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Effects of Residue Returning on Soil Organic Carbon Storage and Sequestration Rate in China's Croplands: A Meta-Analysis

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Abstract: Crop residue returning (RR) is a promising option to increase soil organic carbon (SOC) storage, which is linked to crop yield promotion, ecologically sustainable agriculture, and climate change mitigation. Thus, the objectives of this study were to identify the responses of SOC storage and sequestration rates to RR in China's croplands. Based on a national meta-analysis of 365 comparisons from 99 publications, the results indicated that RR increased SOC storage by 11.3% compared to residue removal ($p < 0.05$). Theoretically, when combined with low nitrogen fertilizer input rates (0–120 kg N ha⁻¹), single cropping system, paddy-upland rotation, lower mean annual precipitation (0–500 mm), alkaline soils (pH 7.5–8.5), other methods of RR (including residue chopping, evenly incorporating, and burying) or long-term use (>10 yrs), an increase in SOC storage under RR by 11.6–15.5% could be obtained. The SOC sequestration rate of RR varied from 0.48 (Central China) to 1.61 (Southwest China) Mg C ha⁻¹ yr⁻¹, with a national average value of 0.93 Mg C ha⁻¹ yr⁻¹. Higher SOC sequestration rates enhanced crop production. However, decreases in SOC sequestration rate were observed with increases in experimental durations. The phenomenon of “C saturation” occurred after 23 yrs of RR. Overall, RR can be used as an efficient and environmentally friendly and climate-smart management practice for long-term use.

Keywords: residue returning; SOC storage; SOC sequestration rate; meta-analysis

1. Introduction

Soil is the largest organic carbon (C) pool on earth [1]. The dynamics of soil organic carbon (SOC) can be used to indicate changes in SOC sequestration capacity (an indicator to evaluate C sequestration ability of soil, which depends on soil type, nutrient reserves, soil depth, etc. The C sequestration capacity could affect soil quality and mitigation function of climate change) and crop productivity [2,3]. Due to the large SOC stock, small fluctuations may cause large changes in atmospheric CO₂ concentration, finally affecting global climate changes. In this sense, increasing SOC sequestration is one of the most important strategies to reduce atmospheric CO₂ concentrations and to mitigate the greenhouse effect [4], with a significant potential to mitigate climate change [5].

The adoption of appropriate farming managements can reduce the mineralization and decomposition of organic matter (OM) and increase SOC storage [6]. Thus, increased C sequestration and reduced

greenhouse gas emissions [7] can be attributed to improved soil fertility, ultimately promoting crop production and economic viability [8].

Crop residue returning (RR), which means to return the aboveground and belowground biomasses into field after harvesting, is a worldwide recommended management practice due to the benefits in enhancing soil quality and productivity. RR can improve soil structure [9], increase systematic biodiversity [10], enhance SOC sequestration capacity, and partially replace fertilizer input [11], thereby increasing crop yield and farmland system production capacity [6,12] in a sustainable manner. Therefore, scientific and rational implementation of RR is critical to maintain soil quality, high crop production, and sustainability. RR can be affected by various factors such as tillage practices [13,14], returning mode [15], climatic conditions [16], and duration [17,18]. Previous studies on RR have mostly focused on single factors such as tillage practices [19], returning mode [20], returning amount [21], and nitrogen fertilizer input rate (NFIR) [6]. For example, a 7-yr field experiment in north-west China revealed that conservation tillage enhanced SOC storage compared to conventional tillage [19]. Similarly, Chalise et al. [20] suggested that mulch retention could be more beneficial to increase soybean yield and soil water storage compared with another returning mode (RR without cover crops). In a 12-yr experiment, the authors found that with an increasing residue amount, C sequestration was enhanced [21]. In a national meta-analysis conducted by Zhao et al. [6], optimal NFIR and RR could also increase SOC sequestration capacity. However, a more comprehensive analysis of the factors affecting SOC storage, particularly at a larger spatial scale, is lacking. In addition, the temporal changes in SOC sequestration under RR are not fully understood, making it essential to quantitatively analyze numerous research results.

Meta-analysis is a statistical method of quantitative comprehensive analysis of different results from similar studies to obtain a consistent conclusion [22–24]. This approach plays a crucial role in effectively revealing the changes, uncertainties, and potential impacts of key factors, especially in the study of large-scale ecological phenomena [23,25]. Thus, the objectives of this study were to (a) assess the effects of different RR methods, field management practices, and climate and soil resources on SOC storage under RR; (b) determine the SOC sequestration rate and its interactive relationships under RR; and (c) deepen the cognitions to adjust field management practices to increase SOC storage.

2. Materials and Methods

2.1. Data Collection

We collected peer-reviewed literature data before 2019, using the China Knowledge Resource Integrated Database and Web of Science. Search terms included “straw or residue” and “return or retention or incorporation or retain or mulch” and “soil organic carbon storage or stock”. To ensure the accuracy of the study, only studies that fulfilled the following criteria were used for this meta-analysis: (1) the experimental area was in China, and experimental duration, location, and other basic information were provided; (2) the experimental design included at least one pair of treatments with the same conditions under RR and RR removal; (3) SOC stock data were provided or could be calculated according to the data given in the papers; (4) definite replicate numbers were provided; (5) the experiment took place under field conditions. Based on the above criteria, a total of 99 eligible documents were obtained, including 28 in English and 71 in Chinese, and 365 pairs of experimental data were available for data analysis.

2.2. Data Preparation

Due to the different contents in different experiments, the data collected mostly lacked soil bulk density (BD) values; we therefore estimated the missing BD by using Equation (1) [26]:

$$y = 1.377e^{-0.0048x} \quad (1)$$

where y is the estimated value of BD, g cm^{-3} ; x is the SOC content, g kg^{-1} .

The SOC storage was computed using the equal mass method [27]:

$$M_{element} = \left[\sum_{i=1}^n M_{soil,i} \times conc_i + \left(M_j - \sum_{i=1}^n M_{soil,i} \right) \times conc_{extra} \right] \times 0.001 \quad (2)$$

$$M_{soil,i} = \rho_{b,i} \times T_i \times 10,000 \quad (3)$$

where $M_{element}$ is equivalent soil mass SOC storage, Mg ha^{-1} ; $i = 1$ and 2 represents 0–10 and 0–20 cm soil depth; M_j (Mg ha^{-1}) is the determined equivalent soil mass, according to how the researchers layered the soil and analyzed the specific layers; for instance, $j = 1$ and 2 means the maximum soil mass at depth of 0–10 and 0–20 cm under different practices (residue returning or residue removal), the corresponding values of n are 1, 2, or $j = 1, 2$, and 3 means the maximum soil mass at soil depth of 0–5, 0–10, and 0–20 cm under different practices; the corresponding values of n are 1, 2, and 3; $M_{soil,i}$ is the soil mass at each soil depth, Mg ha^{-1} ; $conc_i$ is the SOC content in each soil depth, kg Mg^{-1} ; $conc_{extra}$ is the added SOC content, kg Mg^{-1} ; $\rho_{b,i}$ is BD, Mg m^{-3} ; T_i is the thickness of the soil layer, m; 10,000 is the coefficient of area unit m^2 converted to ha; 0.001 is the coefficient of mass unit kg converted to Mg [28].

Based on the differences in SOC storage between treatment and control, we calculated the annual SOC sequestration rate (SOC_{sr} , $\text{Mg ha}^{-1} \text{ yr}^{-1}$) of China's croplands under RR, using the following Equation (4):

$$SOC_{sr} = \frac{(SOC_{stock})_t - (SOC_{stock})_c}{d} \quad (4)$$

where $(SOC_{stock})_t$ and $(SOC_{stock})_c$ represent SOC storage under RR and residue removal, respectively (Mg ha^{-1}); d is the returning duration (yr). Values greater than five times the SD value were deleted. To accurately calculate SOC sequestration rates while obtaining more samples, the data used were all obtained by setting the following screening criteria: returning duration ≥ 1 yr, SOC storage in the 0–20-cm soil layer was provided or could be calculated.

2.3. Data Analysis

We applied the software package MetaWin (ver. 2.1, Sinauer Associates Inc., Sunderland, MA, USA) for meta-analysis [29], taking the natural log of the response ratio (R) as the effect value ($\ln R$) and calculating the effect value of each pair of data by Equation (5) [30]:

$$\ln R = \ln\left(\frac{X_t}{X_c}\right) = \ln X_t - \ln X_c \quad (5)$$

where X_t is the SOC content (g kg^{-1}) under RR; X_c is the SOC content under residue removal. The corresponding weights of each effect value were obtained by Equation (6) [31,32]:

$$w = \frac{(n_t \times n_c)}{(n_t + n_c)} \quad (6)$$

where w is the weight of each $\ln R$, n_t and n_c are repeat numbers for RR and residue removal. The weighted average effect value and the 95% confidence interval (95% CI) were generated by bootstrapping (4999 iterations); between-group heterogeneity was assessed by using randomization procedures with 4999 replications [31,32]. If 95% CI did not overlap 0, the effect value was considered significant (95% CI > 0, significant increase; 95% CI < 0, significant decrease) ($p < 0.05$) [33,34]. If 95% CI contained 0, RR had no significant effect on SOC content. The percentage change (E , %) of the SOC content was calculated by Equation (7).

$$E = (e^{\ln R} - 1) \times 100\% \quad (7)$$

The Gaussian function was fitted by Equation (8):

$$y = a \times e^{-\frac{(x-x_0)^2}{2b^2}} \quad (8)$$

where x is the average value of $\ln R$ in the corresponding interval, y is the frequency (i.e., the number of $\ln R$) in each interval, and a is the coefficient of the expected value of $\ln R_{++}$ at $x = x_0$. The values of x_0 and b are the mean and variance of the $\ln R$ frequency distribution, respectively.

For mapping, we used SigmaPlot (ver. 12.5, Systat Software Inc., San Jose, CA, USA).

2.4. Categorical Meta-Analysis

Due to the large differences in climatic and soil conditions, field management practices, and RR methods in different agricultural production areas in China, to explore the impacts of each factor on SOC storage, we grouped the research data in various ways, using the categorical meta-analysis method to examine the impact of each specific factor on SOC storage, such as returning duration, tillage practice, cropping pattern, and land-use type (Table 1).

Table 1. Different categories in categorical meta-analysis of soil organic carbon (SOC) storage response to crop residue returning (RR).

Categorical Variables	Groups				<i>n</i>	Q_b	<i>p</i>
Irrigation	Irrigation	No irrigation			52	0.0263	0.0098
Cropping pattern	Crop rotation	Without crop rotation			320	0.0083	0.456
Cropping system	Single cropping	Double cropping			323	0.0103	0.3602
Returning mode	others	MR			223	0.0449	0.0694
Tillage practices	Plow tillage	Rotary tillage	No-till		132	0.0018	0.9444
Different crops	Maize	Wheat	Rice		329	0.0094	0.6884
Returning pattern	OSCS	ODCS	TDCS		246	0.0049	0.7318
Returning duration (yr)	1–5	6–10	10		352	0.0241	0.3762
Different residues	Maize	Wheat	Rice		264	0.0023	0.9138
Land-use	Paddy-upland rotation	Paddy field	Dry land		300	0.0454	0.1796
MAP (mm)	0–500	500–1000	>1000		316	0.0297	0.2704
MAT (°C)	0–10	10–15	>15		305	0.0254	0.3356
NFIR (kg N ha ⁻¹)	0	1–120	120–240	>240	309	0.1005	0.0482
Returning percentage	1/3	2/3	Half	All	351	0.0106	0.7802
pH _i	4.5–5.5	5.5–6.5	6.5–7.5	7.5–8.5 8.5–9.5	264	0.0686	0.2664

Categorical variables: including tillage practices, land use, irrigation, and so on. *n*: number of comparisons; Q_b : between group heterogeneity. Others: other methods of RR, including residue chopping, evenly incorporating, and burying, etc.; MR: mulching retention; NFIR: nitrogen fertilizer input rate; OS CS: returning one time in single cropping system; ODCS: returning one time in double cropping systems; TDCS: returning two times in double cropping systems; pH_i: initial soil pH. MAP, mean annual precipitation; MAT, mean annual temperature. All, all residues were returned; Half, half of the residues were returned.

3. Results

3.1. Effects of RR Methods on SOC Storage

Overall, based on 365 observations, $\ln R_{++}$ was calculated as 0.1072, with a 95% CI of 0.090–0.125, indicating that SOC storage could be significantly increased by 11.3% (9.5–13.3%) under RR ($p < 0.05$). The $\ln R$ s of SOC storage followed the Gaussian normal distribution ($R^2 = 0.9536$, $p < 0.0001$) (Figure 1).

As expected, the specific implementation methods of RR had different effects on SOC storage. Although mulch retention (MR) resulted in heat preservation, water retention, and entropy increase, the effect on SOC storage was not as good as those of other methods of RR (such as residue chopping, evenly incorporating, and burying). MR significantly increased SOC storage by 4.0% ($p < 0.05$), while other approaches resulted in an SOC storage increase by 11.6% ($p < 0.05$).

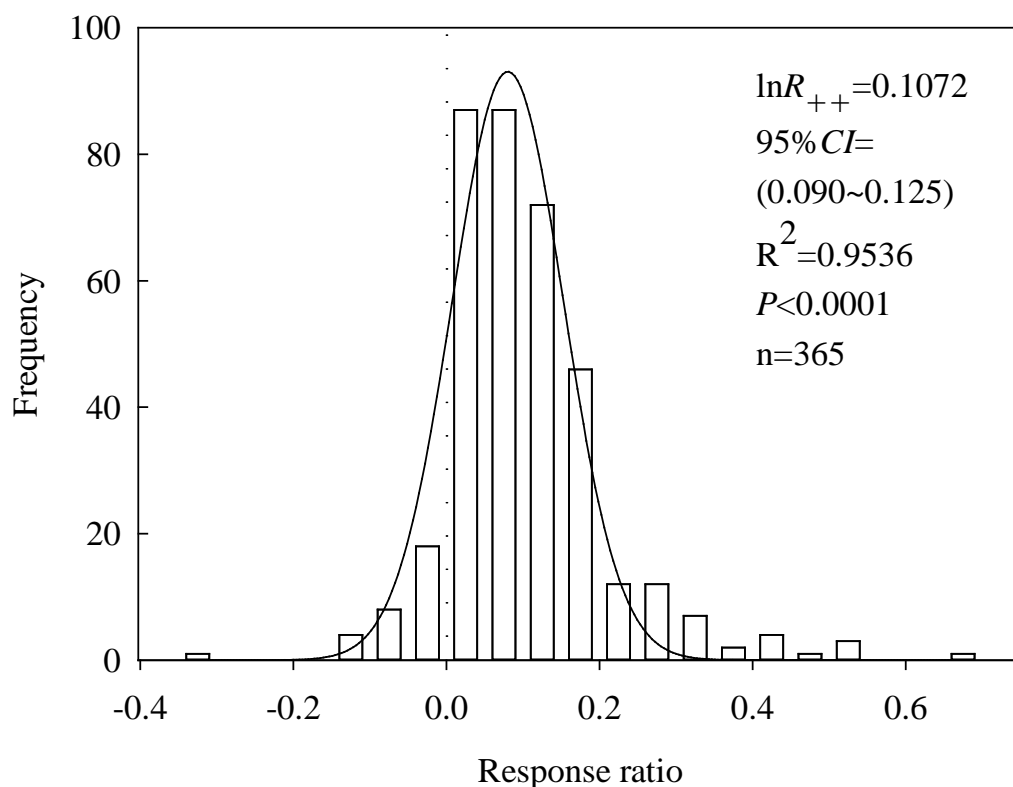


Figure 1. Frequency distributions of response ratios ($\ln R$) for SOC storage responding to RR. The fitted curve is an estimated Gaussian distribution in frequency. The dashed line is at $\ln R_{++} = 0$, 95% CI indicates the 95% confidence interval, and n is the number of comparisons. $\ln R_{++} \pm 95\% \text{ CI}$ does not overlap 0 means $p < 0.05$.

Different return patterns had different effects on SOC storage. For example, RR could significantly increase SOC storage by 10.1%, 8.7%, and 8.0% ($p < 0.05$) when residues were returned once in a single cropping system (OSCS), in a double cropping system (ODCS) and twice in a double cropping system (TDCS) when compared to residue removal, respectively ($p < 0.05$). When all residue from the previous growing season was returned to the field (All) and when only half the amount was returned (Half), the effects on SOC storage were similar, with a significant increase by 11.4% and 11.2%, respectively ($p < 0.05$). Returning two thirds of residue (2/3) significantly increased SOC storage by 18.3% ($p < 0.05$), but since there were only 11 pairs of research data, and thus this result needs to be backed up by subsequent research data.

Residue return duration had a great impact on SOC storage. Short-term RR (1–5 yrs) significantly increased SOC storage by 10.7% ($p < 0.05$), and this effect was slightly lower for medium-term RR (6–10 yrs), which was 9.3% ($p < 0.05$). The effect of long-term RR (>10 yrs) was highest (13.5%, $p < 0.05$) (Figure 2). Residues from maize, wheat, and rice significantly increased SOC storage by 9.7%, 10.6%, and 9.2%, respectively ($p < 0.05$); however, return of different crop residues had little impacts on SOC storage.

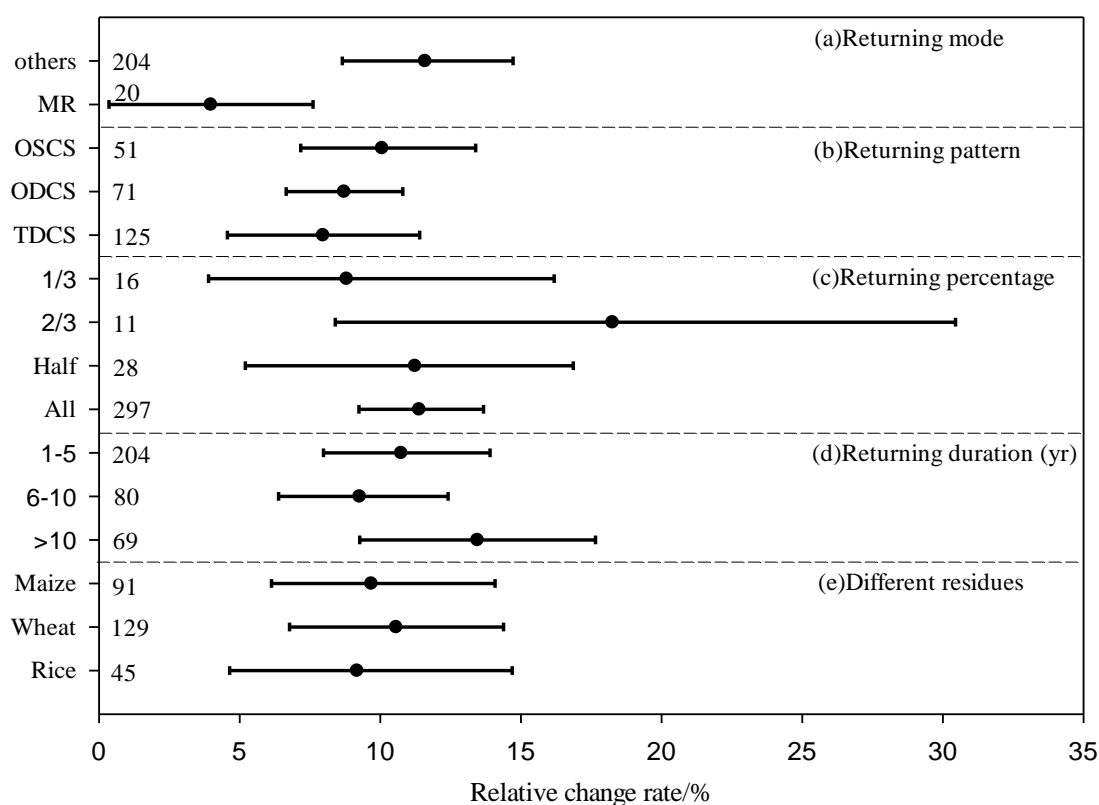


Figure 2. Relative change rate of SOC storage responding to residue retention. Others: other methods of RR, including residue chopping, evenly incorporating, and burying, etc.; MR: mulching retention; OSCS: returning one time in single cropping system; ODCS: returning one time in double cropping systems; TDCS: returning two times in double cropping systems; Half, half of the residues were returned; All, all residues were returned; Vertical axis represents invalid line, error bars represent 95% confidence intervals, the numbers to the right of the vertical axis are numbers of comparisons; if confidence intervals do not overlap with zero, it indicates significant increase (>0) or decrease (<0) ($p < 0.05$).

3.2. Effects of Field Management Practices on SOC Storage under RR

Increasing rates of nitrogen application did not always result in higher SOC storage. The results indicate that NFIR tended to be excessive in crop production, and a higher NFIR ($>240 \text{ kg N ha}^{-1}$) significantly increased SOC storage by 12.5% under RR ($p < 0.05$). However, a lower NFIR ($0\text{--}120 \text{ kg N ha}^{-1}$) significantly increased SOC storage by 15.5% under RR ($p < 0.05$). The SOC storage increased via NFIR ($120\text{--}240 \text{ kg N ha}^{-1}$) under RR was lowest with 10.9% ($p < 0.05$). When NFIR = 0, RR increased SOC storage by 27.6% ($p < 0.05$). Among different tillage practices combined with RR, the effects of plow tillage, rotary tillage, and no-till on SOC storage decreased gradually, with 9.4%, 9.0%, and 7.7% ($p < 0.05$). Irrigation had a significant effect on SOC storage during crop production ($Q_b = 0.0263$, $p = 0.0098$). For experimental fields with or without irrigation under RR, SOC storage increased significantly by 5.1% and 14.5%, respectively ($p < 0.05$).

In addition, SOC storage was closely related to the cropping pattern (Table 2). After 6–10 yrs of RR without crop rotation, SOC storage increased highly significant (16.7%, $p < 0.05$), while after 6–10 yrs of RR with crop rotation, SOC storage slightly increased (8.1%, $p < 0.05$). Compared to production without crop rotation, the application of crop rotation had a lower impact on the increase in SOC storage in >5 yrs of adoption of RR. As returning duration >10 yr, SOC sequestration rate showed decline in fields without crop rotation, which shows that soil reached its maximum potential to store C. This indicated the phenomenon of “C saturation”. Regarding the cropping system, SOC storage dramatically increased in single cropping systems under RR (12.6%, $p < 0.05$). More SOC was consumed

by crop growth in double cropping systems, and therefore, SOC storage was significantly increased by 10.1% under RR ($p < 0.05$) (Figure 3). Cultivation of maize, wheat, and rice had similar effects on SOC storage under RR, with significant increases by 10.5%, 10.3%, and 12.4%, respectively ($p < 0.05$).

Table 2. Relative change rate of SOC storage responding to cropping pattern in different returning duration under RR.

Returning Duration (yr)	Cropping Pattern	Relative Change Rate (%)	95% CI	<i>n</i>	Q_b	<i>p</i>
1–5	Crop rotation	11.3	7.3–16.0	135	0.0021	0.7278
	Without crop rotation	9.9	6.8–13.5	53		
6–10	Crop rotation	8.1	5.3–11.2	67	0.0187	0.0606
	Without crop rotation	16.7	4.6–31.4	10		
>10	Crop rotation	12.8	7.6–18.4	46	0.0019	0.7194
	Without crop rotation	15.2	6.3–26.3	11		

n: number of comparisons; Q_b : between group heterogeneity.

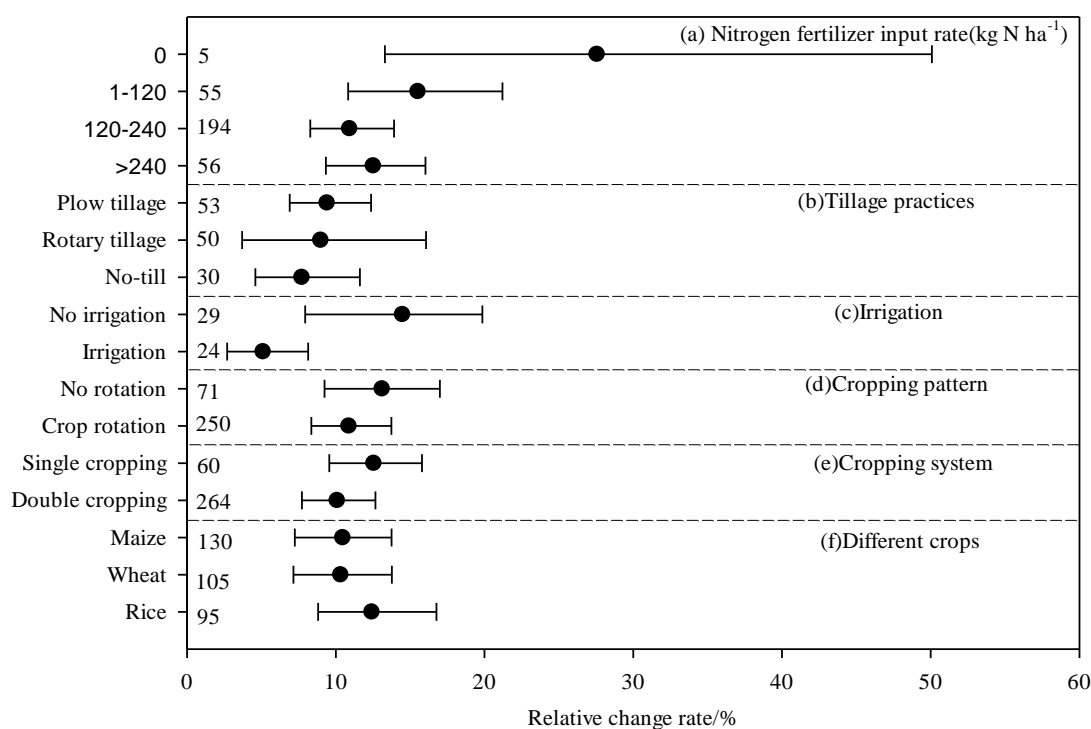


Figure 3. Relative change rate of SOC storage responding to residue retention under field management practices. Vertical axis represents invalid line, error bars represent 95% confidence intervals, the numbers to the right of the vertical axis are numbers of comparisons; if confidence intervals do not overlap with zero, it indicates significant increase (>0) or decrease (<0) ($p < 0.05$).

3.3. Effects of Climatic and Soil Conditions on SOC Storage under RR

Significant variations in the responses of SOC storage to RR were observed among land use types ($p < 0.05$) (Figure 4). Residue returning could significantly increase SOC storage by 14.5%, 10.7%, and 9.1% under paddy-upland rotation, paddy field, and dry land, respectively, when compared to residue removal (Figure 4, $p < 0.05$). Additionally, the responses of SOC storage to RR increased along with sub-groups with mean annual precipitation (MAP) increases (Figure 4). Specifically, when compared to residue removal, RR significantly increased SOC storage by 14.4%, 12.0%, and 8.8% at MAP levels of 0–500, 500–1000, and >1000 mm, respectively ($p < 0.05$). Similarly, significant SOC increases by

12.6%, 9.3%, and 12.5% were observed under RR at a mean annual temperature (MAT) higher than 15, 10–15, and 0–10 °C, respectively ($p < 0.05$). Variations in responses in SOC storage were observed among sub-groups of different initial soil pH values under RR. In weakly alkaline soil (pH 7.5–8.5), the largest increment (14.5%, $p < 0.05$) in SOC storage was observed under RR for all sub-groups, followed by neutral soil (pH 6.5–7.5), weakly acidic soil (pH 5.5–6.5), and alkaline soil (pH 8.5–9.5), with increases by 12.2%, 11.5%, and 11.4%, respectively, under RR ($p < 0.05$). However, no significant effect on SOC storage was observed in acidic soil (pH 4.5–5.5) when responding to RR. Among soil texture sub-groups, SOC storage was significantly increased by 7.0%, 10.9%, and 15.5% in sandy loam, loam, and clay loam under RR, respectively.

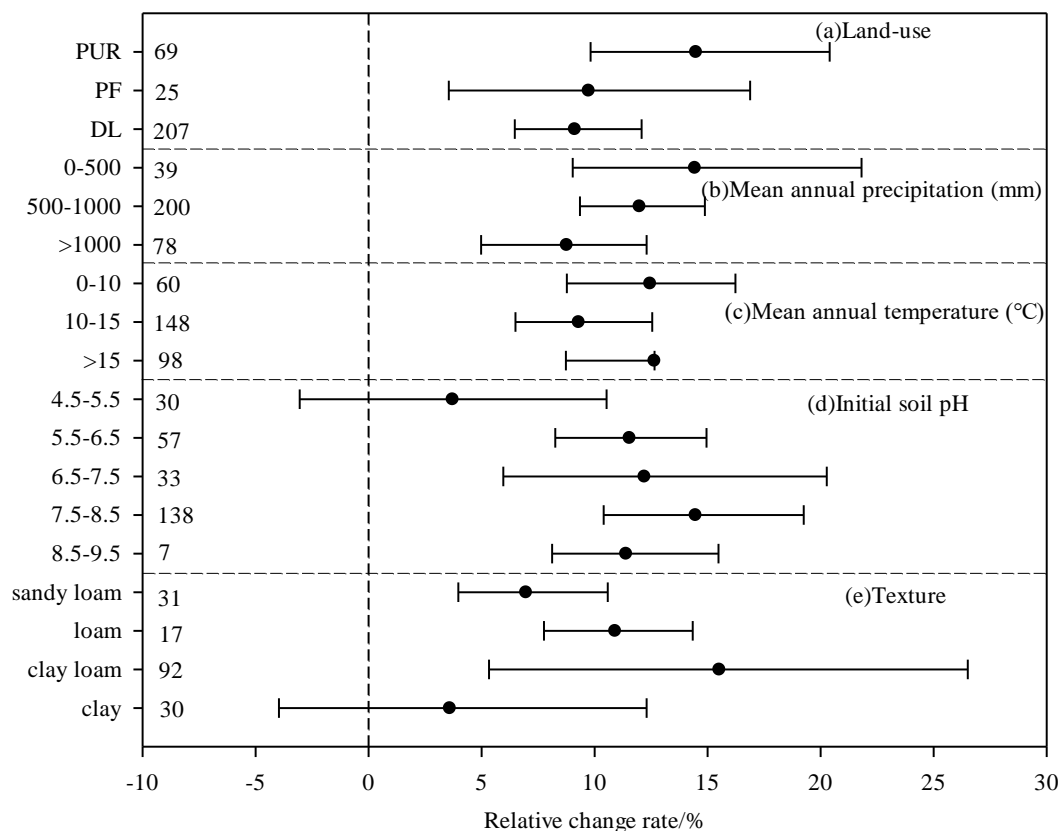


Figure 4. Relative change rate of SOC storage responding to residue retention under climate and soil resources. PUR: paddy-upland rotation; PF: paddy field; DL: dry land. Vertical axis represents invalid line, error bars represent 95% confidence intervals, the numbers to the right of the vertical axis are numbers of comparisons; if confidence intervals do not overlap with zero, it indicates significant increase (>0) or decrease (<0) ($p < 0.05$).

3.4. SOC Sequestration Rate and Its Correlation with Influential Factors under RR

In total, 351 valid observation pairs (Figure 5) were obtained. Based on the availability and validity of the data, SOC sequestration rate data were obtained for different regions. The range of SOC sequestration rates in different regions varied widely from 0.48 (Central China) to 1.61 (Southwest China) Mg C ha⁻¹ yr⁻¹. The national mean SOC sequestration rate was 0.93 Mg C ha⁻¹ yr⁻¹, indicating that, compared with residue removal, the application of RR could enhance SOC sequestration in China’s croplands.

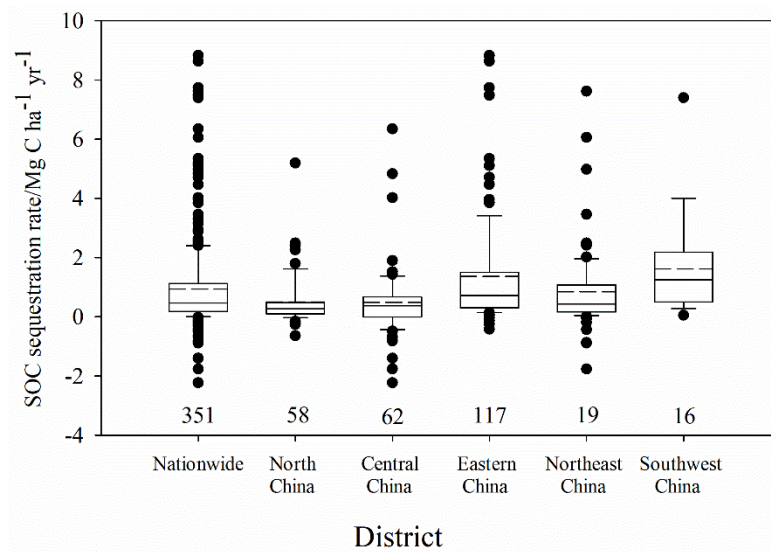


Figure 5. SOC sequestration rate of different districts in China. Data resourced from our meta-analysis dataset; Eastern China includes Anhui, Jiangsu, Zhejiang, Jiangxi, Shandong, Shanghai; North China includes Shanxi, Hebei, Beijing, Tianjin; Central China includes Henan, Hubei and Hunan; Southwest China includes Sichuan, Yunnan; Northwest China includes Shaanxi, Gansu, Qinghai, Ningxia; Northeast China includes Heilongjiang, Jilin, Liaoning. The provinces not listed indicate a lack of research data. Numbers above the horizontal axis represent numbers of comparisons.

As is shown in Table 3, the SOC sequestration rate was significantly related to return duration. Specifically, with the increase in return duration, the SOC sequestration rate gradually decreased and reached a level around zero after 23 yrs of RR ($R^2 = 0.1699$, $p < 0.0001$). This suggests that the phenomenon of “C saturation” regarding the capacity of SOC sequestration under RR.

The SOC sequestration rate was significantly correlated to residue amount ($R^2 = 0.0256$, $p = 0.0197$), initial SOC content ($R^2 = 0.0251$, $p = 0.0210$), NFIR ($R^2 = 0.0475$, $p = 0.0007$), percentage change of rice yield ($R^2 = 0.0943$, $p = 0.0283$), percentage change of wheat yield ($R^2 = 0.1898$, $p = 0.0165$), and SOC storage ($R^2 = 0.0501$, $p < 0.0001$).

Table 3. Relationship between SOC sequestration rate and influential factors under RR in China's croplands.

Influential Factors	<i>n</i>	x_0	y_0	<i>a</i>	Equation	R^2	<i>p</i>
Returning duration (yr)	353	0.9700	1.4342	-0.4653	$y = 1.4342 - 0.4653\ln(x - 0.97)$	0.1699	<0.0001
Soil bulk density (g cm^{-3})	-	-	-	-	-	-	-
Amount of residue (kg ha^{-1})	212	-	-5.6010	0.8182	$y = -5.6010 + 0.8182\ln x$	0.0256	0.0197
Initial SOC content (g kg^{-1})	307	-5.7730	-1.6506	0.9329	$y = -1.6506 + 0.9329\ln(x + 5.773)$	0.0251	0.0210
NFIR (kg N ha^{-1})	302	-2.68×10^{-13}	1.7571	-0.1177	$y = -1.7571 - 0.1177\ln(x + 2.68 \times 10^{-13})$	0.0475	0.0007
MAP (mm)	-	-	-	-	-	-	-
MAT ($^{\circ}\text{C}$)	-	-	-	-	-	-	-
Rice yield (%)	51	-	3.3206	2.1098	$y = 3.3206 + 2.1098\ln x$	0.0943	0.0283
Wheat yield (%)	42	-1.2106	0.4126	11.9805	$y = 0.4126 + 11.9805\ln(x + 1.2106)$	0.1898	0.0165
Maize yield (%)	-	-	-	-	-	-	-
SOC storage (Mg C ha^{-1})	357	-	33.8197	1.7147	$y = 33.8197 + 1.7147x$	0.0501	<0.0001

The scatters are individual data points such as SOC sequestration rate, experimental duration in our meta-analysis. *n*: number of comparisons; -: no significant results; rice (wheat, maize) yield: percentage change of rice (wheat, maize) yield. NFIR: nitrogen fertilizer input rate; MAP: mean annual precipitation; MAT: mean annual temperature. Rows 1–7: *x* represents influential factors; *y* represents SOC sequestration rate; Rows 8–11: *x* represents SOC sequestration rate; *y* represents influential factors.

4. Discussion

4.1. Impacts of RR Methods on SOC Storage

Improved soil quality and more C inputs may be the most important reasons of SOC sequestration by RR. As a C source, the decomposition of newly added residue can increase the soil C pool. However, the various methods of RR can alter the effects on SOC storage. Our results show that the increment in SOC storage by mulch retention (mostly in the 0–20-cm soil layer) was about half of that obtained by other methods of RR. Mulch retention can reduce the contact between the soil and the environment, protect soil from rainwater erosion, and prevent soil moisture loss [35], facilitating the growth of the root system and therefore resulting in higher grain yields [36]; a better C sequestration performance via MR in the 0–5- and 0–10-cm layer has been reported in a previous study [37]. However, MR may lead to an increase in the number of pests in the cropland. Residue floating on the soil surface also affects the contact with soil microorganisms and reduces the decomposition rate of the residue [38,39]. In this sense, it might be suitable to alternate between MR and other methods to compensate for the shortcomings of MR.

Regarding the different return patterns, increases in SOC storage were observed with increased duration and decreased with cropping intensity within 1 yr. Generally, because of the priming effects of RR, interactions between dead and living organic matter and different qualities of biomass would be strengthened, thereby accelerating residue decomposition [6,40]. However, there was a small difference between returning half the residue (Half) and returning all residue (All) regarding SOC storage. Therefore, increasing the frequency of residue retention and decreasing the planting density and frequency could result in improved SOC storage. This implies that greater SOC storage can be achieved when RR is conducted without crop rotation within a single cropping system. Therefore, in areas where plant residue is available, only half of the amount should be returned, while the other half could be used as raw material for industrial paper production, as animal feed, or for fuel and gas production [41].

Liu et al. [17] found that after 12 yrs of continuous RR, the SOC sequestration capacity reached the “saturation” state and stabilized. Similarly, West and Six [42] reported “C saturation” under conservation tillage after 26 yrs of RR. In the presented results, a negative correlation between return duration and SOC sequestration rate was verified. Carbon saturation was estimated to occur after 23 yrs of adoption of RR practices in China’s croplands. To extend the period of C saturation, adjusting crop rotation intensity and tillage practices are feasible approaches [42], in addition to increasing clay content and aggregation potential [43]. Zhao et al. [6] suggest to avoid consecutive RR over 10 yrs to reach the balance between mitigating GHG emissions and maintaining sustainable food production. To explore the phenomenon of “C saturation” at a deeper level needs, a more comprehensive and in-depth database would be needed, containing results from long-term field experiments [44].

4.2. Combined Effects of Field Management Practices on SOC Storage under RR

Soil nitrogen is essential for crop production and soil processes and is mainly derived via fertilizer and crop residue input. Residue retention combined with nitrogen fertilizer input (NFI) facilitates crop growth, especially under an optimal combination [21]. China produces and consumes more chemical fertilizers than any other country in the world [45]. However, the use of NFI (300 kg N ha^{-1}) is often excessive, and an adequate reduction in NFI can reduce N_2O emissions [46]. The results of the meta-analysis show that the lower NFIR value ($0\text{--}120 \text{ kg N ha}^{-1}$) under RR was more conducive to the increase of SOC storage.

Therefore, NFIR should be appropriately reduced in crop production. This will not only save production costs and increase crop yields, but also facilitates the sustainable usage of soil and mitigates climate change.

The carbon and nitrogen cycles in soil are highly correlated and affect each other. By moderate NFI, soil nitrogen content was increased, this contributed to C storage improvement and ultimately,

C sequestration capacity would be enhanced. However, excessive nitrogen fertilizer may lead to soil degradation and reduce C sequestration capacity. To achieve the goal of “4 per 1000” (4p1000), established on the COP21 conference in Paris in 2015 (<http://4p1000.org>), global nitrogen fertilizer production must reach 1.75 times of the current levels, or current symbiotic N₂ sequestration rates have to improve twice globally [47]. However, increased nitrogen fertilizer input does not always increase SOC storage, and in some cases, nitrogen may inhibit the activity of lignin-modifying enzymes (LMEs), thereby reducing SOC storage [48]. In this sense, increasing SOC storage on a global level is a goal difficult to achieve, requiring more diversified and effective management practices.

Tillage practices affected soil aeration and nutrient exchange in the field, and selecting appropriate tillage practices could help improve soil quality and crop yields [13]. Compared with plow tillage, no-till could maintain soil and water resources [49,50], and effectively reduced CH₄ and N₂O emissions from rice fields [51,52]. Regarding our dataset, the effect of no-till on SOC storage was not as pronounced as that of rotary tillage and plow tillage, most likely because more no-till data were obtained for deeper soil layers (0–20 cm) compared to the top soil (0–10 cm). Generally, no-till resulted in a better SOC sequestration rate in the top soil than in deeper layers [43]. A previous study has indicated that with increasing experimental duration, no-till combined with RR will show more obvious advantages in C sequestration and yield promotion [53]. However, long-term no-till may also cause deep soil compaction and loss of fertility [54]. It is therefore recommended to adopt appropriate tillage practices, which increase of SOC storage at the 5–20-cm soil layer and ensure a continuous high crop yield [28].

We found a significant difference in SOC storage under different irrigation conditions based on the results of the different studies, RR without irrigation increased SOC storage, and the increase was higher than that under RR with irrigation in wheat and maize fields. This can be explained by the fact that irrigation increases soil moisture, which could enhance SOC mineralization and stimulates microbial activity and evapotranspiration, resulting in higher root production and, consequently, in enhanced “priming effects” on native SOC [40,55]. The great variation in SOC storage under no irrigation might be due to different field conditions, for instance, farmers did not irrigate because they do not have irrigation conditions in some parts of Northwest China; and some farmers possibly did not irrigate because the cultivar did not require irrigation or amount of precipitation was enough in some parts of Southeast China. Experimental fields with higher MAP usually had a lower increase in SOC storage, most likely because of accelerated soil C loss with increased precipitation. In addition, dryland soil was exposed to air and therefore more prone to wind erosion, which could deplete SOC storage. On the contrary, abundant water and the more confined environment in rice fields could enhance microbial activity and promote residue decomposition, thereby increasing SOC sequestration. The results also suggest that RR in weakly alkaline soil (pH 7.5–8.5) was most conducive to the increase of SOC storage, mainly because weakly alkaline soil facilitates the survival and growth of a variety of soil microorganisms, thereby accelerating residue decomposition and increasing SOC storage. The above results indicate an intimate connection between the activity of soil microorganisms, the decomposition of residue, and the sequestration of soil C.

4.3. SOC Sequestration Rate under RR

The SOC sequestration rate of RR was generally positive, although the diversity was still existing among different districts in China. Lu et al. [56] found that RR had a higher SOC sequestration rate in single-cropping than in double-cropping fields. On the one hand, this may be related to discrepancies in climatic conditions, soil types, and cropping systems in different regions [57]. On the other hand, increases in residue species may be beneficial for microorganisms using the C substrates of the soil, thus accelerating the depletion of SOC [58,59].

The SOC sequestration rate was not only negatively related to return duration and NFIR, but also positively related to the residue amount, the initial SOC content, and the percentage changes in rice and wheat yield. Increased SOC sequestration rates and SOC storage could sequentially improve crop yield. However, with higher NFI levels, the increases in SOC sequestration rate under RR decelerated.

A phenomenon of “C saturation” (SOC sequestration around 0 value) was generally observed after 23 yrs of RR. With the combination of appropriate tillage practices and other field management practices, this saturation would be reached later.

Residue return effectively improved the function of agro-ecosystems, production, and the environmental benefits. However, SOC storage in croplands was affected by a number of factors with complex interactions. In this meta-analysis, soil bulk data were mostly estimated by empirical equation. Although the accuracy could be increased by data analysis and screening, the results might still differ from the actual conditions. To analyze SOC temporal changes, one challenge is to get the consecutive SOC storage data from same location over multiple yrs, and precise data related to changes in soil and climatic indicators is also difficult to obtain. In addition, in the process of data collecting, part of the studies failed to provide accurate experimental repetition numbers, field management practices, and other basic information, and for some provinces and regions, there were few relevant research papers; these factors affected the further expansion of the sample size. Future research should take more field management practices into consideration to gain a deeper insight into the advantages and disadvantages of RR. Such practices may incorporate different soil types, detailed climatic conditions, and longer durations.

5. Conclusions

A national meta-analysis was conducted to explore the factors influencing SOC storage and sequestration under RR. As an environmentally friendly and ecologically sustainable practice, RR improved crop yield and soil fertility by increasing SOC storage (11.3%, $p < 0.05$) and sequestration rate ($0.93 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$) in China’s croplands. Improvements in management practices might further enhance soil C sequestration capacity, and RR combined with a lower nitrogen fertilizer input rate ($0\text{--}120 \text{ kg N ha}^{-1}$), single cropping system, paddy-upland rotation, other methods of RR (including residue chopping, evenly incorporating, and burying), or long-term use (>10 yrs) are recommended to enhance SOC storage by 11.6–15.5%. Additionally, return duration, NFIR, amount of residue, and initial SOC content should be considered when investigating the responses of SOC to RR. Generally, RR can be used as an efficient and climate-smart management practice for long-term use. More complete datasets are needed to obtain results underpinning our understanding of the factors impacting SOC sequestration and storage under RR in China’s croplands.

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