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ABSTRACT

The vast cropland in China is an important carbon pool with substantial carbon sequestration potential. Here, this study estimated the soil organic carbon stock in China's croplands based on a comprehensive investigation of 7.5 million soil samples from 2,209 counties. We show that China's croplands (0-20 cm) store 4.53-4.98 Pg organic carbon in total. The soil organic carbon stock increased from 29.13-34.54 to 33.51-36.90 Mg C ha^{-1} during 1980-2010, with an annual average increase rate of 113.33 kg C ha^{-1} yr^{-1}. The increase in soil organic carbon stock was mainly driven by the increasing inputs of crop residue and livestock manure. Furthermore, we designed four scenarios with different crop residue, livestock manure, and nitrogen fertilizer inputs to assess the soil organic carbon sequestration potential in China's croplands. The results show that the soil organic carbon storage is projected to reach 6.98-7.89 Pg by 2060, representing 6.1%-13.3% of the annual negative carbon emissions required by 2060 China's carbon neutrality target. We also proposed targeted strategies to further increase the soil organic carbon stock of cropland in different regions by considering characteristics such as soil properties and agricultural management practices.

Keywords: soil organic carbon, China, cropland, carbon sequestration, carbon neutrality

1. Introduction

Cropland is widely recognized as an important carbon pool and plays a crucial role in the global carbon balance (Qin et al., 2013; Schlesinger, 1999). It is estimated that carbon sequestration in global cropland has the potential to offset carbon emissions by up to 1.2 Pg per year (Lal, 2004), equivalent to 13.6% of the global carbon emissions from energy combustion in 2020 (IEA, 2021). According to the '4 per 1,000' initiative launched by the French government at the COP21 Paris climate summit in 2015, a 0.4% annual increase in carbon storage in cropland soils can help mitigate climate change (Cornelia et al., 2018). In this regard, maintaining and enhancing soil organic carbon (SOC), which accounts for over 60% of the carbon pool in cropland globally, can greatly enhance climate change adaptation (Lal, 2004).

China has a vast area of croplands (more than 135 million hectares), which accounts for approximately 7% of global cropland. However, the SOC stocks and their changes in China's croplands are not well understood. Although several studies have investigated changes in the SOC stock of China's croplands, their results are inconsistent or even contrasting (Li & Shao, 2014; Liao et al., 2009; Tang et al., 2006; Yu et al., 2013; Zhou et al., 2019). Some estimates using mechanistic models showed net SOC losses (Tang et al., 2006; Zhou et al., 2019), while some literature surveys indicated SOC sequestration (Liao et al., 2009; Yan et al., 2011). The accuracy of previous estimations is likely restricted by the limited sample size and data representativeness and the inconsistency of data sources and methodologies (Tang et al., 2018). A more robust investigation by Zhao et al. (2018) tracked the changes in the SOC stock of China's croplands from 1980 to 2011 based on soil samples from 58 counties. However, the limited size and coverage of samples may result in large uncertainties in calculating changes in SOC stock, preventing an accurate assessment of SOC sequestration.

Cropland SOC fluctuations are determined by the balance between organic carbon inputs and carbon effluxes (Lal, 2001). Studies have attempted to relate this balance to soil properties (e.g., initial SOC stock, soil clay content, and pH) (Thomas et al., 2020), climate variables (e.g., precipitation and temperature) (Carvalhais et al., 2014; Tang et al., 2018), and agricultural management practices (e.g., crop residue input, livestock manure input, and chemical nitrogen fertilizer input) (Zhao et al., 2018). For example, temperature influences SOC turnover by affecting microbial activities and vegetation-derived carbon inputs (Davidson & Janssens, 2006; Knorr et al., 2005), and precipitation influences SOC mineralization and decomposition by changing the soil anaerobic environment (Olk et al., 2006). A higher or lower soil pH value is detrimental to SOC sequestration and stability by affecting microbial activities and the adsorption and binding capacity of soil minerals to organic matter (Jones et al., 2019; Liang & Zhu, 2021). Moreover, current studies have reached a consensus that crop residue carbon and livestock manure carbon inputs are important explainers for the sequestration of SOC, which can directly increase the SOC stock (Li et al., 2021; Zhao et al., 2018). However, their contribution and relative importance to SOC sequestration in China's croplands remain poorly understood. Therefore, it is urgent to accurately quantify the SOC stock and its changes in China's croplands and assess the relative importance of multiple explanatory factors, which are not only essential for predicting the potential for achieving SOC sequestration, but also significant for formulating appropriate cropland SOC management strategies.

To address these aforementioned questions, we estimated the SOC storage and stock in China's croplands based on a comprehensive investigation of 7.5 million soil samples from 2,209 counties (Fig. S1) in 2010 and analyzed SOC stock changes in China's croplands during 1980-2010. We also identified and assessed the effects of the key explanatory factors on changes in the SOC stock of China's croplands; the factors included soil properties (sand, silt, and clay contents, initial soil pH and SOC stock), climate variables (mean annual precipitation and temperature), and agricultural management practices (e.g., crop residue input, livestock manure input, chemical nitrogen fertilizer input, proportion of paddy fields, and multiple-crop index). Finally, we established four scenarios based on the identified influencing factors and projected the potential of SOC sequestration in China's croplands by 2060. By doing so, we aim to provide insights for formulating appropriate strategies to enhance cropland's contribution to China's carbon neutrality target.

2. Methods

2.1. Data sources

From 2005 to 2014, China implemented the Soil Testing and Formulated Fertilization (STFF) project, and 7.5 million cropland topsoil (0-20 cm) samples were collected from 2,209 counties across China (Fig. S1), which is the most up-to-date, comprehensive, and detailed national soil survey data available. The relevant data, mainly soil organic matter

(SOM), were presented in a published monograph named the Soil Basic Nutrient Data Set for Soil Testing and Formulated Fertilization (2005~2014) (National Agricultural Technology Extension Service Center, 2014), and the STFF data were uniformly dated to 2010 in this study, as the topsoil samples were mainly collected during the period of 2008-2012. In 1980, China conducted the Second National Soil Survey (SNSS) on major cropland soils, which covered typical soil types and cropping systems. The SNSS data, including SOM, initial soil sand, silt, and clay contents, initial soil pH and the fraction (%) of > 2 mm fragments in topsoil (0-20 cm), were mainly collected from a series of monographs contained in the China Soil Series Vols. 1-6 (National Soil Survey Office, 1993-1996). The SOM contents in both STFF and SNSS datasets were determined by the potassium dichromate oxidation method.

Mean annual temperature and mean annual precipitation data were collected from the European Centre for Medium-Range Weather Forecasts (Copernicus Climate Change Service, 2019). The data on the planting area of crops that were used to calculate the multiple-crop index and nitrogen fertilizer input were collected from the China Statistical Yearbook (National Bureau of Statistics, 1980-2020). Information on the proportion of paddy fields was collected from remote sensing monitoring data on land use in China in 2020 (Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 2020).

2.2. Calculation of the soil organic carbon stock and its uncertainty

The SOC content was calculated by multiplying SOM by 0.58 (the conversion factor between SOM and SOC) (Pan et al., 2010). The county-level SOC stock was calculated by using the equation provided in Pan et al. (2003):

$$SOC_{stock} = SOC \times BD \times Depth \times (1 - \delta_{2m} \ /100)/10 \quad (1)$$

where SOC_{stock} and *SOC* are the SOC stock (Mg C ha^{-1}) and SOC content (g kg^{-1}), respectively, *BD* is the soil bulk density (g cm^{-3}), *Depth* is the topsoil thickness in centimeters (20 cm in this study), δ_{2mm} is the fraction (%) of > 2 mm fragments in the soil, and *10* is the unit conversion factor. Notably, the δ_{2mm} in cropland soils is low enough to be negligible after 30 years of cultivation, therefore, we did not consider the δ_{2mm} in the calculation of SOC stock in 2010. Then, the county-level SOC stock was further aggregated to the provincial, regional, and national scales using the area-weighted mean method.

Because of the large number of missing *BD* data in the SNSS and STFF datasets, six common pedotransfer functions (PTFs) (Table S1) were selected to estimate *BD* (Alexander, 1980; Huntington et al., 1989; Manrique & Jones, 1991; Song et al., 2005; Wu et al., 2003; Yang et al., 2007), and the final *BD* data was mean of the estimated values from the six PTFs to make the estimation results more accurate.

To obtain a robust estimate of SOC stock, bootstrapping (10000 iterations) method was applied to the topsoil samples of each county in 1980 and 2010, respectively. Then the mean SOC stock and its 95% confidence intervals were calculated using the bootstrapped samples. For each region, area-weighted mean SOC stock was calculated based on the 10,000 SOC stock estimates for each county within the region and the soil area of each corresponding county. Additionally, bootstrapping method was used for estimating the uncertainties of SOC stock predictions. The uncertainty was quantified by 95% confidence interval (CI) and expressed as follows (Zhou et al., 2019):

$$Uncertainty = (UCI - LCI)/SS_{mean} \quad (2)$$

where UCI and LCI are the upper and lower 95% confident limits, and SS_{mean} is the mean SOC stock of the 10,000 bootstrapped samples.

The saturated SOC stock was calculated based on the SNSS data from 1980 according to the equation proposed by Hassink (Hassink, 1996):

$$SOC_{sat} = 4.09 + 0.37 \times PS \quad (3)$$

where SOC_{sat} and PS are the saturated SOC content (g kg^{-1}) and the < 20 μm particle content (%), respectively. Then, SOC_{sat} was introduced into formula (1) to calculate the saturated SOC stock at the provincial, regional, and national scales.

2.3. Calculation of soil organic carbon storage

The SOC storage in 2010 was calculated with the following equation:

$$SOC_{storage} = \sum_{i=1}^{n}(SOC_{stock\,(i)} \times CA_i)/\sum_{i=1}^{n} CA_i \times CA_p \quad (4)$$

where $SOC_{storage}$ is the SOC storage (Tg) in each province in 2010, n is the number of counties in each province, $SOC_{stock\,(i)}$ and CA_i are the SOC stock (Mg C ha^{-1}) and cropland area (M ha) in county i, respectively, and CA_p is the cropland area (M ha) in the provinces. The SOC storage in each region and in all of China was obtained by summing the SOC storage in the corresponding provinces.

2.4. Estimation of carbon input from crop residues

We collected data on the major crop yields in each province, including those of rice, wheat, corn, soybean, cotton, and rapeseed, from 1980 to 2019 from the China Statistical Yearbook. The carbon input from the roots and straw of a given crop in a given year was estimated according to the following equations (Zhao et al., 2018):

$$C_s = Yield \times (1 - WC) \times YS \times RR \times 0.45 \quad (5)$$

$$C_r = Yield \times (1 - WC) \times YS \times RS \times 0.45 \quad (6)$$

where C_s (Mg C ha^{-1}) and C_r (Mg C ha^{-1}) represent the carbon input from the straw or roots of a given crop, *Yield* represents the yield per unit area of a given crop in a given year (Mg ha^{-1}), *WC* represents the water content of the economic yield, *YS* and *RS* represent the conversion coefficients between crop yield and crop straw and between crop straw and crop roots, respectively, *RR* represents the average return ratio of crop straw in a given year (Table S2), and *0.45* is the conversion factor used to convert crop biomass to carbon content.

2.5. Estimation of carbon input from livestock manure

The numbers of major livestock, including horses, donkeys, mules, pigs, cattle, sheep, and poultry, in each province from 1980 to 2019 were collected from the China Statistical Yearbook. The carbon inputs from the manure and urine of a given livestock species in a given year were estimated according to the following equations (Liu & Li, 2018):

$$QM_i = (S_i \times P_i \times M_i/1000 + H_i \times 365 \times M_i/1000) \times (1 - 0.05) \times T_i/100 \times RR/100 \quad (7)$$

$$QM_j = H_j \times 365 \times M_j/1000 \times (1 - 0.05) \times T_j/100 \times RR/100 \quad (8)$$

$$QU_i = (S_i \times P_i \times U_i/1000 + H_i \times 365 \times U_i/1000) \times (1 - 0.5) \times T_i/100 \times RR/100 \quad (9)$$

$$QU_j = H_j \times 365 \times U_j/1000 \times (1 - 0.5) \times T_j/100 \times RR/100 \quad (10)$$

where *QM* (Mg) and *QU* (Mg) represent the carbon input from the manure or urine of a given livestock species in a given year, *i* represents the pig, cow, sheep, or poultry type, *j* represents the horse, donkey, or mule type, *S* represents the number of a given livestock species on hand at the end of a given year, *H* represents the number of a given livestock species sold in a given year, *P* represents the feeding days for a given livestock species (if the feeding period is longer than one year, it is generally calculated as 365 days, and if the production period is less than one year, it is generally calculated as the actual feeding days), *M* (kg) and *U* (kg) represent the daily excretion coefficients for the manure and urine of a given livestock species, *T* (%) represents the SOC content of the manure or urine of a given livestock species, and 0.05 and 0.5 represent the loss rates of livestock manure and urine, respectively. *RR* represents the average return ratio of livestock manure in a given year.

2.6. Correlation and regression analysis

Based on the matched data from the same counties in SNSS and STFF datasets, the influences of multiple factors on the annual change rate of county-level SOC stock during 1980-2010 were assessed using correlation analysis and partial correlation analysis. Regression analysis was used to develop models to explain the variation in the SOC stock changes. A stepwise method was employed, and the AdR^2 and Durbin-Watson selection criteria were used for the models. The significance of the model was tested with the F value. Variables were included in the model only when they were significant at $p < 0.05$, and significance for the complete model was set at $p < 0.05$. Meanwhile, the standardized coefficients in the regression models were used for the contribution analysis of each factor. Additionally, to remove the influence of outliers, only data between $\mu - 3\sigma$ and $\mu + 3\sigma$ were included in the regressions, where μ and σ are the mean and standard deviation of the dataset. All statistical analysis were performed using SPSS 22.0 software (SPSS Inc., USA).

3. Results

3.1. Soil organic carbon storage in China's croplands

The calculated SOC storage (0-20 cm) in China's croplands in 2010 based on a high-resolution sample dataset (7.5 million samples from 2,209 counties) was 4.75 Pg, with a 95% confidence interval of 4.53-4.98 Pg (Fig. 1). Specifically, Northeast China contributed the most to SOC storage among regions, accounting for 25.2% of the national total, followed by Southwest (19.1%), South (19.1%), East (16.6%), North (11.7%), and Northwest China (8.4%). Fig. 1 shows that the county-level SOC storage exhibited substantial variation, with a minimum of 3.2 Tg in Congtai district of North China to a maximum of 45.76 Tg in Nenjiang of Northeast China.

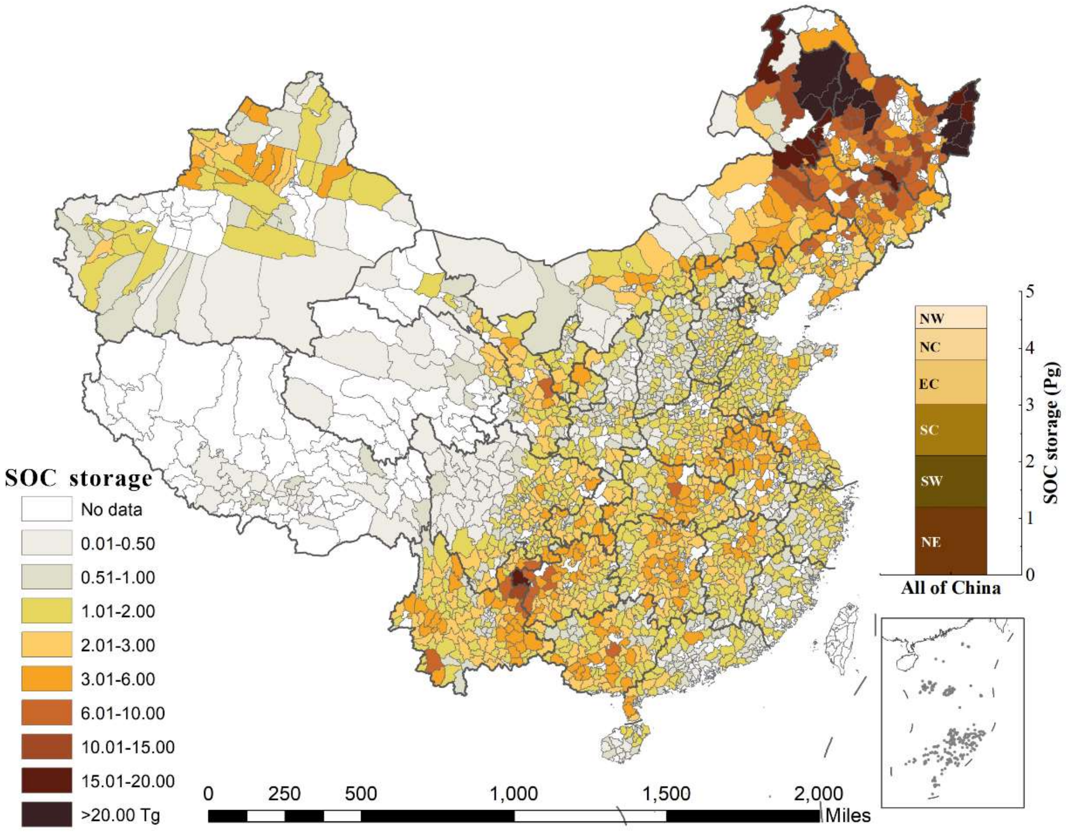

Fig. 1. Distribution of soil organic carbon (SOC) storage at the county and regional scales in China's croplands in 2010. NE, Northeast China. SW, Southwest China. SC, South China. EC, East China. NC, North China. NW, Northwest China.

3.2. Soil organic carbon stock changes in croplands during 1980-2010

Overall, China's croplands functioned as a significant carbon sink from 1980 to 2010. The SOC stock (0-20 cm) in China's croplands increased from 31.78 Mg C ha^{-1} (29.13-34.54 Mg C ha^{-1}) in 1980 (Fig. 2a) to 35.18 Mg C ha^{-1} (33.51-36.89 Mg C ha^{-1}) in 2010 (Fig. 2b). The net increase in the SOC stock during this period was 3.40 Mg C ha^{-1} (1.73-5.11 Mg C ha^{-1}), with an annual average increase rate of 113.33 kg C ha^{-1} yr^{-1} (57.67-170.33 kg C ha^{-1} yr^{-1}). The SOC sequestration rate in China's croplands was significantly higher than those in the United States (28-45 kg C ha^{-1} yr^{-1}) and Europe (a mean loss of 170 kg C ha^{-1} yr^{-1}) (Ciais et al., 2010; Ogle et al., 2010; Ogle et al., 2003). However, significant differences in the changes in SOC stock were observed among regions. The SOC stocks in croplands of South, East, Southwest, North, and Northwest China increased by 6.82, 3.78, 3.44, 2.10, and 0.97 Mg C ha^{-1}, respectively, while croplands in Northeast China lost 7.28 Mg C ha^{-1}. Additionally, the changes in SOC stock varied dramatically among the different counties (Fig. 2c). Burqin, Fuyun, Kaba, Huanren, and Lushan were the top five counties with the highest decreases in SOC stocks during 1980-2010, with 49.56, 42.19, 38.17, 36.72, 35.93 Mg C ha^{-1} respectively. In contrast, the cropland SOC stocks in Heqing, Fuyuan, Taihe, Eryuan, and Tongde experienced the highest increases of 34.41, 33.86, 31.47, 27.94, and 27.41 Mg C ha^{-1}, respectively.

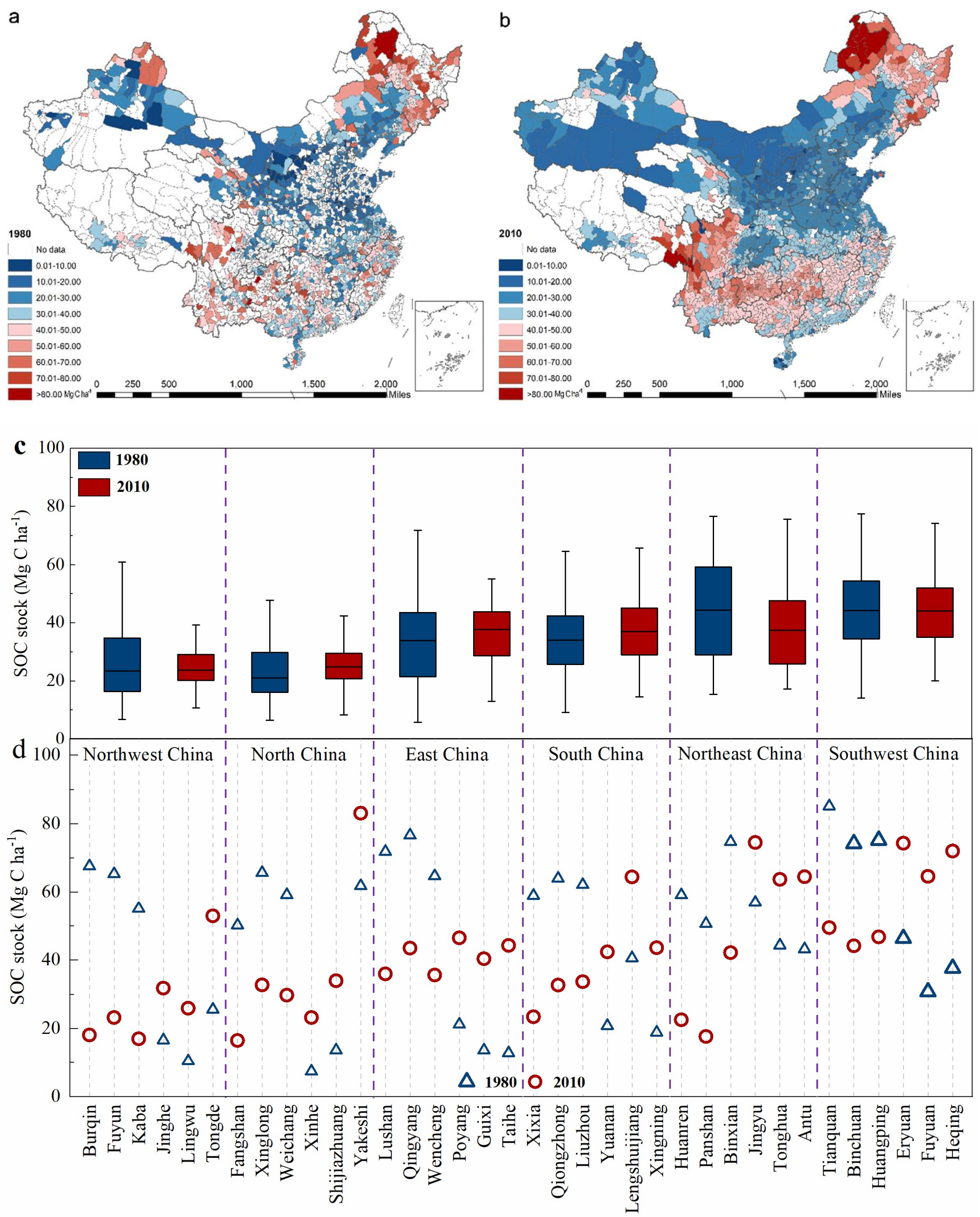

Fig. 2. Spatiotemporal variation in the soil organic carbon (SOC) stock in China's croplands in 1980 and 2010. a and b, spatiotemporal variation in SOC stocks at the county scale in 1980 and 2010. c, distribution of SOC stocks at the regional scale in 1980 and 2010. d, the top three counties with the highest decreases in SOC stock and the counties with the highest increases in SOC stock for each region during 1980-2010.

3.3. Factors influencing changes in soil organic carbon stocks

Correlation analysis incorporating the annual change rate of county-level SOC stock, climate, soil property, and agricultural management practice data (Fig. 3a) showed that MAP, MAT, CR_{Cinput}, LM_{Cinput}, NF_{input}, PFP, and MCI showed significant positive contributions ($p < 0.01$), while SOC_{1980} ($p < 0.01$) had negative influence on SOC stock change. The partial correlation analysis further revealed that MAT ($p < 0.01$) and NF_{input} ($p < 0.01$) had significant negative contributions to SOC stock change, while excluding the effects of all other factors (Fig. 3b). Notably, their variance contribution rates of both correlation and partial correlation analysis were far less than 50% (i.e., $R^2 < 0.5$) (Fig. 3), which implies that these factors may have jointly contributed to the change rates in SOC stock.

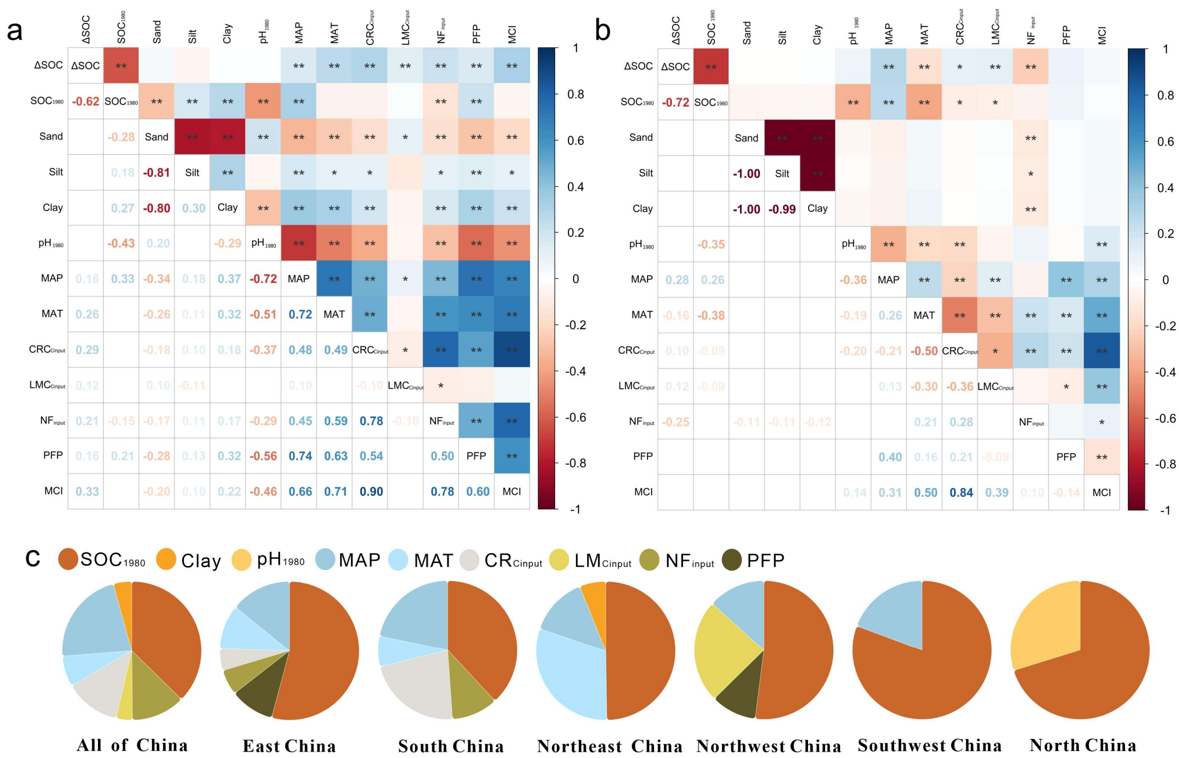

Fig. 3. Correlation coefficients between the annual change rate of county-level soil organic carbon (SOC) stock and initial soil properties, climate variables, and agricultural management practices at the national scale, and the contribution of related explanatory factors to SOC stock changes at the national and regional scales (n=533). a, pearson correlation between SOC stock changes and related factors. b, partial correlation between SOC stock changes and related factors. c, the contribution of related explanatory factors to SOC stock changes. △SOC, the annual change rate of county-level SOC stock during 1980-2010. SOC_{1980}, sand, silt, clay, and pH_{1980}, the initial SOC stock, sand, silt, and clay contents and pH in 1980. MAT and MAP, mean annual temperature and precipitation. CR_{Cinput}, LM_{Cinput}, and NF_{input}, the average annual inputs of crop residue carbon, livestock manure carbon, and nitrogen fertilizer during 1980-2010. PFP and MCI, proportion of paddy field and multiple-crop index. * refers to $p < 0.05$, ** refers to $p < 0.01$.

Stepwise linear regression was further performed to assess their factual significance and relative importance (Table 1). At the national scale, the results revealed that SOC_{1980}, clay, MAP, MAT, CR_{Cinput}, LM_{Cinput}, and NF_{input} were dominant factors explaining SOC stock changes. These seven factors explained 60.2% (i.e., Adj. $R^2 = 0.602$) of the variations in SOC stock changes, of which 29.1% was contributed by agricultural management practices (CR_{Cinput}, LM_{Cinput}, and NF_{input}) (Fig. 3c). SOC_{1980} was the most important factor affecting SOC stock changes and accounted for 37.4% of the total variation in SOC stock changes. Additionally, climate factors (MAP and MAT) explained an additional 29.2% of the total variation in SOC stock changes. PFP and MCI showed significant effects in Fig. 3a, while the two factors did not enter the stepwise regression model (Table 1), probably due to their co-variations with other factors (Fig. 3). The dominant factors affecting SOC stock changes varied dramatically in different regions. SOC_{1980} and climate (MAP and/or MAT) were common factors affecting SOC stock changes, especially in Northeast China, where these two factors accounted for 49.7% and 44.1% of the total variation in SOC stock changes, respectively. For regions with developed agriculture such as East and South China, the combination of CR_{Cinput} and NF_{input} explained 11.0% and 33.0% of the variations in SOC stock changes, respectively. LM_{Cinput} and pH were significant ($p < 0.01$) factors explaining the variations with 24.1% and 29.8% in Northwest and North China, respectively.

Table 1 Summaries of stepwise linear regressions between SOC stock changes and related explanatory factors at the regional and national scales.

Response index	Variable included	Regression F	Regression Sig.	Regression Adj.R^2	Parameters Coefficient	LCI 95%	UCI 95%	t	Sig.
All of China	Constant	9.06	< 0.01	0.602	0.268	0.178	0.358	5.847	< 0.01
	SOC_{1980}				-0.020	-0.022	-0.019	-24.595	< 0.01
	Clay				0.003	0.001	0.006	3.229	< 0.01
	MAP				0.537	0.373	0.702	6.422	< 0.01
	MAT				0.122	0.042	0.202	3.010	< 0.01
	CR_{Cinput}				0.000	0.000	0.000	9.891	< 0.01
	LM_{Cinut}				-0.010	-0.016	-0.004	-3.340	< 0.01
	NF_{input}				-1.270	-1.693	-0.847	-5.898	< 0.01
Northeast China	Constant	4.857	< 0.05	0.649	1.232	0.735	1.730	4.948	< 0.01
	SOC_{1980}				-0.032	-0.037	-0.026	-11.044	< 0.01
	Clay				0.008	0.001	0.015	2.204	< 0.05
	MAP				0.001	0.000	0.001	4.538	< 0.01
	MAT				-0.145	-0.185	-0.104	-7.154	< 0.01
North China	Constant	12.240	< 0.01	0.520	1.681	0.880	2.483	4.197	< 0.01
	SOC_{1980}				-0.016	-0.020	-0.012	-8.228	< 0.01
	pH_{1980}				-0.161	-0.253	-0.069	-3.499	< 0.01
East China	Constant	5.369	< 0.05	0.801	-0.196	-0.580	0.189	-1.010	< 0.05
	SOC_{1980}				-0.027	-0.030	-0.023	-14.663	< 0.01
	MAP				0.000	0.000	0.000	2.915	< 0.01
	MAT				0.037	0.014	0.060	3.211	< 0.01
	CR_{Cinput}				0.418	0.051	0.784	2.263	< 0.05
	NF_{input}				-0.573	-1.063	-0.082	-2.317	< 0.05
	PFP				0.201	0.062	0.341	2.864	< 0.01
Southwest China	Constant	4.494	< 0.05	0.531	0.597	0.316	0.879	4.239	< 0.01
	SOC_{1980}				-0.019	-0.023	-0.014	-8.851	< 0.01
	MAP				0.000	0.000	0.000	2.120	< 0.05
South China	Constant	4.915	< 0.05	0.711	-0.326	-0.713	0.061	-1.669	< 0.05
	SOC_{1980}				-0.026	-0.029	-0.023	-15.419	< 0.01
	MAP				0.000	0.000	0.001	8.093	< 0.01
	MAT				0.019	0.002	0.035	2.217	< 0.05
	CRC_{input}				1.121	0.785	1.456	6.624	< 0.01
	NF_{input}				-1.576	-2.323	-0.828	-4.179	< 0.01
Northwest China	Constant	13.606	< 0.01	0.747	0.154	0.037	0.270	2.611	< 0.01
	SOC_{1980}				-0.026	-0.029	-0.023	-16.676	< 0.01
	MAP				0.000	0.000	0.000	4.115	< 0.01
	LM_{Cinput}				0.612	0.457	0.767	7.815	< 0.01
	PFP				0.306	0.141	0.470	3.689	< 0.01

LCI 95% and UCI 95%, lower and upper limits of the 95% confidence interval. SOC_{1980}, pH_{1980} and clay, initial soil organic carbon stock, pH, and clay content in 1980. MAP and MAT, mean annual temperature and mean annual precipitation during 1980-2010. CR_{Cinput}, LM_{Cinput} and NF_{input}, the average annual inputs of crop residue carbon, livestock manure carbon, and nitrogen fertilizer. PFP, proportion of paddy field.

3.4. Contribution of croplands to China's carbon neutrality

The Ministry of Agriculture and Rural Affairs of China (MARAC) proposed the "Fertilizer Use Zero-Growth Action Plan by 2020" in 2015, which mandated further increases in the percentages of crop residue and livestock manure inputs in the future. We therefore set up four scenarios with different crop residue, livestock manure, and nitrogen fertilizer inputs (Table 2) to assess the changes in SOC stock from 2020 to 2060 and further projected the possible contribution of cropland SOC sequestration to carbon neutrality in China.

Table 2

Scenarios of crop residue, livestock manure, and nitrogen fertilizer inputs.

Scenarios	2020-2030	2030-2060
Baseline scenario	Maintain 60% crop residue and livestock manure inputs and maintain existing nitrogen fertilizer input (0.136 Mg ha^{-1})	Maintain 60% of crop residue and livestock manure and 0.136 Mg ha^{-1} of nitrogen fertilizer inputs
Middle-of-the-road scenario	Linear increase from 60% to 80% crop residue and livestock manure inputs and maintain existing nitrogen fertilizer input (0.136 Mg ha^{-1})	Maintain 80% of crop residue and livestock manure and 0.136 Mg ha^{-1} of nitrogen fertilizer inputs
High organic carbon input scenario	Linear increase from 60% to 100% crop residue and livestock manure inputs and maintain existing nitrogen fertilizer input (0.136 Mg ha^{-1})	Maintain 100% of crop residue and livestock manure and 0.136 Mg ha^{-1} of nitrogen fertilizer inputs
Reducing nitrogen fertilizer input scenario	Linear increase from 60% to 100% crop residue and livestock manure inputs and reduce nitrogen fertilizer input by 20% (0.109 Mg ha^{-1})	Maintain 100% of crop residue and livestock manure and 0.109 Mg ha^{-1} of nitrogen fertilizer inputs

All scenarios are based on the assumption that the yields of crops and livestock will remain stable after 2020, using mean actual yields from 2015 to 2019 as the baseline.

Fig. 4 shows the trajectories of SOC stock projections under different scenarios by 2060.

Under the baseline scenario, the SOC stock and storage will increase to 51.71 Mg C ha^{-1} and 6.98 Pg in 2060, respectively. This result suggests that China's croplands will maintain their capacity to sequester carbon over the next 40 years, even if the yields of crop and livestock and the inputs of organic carbon and nitrogen fertilizer remain unchanged. China's 2060 carbon neutrality goal will require up to 2-3 Pg CO_2 yr^{-1} of negative emissions based on the estimates of different interventions (Fuhrman et al., 2021). SOC sequestration in China's croplands under the baseline scenario can contribute 6.1%-9.2% of the negative carbon emissions annually. Under the middle-of-the-road scenario, the SOC stock (57.93 Mg C ha^{-1}) will approach its saturation value (58.39 Mg C ha^{-1}) (Table S3) in 2060, and the SOC sequestration will represent 8.9%-13.3% of the annual negative carbon emissions required by China's 2060 carbon neutrality target. Under the high organic carbon input scenario, the SOC stock in China's croplands will reach saturation 10 years earlier. Reducing nitrogen fertilizer input by 20% will promote SOC sequestration over the next 40 years, but this increment is not significant.

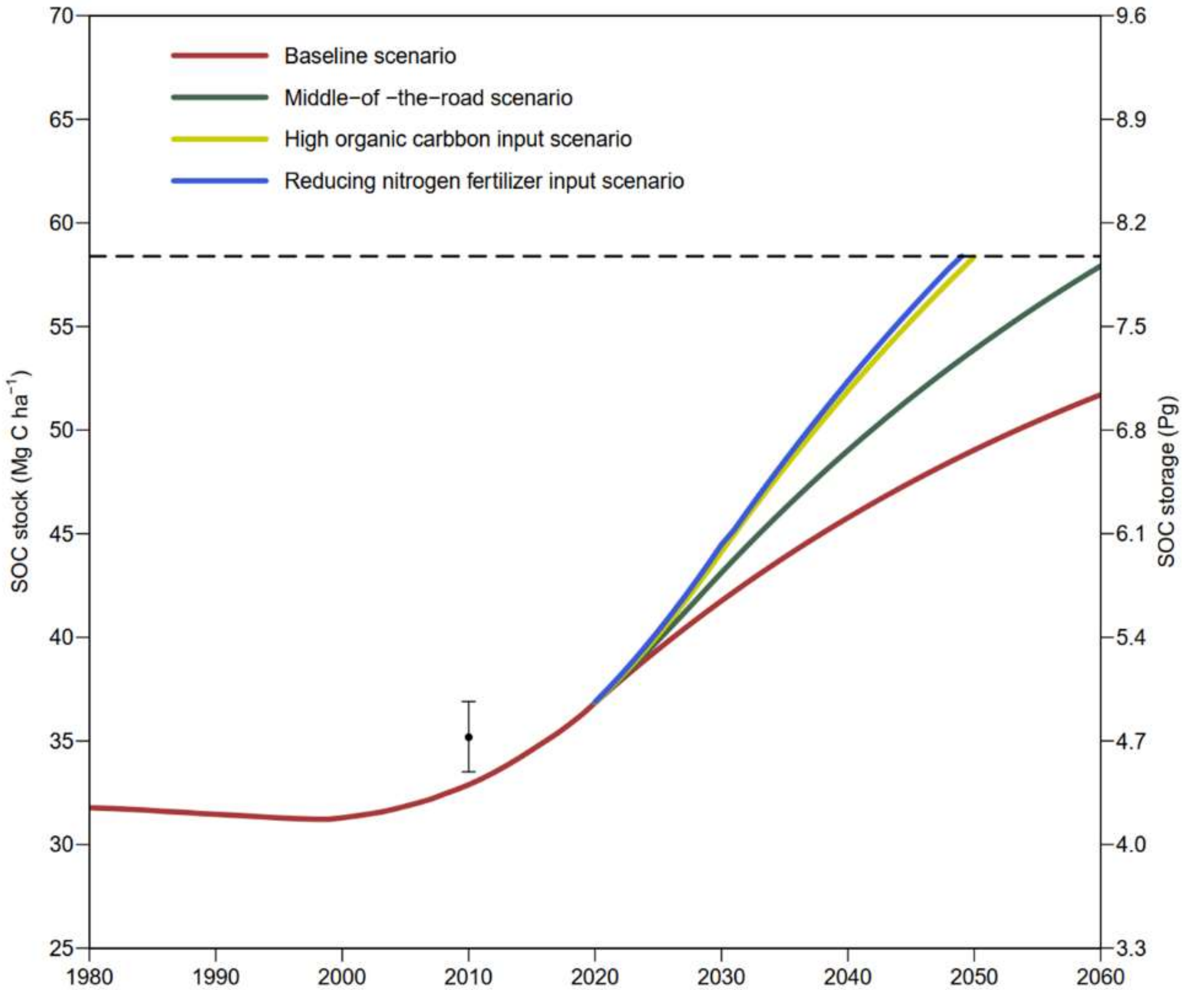

Fig. 4. Trends in soil organic carbon (SOC) stock and storage in China's croplands under four scenarios by 2060. The black solid dot represents the actual value of SOC stock at the national scale in 2010. The dashed line represents the saturation value of SOC stock in croplands at the national scale.

4. Discussion

4.1. Estimation of soil organic carbon stock and its uncertainty

The overall changes in China's SOC stocks found in this study vary significantly from the estimates in existing studies, as revealed by the comparison in Table S4. The national average SOC sequestration rate observed in this study was 34.2% and 53.5% higher than those based on measured data with 224 (Yu et al., 2009) and 1394 samples (Yan et al., 2011), respectively, and 19.1% less than that based on measured data with 4060 samples (58 counties) (Zhao et al., 2018). Such differences in SOC stock change estimates might be attributed to the strikingly different sample sizes used in various studies. The SOC stock data used in this study are 3-4 orders of magnitude larger than the sample sizes used in previous studies. To verify whether higher-resolution data lead to more accurate estimates, we randomly selected data from 5% (named the 5% level) of the 7.5 million samples (named the 100% level) to recalculate the SOC stock in each county and then randomly selected 25 counties from each province to calculate the SOC stock at provincial, regional, and national scales. The deviation of the results at the 5% level from those at the 100% level can exceed 10% at the regional and provincial scales, indicating the bias induced by sample size (Table S5). Therefore, previous SOC estimates for China's croplands might be biased due to their small sample sizes (i.e., <0.1% of the sample size in the current study) (Zhao et al., 2018).

Uncertainty analysis showed that the uncertainty value of SOC stock in 2010 was 43.1% lower than that in 1980 at the national scale (Table S6). Similar results were found at the regional and provincial scales that SOC stock calculated based on more county samples in

2010 was more accurate. This result further confirms that higher-resolution data lead to more accurate estimates. Although based on 7.5 million soil samples from 2,209 counties, there are still some uncertainties in this study. The first uncertainty is that the bulk density used was estimated by six PTFs, which may lead to uncertainty in SOC stock estimation, especially given the compaction effect of long-term intensive agricultural production. Notably, the uncertainty caused by the inaccuracy of bulk density data, which is one of the main sources of uncertainty in SOC stock estimation (Schrumpf et al., 2011), can be reduced by integrating different PTFs (Xu et al., 2015; Zhou et al., 2019). Additionally, the trend in SOC stock changes estimated by the disparate PTFs remained similar in each PTF (Fig. S2), which indicated that predicting bulk density by combination of various PTFs obtained relatively accurate estimates of SOC stock in this study. Besides bulk density, another uncertainty source originates from stepwise regression model. Although as many as 2,209 and 952 counties were used to calculate the SOC stocks in 2010 and 1980, respectively, only 533 matched counties were ultimately used in the correlation and stepwise regression analysis due to the missing of relevant influence factors in some counties. Notably, these 533 counties are relatively evenly distributed in Northeast (68), North (64), East (112), Southwest (69), South (114), and Northwest China (106), and represent the typical cropping systems across China (Fig. S3). Therefore, the stepwise regression models obtained are representative.

4.2. Factors driving soil organic carbon stock change in China's croplands

At the national scale, the regression analysis revealed that SOC_{1980}, clay content, climate (MAP and MAT), and agricultural management practices (CR_{Cinput}, LM_{Cinput} and NF_{input}) were important factors in simulating SOC changes. The low initial SOC stock in China's croplands provided a large potential for SOC sequestration (Zhao et al., 2018). The initial SOC stock (31.78 Mg C ha^{-1}) in China's croplands in 1980 was significantly lower than the values of 53.2 Mg C ha^{-1} in Europe and 43-56 Mg C ha^{-1} globally (Lal, 2004; Smith et al., 1997; Smith et al., 2000) and was only approximately half of the potential saturation level (58.39 Mg C ha^{-1}) (Table S3). Soil with a high clay content can provide physical protection of organic carbon by spatially isolating organic carbon from microorganisms (Amato & Ladd, 1992; Yoo et al., 2011). Crop residues and livestock manure, the main organic carbon sources in cropland soil, can directly increase SOC in cropland (Mary et al., 2020; Xue et al., 2015; Zhao et al., 2015). The average crop residue and livestock manure inputs increased from 0.11 to 0.86 Mg C ha^{-1} and 0.38 to 0.52 Mg C ha^{-1} during 1980-2010, respectively (Fig. S4), and the net carbon inputs by crop residue and livestock manure reached 1.49 and 1.83 Pg during this period, respectively (Table S7). Moreover, correlation analysis (Fig. S5) shows that suitable nitrogen fertilizer input may accelerate SOC sequestration in soil by enhancing crop biomass production, while excessive nitrogen fertilizer input may constrain SOC sequestration by accelerating SOC decomposition and reducing carbon retention efficiency (Fang et al., 2014; Hijbeek et al., 2019; Lu et al., 2021; Six et al., 2006). China's average chemical fertilizer application rate is 328.5 kg ha^{-1}, 2.7 times higher than the world average (120 kg ha^{-1}) (China Ministry of Agriculture and Rural Affairs, 2015). Therefore, reducing nitrogen fertilizer input may be contributing to SOC sequestration.

Similar results revealed that initial SOC stock was identified as the most important factor in simulating SOC stock changes in different regions. Specially, cropland in Northeast China had the highest initial SOC stock (50.25 Mg ha^{-1}), which may explain the decrease in SOC, with a loss of 242.33 kg C ha^{-1} yr^{-1}. Most of the croplands in this region have a relatively short cultivation history that followed intensive conversion from natural land with a high initial SOC stock, and thus, the probability of cropland SOC loss is high (Yan & Gong, 2010; Yu et al., 2006). Climate (MAP and/or MAP) showed a significant contribution to SOC stock changes in Northeast (44.1%), East (24.5%), Southwest (19.3%), South (28.9%), and Northwest China (24.1%) (Fig. 4). Especially, the low MAT in Northeast China might mitigate the loss of SOC stock by reducing microbial activities (Davidson & Janssens, 2006; Knorr et al., 2005), and the high MAP in South China might decrease SOC mineralization and decomposition by changing the soil anaerobic environment (Table S8) (Olk et al., 2006).

Agricultural management practices (CR_{Cinput}, LM_{Cinput}, and NF_{input}) were also dominant factors affecting SOC stock changes in different regions. In South China, the high organic carbon input, 32.9% higher than the national average (Table S7), may explain why it had the highest SOC sequestration rate (227.33 kg C ha^{-1} yr^{-1}) among regions. In East China, with the above-average organic carbon input (Table S7), the SOC sequestration rate was only 126.0 kg C ha^{-1} yr^{-1}, approximately half of that in South China. This result may be mainly due to the excessive N fertilizer input, which was 71.2% higher than the national average (Table S8). In Northwest China, LM_{Cinput} was the most important factor affecting SOC stock changes besides SOC_{1980}, which directly increased SOC as an external organic carbon input. Agricultural management practices such as CR_{Cinput} and LM_{Cinput} did not enter the stepwise regression models in Northeast and North China. However, in Northeast China, the new carbon inputs from crop residue and livestock manure in this region were only 0.53 Mg C ha^{-1} yr^{-1}, far below the national average (0.82 Mg C ha^{-1} yr^{-1}) (Table S7), which may be another reason for SOC loss (Table S3). In North China, pH was negatively correlated with SOC stock change and explained 29.8% of the total variation (Fig. 4). Organic carbon input such as livestock manure and crop residue may indirectly contribute to SOC accumulation by lowering soil pH through organic acids released during decomposition in North China. Additionally, organic carbon input such as livestock manure can indirectly contribute to SOC accumulation by increasing crop biomass production and thereby increasing crop residue carbon input (Cai et al., 2019; Chen et al., 2017; Luo et al., 2018). These results imply that crop residue and livestock manure inputs would be effective agricultural measures to increase cropland SOC sequestration in different regions.

4.3. Policy implications based on scenario analysis

Our study confirmed that SOC sequestration in croplands can make a remarkable contribution to China's carbon neutrality. We identified the driving factors of SOC sequestration by stepwise regression analysis and quantified the contribution of SOC sequestration to carbon neutrality under dominant factors, mainly crop residue, livestock manure, and nitrogen fertilizer inputs through scenario analysis. Specially, increasing crop residue return is an effective measure to increase cropland SOC sequestration, which is consistent with previous studies (Zhang et al., 2017). Furthermore, our analysis provided insights for more differentiated management measures for crop residue return in different regions. As the direct return of crop residue by tillage in Northeast China may accelerate the mineralization of initial high SOC, it is recommended to adopt the “Lishu county mulching model” (Li & Wang, 2019), in which the ground is covered by slightly treated straw without tillage to increase the soil water retention capacity and maintain the initial high SOC content. In arid Northwest China, corn straw can be returned using “straw belt-mulching”, which is conducive to straw decomposition and transformation into SOC. Paddy fields in warm and humid South and East China can be managed by adopting residue return with deep tillage, which is an effective practice to facilitate organic matter accumulation in deep soil layers. However, high-cost and powerful deep-tillage machinery, which is required to carry out large-scale residue return with deep tillage, is not easily accessible to farmers. Therefore, current subsidy policies for residue return, such as cash rewards for farmers and discounts for deep-tillage machinery acquisition, need to be implemented on a sustained basis to increase the contribution of crop residue return to SOC sequestration.

Increasing the amount of livestock manure input has been verified to be a useful way to increase the SOC sequestration rate in croplands, thus facilitating the capture of more carbon. Promoting the input of livestock manure in nearby fields is prioritized in policies on resource utilization of livestock manure by MARAC and the Ministry of Ecology and Environment of China (General Office of the State Council of China, 2017; Ministry of Ecology and Environment of China, 2020). To promote potential SOC sequestration through livestock manure input, specialized standards, and requirements, such as the Technical Specification for Returning Livestock Manure to the Field (GB/T 25246), should be established and enforced. Moreover, an ecological compensation mechanism, i.e., subsidy policies regarding land, electricity, credit, taxation, etc., should be established to encourage livestock-breeding enterprises to be responsible for the return of livestock manure. In addition, excessive livestock manure inputs may cause negative effects on soil and environmental quality, such as soil salinization, nutrient loss, and heavy metal contamination (Tang et al., 2019). Therefore, pursuing maximum SOC sequestration through excessive livestock manure application may not be feasible, and the amount of livestock manure input needs to be strictly controlled according to the Technical Guide for Measuring the Livestock Manure Bearing Capacity of Land established by MARAC (China Ministry of Agriculture and Rural Affairs, 2018). In addition, nonhazardous treatment standards should be formulated to prevent cropland contamination by livestock manure input.

Moreover, stepwise regression analysis revealed that high nitrogen fertilizer input may constrain SOC sequestration. Under the premise of ensuring food security, it seems that the reduction of nitrogen fertilizer input is crucial for SOC sequestration in China's croplands (Li et al., 2021). However, a 20% reduction in nitrogen fertilizer input based on scenario analysis only slightly increased SOC sequestration by no more than 1% over the next 40 years (Fig. 4). Notably, nitrogen fertilizer input per unit area has decreased from 0.174 Mg ha^{-1} to 0.136 Mg ha^{-1} during 2010-2020 (Fig. S4). This result indicates that further reduction in nitrogen fertilizer input in the future may not be an effective agricultural measure to increase SOC sequestration, but instead may adversely affect food security. Given this, the substitution of organics for chemical fertilizer is recommended as a feasible measure according to the “Fertilizer Use Zero-Growth Action Plan by 2020” policy of MARAC (China Ministry of Agriculture and Rural Affairs, 2015), as this measure not only enhances crop production but also promotes SOC sequestration (Wei et al., 2020). However, one major challenge facing organic fertilizer substitution is a severe shortage of farmers’ enthusiasm because additional labor and higher input costs are required. Life-cycle services, such as production, transportation, and application, for organic fertilizer substitution need to be established to reduce labor and fertilizer costs. Long-term gradual soil fertility improvement is required before farmers can harness significant economic benefits. Therefore, economic incentives should be established to compensate for the potential short-term losses experienced by farmers who adopt organic fertilizer substitution practices. In fact, farmers are directly involved in the three aforementioned policies (crop residue return, livestock manure input, and fertilizer reduction) related to cropland carbon sequestration management. As the main purpose of agricultural management by farmers is to maximize economic benefits, a “win–win” solution in terms of farmers’ economic benefits and soil carbon sequestration must be found.

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CRediT authorship contribution statement

Wengang Zuo and Binxian Gu: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. Xiaowei Zou, Kun Peng, and Siqiang Yi: Methodology, Investigation, Software. Yuli Shan and Yuhua Shan: Methodology, Writing – review & editing. Chuanhui Gu and Yanchao Bai: Conceptualization, Writing – review & editing. All authors have read and agreed to the published version of the manuscript.

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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