ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE
10.1029/2025EF007810

Key Points:

- The farmland management unit (FMU) integration contributes significantly to Soil organic carbon (SOC) sequestration
- Well-Facilitated Farmland Construction (WFC) offers substantial carbon sequestration potential
- Climate changes, optimizing irrigation, straw incorporation, and balancing nitrogen fertilization influence farmland SOC dynamics in future

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

S. Chen,
chensongchao@zju.edu.cn

Citation:

Wang, Z., Zhao, R., Xue, J., Lu, R., Chen, Z., Yu, Q., et al. (2026). A preliminary comparison of SOC storage between the traditional farmland and well-facilitated farmland management. *Earth's Future*, *14*, e2025EF007810. https://doi.org/10.1029/2025EF007810

Received 24 NOV 2025
Accepted 23 MAR 2026

Author Contributions:

Conceptualization: Zhou Shi
Formal analysis: Zheng Wang
Investigation: Zheng Wang, Jie Xue, Rui Lu, Zhongxing Chen, Wei Chen
Methodology: Zheng Wang, Ruiying Zhao, Jie Xue, Rui Lu, Zhongxing Chen, Qiangyi Yu, Qichun Zhang, Songchao Chen
Supervision: Qiangyi Yu, Qichun Zhang, Zhou Shi
Writing – original draft: Zheng Wang, Ruiying Zhao, Songchao Chen
Writing – review & editing: Zheng Wang, Ruiying Zhao, Qichun Zhang, Zhou Shi, Songchao Chen

A Preliminary Comparison of SOC Storage Between the Traditional Farmland and Well-Facilitated Farmland Management

Zheng Wang[1,2], Ruiying Zhao[3], Jie Xue[1,2], Rui Lu[1,2], Zhongxing Chen[1,2], Qiangyi Yu[4], Wei Chen[5], Qichun Zhang[1,2], Zhou Shi[1,2], and Songchao Chen[1,2]

[1]State Key Laboratory of Soil Pollution Control and Safety, Zhejiang University, Hangzhou, China, [2]Zhejiang Key Laboratory of Agricultural Remote Sensing and Information Technology, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China, [3]Department of Geography, National University of Singapore, Singapore, China, [4]State Key Laboratory of Efficient Utilization of Arable Land in China/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China, [5]Bureau of Agriculture and Rural Affairs of Jiashan County, Jiaxing, China

Abstract Soil organic carbon (SOC) is central to the global carbon cycle, yet unsustainable cultivation has resulted in a continuing SOC loss and has made it highly vulnerable to future climate change. In China, the Well-Facilitated Farmland Construction (WFC) initiative has sought to enhance soil conditions by integrating farmland management units (FMUs) and adopting improved practices, including optimized irrigation, straw incorporation, and targeted fertilization strategies. Since its launch in 2013, the WFC project has been implemented across more than 50 million hectares of farmland. However, its spatio-temporal impacts on SOC remain poorly understood. To address this gap, we focused on three representative regions, Shunyi, Rudong, and Dangtu, to examine the impact of farmland management unit integration. A total of 1,549 soil profiles were compiled to calibrate the CENTURY model and simulate long-term variations in topsoil (0–20 cm) SOC density (SOCD) across Chinese farmlands. Results show that, following the WFC project, farmland fragmentation decreased while SOCD increased, with strong negative correlations between fragmentation degree and SOCD. These findings indicate that farmland patch integration contributes significantly to SOC sequestration. According to the results of future simulation, the WFC practices would increase the farmland SOC storage under the SSP1-2.6 and SSP5-8.5 climate scenarios during the 2030–2100. This sustained increase reflects the CO_2 fertilization effect, enhanced crop productivity through optimized irrigation, greater organic inputs from straw incorporation, and reduced microbial decomposition under balanced nitrogen fertilization. In conclusion, WFC demonstrates a sustainable pathway toward more resilient and climate-smart food systems.

Plain Language Summary Soil organic carbon is vital for the carbon cycle, yet unsustainable farming has led to widespread SOC loss. In China, the Well-Facilitated Farmland Construction (WFC) initiative has sought to enhance soil conditions by integrating farmland management units (FMUs) and adopting improved practices. Since its launch in 2013, the WFC project has been implemented across more than 50 million hectares of farmland in China. However, its spatio-temporal impacts on SOC remain poorly understood. To address this gap, we used 1,549 soil profiles and the CENTURY model to analyzed farmland topsoil SOC density (SOCD) dynamics. Results show that reduced farmland fragmentation correlated with increased SOCD, indicating that farmland patch integration contributes to SOC sequestration. According to the results of future simulation, the WFC practices would increase the farmland SOC storage under the SSP1-2.6 and SSP5-8.5 climate scenarios during the 2030–2100 in Chinese farmlands. This sustained increase reflects the CO_2 fertilization effect, enhanced crop productivity through optimized irrigation, greater organic inputs from straw incorporation, and reduced microbial decomposition under balanced nitrogen fertilization. In conclusion, WFC demonstrates a scalable pathway toward more resilient and climate-smart food systems.

1. Introduction

Agricultural soil health is profoundly influenced by anthropogenic activities, including cultivation, irrigation, land resources integration, and other soil management practices (Chemnitz & Weigelt, 2015; Lal, 2013). Being a critical indicator of soil health, soil organic carbon (SOC) serves multiple essential functions, such as enhancing the water retention capacity, facilitating nutrient cycling, stabilizing the biochemical and physical environment, and contributing to climate regulation (Fontaine et al., 2007; Piao et al., 2010). These functions benefit soil quality and crop growth (Bationo et al., 2007; Chen et al., 2022; Rawls et al., 2003; Wiesmeier et al., 2019). However, global farmland SOC stocks have steadily declined under climate change and unsustainable management (Lessmann et al., 2021; Smith, 2004), emphasizing the need for practices that conserve and enhance SOC storage.

Most studies on the impact of management concentrated on the regional and local scales with isolated management, such as field following green measure and straw incorporation. The influence of these managements on SOC dynamics is generally achieved through improving carbon input and reducing the decomposition and oxidation process (Crystal-Ornelas et al., 2021; Davidson & Janssens, 2006; Hao et al., 2023; Liu et al., 2024). However, the farmland SOC change and sequestration cannot be solely regulated by one type of management approach, and are influenced by the comprehensive strategy. In China, the Well-facilitated Farmland Construction (WFC) Project is unique in being the largest coordinated farmland management initiative in the world that explicitly integrates soil health, food security, and carbon sequestration at the national scale (National Development and Reform Commission, 2021).

Unlike isolated or local interventions, WFC promotes systematic improvements through irrigation infrastructure, systematic straw incorporation, precision fertilization, minimum soil thickness requirements, and consolidation of fragmented farmland into unified management units (National Development and Reform Commission, 2021). This integrated framework not only secures grain yield and resilience but also represents an unprecedented opportunity for enhancing SOC storage across vast agricultural landscapes, positioning WFC as a potential model for national-scale soil carbon sequestration strategies. Yet, the long-term SOC trajectories under WFC, particularly under climate change, remain uncertain, leaving a critical knowledge gap for both science and policy.

Assessing management impacts on SOC is therefore a priority for agricultural planning and environmental policy (Katsalirou et al., 2010; Ouyang et al., 2014). Traditional monitoring methods, though precise, are costly, labor-intensive, and spatially limited (Falloon & Smith, 2002; Laskar & Mukherjee, 2016). Advances in remote sensing and machine learning (ML) have enabled large-scale SOC prediction (Mahmoudzadeh et al., 2020; Minasny et al., 2024; Orton et al., 2014; Szatmári et al., 2021; Wang et al., 2024; Zhang, Chen, et al., 2023), but these approaches depend on multi-period sampling for training and face challenges with extrapolation, often producing unrealistic spatial estimates. Process-based models provide a complementary approach by simulating SOC dynamics based on carbon turnover mechanisms (Liu et al., 2021; Ogle et al., 2010; Yu et al., 2017; Zhang et al., 2024). The CENTURY model, in particular, has been widely applied to farmlands, incorporating both climate variables and management practices such as irrigation, fertilization, and crop type (Bhattacharyya et al., 2007; Chen et al., 2025; Falloon & Smith, 2002; Parton, 1996; Zhao et al., 2023). This makes it a valuable tool for exploring long-term SOC responses to management and climate change.

This study is the first to integrate soil investigation data, remote sensing, and the CENTURY model to evaluate large-scale SOC dynamics under the WFC Project. Our objectives were: (a) to examine the relationship between FMU integration and SOC dynamics, and (b) to compare projected SOC changes (2030–2100) under well-facilitated farmland versus traditional management systems across different climate scenarios. Linking national-scale farmland management with long-term SOC projections, this work highlights the role of WFC not only in sustaining agricultural productivity but also as a cornerstone of national carbon sequestration strategy. It thereby offers a comprehensive understanding of how large-scale climate-smart agriculture impacts SOC dynamics, which is crucial for formulating effective land-use policies.

2. Materials and Methods

2.1. Study Area

2.1.1. Environmental Conditions and Farmland Distribution Across China

Situated in the eastern Eurasian continent (75°−135°E, 3°−50°N), China spans tropical, temperate, and cold climate zones, dominated by the distinct monsoon and continental climate systems (Figure 1). The topography across China is highly complex, transitioning from mountainous regions in the west to plains in the east, with altitude dropping from over 4,000 m to below 30 m. The varied environmental conditions resulted in many different soil types of farmland, such as Chernozem, Cinnamon soil, Red soil, Loess soil, and Paddy soil. The complex interplay of climatic gradients, topographic features, and soil diversity creates distinct agroecological zones that influence regional farming practices and crop productivity patterns. The farmland area of China covers

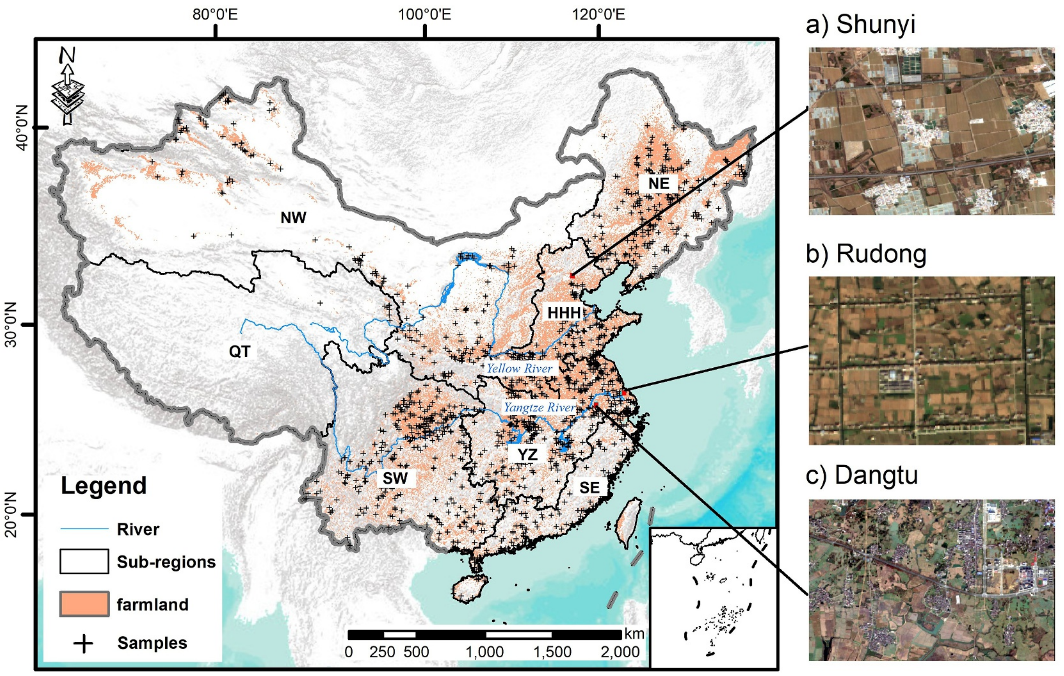

Figure 1. The location of three case areas (Shunyi, Rudong, and Dangtu), the distribution of farmland in China and construction sub-regions divided into well-facilitated farmland construction. The sub-regions include Huanghuaihai (HHH), Northeast (NE), Northwest (NW), Qinghai-Tibet (QT), Southeast (SE), Southwest (SW), and Middle and Lower of the Yangtze River (YZ).

approximately 1.8 million km^2 and is mainly distributed in the eastern plains and southwestern basins (Figure 1), notably the Northeast Plain, North Plain, Middle-lower Yangtze Plain, and Sichuan Basin. The primary crops across these regions include corn, wheat, and rice.

2.1.2. Well-Facilitated Farmland Construction (WFC)

In the past, the farmland management system suffered from inconsistent practices, with traditional farmland relying on empirical approaches that potentially degraded soil quality and limited crop productivity. To address these issues, the Chinese government implemented the WFC project, an integrated strategy for food security and agricultural modernization through standardized farmland management protocols (National Development and Reform Commission, 2021). For better construction, the study area was divided into seven sub-regions according to the characteristics of the natural environment and agricultural activities, including the Huanghuaihai area (HHH), Northeast area (NE), Northwest area (NW), Qinghai-Tibet area (QT), Southeast area (SE), Southwest area (SW), and Middle and Lower of the Yangtze River area (YZ) (Ding et al., 2019; Wang et al., 2023; Xiao et al., 2024; Zhou, Wang, et al., 2025). Besides, the WFC project proposed scientific approaches for agricultural operations to improve soil quality, enhance crop yield, and promote agricultural sustainability. Notably, the WFC project suggested that the management should integrate the small plots of farmland, aiming to reduce the fragmentation of the farmland, which might directly or indirectly influence the SOC spatio-temporal variation. Besides, several practices emphasized improving the soil environment related to SOC evolution, including irrigation systems to maintain optimal soil moisture levels, systematic straw incorporation to increase soil organic matter (SOM) content, and regulated fertilization programs based on soil nutrient diagnostics.

2.2. Data Collection

This study aimed to explore the spatio-temporal dynamics of soil organic carbon density (SOCD) using the CENTURY model. To ensure robust model simulations, we collected the high-quality data set: (a) the spatial distribution of Chinese farmland derived from the China Land Cover Data set (CLCD); (b) soil information from the National Soil Series Survey and Compilation of Soil Series of China (2009–2019) and China Soil Information Grid; (c) future climate data obtained from ISIMIP3b. The details about these data sets are as follows.

2.2.1. Farmland Data

The Chinese farmland was extracted from the CLCD, which represents one of the most accurate and comprehensive land cover products currently available for China (Yang & Huang, 2021). This data set was generated through integrating China's Land-Use/Cover Data sets (CLUD) and extensive reference data derived from the visually interpreted samples from time-series satellite data, Google Earth, and Google Maps. The Random Forest classifier was trained and used to identify different land cover types, and then a post-processing method incorporating spatial-temporal filtering and a logical reasoning method was applied to carry out the proposed approach to improve the spatio-temporal consistency. Finally, the CLCD at a spatial resolution of 30 m was produced by Random Forest using 335,709 Landsat images, with an accuracy of CLCD reaching 79.31 %. We selected farmland extracted from CLCD as the base map, and the extent of farmland is shown in Figure 1.

2.2.2. Soil Data

The soil sampling data were collected from the National Soil Series Survey and Compilation of Soil Series of China (2009–2019) (Chen et al., 2024; Liu et al., 2022). This data set contained detailed soil information, including soil profile depth, SOC, bulk density (BD), soil pH, soil texture (sand, silt, and clay), and coarse particles with a diameter of >2 mm. In addition, we also collected the digital map of soil properties from the China Soil Information Grid, which was delineated by the Digital Soil Mapping technology using the National Soil Series Survey and Compilation of Soil Series of China soil samples (Liu et al., 2022). In this study, these two soil data sets were utilized to calibrate and test the model performance and simulate the SOC dynamics on all farmland, respectively. We focused on the SOC changes in topsoil (0–20 cm) in farmland, as this soil layer is most directly influenced by agricultural practices. Soil property data sets were recorded by soil horizons at various intervals in profiles and contain the soil information of other land use types (e.g., farmland, forest, grassland and others), so we first selected the sample site on the farmland based on the CLCD farmland distribution data; then the equal-area spline method was used to obtain soil information at 0–20 cm depth (Bishop et al., 1999; Odgers et al., 2012).

2.2.3. Climate Data

Future climate data for driving the CENTURY model simulation were obtained from complementary sources covering 2022–2100 and were obtained from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b), including five climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2HR, MRI-ESM2-0, and UKESM1-0-LL) which selected from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Lange, 2021). This future climate data set consists of three Shared Socioeconomic Pathways and Representative Concentration Pathway (SSP1-2.6, SSP3-7.0, and SSP5-8.5) (Meinshausen et al., 2020). SSP1-2.6 represented the Green road and sustainability development; SSP3-7.0 was a Rocky Road, and the development would be influenced by the regional rivalry; SSP5-8.5 was the fossil-fueled rapid development way. Under these three climate scenarios, the global temperature would be warmer by 1.5°C, 2.5°C, and more than 4°C, respectively. In this study, we selected the SSP1-2.6 and SSP5-8.5 climate scenarios, which not only represent the lowest and highest SSP stabilizing the CO_2 emission post-2100, but also represent the sustainable development pathway and rapid development pathway, respectively. In addition, we averaged the simulation results for each representative scenario, aiming to minimize the differences among every climate scenario provided by the ISIMIP3b data set (Zhang, Ding, et al., 2023).

2.3. CENTURY Model

2.3.1. Brief Introduction

The CENTURY model was originally developed to simulate long-term carbon dynamics in grassland and has been extended to forest and farmland systems (Parton, 1996). This well-developed model features a modular structure comprising four submodels: the SOC submodel, plant biomass submodel, soil water balance submodel, and N submodel. The SOC submodel incorporates surface and below-ground structural and metabolic pools, along with active, slow, and passive SOC pools (Bandaranayake et al., 2003). Given that the default parameters of CENTURY v4.7 were calibrated based on US ecosystems, which may not be applicable to ecosystems in China. Therefore, the localized parameters for crop rotation and tillage management (e.g., tillage, fertilization amount,

Table 1
The Key Parameters of Traditional Farmland and Well-Facilitated Farmland for the CENTURY Model Simulation

Area	Farmland management	Irrigation	Harvest	Fertilization
HHH	Traditional farmland	0.30 (wheat) 0.55 (corn)	0.10	15 (wheat) 13 (corn)
	Well-facilitated farmland	0.80 (wheat) 0.70 (corn)	0.40	22 (wheat) 20 (corn)
NE	Traditional farmland	0.25 (corn)	0.10	8 (corn)
	Well-facilitated farmland	0.65 (corn)	0.40	15 (corn)
NW	Traditional farmland	0.30 (wheat)	0.10	10 (wheat)
	Well-facilitated farmland	0.80 (wheat)	0.40	18 (wheat)
QT	Traditional farmland	0.25 (highland barley)	0.10	10 (highland barley)
	Well-facilitated farmland	0.70 (highland barley)	0.40	15 (highland barley)
SE	Traditional farmland	0.30 (wheat) 0.7 (rice)	0.10	4 (wheat) 10 (rice)
	Well-facilitated farmland	0.80 (wheat) 0.9 0 (rice)	0.40	10 (wheat) 15 (rice)
SW	Traditional farmland	0.30 (wheat) 0.70 (rice)	0.10	10 (wheat) 8 (rice)
	Well-facilitated farmland	0.80 (wheat) 0.90 (rice)	0.40	15 (wheat) 10 (rice)
YZ	Traditional farmland	0.30 (wheat) 0.70 (rice)	0.10	6 (wheat) 10 (rice)
	Well-facilitated farmland	0.80 (wheat) 0.90 (rice)	0.40	16 (wheat) 10 (rice)

irrigation rate, and harvest fraction) were collected (see Section 2.3.2) to adapt the model suitable for simulate the SOC dynamics in China (National Development and Reform Commission, 2021).

2.3.2. The Key Parameters Setup Under Different Farmland Management

The differences of future (2030–2100) SOCD dynamics in traditional farmland and well-facilitated farmland were compared by adjusting the specific key parameters regarding management practices (Table 1). According to the WFC project plan, irrigation, harvest, and fertilization were the primary changing factors influencing SOCD in farmland. Therefore, these three critical management parameters were adjusted in the CENTURY model: (a) irrigation (IRRI), defined as the fraction of available water holding capacity triggering automatic irrigation; (b) harvest (HARV), the fraction of aboveground live that will not be affected by harvest operations; (c) fertilization (FERT), the amount of nitrogenous (N) fertilizer to be application rate. In this study, the parameters set for traditional farmland were based on field investigation, expert experience, and related references, while the parameters set for well-facilitated farmland were based on the references and recommendations based on the relevant documents from the agriculture department, which are most suitable for crop growth and soil environment. The parameter settings were referenced from the following literature and the statistical yearbook (Liang et al., 2023; Lu et al., 2009; Ren et al., 2022; Wang et al., 2025; Yin et al., 2020; Yu et al., 2022). Taking the parameters in HHH sub-region as an example, the parameter of irrigation for traditional farmland were 0.30 and 0.55 for wheat and corn, which means the irrigation would be carried out when available water holding capacity below 30% for wheat and 55% for rice; the parameter of the harvest was 0.10, meaning that only aboveground lives of 10% were left (straw incorporation) and others were harvested; the fertilization parameter indicated the accounts of fertilizer utilization for crop growth, which was the 15 g N m^{-2} for wheat and 13 g N m^{-2} for corn.

The CENTURY model could simulate carbon cycling dynamics in soil and vegetation systems under climatic drivers. Firstly, the spin-up procedure was conducted to make the SOC dynamics stable; then the calibrating parameters related to soil properties, agricultural practices, and crop rotation systems were input to the CENTURY model, and the model was applied with future climate data to project the spatio-temporal variation of farmland SOC in this study.

10.1029/2025EF007810

2.3.3. Model Calibration and Validation

In this study, the CENTURY model simulations were optimized for every sub-region. Soil samples were collected from each sub-region with the following distribution: HHH ($n = 178$), NE ($n = 247$), NW ($n = 177$), QT ($n = 8$), SE ($n = 176$), SW ($n = 322$), and YZ ($n = 441$). For each sub-region, the samples were randomly split into a calibration data set (70%), and a testing data set (30%), and were applied to evaluate the model performance by comparing the year of observations with the same year of the CENTURY simulation results. The coefficient of determination (R^2) and the root mean square error (RMSE) were selected to evaluate the CENTURY model. The equations are as follows:

$$R^2 = 1 - \frac{\sum_i^n (\hat{y}_i - y_i)^2}{\sum_i^n (y_i - \bar{y})^2} \tag{1}$$

$$\text{RMSE} = \sqrt{\frac{\sum_i^n (\hat{y}_i - y_i)^2}{n}} \tag{2}$$

where n represents the number of samples, y_i and $\hat{y}_i$ are the observations and predictions for sample i, respectively. $\bar{y}$ is the average of observations. These indicators were calculated in R 4.2.1 (R Core Team, 2022).

2.4. Farmland Management Unit

This study explores the relationship between the consolidation of FMUs and variations in SOCD. An FMU is defined as a contiguous area of farmland or a set of discrete patches under unified management (Zangue et al., 2022; Zhang et al., 2010; Zhao et al., 2024). In our study regions, a transition from "small farmland" to "large farmland" occurred under the WFC project, where managers consolidated fragmented plots into larger FMUs. Following guidance from the Ministry of Agriculture and Rural Affairs of the People's Republic of China, we selected three representative areas undergoing this transition. The CENTURY model was employed to simulate SOCD changes at an annual time step from 2018 to 2025 within these case areas. To do this, farmland patches were delineated through visual interpretation of Sentinel-2 imagery (10 m spatial resolution). Images from May to September with the least cloud cover were selected annually to optimize the clarity of patch boundaries, as illustrated in Figure S1 in Supporting Information S1. The patches density (PD) is used to evaluate the fragmentation degree of FMU, and the equation of PD is as follows:

$$PD = \frac{N}{A} \tag{3}$$

where the N and A are the number of the FMU and the area of total farmland; the PD (patches km^{-2}) represents the density of farmland, the larger the value, the more scattered and fragmented the patches are.

3. Results

3.1. The Descriptive Statistics of Soil SOCD in the 2010s

The descriptive statistics of soil properties on the national scale and each sub-region are shown in Table 2 and Table S1 in Supporting Information S1, respectively. The SOCD of all farmland in China ranged from 0.06 to 18.90 kg m^{-2}, with an average value of 3.34 kg m^{-2}. The mean value in QT was 5.14 kg m^{-2}, which was much higher than the other sub-regions, following the SOCD in NE (4.20 kg m^{-2}), and the lowest SOCD area was HHH, with the average value of 2.47 kg m^{-2}. The coefficient of variation of SOCD was 56.9%, and the skewness and kurtosis values were 2.13 and 9.66, respectively, representing substantial spatial heterogeneity. Soil pH averaged at 6.74 with skewness and kurtosis of −0.17 and −1.00, suggesting that the soil exhibited slight acidity. The range of BD was between 0.45 and 2.06 g cm^{-3}, with an average of 1.30 g cm^{-3}. The mean sand, silt, and clay were 30%, 47%, and 24%.

Table 2
The Descriptive Statistics of Topsoil Soil Properties in 0–20 cm

Soil properties	Number	Min	Max	Mean	SD[a]	CV[b] (%)	Skewness	Kurtosis
SOCD (kg m^{-2})	1,549	0.06	18.90	3.34	1.90	56.9	2.13	9.66
pH	1,549	3.02	10.57	6.74	1.37	20.3	−0.17	−1.00
BD (g cm^{-3})	1,549	0.45	2.06	1.30	0.17	13.1	−0.14	1.92
Sand (%)	1,549	0.10	95.75	29.64	0.20	66.7	0.77	−0.10
Silt (%)	1,549	0.25	92.58	46.58	0.17	36.2	−0.13	−0.56
Clay (%)	1,549	0.66	93.77	23.78	0.12	50.0	1.08	2.19

[a]SD: standard deviation. [b]CV: coefficient of variation.

3.2. The Variation of FMU and SOCD From 2018 to 2023

To explore the relationship between the number of FMUs and spatio-temporal variation in SOCD, we analyzed three case areas: Shunyi, Rudong, and Dangtu. These areas completed major farmland consolidation projects in 2022, 2023, and 2021, respectively, and the entire construction period was within one or two years. We delineated FMUs and simulated SOCD changes between 2018 and 2023 using Sentinel-2 imagery and the CENTURY model. Results showed that from 2018 to 2023, the number of FMUs decreased in Shunyi (101–29) and Rudong (44–25), but notably increased in Dangtu (44–56) (Table S2 in Supporting Information S1). Soil organic carbon density trends corresponded with these changes; SOCD increased where farmland fragmentation was reduced (Shunyi and Rudong), indicating an inverse relationship between PD and SOCD (Figure 2).

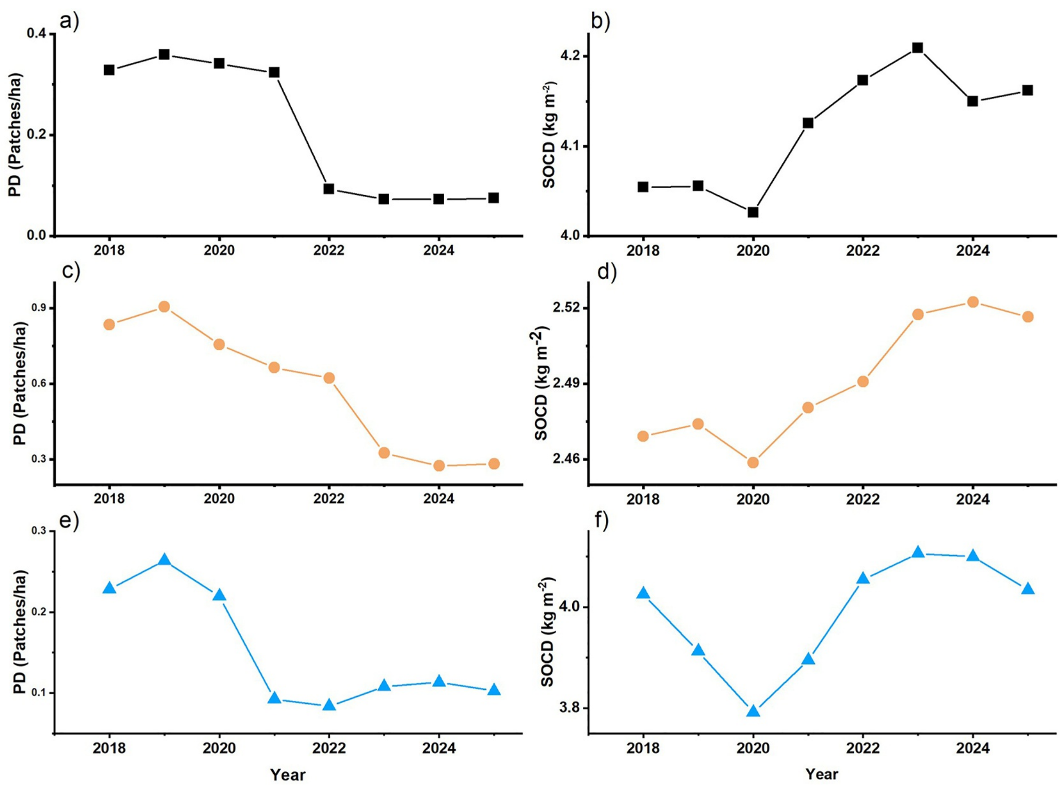

Figure 2. The variation of patches density and soil organic carbon density in the Shunyi (a) and (b), Rudong (c) and (d), and Dangtu (e) and (f) from 2018 to 2025.

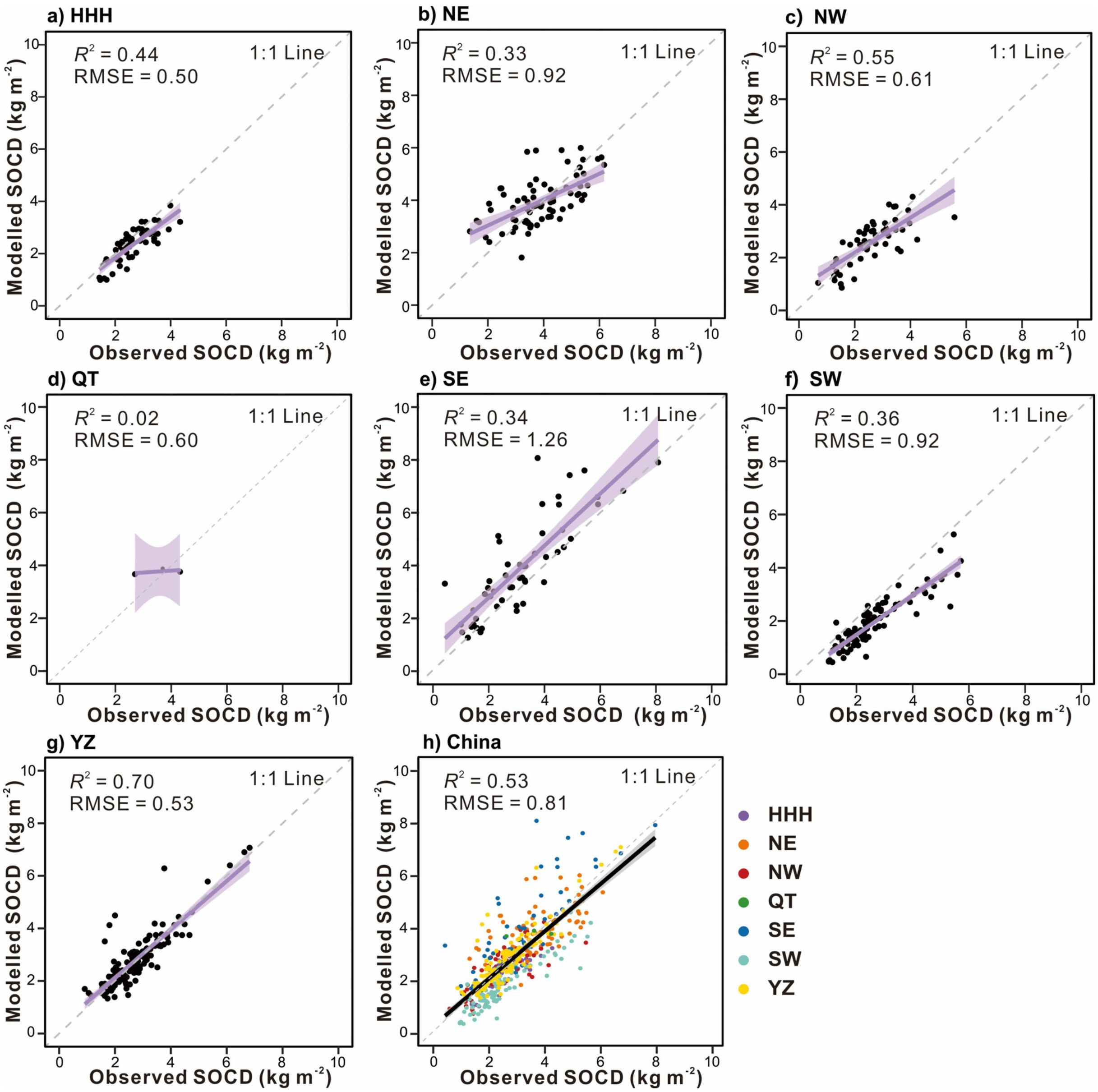

Figure 3. The performance of the CENTURY model for predicting the soil organic carbon density (SOCD) for each construction sub-region, with linear fits indicated by purple solid lines and 95% uncertainty intervals represented by shaded range.

3.3. Model Performance

The CENTURY model simulations of SOCD in Chinese farmland were conducted using comprehensive input data, including soil properties, climate data, and tillage management practices. Model parameters were subsequently calibrated for each sub-region to account for regional variations in natural environments and agricultural management practices. The model successfully captured the SOCD variations across Chinese farmland with an R^2 of 0.53 and RMSE of 0.81 kg m^{-2}, and the observations and simulations were well aligned around the 1:1 line (Figure 3). The sub-regions analysis revealed variation in model performance, with YZ exhibiting the best performance (R^2 = 0.70 and RMSE = 0.53 kg m^{-2}), while the QT showed the lowest accuracy (R^2 of 0.02 and RMSE of 0.60 kg m^{-2}). This discrepancy primarily reflected the challenge of SOCD simulation based on sparse soil sampling in the high-altitude area and the few farmlands distributed in the QT sub-region. Besides, the accuracy in the other sub-regions was between 0.33 and 0.55. Consequently, the model performance was acceptable and could reflect the SOCD spatio-temporal dynamics.

10.1029/2025EF007810

3.4. Future Spatial-Temporal Variation of SOCD

Future SOCD dynamics were projected using the CENTURY model to contrast two management scenarios: traditional practices (Figures 4a–4f) and WFC implementation (Figures 4g–4l), each under both the SSP1-2.6 and SSP5-8.5 climate pathways. The analysis revealed a persistent spatial pattern across all scenarios, with the highest SOCD values consistently found in the northeast (NE) and the lowest in the northwest (NW). However, the simulations highlighted two critical differences. First, for any given management practice, the high-emissions SSP5-8.5 pathway resulted in higher SOCD levels than the SSP1-2.6 pathway, a gap that became particularly pronounced in the NE by 2100 (e.g., Figure 4c vs. Figure 4f). Second, WFC practices consistently stored more carbon than traditional methods under the same climate scenario. For example, SOCD in 2100 under SSP1-2.6 was substantially higher in WFC farmland compared to its traditionally managed counterpart (Figure 4i vs. Figure 4c).

4. Discussion

4.1. The Relationship Between the FMU and SOCD Variation

Our analysis revealed a strong negative correlation between PD and SOCD, with correlation coefficients of −0.88, −0.94, and −0.52 (Table 3). This inverse relationship affirms the trends observed before and after the WFC project (Figure 2), indicating that consolidating fragmented FMUs significantly enhanced SOC storage. This finding is consistent with previous research showing that integrating management units can decrease greenhouse gas emissions, improve food security, and increase agricultural profits (Deng et al., 2024; Duan et al., 2021; Hao et al., 2023; Lu et al., 2025). For instance, Liu et al. (2024) indicated that reducing fragmentation could buffer soil carbon against the negative effects of agricultural intensification. The primary mechanism is the improvement of farm practices; land consolidation facilitates mechanized farming and boosts crop productivity, which in turn increases carbon input from plant residues (Pingali, 2007; Qing et al., 2019; Verma, 2006). Therefore, while reducing farmland fragmentation does not directly increase carbon input, it enables management changes that indirectly lead to a significant increase in SOC.

4.2. The Influence of the WFC Project on Future SOC in Farmland

The implementation timeline of the WFC project, initiated in 2013, varied across regions, with nationwide completion targeted for 2030. Therefore, this study designated 2030 as the critical transition point between traditional and well-facilitated farmland regimes. Comparative analysis of SOCD changes under different management and climate scenarios revealed a substantially greater SOC sequestration potential in well-facilitated farmland compared to traditional farmland, evident under both SSP1-2.6 and SSP5-8.5 climate pathways (Figures 5b–5e). Quantitatively, the WFC scenario is projected to increase cumulative SOC stocks by 3.34 Pg (0.048 Pg C yr^{-1}) under SSP1-2.6 and 2.86 Pg (0.041 Pg C yr^{-1}) under SSP5-8.5. This stands in stark contrast to the traditional management scenario, which projects a net loss or negligible gain (−0.107 Pg and 0.014 Pg, respectively) over the same period (Table 4).

The influence of climate change on SOC was highly dependent on the management system. Firstly, the SOC stocks would increase in the future under these two climate scenarios, and in a well-facilitated farmland system, both SOCD and SOC stocks were higher than in traditional farmland under both climate scenarios. This is likely due to the CO_2 fertilization effect, where elevated atmospheric CO_2 enhances plant productivity and subsequent soil carbon input (Harrison et al., 1993). Secondly, it was noted that SOC accumulation under SSP5-8.5 was lower than under SSP1-2.6. This discrepancy could be linked to the soil carbon saturation effect, where carbon storage efficiency declines or reaches zero once the soil nears its saturation threshold (Chen et al., 2019; Stewart et al., 2007). Additionally, previous studies have shown that elevated CO_2 concentration and climate warming can have counteracting effects, accelerating carbon decomposition and reducing SOC contents (Kirschbaum, 2000; Lin & Zhang, 2012). Therefore, the combined influence of soil carbon saturation and counteracting effects likely outweighed the benefits of CO_2 fertilization, leading to reduced SOC stocks accumulation under the SSP5-8.5 scenario.

Besides, the FMU was integrated and carried out the unified management practices, the irrigation, straw incorporation, and fertilization also contributed to the SOC sequestration. Adequate irrigation water could improve the SOC, especially in the topsoil (Emde et al., 2021). Furthermore, precision irrigation could balance the microbial

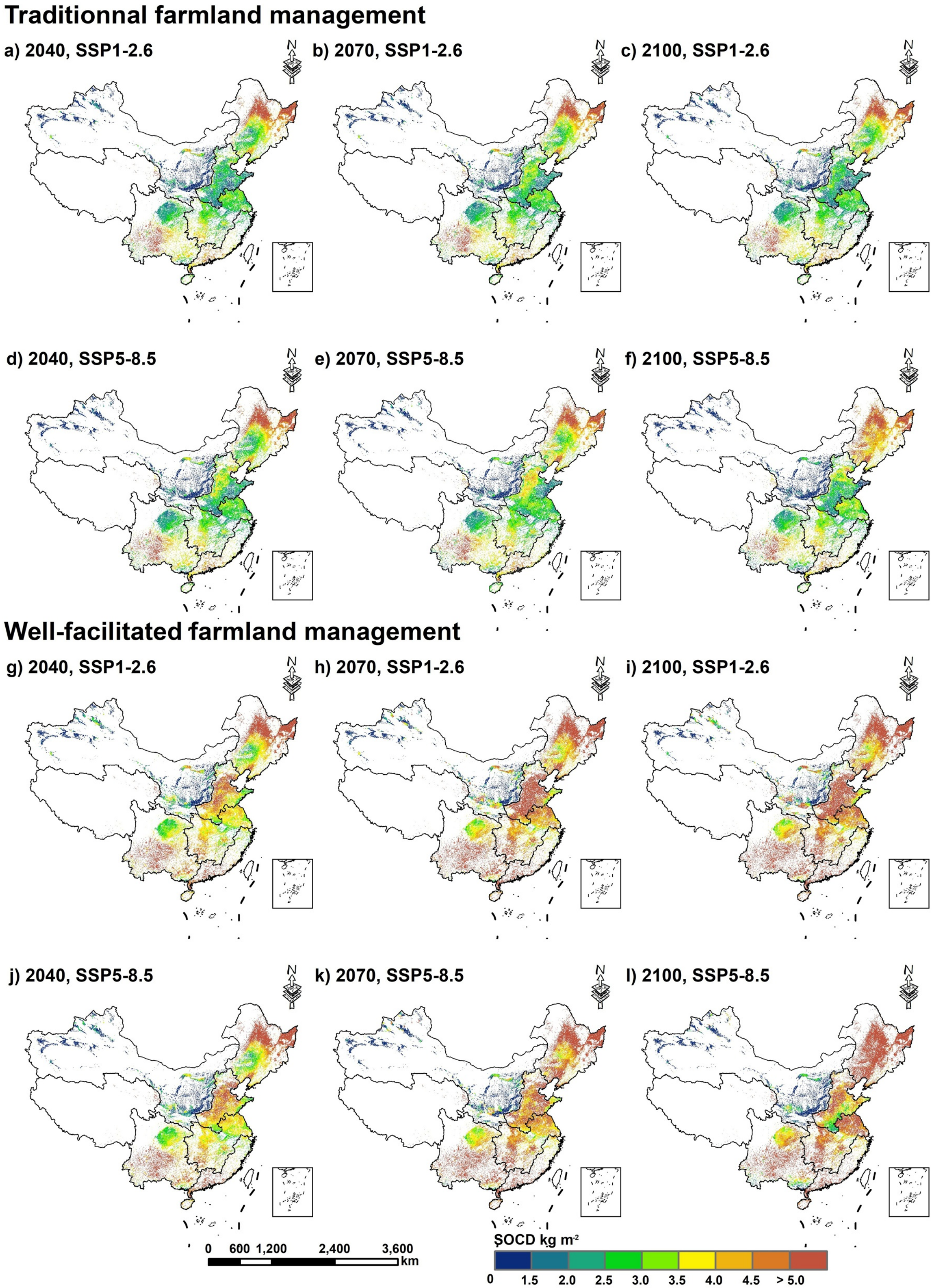

Figure 4. Spatial distribution of soil organic carbon density with traditional farmland management (a–f) and well-facilitated farmland construction management (g–l) in 2040, 2070 and 2100 under low and high carbon emission pathways (SSP1-2.6 and SSP5-8.5).

Table 3
The Correlation Analysis Between SOCD and PD in Shunyi, Rudong, and Dangtu Counties

	PD- Shunyi	PD-Rudong	PD-Dangtu
SOCD-Shunyi	−0.88[a]	\	\
SOCD-Rudong	\	−0.94[a]	\
SOCD-Dangtu	\	\	−0.52

[a]Represents significance at the 0.01 level.

activities and improve biomass production, thereby resulting in higher carbon input to the soil in the form of roots and dead plant material (Entry et al., 2002; Kochsiek et al., 2009; Roldán et al., 2005; Trost et al., 2013). Straw incorporation was an important way of carbon input in farmland and was influenced by anthropogenic management (Liu et al., 2014; Xin et al., 2024). Since the 1980s, the straw incorporation rate has increased from less than 20% to more than 40% (Liang et al., 2023). According to the study by Xin et al. (2024), SOC in Chinese farmland increased, and the increased rates of SOC on wheat, rice, and maize were 15.88%, 12.70%, and 12.42%, respectively. Well-Facilitated Farmland Construction farmland implemented the Soil Testing and Formulated Fertilization, it could accurately control and optimize nitrogen availability, reducing the microbial decomposition of SOM and increasing carbon sequestration (Li et al., 2017). Meanwhile, straw incorporation and nitrogen fertilization had synergistic effects as nitrogen fertilization potentiates the carbon sequestration benefits of straw incorporation (Alvarez, 2006).

In conclusion, the integrated strategies mandated by the WFC project are critical for transforming China's farmland into a reliable carbon sink. This framework not only boosts SOC sequestration far beyond traditional

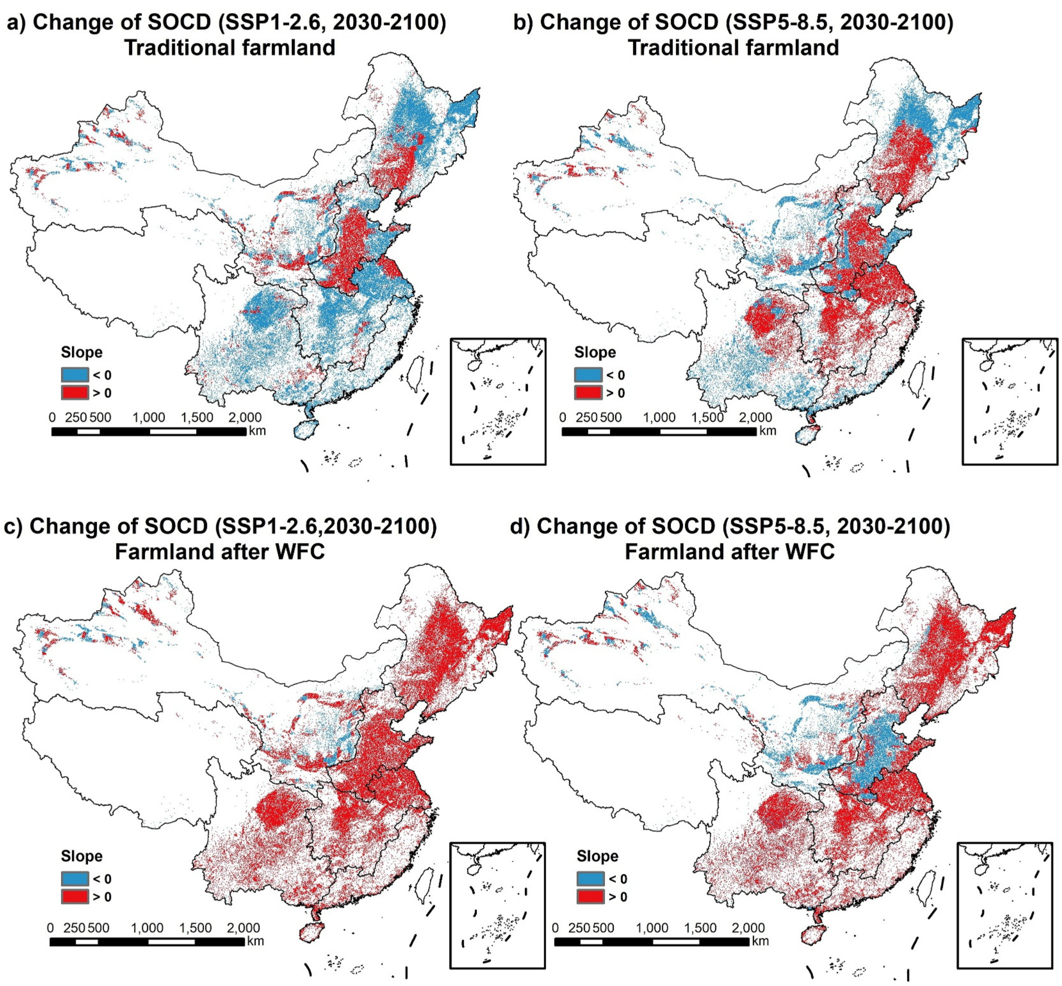

Figure 5. Spatial changes in topsoil (0–20 cm) soil organic carbon density (SOCD) during 2030–2100 under traditional farmland management (a) SSP1-2.6 and (b) SSP5-8.5) and well-facilitated farmland construction management (c) SSP1-2.6 and (d) SSP5-8.5). Changes in SOCD are represented by the slope, with positive values indicating an increasing trend and negative values indicating a decreasing trend.

Table 4
The Variations in SOC Storage (Pg) Under the Different Scenarios From 2030 to 2100

	SSP1-2.6		SSP5-8.5	
Area	TF[a]	WF[b]	TF	WF
HHH	−0.036	0.959	−0.064	0.450
NE	−0.023	0.579	0.206	0.916
NW	0.023	0.301	−0.100	−0.005
QT	−0.002	0.041	−0.007	0.029
SE	−0.008	0.172	0.001	0.204
SW	−0.032	0.680	−0.070	0.581
YZ	−0.029	0.604	0.048	0.688
China	−0.107	3.336	0.014	2.864

[a]TF: traditional farmland. [b]WF: well-facilitated farmland.

methods but also builds resilience against the complex and sometimes counterintuitive effects of future climate change.

4.3. Limitations and Perspectives

While this study provides valuable insights, we acknowledge two limitations that present clear opportunities for future research. First, our reliance on the CENTURY model, a classic C pool-based model, is a methodological constraint. The field is advancing toward models based on measurable carbon pools, which can be more directly validated with empirical data and may offer more robust simulations (van de Broek et al., 2025; Zhang et al., 2021). Future work should therefore employ these next-generation models to refine our projections. Second, our analysis was intentionally focused on topsoil (0–20 cm), the layer most directly influenced by agricultural management. However, as carbon dynamics in the topsoil are linked to those in deeper layers, a crucial next step is to extend our simulations to the entire soil profile (Zhou, Wei, et al., 2025; Zhu & Davis, 2025). This will provide a more holistic understanding of how WFC practices impact total ecosystem carbon sequestration. Finally, the process-based model involved many parameters that related to the soil properties, climate changes, crop growth, and others, so how to initialize the critical parameters remained a significant challenge for large-scale modeling. In the future study, we would try to use the knowledge-guided ML to explore these issues.

5. Conclusion

Restructuring agricultural landscapes through land consolidation represents a powerful, yet often overlooked, strategy for climate change mitigation. Our research demonstrates that China's vast farmlands, which exhibit significant baseline variability in SOC, can be transformed into a more potent carbon sink. We establish a strong inverse relationship between farmland fragmentation and SOCD, showing that the consolidation of management units under the WFC project directly enhances SOC sequestration. This finding provides a mechanistic link between landscape structure and soil health, confirming that policies targeting land tenure can yield significant biogeochemical benefits.

The future potential of this strategy is globally significant. Our projections indicate that the nationwide implementation of WFC practices could sequester an additional ∼3 Pg of carbon by 2100, turning a substantial portion of the nation's agricultural land into a net carbon sink. This remarkable potential is driven by a suite of synergistic improvements in management, including optimized irrigation, systematic straw incorporation, and precision fertilization, which together enhance carbon inputs while limiting decomposition losses.

Crucially, our findings reveal that the effectiveness of these interventions is tightly coupled with future climate pathways. The interplay between management intensity and climate drivers suggests that under the WFC system, the benefits of a high-emissions future may be constrained by soil carbon saturation and accelerated warming-induced decomposition, making a low-emissions pathway potentially more favorable for long-term carbon storage. This highlights the critical need to pursue land management and climate mitigation goals in concert.

Ultimately, China's WFC project serves as a compelling model for sustainable agricultural intensification. By addressing land fragmentation, it creates a triple-win scenario: strengthening national food security, improving soil health, and making a substantial contribution to global climate change mitigation. This approach offers a scalable pathway for other nations grappling with the dual challenges of agricultural productivity and environmental sustainability in a changing world.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The soil data, farmland data and climate data on which this article is based are available in Liu et al. (2022), Yang and Huang (2021), Wang (2025), and Lange (2021).

Acknowledgments
This work was supported by the National Key Research and Development Program of China (No. 2022YFB3903505; 2022YFB3903503), the Fundamental and Interdisciplinary Disciplines Breakthrough Plan of the Ministry of Education of China (JYB2025XDXM909), and the Innovation and Development Special Fund for Hangzhou West Science and Technology Innovation Corridor. We thank Budiman Minasny for his helpful comments on the manuscript.

References

Alvarez, R. (2006). A review of nitrogen fertilizer and conservation tillage effects on soil organic carbon storage. *Soil Use & Management*, *21*(1), 38–52. https://doi.org/10.1111/j.1475-2743.2005.tb00105.x

Bandaranayake, W., Qian, Y. L., Parton, W. J., Ojima, D. S., & Follett, R. F. (2003). Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. *Agronomy Journal*, *95*(3), 558–563. https://doi.org/10.2134/agronj2003.5580

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., & Kimetu, J. (2007). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, *94*(1), 13–25. https://doi.org/10.1016/j.agsy.2005.08.011

Bhattacharyya, T., Pal, D. K., Easter, M., Williams, S., Paustian, K., Milne, E., et al. (2007). Evaluating the century C model using long-term fertilizer trials in the indo-gangetic plains, India. *Agriculture, Ecosystems and Environment*, *122*(1), 73–83. https://doi.org/10.1016/j.agee.2007.01.009

Bishop, T. F. A., McBratney, A. B., & Laslett, G. M. (1999). Modelling soil attribute depth functions with equal-area quadratic smoothing splines. *Geoderma*, *91*(1–2), 27–45. https://doi.org/10.1016/S0016-7061(99)00003-8

Chemnitz, C., & Weigelt, J. (2015). Soil atlas. Facts and figures about Earth, land and fields. *Heinrich-Böll Stiftung*.

Chen, S., Arrouays, D., Angers, D. A., Martin, M. P., & Walter, C. (2019). Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. *Soil and Tillage Research*, *188*, 53–58. https://doi.org/10.1016/j.still.2018.11.001

Chen, S., Arrouays, D., Mulder, V. L., Poggio, L., Minasny, B., Roudier, P., et al. (2022). Digital mapping of GlobalSoilMap soil properties at a broad scale: A review. *Geoderma*, *409*, 115567. https://doi.org/10.1016/j.geoderma.2021.115567

Chen, Z., Chen, L., Lu, R., Lou, Z., Zhou, F., Jin, Y., et al. (2025). A national soil organic carbon density dataset (2010-2024) in China. *Scientific Data*, *12*(1), 1480. https://doi.org/10.1038/s41597-025-05863-3

Chen, Z., Xue, J., Wang, Z., Zhou, Y., Deng, X., Liu, F., et al. (2024). Ensemble modelling-based pedotransfer functions for predicting soil bulk density in China. *Geoderma*, *448*, 116969. https://doi.org/10.1016/j.geoderma.2024.116969

Crystal-Ornelas, R., Thapa, R., & Tully, K. L. (2021). Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. *Agriculture, Ecosystems and Environment*, *312*, 107356. https://doi.org/10.1016/j.agee.2021.107356

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Deng, O., Ran, J., Huang, S., Duan, J., Reis, S., Zhang, J., et al. (2024). Managing fragmented croplands for environmental and economic benefits in China. *Nature Food*, *5*(3), 230–240. https://doi.org/10.1038/s43016-024-00938-7

Ding, J., Wang, T., Piao, S., Smith, P., Zhang, G., Yan, Z., et al. (2019). The paleoclimatic footprint in the soil carbon stock of the Tibetan permafrost region. *Nature Communications*, *10*(1), 4195. https://doi.org/10.1038/s41467-019-12214-5

Duan, J., Ren, C., Wang, S., Zhang, X., Reis, S., Xu, J., & Gu, B. (2021). Consolidation of agricultural land can contribute to agricultural sustainability in China. *Nature Food*, *2*(12), 1014–1022. https://doi.org/10.1038/s43016-021-00415-5

Emde, D., Hannam, K. D., Most, I., Nelson, L. M., & Jones, M. D. (2021). Soil organic carbon in irrigated agricultural systems: A meta-analysis. *Global Change Biology*, *27*(16), 3898–3910. https://doi.org/10.1111/gcb.15680

Entry, J. A., Sojka, R. E., & Shewmaker, G. E. (2002). Management of irrigated agriculture to increase organic carbon storage in soils. *Soil Science Society of America Journal*, *66*(6), 1957–1964. https://doi.org/10.2136/sssaj2002.1957

Falloon, P., & Smith, P. (2002). Simulating SOC changes in long-term experiments with RothC and CENTURY: Model evaluation for a regional scale application. *Soil Use & Management*, *18*(2), 101–111. https://doi.org/10.1111/j.1475-2743.2002.tb00227.x

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., & Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, *450*(7167), 277–280. https://doi.org/10.1038/nature06275

Hao, W., Hu, X., Wang, J., Zhang, Z., Shi, Z., & Zhou, H. (2023). The impact of farmland fragmentation in China on agricultural productivity. *Journal of Cleaner Production*, *425*, 138962. https://doi.org/10.1016/j.jclepro.2023.138962

Harrison, K., Broecker, W., & Bonani, G. (1993). A strategy for estimating the impact of CO2 fertilization on soil carbon storage. *Global Biogeochemical Cycles*, *7*(1), 69–80. https://doi.org/10.1029/92GB02938

Katsalirou, E., Deng, S., Nofziger, D. L., & Gerakis, A. (2010). Long-term management effects on organic C and N pools and activities of C-transforming enzymes in prairie soils. *European Journal of Soil Biology*, *46*(5), 335–341. https://doi.org/10.1016/j.ejsobi.2010.06.004

Kirschbaum, M. U. F. (2000). Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry*, *48*(1), 21–51. https://doi.org/10.1023/A:1006238902976

Kochsiek, A. E., Knops, J. M. H., Walters, D. T., & Arkebauer, T. J. (2009). Impacts of management on decomposition and the litter-carbon balance in irrigated and rainfed no-till agricultural systems. *Agricultural and Forest Meteorology*, *149*(11), 1983–1993. https://doi.org/10.1016/j.agrformet.2009.07.004

Lal, R. (2013). Intensive agriculture and the soil carbon pool. *Journal of Crop Improvement*, *27*(6), 735–751. https://doi.org/10.1080/15427528.2013.845053

Lange, S. (2021). ISIMIP3BASD (version 2.5.0) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.4686991

Laskar, S., & Mukherjee, S. (2016). Optical sensing methods for assessment of soil macronutrients and other properties for application in precision agriculture: A review. *ADBU-Journal of Engineering Technology*, *4*, 206–210.

Lessmann, M., Ros, G. H., Young, M. D., & de Vries, W. (2021). Global variation in soil carbon sequestration potential through improved cropland management. *Global Change Biology*, *28*(3), 1162–1177. https://doi.org/10.1111/gcb.15954

Li, X. G., Jia, B., Lv, J., Ma, Q., Kuzyakov, Y., & Li, F.-m. (2017). Nitrogen fertilization decreases the decomposition of soil organic matter and plant residues in planted soils. *Soil Biology and Biochemistry*, *112*, 47–55. https://doi.org/10.1016/j.soilbio.2017.04.018

Liang, F., Li, B., Vogt, R. D., Mulder, J., Song, H., Chen, J., & Guo, J. (2023). Straw return exacerbates soil acidification in major Chinese croplands. *Resources, Conservation and Recycling*, *198*, 107176. https://doi.org/10.1016/j.resconrec.2023.107176

Lin, Z. B., & Zhang, R. D. (2012). Dynamics of soil organic carbon under uncertain climate change and elevated atmospheric CO_2. *Pedosphere*, *22*(4), 489–496. https://doi.org/10.1016/S1002-0160(12)60033-2

Liu, C., Lu, M., Cui, J., Li, B., & Fang, C. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology*, *20*(5), 1366–1381. https://doi.org/10.1111/gcb.12517

Liu, F., Wu, H., Zhao, Y., Li, D., Yang, J.-L., Song, X., et al. (2022). Mapping high resolution national soil information grids of China [Dataset]. *Science Bulletin*, *67*(3), 328–340. https://doi.org/10.1016/j.scib.2021.10.013

Liu, X., Lin, F., Bian, Z., & Dong, Z. (2024). Soil organic carbon sequestration can be promoted through the improvement of landscape configuration heterogeneity in typical agricultural regions of northeast China. *Journal of Environmental Management*, *370*, 122623. https://doi.org/10.1016/j.jenvman.2024.122623

Liu, X., Zhao, Y., Shi, X., Wang, S., Feng, X., & Yan, F. (2021). Spatio-temporal changes and associated uncertainties of CENTURY-Modelled SOC for Chinese upland soils, 1980-2010. *Chinese Geographical Science*, *31*(1), 126–136. https://doi.org/10.1007/s11769-021-1179-7

Lu, F. E. I., Wang, X., Han, B., Ouyang, Z., Duan, X., Zheng, H. U. A., & Miao, H. (2009). Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland. *Global Change Biology*, *15*(2), 281–305. https://doi.org/10.1111/j.1365-2486.2008.01743.x

Lu, R., Liao, R., Meng, R., Hu, Y., Zhao, Y., Guo, Y., et al. (2025). Strategic sampling for training a semantic segmentation model in operational mapping: Case studies on cropland parcel extraction. *Remote Sensing of Environment*, *331*, 115034. https://doi.org/10.1016/j.rse.2025.115034

Mahmoudzadeh, H., Matinfar, H. R., Taghizadeh-Mehrjardi, R., & Kersry, R. (2020). Spatial prediction of soil organic carbon using machine learning techniques in Western Iran. *Geoderma Regional*, *21*, e00260. https://doi.org/10.1016/j.geodrs.2020.e00260

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., et al. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Minasny, B., Bandai, T., Ghezzehei, T. A., Huang, Y. C., Ma, Y., McBratney, A. B., et al. (2024). Soil science-informed machine learning. *Geoderma*, *452*, 117094. https://doi.org/10.1016/j.geoderma.2024.117094

National Development and Reform Commission. (2021). National well-facilitated farmland construction plan. 2021-2030.

Odgers, N. P., Libohova, Z., & Thompson, J. A. (2012). Equal-area spline functions applied to a legacy soil database to create weighted-means maps of soil organic carbon at a Continental scale. *Geoderma*, *189*, 153–163. https://doi.org/10.1016/j.geoderma.2012.05.026

Ogle, S. M., Breidt, F. J., Easter, M., Williams, S., Killian, K., & Paustian, K. (2010). Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. *Global Change Biology*, *16*(2), 810–822. https://doi.org/10.1111/j.1365-2486.2009.01951.x

Orton, T. G., Pringle, M. J., Page, K. L., Dalal, R. C., & Bishop, T. F. A. (2014). Spatial prediction of soil organic carbon stock using a linear model of coregionalisation. *Geoderma*, *230–231*, 119–130. https://doi.org/10.1016/j.geoderma.2014.04.016

Ouyang, W., Shan, Y., Hao, F., & Lin, C. (2014). Differences in soil organic carbon dynamics in paddy fields and drylands in northeast China using the CENTURY model. *Agriculture, Ecosystems and Environment*, *194*, 38–47. https://doi.org/10.1016/j.agee.2014.05.003

Parton, W. J. (1996). The CENTURY model. In D. S. Powlson, P. Smith, & J. U. Smith (Eds.), *Evaluation of soil organic matter models. NATO ASI series* (Vol. 38, pp. 283–291). Springer. https://doi.org/10.1007/978-3-642-61094-3_23

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., et al. (2010). The impacts of climate change on water resources and agriculture in China. *Nature*, *467*(7311), 43–51. https://doi.org/10.1038/nature09364

Pingali, P. (2007). Agricultural mechanization: Adoption patterns and economic impact. *Handbook of Agricultural Economics*, *3*, 2779–2805. https://doi.org/10.1016/S1574-0072(06)03054-4

Qing, Y., Chen, M., Sheng, Y., & Huang, J. (2019). Mechanization services, farm productivity and institutional innovation in China. *China Agricultural Economic Review*, *11*(3), 536–554. https://doi.org/10.1108/CAER-12-2018-0244

Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, *116*(1–2), 61–76. https://doi.org/10.1016/S0016-7061(03)00094-6

R Core Team. (2022). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. (URL) Retrieved from https://cran.rproject.org/

Ren, P., Huang, F., & Li, B. (2022). Spatiotemporal patterns of water consumption and irrigation requirements of wheat-maize in the Huang-Huai-Hai plain, China and options of their reduction. *Agricultural Water Management*, *263*, 107468. https://doi.org/10.1016/j.agwat.2022.107468

Roldán, A., Salinas-García, J. R., Alguacil, M. M., & Caravaca, F. (2005). Changes in soil enzyme activity, fertility, aggregation and C sequestration mediated by conservation tillage practices and water regime in a maize field. *Applied Soil Ecology*, *30*(1), 11–20. https://doi.org/10.1016/j.apsoil.2005.01.004

Smith, P. (2004). Carbon sequestration in croplands: The potential in Europe and the global context. *European Journal of Agronomy*, *20*(3), 229–236. https://doi.org/10.1016/j.eja.2003.08.002

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2007). Soil carbon saturation: Concept, evidence and evaluation. *Biogeochemistry*, *86*(1), 19–31. https://doi.org/10.1007/s10533-007-9140-0

Szatmári, G., Pásztor, L., & Heuvelink, G. B. M. (2021). Estimating soil organic carbon stock change at multiple scales using machine learning and multivariate geostatistics. *Geoderma*, *403*, 115356. https://doi.org/10.1016/j.geoderma.2021.115356

Trost, B., Prochnow, A., Drastig, K., Meyer-Aurich, A., Ellmer, F., & Baumecker, M. (2013). Irrigation, soil organic carbon and N2O emissions. A review. *Agronomy for Sustainable Development*, *33*(4), 733–749. https://doi.org/10.1007/s13593-013-0134-0

Van de Broek, M., Govers, G., Schrumpf, M., & Six, J. (2025). A microbially driven and depth-explicit soil organic carbon model constrained by carbon isotopes to reduce parameter equifinality. *Biogeosciences*, *22*(5), 1427–1446. https://doi.org/10.5194/bg-22-1427-2025

Verma, S. R. (2006). Impact of agricultural mechanization on production, productivity, cropping intensity income generation and employment of labour. *Status of farm mechanization in India*, *2006*, 133–153.

Wang, N., Chen, S., Huang, J., Frappart, F., Taghizadeh, R., Zhang, X., et al. (2024). Global soil salinity estimation at 10 m using multi-source remote sensing. *Journal of Remote Sensing*, *4*, 0130. https://doi.org/10.34133/remotesensing.0130

Wang, X., Li, S., Wang, L., Zheng, M., Wang, Z., & Song, K. (2023). Effects of cropland reclamation on soil organic carbon in China's Black soil region over the past 35 years. *Global Change Biology*, *29*(18), 5460–5477. https://doi.org/10.1111/gcb.16833

Wang, Z. (2025). Farmland and SOCD [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.17696715

Wang, Z., Chen, S., Zhao, R., Xue, J., Yu, Q., Wei, D., et al. (2025). Modelling spatio-temporal dynamics of soil organic carbon in paddy soil by coupling digital soil mapping with a process model. *Journal of Integrative Agriculture*. https://doi.org/10.1016/j.jia.2025.11.006

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., et al. (2019). Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma*, *333*, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Xiao, L., Wang, G., Wang, E., Liu, S., Chang, J., Zhang, P., et al. (2024). Spatiotemporal co-optimization of agricultural management practices towards climate-smart crop production. *Nature Food*, *5*(1), 59–71. https://doi.org/10.1038/s43016-023-00891-x

Xin, J., Yan, L., & Cai, H. (2024). Response of soil organic carbon to straw return in farmland soil in China: A meta-analysis. *Journal of Environmental Management*, *359*, 121051. https://doi.org/10.1016/j.jenvman.2024.121051
Yang, J., & Huang, X. (2021). The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019 [Dataset]. *Earth System Science Data*, *13*(8), 3907–3925. https://doi.org/10.5194/essd-13-3907-2021
Yin, L., Feng, X., Fu, B., Chen, Y., Wang, X., & Tao, F. (2020). Irrigation water consumption of irrigated cropland and its dominant factor in China from 1982 to 2015. *Advances in Water Resources*, *143*, 103661. https://doi.org/10.1016/j.advwatres.2020.103661
Yu, D., Pan, Y., Zhang, H., Wang, X., Ni, Y., Zhang, L., & Shi, X. (2017). Equality testing for soil grid unit resolutions to polygon unit scales with DNDC modeling of regional SOC pools. *Chinese Geographical Science*, *27*(4), 552–568. https://doi.org/10.1007/s11769-017-0887-5
Yu, Z., Liu, J., & Kattel, G. (2022). Historical nitrogen fertilizer use in China from 1952 to 2018. *Earth System Science Data*, *14*(11), 5179–5194. https://doi.org/10.5194/essd-14-5179-2022
Zangue, Y. D., Melot, R., & Martin, P. (2022). Diversity of farmland management practices (FMP) and their nexus to environment: A review. *Journal of Environmental Management*, *302*, 114059. https://doi.org/10.1016/j.jenvman.2021.114059
Zhang, J., Gu, X., Wang, J., Huang, W., He, X., & Luo, J. (2010). Automatic extraction of farmland management unit based on moderate-resolution images. *Scientia Agricultura Sinica*, *43*(17), 3259–3537. https://doi.org/10.3864/j.issn.0578-1752.2010.17.006
Zhang, L., Heuvelink, G. B., Mulder, V. L., Chen, S., Deng, X., & Yang, L. (2024). Using process-oriented model output to enhance machine learning-based soil organic carbon prediction in space and time. *Science of the Total Environment*, *922*, 170778. https://doi.org/10.1016/j.scitotenv.2024.170778
Zhang, X., Chen, S., Xue, J., Wang, N., Xiao, Y., Chen, Q., et al. (2023). Improving model parsimony and accuracy by modified greedy feature selection in digital soil mapping. *Geoderma*, *432*, 116383. https://doi.org/10.1016/j.geoderma.2023.116383
Zhang, Y., Lavallee, J. M., Robertson, A. D., Even, R., Ogle, S. M., Paustian, K., & Cotrufo, M. F. (2021). Simulating measurable ecosystem carbon and nitrogen dynamics with the mechanistically defined MEMS 2.0 model. *Biogeosciences*, *18*(10), 3147–3171. https://doi.org/10.5194/bg-18-3147-2021
Zhang, Z., Ding, J., Zhu, C., Wang, J., Ge, X., Li, X., et al. (2023). Historical and future variation of soil organic carbon in China. *Geoderma*, *436*, 116557. https://doi.org/10.1016/j.geoderma.2023.116557
Zhao, N., Chen, K., Wu, X., Zhang, L., & Wang, W. (2024). Cropland fragmentation change across China over the last two decades. *Agricultural Systems*, *218*, 104010. https://doi.org/10.1016/j.agsy.2024.104010
Zhao, R., Zhang, W., Duan, Z., Chen, S., & Shi, Z. (2023). An improved estimate of soil carbon pool and carbon fluxes in the Qinghai-Tibetan grasslands using data assimilation with an ecosystem biogeochemical model. *Geoderma*, *430*, 116283. https://doi.org/10.1016/j.geoderma.2022.116283
Zhou, H., Wei, Y., Wang, M., Xiao, L., & Luo, Z. (2025). Enhancing whole-profile soil organic carbon predictions in croplands through a depth-resolved modelling approach. *Soil & Environmental Health*, *3*, 100156. https://doi.org/10.1016/j.seh.2025.100156
Zhou, Z., Wang, C., Li, Y. e., Wang, X., He, X., Xu, M., & Cai, A. (2025). Carbon gain in upper but loss in deeper cropland soils across China over the last four decades. *Proceedings of the National Academy of Sciences*, *122*(1), e2422371122. https://doi.org/10.1073/pnas.2422371122
Zhu, B., & Davis, C. (2025). Vulnerability of whole-soil carbon in a future warmer world. *Nature Reviews Earth and Environment*, *6*(5), 321. https://doi.org/10.1038/s43017-025-00677-8