 20.23 Mg C ha^{-1}.

3.3. Changes in soil properties and their correlation with SOC stocks

Soil nutrients increased significantly in both cropping systems beginning in 1980 (Table S3). The pH increased significantly over the next 40 years, with 7.17 to 8.15 in the WM system, and 7.17 to 7.96 in the SC system; however, there was no significant difference between the two cropping systems. SNS, Avail. P, and Avail. K increased significantly in both cropping systems, and the soil nutrients of the WM croplands were higher than those of the SC croplands. Over the last 10 years, SNS and Avail. K content have remained stable, whereas Avail. P content has increased significantly. In WM croplands, the Avail. P after 2018 (22.08–23.50 mg kg^{-1}) was significantly higher than that in 2007–2017 (12.47–20.08 mg kg^{-1}), while the Avail. P in SC croplands after 2016 (13.93–14.39 mg kg^{-1}) was significantly higher than that before 2008 (7.33–8.45 mg kg^{-1}). The soil salinity in river delta croplands has significantly decreased over the past 40 years. For instance, in *Salic Fluvisols* soils, the average salinity content has decreased from 3.2 ‰ in 1980 to approximately 1.5 ‰ at present.

Correlation analysis of SOC stocks and soil nutrients (Fig. 4) showed that SOC stocks had a significant positive correlation ($p < 0.01$) with SNS and Avail. K. Nevertheless, there was no significant correlation between SOC stocks and soil pH in either cropping system.

3.4. Driving factors behind SOC stock changes based on the random forest model

A random forest model was established (Fig. 5), and the results indicated 60.0 %, 75.0 %, and 72.0 % of the SOC stock dynamics in the WM, SC, and WM + SC croplands (all croplands), respectively, with good model performance (RMSEP ≤ 1.58).

Soil properties were the most important driving factors in both systems. In the SC croplands (Fig. 5d), soil salinity, soil type, and SNS were among the top four factors with relative importance values of 16.49 %, 16.22 %, and 13.07 %, respectively. Notably, while soil salinity and soil

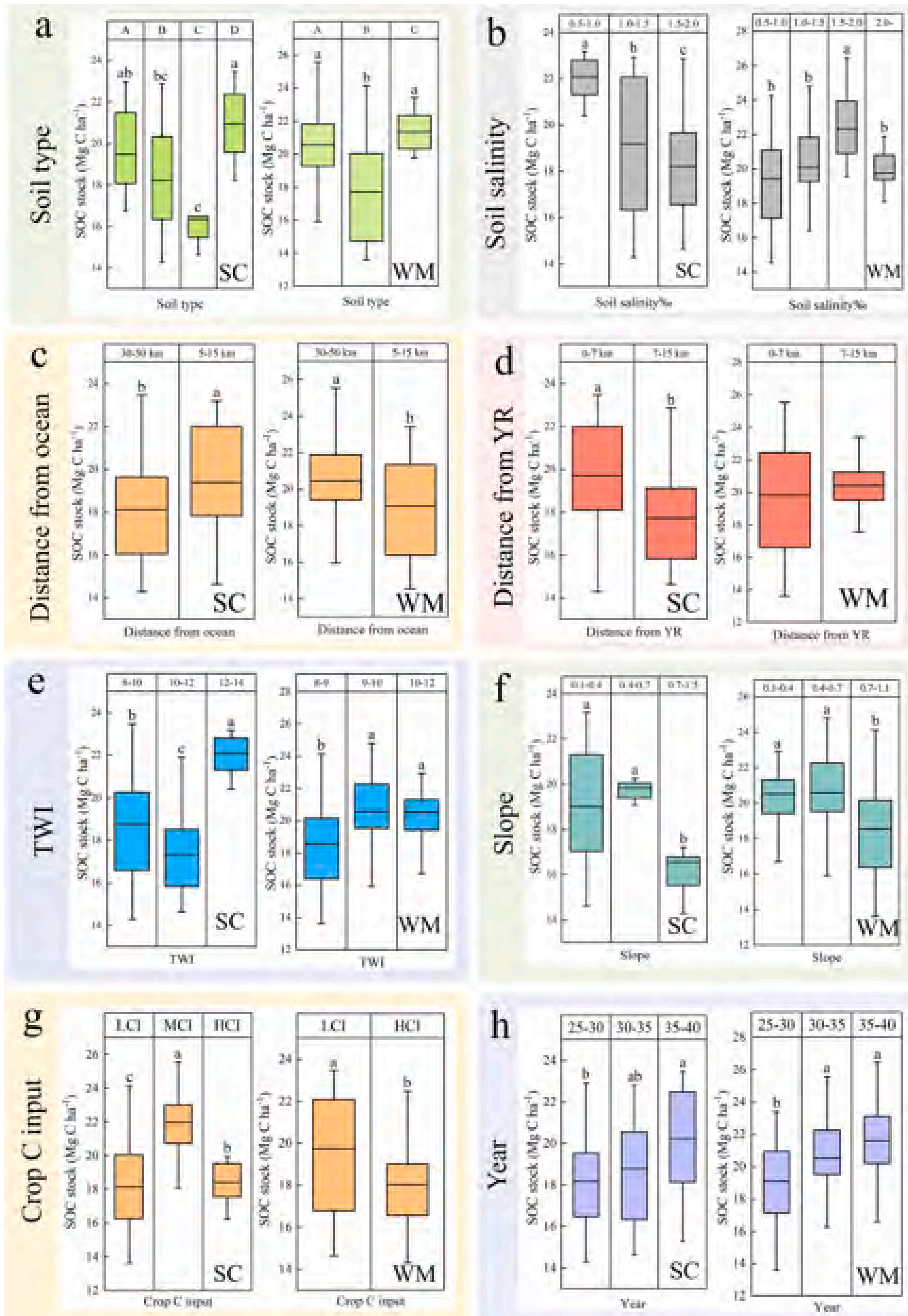

Fig. 3. Changes in soil organic carbon (SOC) stocks in two cropping systems under different (a) Soil type, where A, B, C, and D are *Salic Fluvisols*, *Anthrosols*, *Solonchak*, and *Fluvisols*, respectively; (b) Soil salinity %; (c) Distance from the Bohai Sea (ocean), (d) Distance from the Yellow River (YR); (e) TWI; (f) Slope; (g) Crop C input, where LCI, MCI and HCI refer to low carbon input, medium carbon input and high carbon input, respectively. In SC croplands, LCI and HCI are 46–52 kg ha^{-1} and 52–54 kg ha^{-1}, whereas in WM croplands, LCI, MCI, and HCI are <970 kg ha^{-1}, 970–1030 kg ha^{-1} and >1030 kg ha^{-1}; and (h) Year, which indicates the years since the intensive agricultural development in 1980.

type had the largest impact, they had no impact on the WM. In the WM croplands (Fig. 5f), SNS and Avail. K were more important, with relative importance values of 18.87 % and 14.07 %, respectively. The SNS was the most important driving factor (28.74 %) for all croplands (Fig. 5b). In terms of agricultural management, crop C input was more prominent in the WM (12.99 %) than in the SC (10.12 %). The K input (8.01 %) was conducive to SOC stock changes in SC croplands, whereas it had less impact on WM croplands (5.09 %). In terms of topographic factors, distance from the ocean (15.50 %) affected SOC stocks in SC croplands, whereas TWI (8.34 %) and slope (8.04 %) were more important in WM croplands. Both croplands were affected by distance from the YR, which was a larger driving factor in the SC croplands (10.08 %) than in the WM croplands (6.64 %).

The results showed that some agricultural management practices, such as irrigation and fertilization, were relatively unimportant (ranking behind the top 10 variables). Moreover, the effects of climatic factors (MAT and MAP) on SOC stock dynamics were very weak (<4.13 %), and the groundwater level, which fluctuated greatly from year to year, did

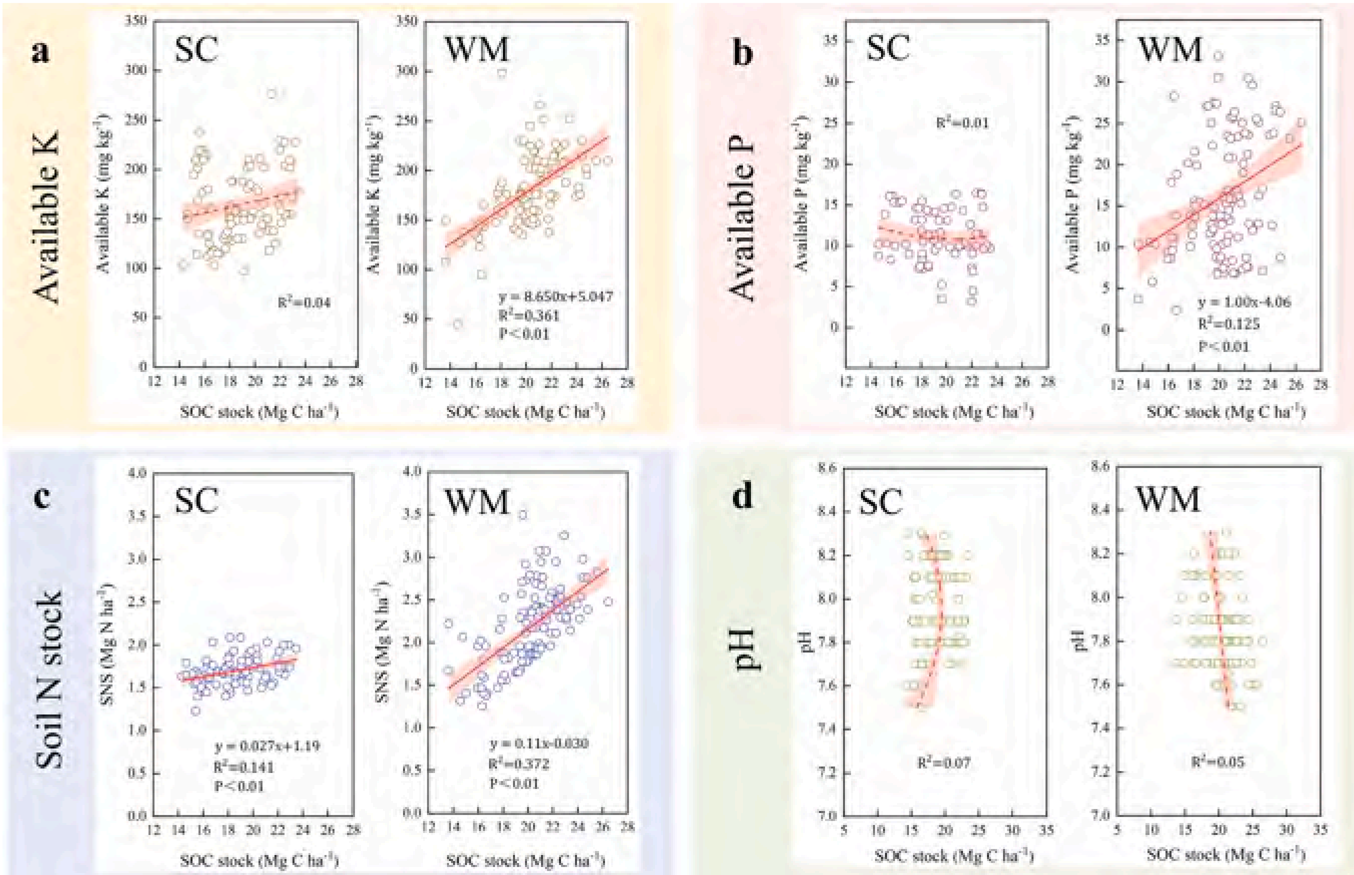

Fig. 4. Correlation relationships between soil organic carbon stocks (SOC stocks) and soil chemical properties (available P, available K, SNS and pH). The red line in each plot is the linear fit, and the light-red shaded area indicates its standard deviation range.

not affect SOC stocks in either cropland (<2.10 %).

4. Discussion

4.1. The WM rotation system is more conducive to promoting SOC sequestration in river delta croplands than SC

With reclamation and utilization taking place in the YRD for over 40 years, croplands have acted as a carbon sink, and until now, SOC stocks have been increasing. The average SOC stock rate of increase for croplands in river deltas (1980–2020) is approximately 0.063 g kg^{-1} yr^{-1}, which is slightly higher than that of croplands in China (0.056 g kg^{-1} yr^{-1}) but reaches only 57 % of that of the *Fluvisols* croplands in the North China Plain (0.11 g kg^{-1} yr^{-1}) (Han et al., 2016). This shows that, compared with other croplands in the North China Plain, the carbon sequestration efficiency in the YRD croplands needs improvement. Previous studies have found that after the reclamation of saline wasteland into croplands, the rate of C increase was highest in the first few years and subsequently slowed down (Hou et al., 2021; Lacerda et al., 2023). However, our results indicate that the latter 14 years (2007–2020) was a period of rapid carbon accumulation, and the rate of increase was 0.22 Mg C ha^{-1} yr^{-1}, which is approximately 1.83 times that before 2007. This is mainly because China's agriculture has undergone a rapid transformation over the past 40 years. In the early period of reclamation (approximately 1980–2000), straw burning generally led to little crop C entering the soil, thereby limiting the initial soil C accumulation rate (Gao et al., 2006; Qu et al., 2012; Vitousek et al., 2009). After 2000, the government introduced subsidy policies for straw incorporation, which greatly increased the crop C input into cropland soil. This promoted the SOC accumulation rate (Zhao et al., 2018).

The SOC stock of the WM system was 8.4 % higher than that of the SC system and the rate of increase was 35.7 % higher. Although some studies have suggested that crop rotation may lead to more frequent tillage, eventually leading to more soil C loss (Angers and Eriksen-Hamel, 2008), our findings indicate that WM cropping systems sequester SOC at a rapid rate due to differences in straw utilization practices. In the YRD, all wheat and maize residues have been returned to the fields since 2000. In contrast, during cotton production, only the belowground portion of the biomass remains in the soils, as the aboveground biomass is completely removed after harvest. Straw residue returning contributes a greater amount of fresh organic C input to soils, which may lead to a small portion of stable C being mineralized through bacterial "priming", resulting in C loss (Blagodatskaya and Kuzyakov, 2008). However, most exogenous organic C becomes fixed through humification and aggregation processes, resulting in an overall increase in SOC stocks in farmland (Huang et al., 2021; Lessmann et al., 2022). Moreover, the rotation cropping system ensures continuous crop coverage over the long time, preventing soil exposure during fallow periods, which in turn inhibits soil nitrate loss and provides a consistent source of C input (Janzen et al., 2022). Compared with other croplands with crop cover in winter and spring every year, fallowing in cotton croplands causes a large amount of evaporation, resulting in salt accumulation on the soil surface, which inhibits cotton biomass formation (Haj-Amor et al., 2022). Cotton is a woody plant that is known to contain high levels of lignin, which may constrain microbial decomposition and utilization of the plant material (Kamimura et al., 2019). Hence, the WM rotation system in river delta croplands achieves higher C sequestration by increasing biomass and reducing surface salinity with less evaporation to inhibit its adverse effects on SOC sequestration.

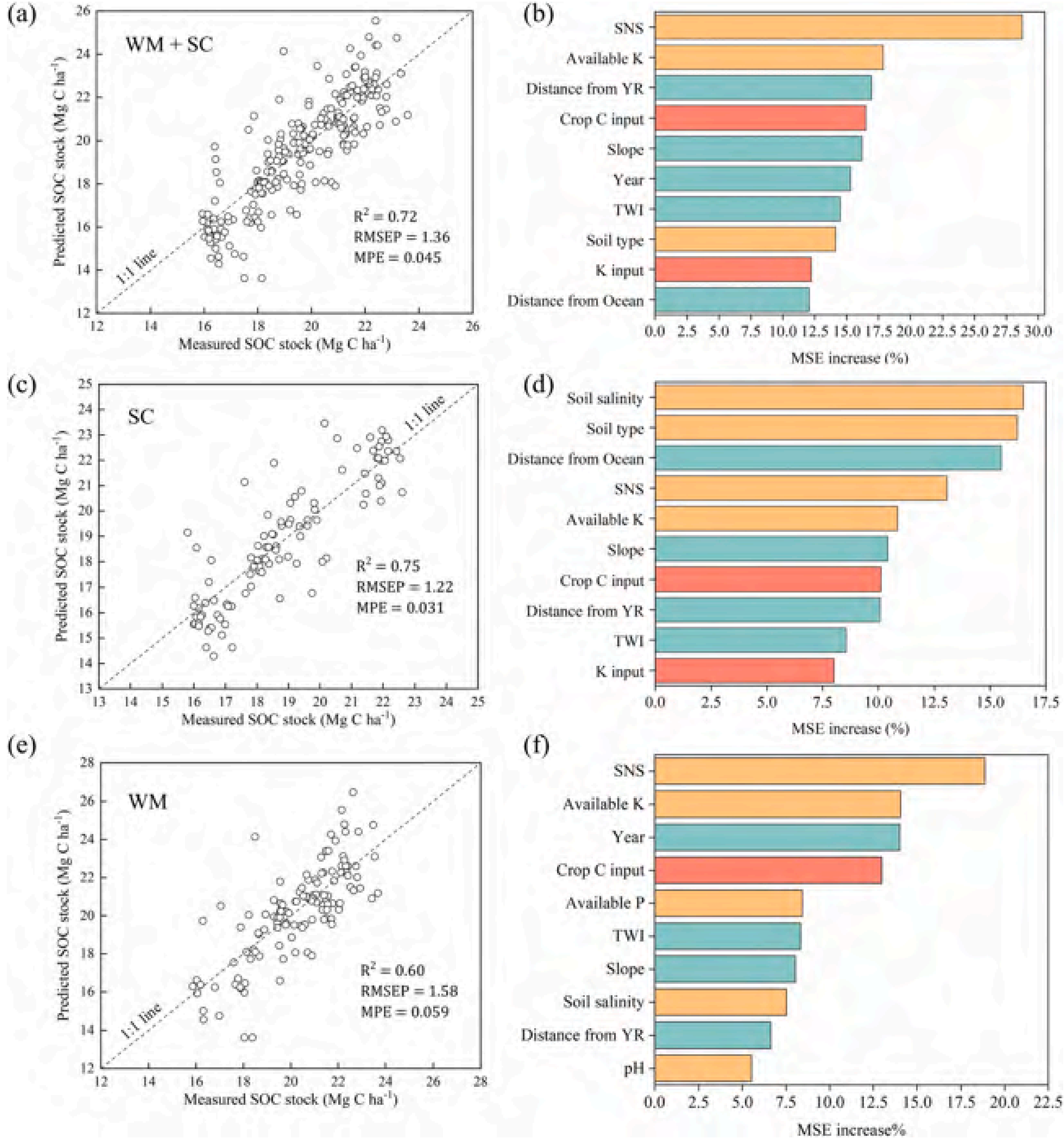

Fig. 5. Performance of random forest models in (a) wheat-maize (WM) + singe crop (SC) croplands, (c) SC croplands, and (e) WM croplands and the top 10 variables in (b) WM + SC croplands, (d) SC croplands, and (f) WM croplands. K input (kg ha^{-1}) denotes the converted amount of potassium in both organic and chemical fertilizers.

4.2. *Driving mechanisms of SOC stock changes in river delta croplands*

In this study, we quantified and compared the long-term effects of soil salinity on SOC stocks in two cropping systems. Our research found that with an increase in soil salinity (0.5–2.0 ‰), the SOC stocks in SC croplands decreased significantly by 17.5 %, whereas in WM croplands, the SOC stocks in low salinity conditions (<1.5 ‰) and high salinity conditions (>2.0 ‰) was 11.7 % lower than that under 1.5–2.0 ‰ salinity conditions. In some cases, we found that reducing soil salinity in the WM croplands did not improve SOC accumulation. This confirms the hypothesis that the correlation between soil salinity and SOC stocks in croplands is not a simple negative correlation, as traditionally thought (Setia et al., 2013; Wong et al., 2010; K.J. Zhang et al., 2021). A possible explanation for this is that when salinity is low, its increase first reduces microbial activity in the soil, thereby inhibiting SOM mineralization (Shahariar et al., 2021). With a further increase in salinity, the formation of crop biomass is significantly inhibited, which greatly reduces the input of exogenous C into the soil and negatively affects the physical protection of soil aggregates against SOC. This, in turn, intensifies water and salt transport and accelerates soil C loss (Wong et al., 2010), leading to a decrease in SOC stocks. This process resulted in the highest SOC stocks in the medium salt content in WM croplands. In the SC croplands, soil salinity and SOC stocks were significantly negatively correlated. The distinctive responses of SOC stocks to soil salinity may be due to the variability in soil microbial species and their different salt adaptabilities in the two cropping systems (Rath et al., 2019). In general, croplands with WM rotation systems in river deltas tend to weaken the negative impact of salinity on soil C sequestration, which is also reflected in the RF results (soil salinity had little importance in WM croplands).

Anthropogenic activities (such as crop C input and chemical organic fertilizer application) and soil nutrients are highly manageable in farmlands and have a notable influence on the SOC stock in croplands, which is the focus of our research on the mechanism of soil C sequestration. Soil nitrogen was the most important nutrient driving SOC stocks (28.74 %), and its relative importance was far greater than that of any other factor. Many studies have confirmed the simultaneous changes in SOC stocks and soil nitrogen (Castellano et al., 2015; Esser et al., 2011). Over the past 40 years, enhanced agricultural management has improved soil fertility, particularly SNS, in river deltas. Notably, during the last decade, we observed significantly higher SNS levels in WM croplands compared to SC croplands (Table S3). This heightened soil fertility has provided crops with ample available nutrients, fostering increased crop biomass and consequently augmenting the external carbon sources available to the soils (Campbell et al., 2000). Moreover, research has shown that deficiencies in soil nutrients can be a primary limiting factor in the conversion of fresh residues into organic matter. This limitation arises from the inability of decomposers to meet their nutrient requirements, resulting in low humidification rates and organic matter destruction (Blagodatskaya and Kuzyakov, 2008; Recous et al., 1995). Therefore, the combination of high nutrient levels and efficient residue utilization renders SOC sequestration in rotation cropping systems more responsive to the positive effects of SNS. Avail. K was the second most important nutrient factor for SOC stocks in WM croplands (14.07 %) but had only a slight impact on SC croplands (10.86 %). Similarly, Avail. P explained 8.43 % of the variation in SOC stocks in WM croplands but had little impact on SC croplands. Currently, there are few reports on the potential mechanisms underlying the effects of Avail. P and K on soil C sequestration. Based on our research, we believe that this is mainly because the growth of field crops is promoted under high fertility conditions and crop C input is maintained at a high level throughout the year. In terms of crop C input, the positive effect on carbon sequestration in the WM croplands was greater than that in the SC croplands because of the discrepancies in the local straw incorporation rate between the two cropping systems. In addition, the RF results showed that the input of exogenous N, P, and K had relatively little influence on SOC stock dynamics. However, this does not imply that chemical and organic fertilizers have no effect on soil C sequestration; in contrast, they are important factors. The reason for this contrasting conclusion is that long-term intensive farming involves relatively constant fertilizer application, which weakens the results of the statistical model to a certain extent. Nevertheless, fertilization can affect the soil C pool by promoting crop growth and changing root input. However, exogenous N and P inputs may change the stoichiometric balance of soil microorganisms, thereby affecting the mineralization of SOC (Ashrae et al., 2020; Huang et al., 2010; Zhang et al., 2020). Overall, in river delta croplands, soils that have high fertility over a long period contribute to soil carbon sequestration, which becomes more evident in WM croplands.

The classic paradigm of SOC change suggests that plant C input and SOM decomposition play important roles in driving SOC sequestration and persistence (Jackson et al., 2017; Schmidt et al., 2011). Our research found that farmlands with the two planting systems in river deltas exhibited two distinct pathways for SOC stock changes under the impacts of agricultural management and soil salinity. In the WM croplands, changes in SOC stock are primarily regulated by soil nutrients. Specifically, high levels of soil nutrients (N, P, and K) are beneficial for crop growth and lead to increased aboveground and belowground biomasses. Consequently, plant carbon input is promoted through residue return and root growth, thereby enhancing SOC sequestration, and SOC stock changes are primarily regulated by soil salinity. In the specific pathway, soil salinity affects the activity of soil microorganisms and related SOC-degrading enzymes, thereby delaying or accelerating SOC decomposition and turnover. A possible explanation for the pathway difference is that in long-term agricultural practices, the decomposition of cotton residues is difficult and uneconomical, resulting in a low rate of return of plant-derived carbon to the soil. Consequently, the contribution of plant C input was relatively small in the SC croplands. Additionally, high evapotranspiration caused by surface exposure during long-term fallow periods in winter under monoculture cropping systems exacerbates the activity of soil microbial communities (Wang et al., 2014). This further emphasizes the role of microbial activity in regulating the SOC dynamics in monocultured croplands.

Environmental factors (such as topographical conditions, soil types, and climatic conditions) are difficult to artificially change during the farming process, but they have an important impact on agricultural production and soil C sequestration (Orgill et al., 2014; Wang et al., 2022). Soil temperature and moisture are generally considered important regulatory factors of SOC stocks (Kirschbaum, 2000; Post et al., 1982), but our RF results showed that interannual changes in MAP and MAT had very weak effects on SOC stock dynamics. This may be, in large part, due to the small variability in temperature and precipitation conditions at the regional scale over >10 years. Years of constant regional climatic conditions had less influence on soil C sequestration, which is consistent with the findings of Gonzalez-Dominguez et al. (2019). Compared with inland croplands, the groundwater level in the YRD is shallow and fluctuates greatly within a year because of climate and ocean–land interactions (Xie et al., 2011). Our study did not find a significant correlation between the groundwater level and SOC stocks in river delta croplands, which may be due to the relative stability of the groundwater table in autumn and winter. Moreover, the seasonal fluctuation in groundwater level and its impact on SOC stocks are weaker at the interannual scale.

4.3. *Suggestions for future carbon management efforts in river delta croplands*

It is feasible and reliable for farmers to take appropriate action to help achieve C sequestration in agricultural systems. Intensive agricultural practices, such as excessive fertilizer application and tillage, have been widely used to improve crop productivity, but this also results in the deterioration of soil quality and the unsustainable development of river delta croplands (Han et al., 2015; Ju et al., 2009; Waqas et al., 2020). The choice of planting system in river deltas directly affects the C sequestration ability of cropland soils. Increasing the plating area of WM rotation systems is a feasible way to increase soil C sequestration. Because the process of soil C sequestration in croplands with WM rotation systems is more sensitive to soil nutrients, more scientific nutrient monitoring and necessary measures to improve soil fertility should be taken to optimize and guide soil carbon management in WM croplands. Cotton has become the main monoculture crop in the YRD region because of its salt tolerance. Although soil salinity is one of the most important results from the RF results (Fig. 5b), it is not feasible to reduce the salinity of SC croplands considering the cost and difficulties in dealing with saline and shallow groundwater. However, manipulating SNS, Avail. K, and crop C input are feasible ways to improve SOC stocks through agricultural management in SC croplands. Therefore, we suggested that farmers be encouraged to increase the amount of organic fertilizer through policy subsidies to achieve C sequestration because organic fertilizer can directly meet the SNS, Avail. K and crop C input requirements.

Our research confirms the impact of agricultural policies at various stages on SOC stocks. At the current stage of the transition from intensive farming to sustainable development, the government and farmers need to make joint efforts to implement soil carbon policies. We studied the dynamic mechanism of SOC in river delta farmlands in the YRD. However, in the current study, there were certain limitations in the investigation of SOC sequestration in river delta croplands. Firstly, while this study established a decade-long in-site observational experiment in delta farmland, some indicators could not be continuously measured due to constraints in experimental conditions, suggesting potential avenues for improvement in future research. WM cropping systems consume more water during crop growth compared to the SC croplands (Li et al., 2023). Therefore, it is essential to consider that optimizing agricultural management measures may lead to impending water scarcity in the YRD. Future research should prioritize deltas' water supply to mitigate the risk of potential declines in agricultural productivity and carbon sequestration capacity due to water scarcity (Zhou et al., 2016). Moreover, the delta regions are notably susceptible to intense flooding due to significant climate variability (Tang et al., 2017). Future research on the changes of SOC stocks in delta croplands under flooding conditions during years characterized by substantial water inundation has significant practical significance. The inundation of fields during episodes of intense flooding can have multifaceted consequences on crop health, soil structure, and nutrient availability, potentially affecting yields and SOC dynamics (Lesk et al., 2016). In addition, the most appropriate approach may differ across the regions. Therefore, further research is needed to explore how to maximize the C sequestration of croplands in specific regions to carry out sustainable carbon management in global river-delta agroecosystems.

5. Conclusion

Based on historical and long-term observational data, this study quantified the dynamic changes in soil carbon stocks in river delta croplands under long-term intensive farming for the first time. The effects of soil nutrients, environmental characteristics, and anthropogenic activities on SOC stocks were also identified. The increase in SOC stocks (10.05 Mg C ha^{-1}) and rate of increase (0.25 Mg C ha^{-1} yr^{-1}) in WM croplands were 1.35 and 1.25 times that of SC croplands, respectively, over the past 40 years. This indicates that croplands with WM rotation systems in river deltas have better potential for soil C sequestration. Soil N, P, and K had good correlations with SOC stocks and were the most important driving factors behind SOC stock dynamics in WM croplands. Our results revealed that promoting crop C input under high soil nutrient conditions and affecting SOC decomposition by soil salinity are the two different pathways of SOC sequestration in the WM and SC croplands, respectively. Climate conditions and interannual variability in groundwater levels did not contribute to SOC stock dynamics in the river delta croplands. We provide evidence that cropland-scale management can be effective in C sequestration in river deltas and that greater involvement from policymakers should be sought to maximize the ability of river deltas to provide food and mitigate global climate change. This study provides scientific guidance for the sustainable development of carbon management in river delta agroecosystems.

CRediT authorship contribution statement

Deyao Liu: Conceptualization, methodology, data curation, software, writing – original draft; Huarui Gong: Conceptualization, methodology, writing – review & editing; Jing Li: Conceptualization, data resources, writing – review & editing and supervision; Zhen Liu: Methodology; Lingqing Wang: Methodology; Zhu Ouyang: Writing – review & editing; Li Xu: Methodology; Tieyu Wang: Methodology.

Declaration of competing interest

No conflict of interest exits in the submission of this manuscript.

Data availability

Data will be made available on request.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167749.

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