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Effects of straw returning depth on soil organic carbon sequestration and crop yield in China: A meta-analysis

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ABSTRACT

Carbon sequestration is a crucial strategy for mitigating carbon dioxide emissions and addressing global climate change, with straw returning playing a key role in enhancing soil organic carbon (SOC) storage. However, most studies have focused on surface-level straw returning and its impact on topsoil SOC, with limited attention to how different straw returning depths (RD) on SOC stocks (SOCS) in topsoil (0–30 cm) and subsoil (30–60 cm). This study conducted a meta-analysis of 2290 observations from China to evaluate the effects of varying straw returning depths [0 cm (RD_0), 0–20 cm (RD_{0-20}), 20–30 cm (RD_{20-30}), and 30–60 cm (RD_{30-60})] on SOCS in two soil layers and their relationship with crop yield. All straw returning depths significantly improved topsoil and subsoil SOCS and enhanced soil physicochemical properties. RD_{20-30} showed the strongest effect on topsoil SOCS (14.3 %), whereas RD_{30-60} had the weakest (5.6 %). Conversely, RD_{30-60} had the strongest effect on subsoil SOCS (30.3 %), followed by RD_{20-30} (15.8 %). Crop yield increased under all straw returning depths, with the greatest gains under RD_{0-20} (11.2 %) and RD_{20-30} (10.0 %). However, the effectiveness of each depth varied with environmental and management conditions. For example, RD_0 increased SOCS the most under straw inputs below 8000 kg·ha^{-1} and loam soils, while RD_{0-20} was most effective in single cropping systems, upland regions, clay loam soils, low temperature and precipitation regions, and maize straw returning. RD_{20-30} proved beneficial in regions with double cropping systems, paddy and paddy-upland soils, high temperatures, rainy regions, and wheat or rice straw returning. These findings offer evidence-based insights to support sustainable straw returning strategies in China's agricultural systems.

1. Introduction

Soil is the largest terrestrial carbon reservoir, storing an estimated 2500 Pg of organic carbon in the top two meters—approximately three times more than in the atmosphere and accounting for 80 % of terrestrial carbon stocks (Lal, 2004). Even minor soil organic carbon (SOC) changes can significantly affect atmospheric carbon dioxide levels and influence global climate trends (Davidson and Janssens, 2006; Schmidt et al., 2011). Consequently, SOC sequestration has become a crucial strategy for mitigating global carbon emissions and limiting global temperature rise, as outlined in the Paris Agreement (Grassi et al., 2021).

Farmland SOC stocks (SOCS) are particularly important in this effort (Lal, 2008; Yin et al., 2025). However, most studies measuring SOC content in farmland concentrate on the top 0–30 cm of soil (Jian et al., 2020; Cui et al., 2024; Lin et al., 2024; Mo et al., 2024; Yao et al., 2025). For instance, among 360 studies investigating SOC responses to land management, 90 % monitored up to 30 cm soil depth (Richter and Billings, 2015). While topsoil is rich in SOC, it also has limited capacity for further carbon sequestration (Hobley et al., 2017) and may reach saturation within several decades under current practices (Smith, 2016; Minasny et al., 2017). In contrast, subsoil typically contains lower SOC levels but is influenced by distinct factors such as different organic matter inputs, microbial biomass and diversity, and physicochemical properties (Liu et al., 2018; Chen et al., 2021). Despite its potential, subsoil SOC remains under-researched, and strategies to improve its storage are not well developed.

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With more than 29 % of global farmland experiencing soil degradation (Nkonya et al., 2016; Arneth et al., 2019), improving soil health through carbon sequestration is essential to sustaining productivity and food security (Lessmann et al., 2022). Global crop straw production is estimated to reach about 4 billion tons annually (Chen et al., 2020), and farmland management practices like straw returning contribute an estimated 0.44–0.68 Pg C per year globally (Lessmann et al., 2022). One study estimated that straw returning could replace all potassium oxide fertilizers, most phosphoric anhydride fertilizers, and some chemical nitrogen (N) fertilizers, thereby mitigating farmland degradation linked to overuse (Yin et al., 2018). A meta-analysis showed that straw returning increased SOCS by 11.2 % worldwide (Lin et al., 2024). Given the growing emphasis on sustainable agriculture, straw returning is widely used to improve soil structure, enhance nutrient cycling, boost crop performance, and resilience to climate change (Zhao et al., 2020; Liu et al., 2021a; Zhang et al., 2024; Yin et al., 2025).

Straw returning practices vary in effectiveness depending on the depth of incorporation. Techniques include surface mulching, rotary tillage, and deep plowing—each with unique impacts on soil carbon and nutrient dynamics. However, most studies have focused on topsoil outcomes, neglecting the subsoil's role (Button et al., 2022; Mo et al., 2024; Yao et al., 2025). Conventionally, 30 cm is the threshold for cultivated soil disturbance, reflecting the historical use of a 12-inch plow (Davis et al., 2018). However, one study recommended extending carbon assessments to at least 60 cm depth (Qin et al., 2023). Therefore, a comprehensive evaluation of how straw returning at varying depths influences topsoil and subsoil SOC in China is urgently needed. Such insight is essential to inform SOC sequestration strategies and policies to mitigate global climate change and soil degradation. Understanding the cumulative effects of SOC in topsoil and subsoil is critical for accurately predicting soil C dynamics and their environmental impacts.

The current literature reveals a lack of comprehensive assessments of the effects of environmental and management variability (Shang et al., 2021; Xu et al., 2022). These studies fail to account for the spatiotemporal variability of soil properties, climate, and agronomic management practices at the regional scale (Yang et al., 2019b; Li et al., 2021). Yet these factors influence both carbon and decomposition (Doetterl et al., 2015; Chen et al., 2021, 2024; Lessmann et al., 2022; Lin et al., 2024), and their effects may differ between soil layers (Pan et al., 2023). Understanding this variability is critical for designing effective strategies at regional and national levels.

In this context, we conducted a meta-analysis based on studies from China to (1) compare the effects of different straw returning depths on soil physicochemical properties and SOCS in topsoil and subsoil, (2) evaluate the contribution of straw returning depth to topsoil and subsoil SOCS under varying environmental and management conditions, (3) identify key factors influencing topsoil and subsoil SOCS responses at different straw returning depths, and (4) examine how SOCS at each depth relates to crop yield. We hypothesize that straw returning enhances SOCS and crop yield across depths, but the magnitude of these benefits depends on environmental and management factors.

2. Materials and methods

2.1. Data collection

A comprehensive literature search was conducted using China National Knowledge Infrastructure (https://www.cnki.net), Google Scholar (http://scholar.google.com), and Web of Science (https://www.webofscience.com/) databases up until February 2022. The following keywords were used: 'crop residue' OR 'straw return' OR 'straw retain' OR 'straw retention' OR 'straw mulching' OR 'straw incorporation' AND 'organic carbon' OR 'organic matter'. The following inclusion criteria were applied to avoid bias and ensure data accuracy: (1) experimental sites were located in field or research stations within China; (2) studies included straw returning and control (no straw) treatments at the same site under similar microclimatic, crop, soil, and tillage conditions; (3) straw returning depth and sampling depth (SD) were clearly reported; (4) mean values for SOC or soil organic matter (SOM) were provided for the corresponding sampling depths.

In total, 2290 observations (1145 pairs) were extracted from 105 peer-reviewed publications (Figs S1 and S2). Data presented in figures were extracted using GetData software (http://getdata-graph-digitizer.com). The extracted data included means, sample sizes, and standard deviations (or standard errors) for straw returning and control treatments. Key variables included bulk density (BD), SOC, total nitrogen (TN), yield, soil available phosphorus (AP), available potassium (AK), pH, nitrate nitrogen (NO_3^--N), and ammonium nitrogen (NH_4^+-N). Additional data recorded, including geographical location (country, latitude, and longitude), annual average precipitation (AAP), annual average temperature (AAT), initial soil properties (initial TN (TN_i), initial SOC (SOC_i), and initial pH (pH_i)), soil type, soil texture, returning straw types, straw C: N, straw application rate (SAR), NAR, phosphorus application rate (PAR), potassium application rate (KAR), duration, and cropping system. For studies that did not report geographical coordinates, site locations were identified using Baidu Maps (https://map.baidu.com/). Missing AAT or AAP values were estimated using data from relevant meteorological stations (Chinese Meteorological Data Network, http://data.cma.cn/).

2.2. Data processing

Soil organic matter (SOM, $g \cdot kg^{-1}$) values were converted to SOC ($g \cdot kg^{-1}$) by Eq. 1 (Gattinger et al., 2012):

$$SOC = SOM/1.724 \tag{1}$$

Soil organic carbon stock (SOCS, $Mg \cdot ha^{-1}$) was calculated by Eq. 2

$$SOCS = SOC \times BD \times H/10 \tag{2}$$

where H is soil sampling depth (cm), BD is soil bulk density ($g \cdot cm^{-3}$), and 10 is the conversion coefficient.

When soil BD was unavailable, it was estimated for paddy-upland and paddy soils using Eq. 3 developed by Pan et al. (2004):

$$BD = -0.22\ln(SOC) + 1.78 \tag{3}$$

For upland soils, BD was estimated using Eq. 4 developed by Song et al. (2005):

$$BD = 1.377\exp(-0.0048SOC) \tag{4}$$

Sampling depths were categorized as 0−30 cm (topsoil, SD_{0-30}) and 30−60 cm (subsoil, SD_{30-60}) to evaluate SOC responses in different soil layers. Straw returning depths were grouped into four categories: 0 cm (RD_0), 0−20 cm (RD_{0-20}), 20−30 cm (RD_{20-30}), and 30−60 cm (RD_{30-60}). SOCS values were calculated for each treatment group and sampling depth. Environmental variables and management practices were also categorized to assess their effects on SOCS across soil layers and straw return depths, ensuring uniformity of data across categorical groups (see Table S1; Liu et al., 2014; Zhang et al., 2018; Huang et al., 2021).

2.3. Data analysis

The natural log-transformed response ratio (lnRR) was calculated to quantify the effect size of straw returning on SOCS by Eq. 5:

$$\ln RR = \ln(X_s) - \ln(X_c) \tag{5}$$

where X_s and X_c are the mean values for straw returning and control treatments, respectively. The variance (v) for each lnRR was calculated by Eq. 6:

$$v = \frac{(S_s)^2}{n_s(X_s)^2} + \frac{(S_c)^2}{n_c(X_c)^2} \quad (6)$$

where S_s and S_c are the standard deviations for straw returning and control treatments, and n_s and n_c represent the sample sizes for straw returning and control treatments, respectively. When standard deviations were not reported, the mean coefficient of variation was calculated for each observed value, with the missing standard deviations estimated by multiplying the mean value by the mean coefficient of variation.

The mean effect size ($\ln\overline{RR}$) was calculated by using Eq. 7:

$$\ln\overline{RR} = \frac{\sum_{i=1}^{k} W_i \times \ln RR_i}{\sum_{i=1}^{k} W_i} \quad (7)$$

where $\ln RR_i$ is the effect size for the corresponding comparison, and k is the number of comparisons in the group. The weight for each comparison (w_i) was calculated by Eq. 8:

$$W_i = \frac{1}{V_i} \quad (8)$$

where v_i represents the variance of the *i*th study.

The lnRR values were converted to a percentage change (E) to

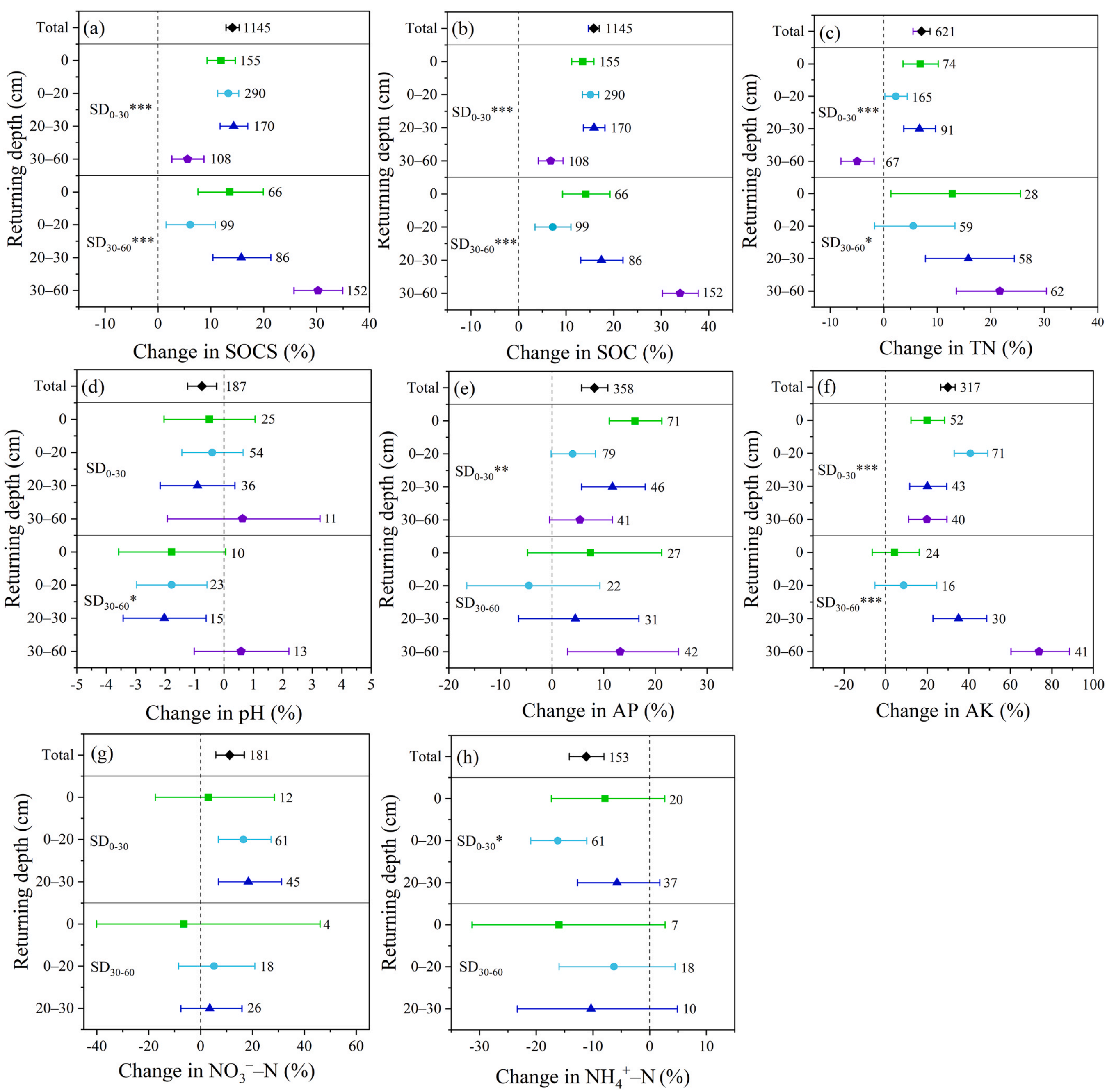

Fig. 1. Effect of straw returning depth on (a) soil organic carbon stocks (SOCS), (b) soil organic carbon (SOC), (c) soil total nitrogen (TN), (d) pH, (e) available phosphorus (AP), (f) available potassium (AK), (g) NO_3^--N, (h) NH_4^+-N at two sampling depths (SD): 0–30 cm ($SD_{0–30}$) and 30–60 cm ($SD_{30–60}$). Points and error bars represent mean effect sizes and 95 % confidence intervals, respectively. *, **, and *** denote significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

facilitate interpretation by Eq. 9:

$$E = (e^{\ln RR} - 1) \times 100\% \quad (9)$$

The effect size of straw returning on SOCS was determined using MetaWin 2.1 (Sinauer Associates Inc., Sunderland, MA, USA) with a random-effects model (Rosenberg et al., 2000), applying bootstrapping with 4999 iterations to generate 95 % confidence intervals. A variable was considered statistically significant if the confidence interval did not overlap zero. For categorical group analyses, significant between-group heterogeneity indicated that the mean effect size varied significantly between groups (Tables S2–S4). Publication bias was assessed using Egger's regression test, which showed no significant publication bias (Table S5).

A random forest analysis (ntree = 500, mtry = sqrt(n)) was

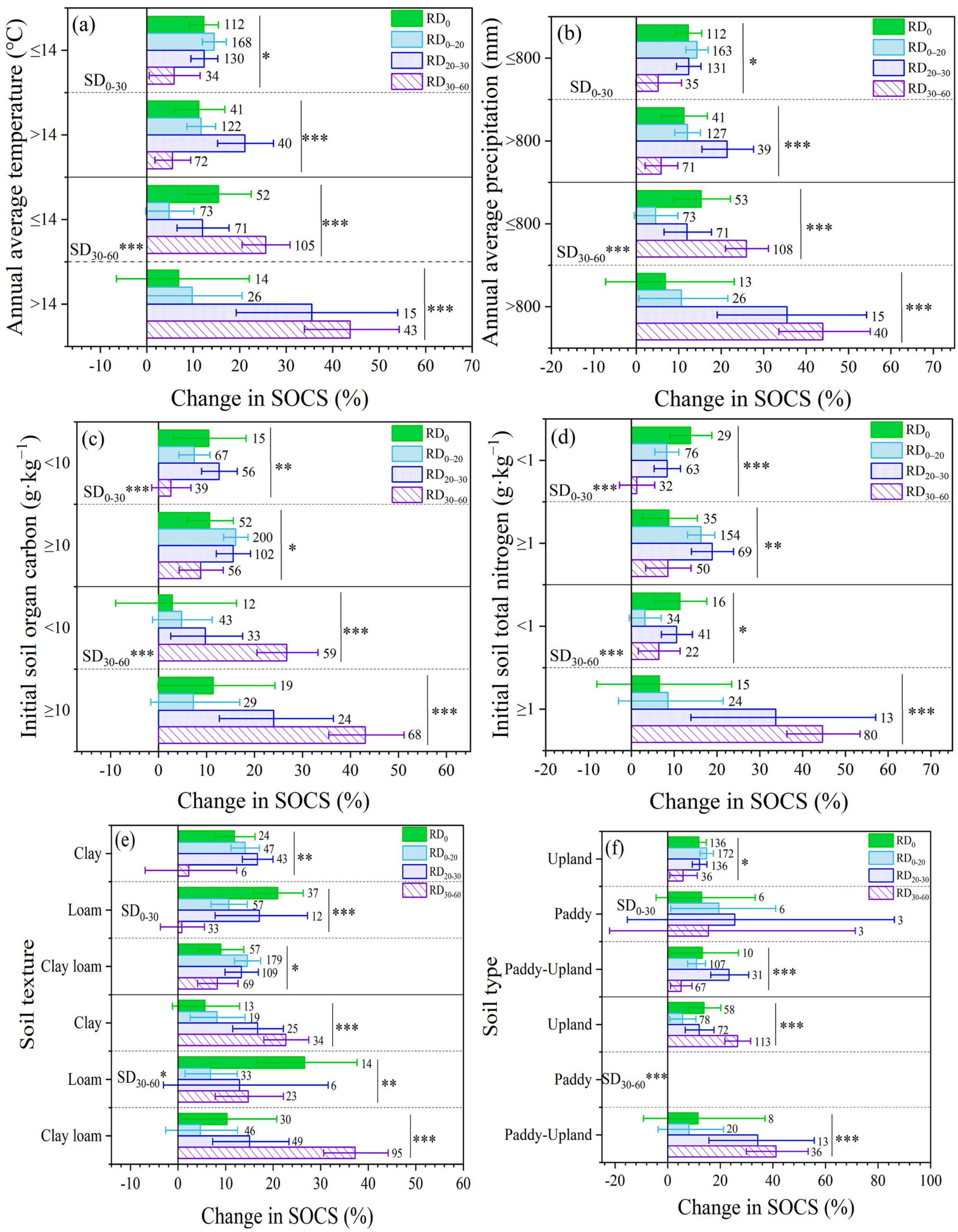

Fig. 2. Effect of straw returning depths on soil organic carbon stocks (SOCS) at 0–30 cm ($SD_{0–30}$) and 30–60 cm ($SD_{30–60}$) under different categories: (a) annual average temperature, (b) annual average precipitation, (c) initial soil organic carbon, (d) initial soil total nitrogen, (e) soil texture, and (f) soil type. Column strips and error bars represent mean effect sizes and 95 % confidence intervals, respectively. *, **, and *** denote significant differences at p < 0.05, p < 0.01, and p < 0.001, respectively.

implemented using the 'randomForest' and 'rfPermute' packages in R to evaluate the relative importance of different predictors influencing the SOCS response to straw returning. Five-fold cross-validation was performed to improve transparency. Linear regression analyses explored relationships between the effect sizes of SOCS and soil, environmental, and management variables. Data visualization was performed using OriginPro 2022 (OriginLab Corporation, Northampton, MA, USA), and spatial analysis was conducted in ArcGIS 10.8.

3. Results

3.1. Topsoil and subsoil SOCS and physicochemical properties

Straw returning significantly increased SOCS by 14.1 % (12.9–15.3 %), SOC by 15.8 % (14.7–17.0 %), TN by 7.1 % (5.5–8.7 %), AP by 8.2 % (5.7–10.8 %), AK by 29.9 % (26.5–33.5 %), and NO_3^--N by 11.2 % (5.9–16.8 %), and decreased soil pH by 0.8 % (–1.2 to –0.3 %) and NH_4^+-N by 11.2 % (–14.2 to –8.1 %) across both layers (Fig. 1). The effects of straw returning on SOCS, SOC, TN, and AK varied significantly between topsoil and subsoil ($p < 0.05$). Straw returning also significantly affected AP and NH_4^+-N in topsoil, which remained relatively stable in the subsoil, whereas soil pH exhibited contrasting trends in the two layers (Fig. 1, $p < 0.05$).

Straw returning at different depths significantly increased topsoil SOCS by 5.6–14.3 % and subsoil SOCS by 6.1–30.3 %, with deeper incorporation producing more pronounced increases in subsoil SOCS (Fig. 1a, b). Among the treatments, RD_0 exhibited the highest increases in topsoil TN (6.8 %) and AP (16.1 %), while $RD_{0–20}$ had the greatest impact on topsoil AK (40.8 %). Neither RD_0 nor $RD_{0–20}$ significantly affected subsoil AP, AK, NO_3^--N, or NH_4^+-N ($p > 0.05$). $RD_{20–30}$ resulted in the largest increases in topsoil SOCS (14.3 %), SOC (15.9 %), and NO_3^--N (18.4 %), whereas $RD_{30–60}$ had the weakest effect on topsoil properties, decreasing TN by 5.0 %. In contrast, $RD_{30–60}$ significantly enhanced subsoil SOCS (30.3 %), SOC (34.0 %), TN (21.7 %), AP (13.2 %), and AK (73.8 %), followed by $RD_{20–30}$, while $RD_{0–20}$ had the weakest effects (Fig. 1).

3.2. Topsoil and subsoil SOCS in different environmental contexts

Topsoil SOCS under straw returning did not significantly differ across the AAT, AAP, soil texture, or soil type subgroups ($p > 0.05$). However, subsoil SOCS increased more substantially under higher AAT (>14 °C; 6.8–43.7 %), higher AAP (>800 mm; 6.9–44.0 %), and in paddy-upland systems (8.1–41.2 %) than under lower AAT (≤14°C; 4.8–25.6 %), lower AAP (≤800 mm; 4.5–25.9 %), and in upland systems (5.7–26.6 %) (Fig. 2a, b, and f). Among soil textures, clay loam resulted in the largest increase in subsoil SOCS (37.2 %) (Fig. 2e). Subgroups with higher SOC_i (≥10 $g\cdot kg^{-1}$) and TN_i (≥1 $g\cdot kg^{-1}$) had significantly greater increases in topsoil and subsoil SOCS under straw returning ($p < 0.05$; Fig. 2c and d).

Straw returning depth significantly influenced SOCS across the AAT, AAP, SOC_i, TN_i, soil texture, and soil type subgroups ($p < 0.05$, Fig. 2a–f). RD_0 had the highest increases in topsoil (21.0 %) and subsoil (26.6 %) SOCS in loam soil (Fig. 2e). $RD_{0–20}$ had the most beneficial effects on topsoil SOCS in environments with AAT ≤ 14°C (14.5 %), AAP ≤ 800 mm (14.3 %), SOC_i ≥ 10 $g\cdot kg^{-1}$ (16.1 %), clay loam soil (14.6 %), and upland regions (14.8 %), but it had the weakest effect on subsoil SOCS. $RD_{20–30}$ performed best under AAT > 14°C (21.1 %), AAP > 800 mm (21.4 %), SOC_i < 10 $g\cdot kg^{-1}$ (12.6 %), TN_i ≥ 1 $g\cdot kg^{-1}$ (18.9 %), clay soil (16.7 %), paddy (25.6 %), and paddy-upland regions (23.4 %) (Fig. 2a–f). Regardless of environmental context, $RD_{30–60}$ consistently had the weakest impact on topsoil SOCS but had the strongest positive effect on subsoil SOCS for most conditions, followed by $RD_{20–30}$ (Fig. 2a–f).

3.3. Topsoil and subsoil SOCS under different management practices

Subsoil SOCS under straw returning was more responsive than topsoil SOCS to variations in management practices, including straw type, NAR, PAR, and straw returning duration ($p < 0.05$, Fig. 3a–g). Wheat and rice straw significantly increased subsoil SOCS (22.2–33.3 % and 9.0–44.5 %, respectively), while maize straw had more modest effects (4.2–25.7 %). Greater subsoil SOCS increases occurred under NAR ≤ 200 $kg\cdot ha^{-1}$ (5.1–17.4 %), PAR > 90 $kg\cdot ha^{-1}$ (9.3–16.6 %), and straw returning duration ≥ 3 years (5.2–51.2 %) than NAR > 200 $kg\cdot ha^{-1}$ (5.2–12.3 %), PAR ≤ 90 $kg\cdot ha^{-1}$ (2.3–10.8 %), and straw returning duration < 3 years (6.3–24.4 %). Topsoil and subsoil SOCS also responded differently to straw C: N ratios, SAR, and KAR ($p < 0.05$), with significant increases observed for straw C: N ratio ≤ 75, SAR ≥ 8000 $kg\cdot ha^{-1}$, and KAR > 75 $kg\cdot ha^{-1}$. Cropping system had no significant impact on SOCS in either soil layer ($p > 0.05$, Fig. 3h).

Straw returning depth under various management practices significantly influenced topsoil and subsoil SOCS ($p < 0.05$, Fig. 3a–h). At higher NAR (> 200 $kg\cdot ha^{-1}$) and PAR (> 75 $kg\cdot ha^{-1}$), the beneifical effects of increased depth on topsoil SOCS diminished (Fig. 3d and f). Under SAR < 8000 $kg\cdot ha^{-1}$, RD_0 significantly enhanced topsoil (12.7 %) and subsoil (17.0 %) SOCS (Fig. 3c). $RD_{0–20}$ exhibited the greatest increases in topsoil SOCS under maize straw (14.7 %), longer returning duration (≥ 3 years; 15.0 %), and single cropping (15.2 %). $RD_{20–30}$ produced the largest topsoil SOCS gains under wheat (23.1 %) or rice (18.9 %) straw returning, straw C: N ratio ≤ 75 (18.8 %), NAR ≤ 200 $kg\cdot ha^{-1}$ (14.6 %), PAR > 90 $kg\cdot ha^{-1}$ (15.2 %), KAR ≤ 75 $kg\cdot ha^{-1}$ (8.4 %), and double cropping (17.4 %) (Fig. 3a–h). In contrast, $RD_{30–60}$ consistently had the weakest effect on topsoil SOCS but significantly promoted subsoil SOCS across management scenarios (Fig. 3a–h).

3.4. Importance of environmental and management practices for topsoil and subsoil SOCS

Random forest analysis identified KAR as the most significant predictor of topsoil SOCS under straw returning, followed by AAP, pH_i, duration, AAT, SOC_i, PAR, TN_i, SAR, NAR, RD, soil texture, straw type, and cropping system ($p < 0.05$), while straw C: N ratio and soil type had no significant effect ($p > 0.05$, Fig. 4a). Topsoil SOCS positively correlated with KAR, SOC_i, TN_i, SAR, and PAR, and negatively correlated with AAT, pH_i, straw C: N ratio, and RD ($p < 0.05$, Table 1). In contrast, the most important predictor for subsoil SOCS was RD, followed by TN_i, pH_i, SOC_i, AAT, straw type, NAR, AAP, duration, straw C: N ratio, cropping system, and SAR ($p < 0.05$), while KAR, soil texture, PAR and soil type had no significant effect ($p > 0.05$, Fig. 4b). Subsoil SOCS positively correlated with AAP, TN_i, SAR, PAR, and KAR, and negatively correlated with NAR and straw C: N ratio ($p < 0.05$, Table 1).

Furthermore, the effect size of topsoil SOCS positively correlated with the effect sizes of TN, AK, NO_3^--N, and NH_4^+-N ($p < 0.05$), while the effect size of subsoil SOCS only positively correlated with the effect sizes of TN and AK ($p < 0.05$, Fig. 5).

3.5. Relationship between crop yield and topsoil and subsoil SOCS

Straw returning improved crop yield, with the largest increases observed under $RD_{0–20}$ (11.2 %) and $RD_{20–30}$ (10.0 %), while RD_0 exhibited the smallest effect (8.4 %) (Fig. 6a). Yield effect size positively correlated with the effect sizes of topsoil and subsoil SOCS ($p < 0.05$, Fig. 6b, d). This relationship was significant only for $RD_{20–30}$ ($p < 0.05$), while $RD_{0–20}$ showed no significant correlation with SOCS in either layer ($p > 0.05$, Fig. 6c, e). Moreover, the effect size of yield positively correlated with the effect size of topsoil SOCS under RD_0 and subsoil SOCS under $RD_{30–60}$ ($p < 0.05$, Fig. 6c, e).

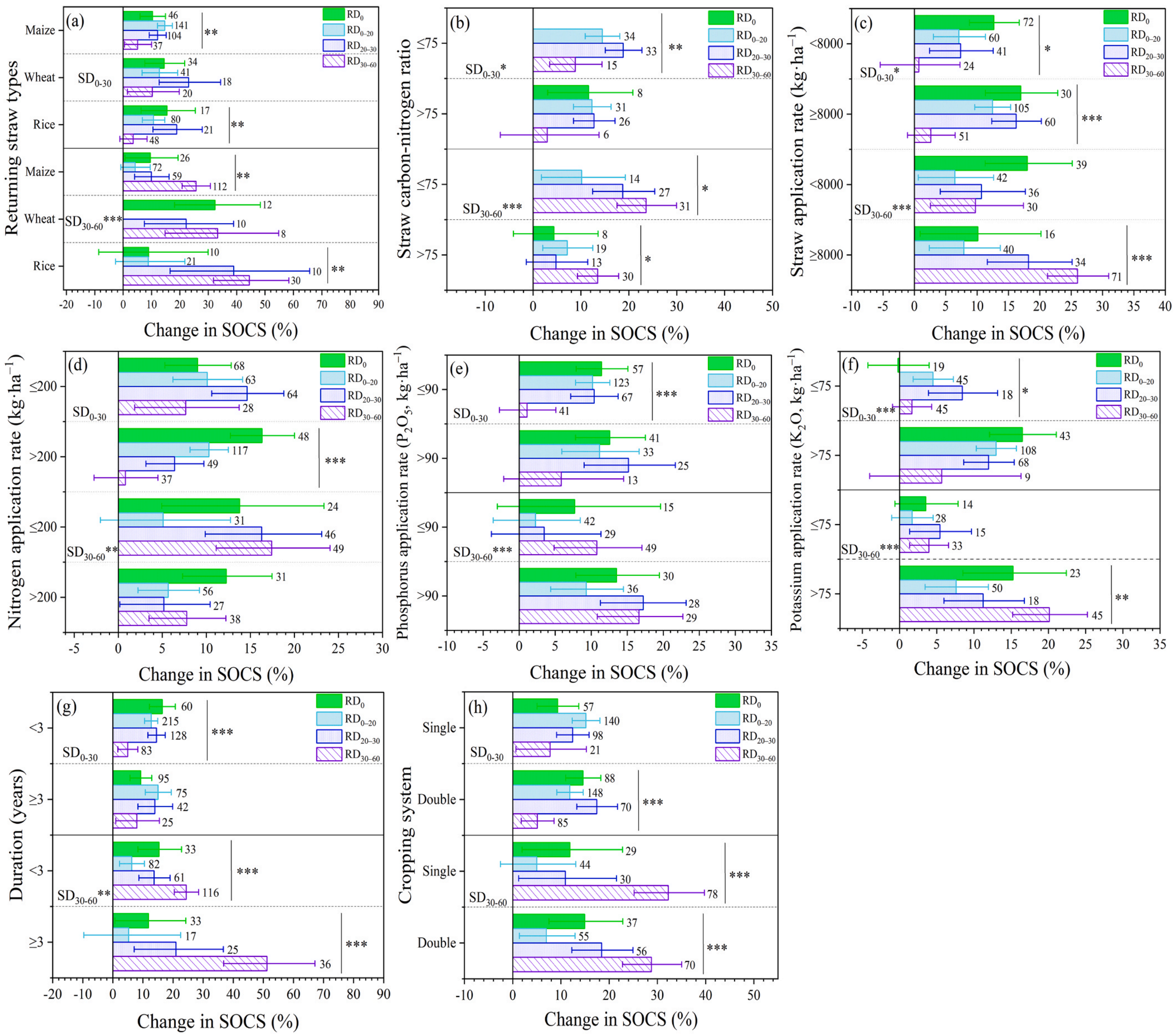

Fig. 3. Effect of straw returning depth on soil organic carbon stocks (SOCS) at 0–30 cm (SD_{0-30}) and 30–60 cm (SD_{30-60}) across different (a) straw returning types, (b) straw carbon: nitrogen ratios, (c) straw application rates, (d) nitrogen application rates, (e) phosphorus application rates, (f) potassium application rates, (g) straw returning durations, and (h) cropping systems. Column strips and error bars represent mean effect sizes and 95 % confidence intervals, respectively. *, **, and *** denote significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

4. Discussion

4.1. Effects of straw returning depth on topsoil SOCS

The topsoil layer plays a critical role in agricultural productivity but is highly sensitive to environmental factors and management practices such as straw returning (Sanderman et al., 2017; Keel et al., 2019). The depth of straw returning can significantly influence the input and distribution of SOC and other soil physicochemical properties (Martinez et al., 2008). While most previous studies have focused on general straw returning methods, typically reporting increases in SOCS of 10–15 % (Huang et al., 2021; Liu et al., 2023a, 2023b; Lin et al., 2024), few have systematically assessed the impact of different straw incorporation depths. Our results align with those studies, with topsoil SOCS increases of 12.9–15.3 %. Consistent with our hypothesis, all four straw returning depths increased topsoil SOC and SOCS (Fig. 1a, b), likely due to enhanced nutrient release from decomposing straw. Topsoil SOCS increased with deeper incorporation from 0–30 cm (RD_0, RD_{0-20}, and RD_{20-30}, Fig. 1a). The RD_0 treatment had the smallest increase, likely due to the limited contact area between straw and soil, resulting in greater carbon loss through gaseous emissions during decomposition. However, RD_0 significantly improved TN levels (Fig. 1c), likely by moderating surface soil temperature, reducing water evaporation, decelerating soil erosion by rainwater, and minimizing nitrogen losses via leaching and volatilization (Chen et al., 2009; Zhou et al., 2022). In contrast, RD_{20-30} offered a larger contact area between straw and soil, forming a nutrient pool below the 0–20 cm fertile soil layer. The 20–30 cm soil layer typically has lower SOC than the 0–20 cm soil layer (Zhang et al., 2022a, 2022b), providing more potential for nutrient enhancement and facilitating the coordinated increase in nutrients (TN, AP, AK, and NO_3^--N) and overall soil quality from 0–30 cm (Fig. 1). However, RD_{30-60} had the weakest increase in topsoil SOCS (5.6 %) (Fig. 1a), likely due to reduced straw decomposition in deeper soils, where lower temperatures, less oxygen, and reduced microbial

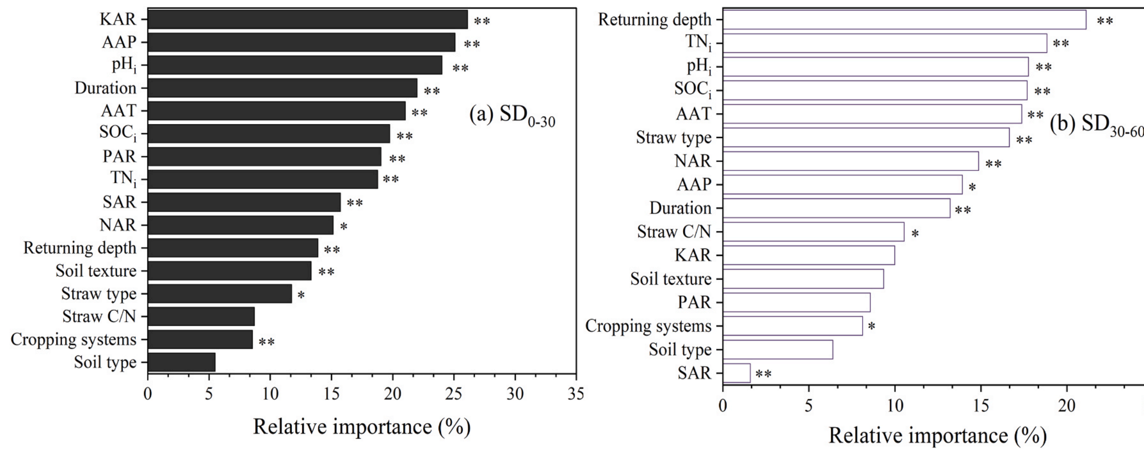

Fig. 4. Relative importance (%) of variables for the soil organic carbon stock (SOCS) responses under straw returning at (a) 0–30 cm and (b) 30–60 cm sampling depths based on a random forest regression model. AAT: annual average temperature, AAP: annual average precipitation, SOC_i: initial soil organic carbon, TN_i: initial soil total nitrogen, pH_i: initial soil pH, SAR: straw application rate, NAR: nitrogen application rate, PAR: phosphorus application rate, and KAR: potassium application rate. * and ** denote significant differences at $p < 0.05$ and $p < 0.01$, respectively.

Table 1
Relationships between the effect sizes of soil organic carbon stocks (SOCS) in topsoil (0–30 cm) and subsoil (30–60 cm) under various environmental and management factors.

	Effect size of SOCS (0–30 cm)			Effect size of SOCS (30–60 cm)		
	r	R^2	*P*	r	R^2	*P*
Duration	0.008	< 0.001	0.836	0.017	< 0.001	0.741
AAT	–0.100	0.009	0.009**	–0.044	0.002	0.384
AAP	–0.042	0.002	0.264	0.154	0.024	0.002**
SOC_i	0.096	0.009	0.021*	0.071	0.005	0.228
TN_i	0.117	0.014	0.008**	0.325	0.106	< 0.001***
pH_i	–0.135	0.018	0.023*	–0.148	0.022	0.061
NAR	–0.018	< 0.001	0.686	–0.171	0.029	0.002**
SAR	0.223	0.050	< 0.001***	0.175	0.030	0.002**
PAR	0.151	0.023	0.003**	0.155	0.024	0.013*
KAR	0.255	0.065	< 0.001***	0.220	0.049	< 0.001***
Straw C: N ratio	–0.176	0.031	0.029*	–0.331	0.109	< 0.001***
Returning depth	–0.078	0.006	0.036*	0.314	0.098	< 0.001***

AAT: annual average temperature, AAP: annual average precipitation, SOC_i: initial soil organic carbon, TN_i: initial soil total nitrogen, pH_i: initial soil pH, SAR: straw application rate, NAR: nitrogen application rate, PAR: phosphorus application rate, and KAR: potassium application rate. *, **, and *** denote significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

abundance limit decomposition (Latifmanesh et al., 2020). Furthermore, the straw carbon remained concentrated in deep soil layers under $RD_{30–60}$, contributing less to topsoil SOC.

Several factors influence the effect of crop straw returning on soil carbon dynamics, including climate, soil properties, and management practices (Liu et al., 2023b; Chen et al., 2024). Random forest analysis identified key factors affecting the topsoil SOCS response to straw returning: KAR, AAP, pH_i, duration, AAT, and SOC_i (Fig. 4a). Climate (AAP and AAT) and initial soil conditions (pH_i and SOC_i) are particularly influential (Doetterl et al., 2015; Chen et al., 2024; Lin et al., 2024), with temperature and pH regulating crop growth and microbial activity (Liu et al., 2021b). Topsoil SOCS under straw returning negatively correlated with AAT ($p < 0.05$, Table 1), likely because higher temperatures enhance microbial activity and SOC decomposition (Guan et al., 2020; Li et al., 2024; Song et al., 2025). Conversely, lower temperatures may favor SOC accumulation (Oldfield et al., 2019; Ofiti et al., 2021; Hansen et al., 2024) unless restricted by factors like low precipitation (Franzluebbers et al., 2001). Lower soil pH also positively affected topsoil SOCS ($p < 0.05$, Table 1), as acidic conditions can suppress microbial decomposition, promote microbial community shifts, and enhance SOC stability (Pietri and Brookes, 2009; Wang et al., 2017). In contrast, high pH can adversely affect microbial processes, inhibiting activities involved in plant straw decomposition (Rousk et al., 2009) and thus reducing SOCS. Changes in topsoil SOCS under straw returning positively correlated with SOC_i ($p < 0.05$, Table 1), consistent with our subgroup analysis showing that $SOC_i \geq 10$ g·kg^{-1} favored topsoil SOCS increases (Fig. 2c). While a previous study suggested $SOC_i < 15$ g·kg^{-1} may be more favorable (Wang et al., 2023b), likely due to limited SOC_i data in that study (only 8 % of $SOC_i > 15$ g·kg^{-1}). Straw applied to soils with high SOC_i may not improve SOC because these soils are nearing saturation (Stewart et al., 2007).

4.2. Effects of straw returning depth on subsoil SOCS

Subsoil holds most soil carbon stocks (Min et al., 2020), yet most research has focused on the topsoil (0–30 cm) (Huang et al., 2021; Liu et al., 2023b; Lin et al., 2024; Yao et al., 2025), overlooking subsoil's crucial role in long-term carbon sequestration. Despite its lower SOC content, subsoil offers considerable potential for stable carbon storage due to its age (Button et al., 2022) and higher mineral surface area, which promotes microbial activity and growth, stabilizing buried organic carbon and slowing decomposition (Feng et al., 2020). Straw returning depth significantly influenced SOCS in the subsoil ($p < 0.05$, Fig. 1). Factors such as lower temperatures, limited oxygen, reduced microbial abundance, and the presence of high-quality carbon substrates in subsoils slow SOC decomposition (Salome et al., 2010). Our random

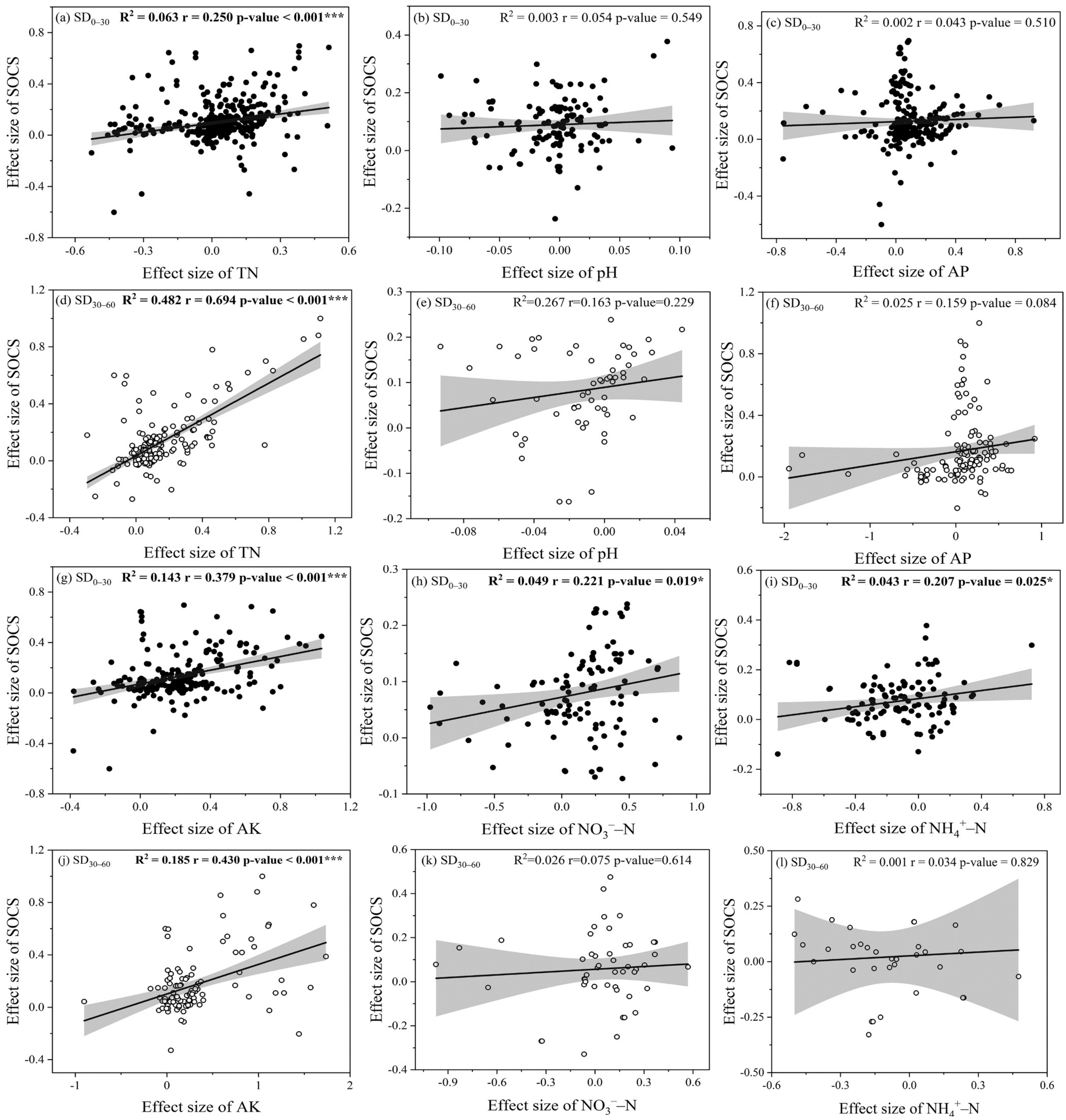

Fig. 5. Relationships between the effect sizes of soil organic carbon stocks (SOCS) and the effect sizes of (a, d) total nitrogen (TN), (b, e) pH, (c, f) available phosphorus (AP), (g, j) available potassium (AK), (h, k) NO_3^--N, and (i, l) NH_4^+-N at 0–30 cm ($SD_{0–30}$) and 30–60 cm ($SD_{30–60}$) sampling depths. *, **, and *** denote significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

forest analysis identified straw returning depth as the strongest predictor of subsoil SOCS, demonstrating a positive correlation ($p < 0.05$, Fig. 4b, Table 1). Root deposition (living and dead) plays a larger role in subsoil carbon formation than aboveground litter inputs (Sokol and Bradford, 2019; Villarino et al., 2021), and $RD_{30–60}$ enhanced subsoil SOCS under various environmental conditions and management practices by placing straw directly into deeper soil layers while encouraging root growth (Figs. 1–3). In contrast, RD_0 and $RD_{0–20}$ led to compaction, hindering root penetration and reducing carbon input into the subsoil (Hu et al., 2021). Deep incorporation improves soil structure and facilitates root and straw distribution, compensating for any carbon losses from soil disturbance (Alcantara et al., 2016). As roots can transport up to 50 % of photosynthetically fixed carbon belowground (Jones et al., 2009), this input is vital for subsoil SOC formation (Rasse et al., 2005). Global data show a strong correlation between root biomass and vertical SOC distribution (Jobbagy and Jackson, 2000). $RD_{20–30}$ was particularly effective in promoting downward root growth and facilitating root carbon input, resulting in the second-highest subsoil increases in SOCS, SOC, TN, and AK, whereas $RD_{0–20}$ showed the weakest effect (Fig. 1). $RD_{20–30}$ likely enhanced root exudation, reduced root hormone levels, and

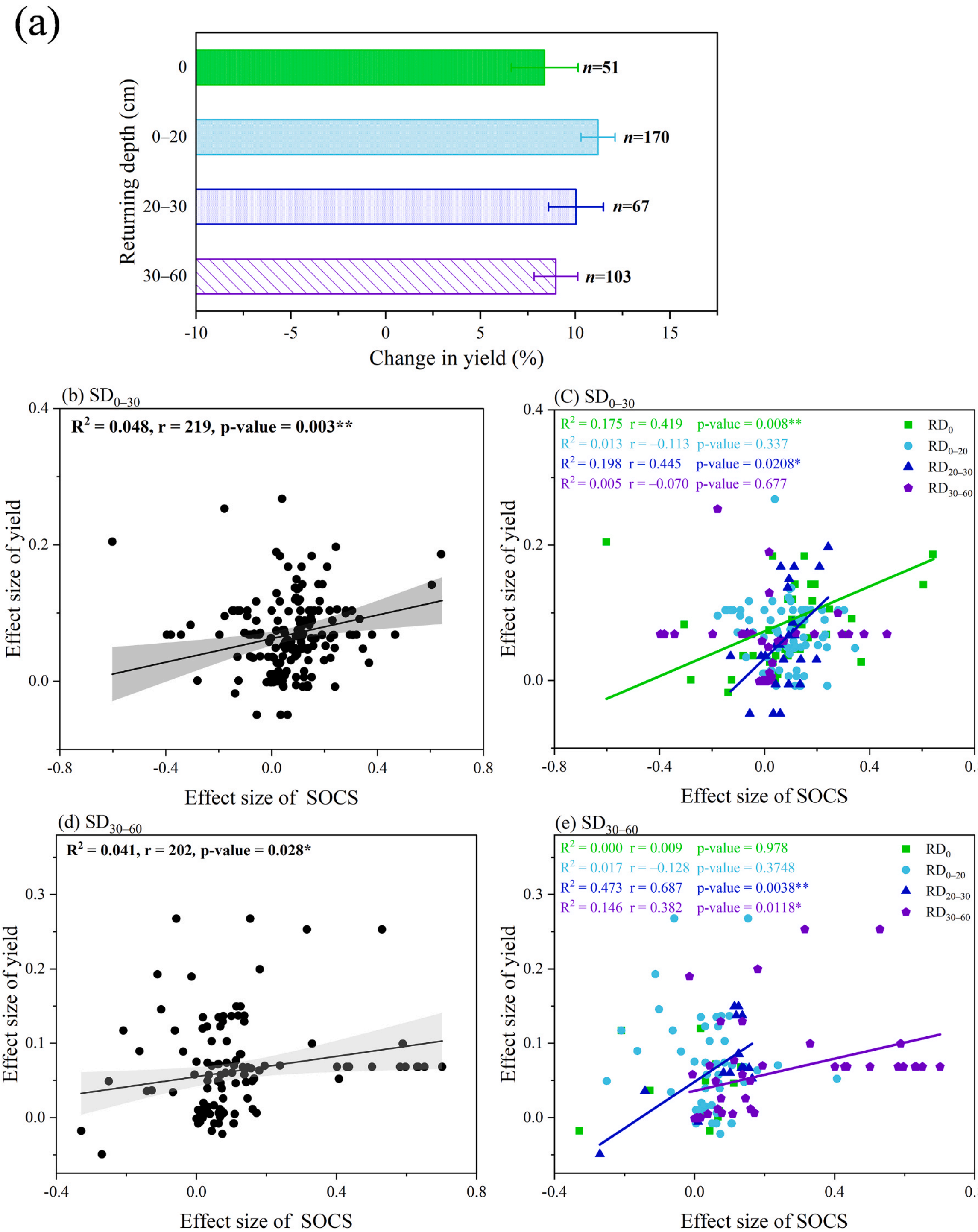

Fig. 6. (a) Effect of straw returning depth on yield. Column strips and error bars represent mean effect sizes and 95 % confidence intervals, respectively. Relationships between the effect size of yield and the effect size of soil organic carbon stocks (SOCS) at (b) 0–30 cm ($SD_{0–30}$) and (d) 30–60 cm ($SD_{30–60}$) sampling depths and across four returning depths [RD_0 (0 cm), RD_{0-20} (0−20 cm), RD_{20-30} (20−30 cm), RD_{30-60} (30−60 cm)] at (c) $SD_{0–30}$ and (e) $SD_{30–60}$. *, **, and *** denote significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

promoted rhizosphere soil C deposition (Wang et al., 2021), thus supporting subsoil SOC sequestration.

Besides depth, subsoil SOCS was also significantly influenced by TN_i, pH_i, SOC_i, AAT, straw type, and NAR ($p < 0.05$, Fig. 4b). High AAT (> 14 °C), high AAP (> 800 mm), and paddy-upland soils promoted decomposition and carbon sequestration more than low AAT (≤ 14 °C), low AAP (≤ 800 mm), and upland soils (Fig. 2a, b, and f). Nitrogen inputs can affect SOC by altering the C: N ratio and microbial dynamics (Liu et al., 2021b). TN_i positively correlated with subsoil SOCS ($p < 0.05$, Table 1), as higher NAR and TN_i increase straw and root biomass inputs (Lu et al., 2009). However, excessive NAR (>200 kg·ha^{-1}) negatively affected subsoil SOC (Fig. 3d), likely due to soil acidification, salinization, accelerated SOC mineralization, and nutrient imbalances (Xu et al., 2018; Lin et al., 2024). Compared to topsoil, subsoil SOCS was more sensitive to management practices (Fig. 3), showing positive correlations with SAR, PAR, and KAR and negative correlations with NAR and straw C: N ratio ($p < 0.05$, Table 1). Maize straw, with its high C: N ratio and lignin content, decomposes more slowly than wheat or rice straw (Wang et al., 2023a), leading to a lower subsoil SOCS increase (4.2–25.7 %) (Fig. 3a). While high C: N material may initially fulfill short-term carbon demands and reduce carbon respiration, it can also stimulate microbial growth and mineralization of native SOC and nitrogen (Jones et al., 2018; Meyer et al., 2018).

4.3. *Straw returning enhances topsoil and subsoil carbon sequestration and crop yield*

Incorporating plant-derived organic carbon into soils is key to enhancing SOC sequestration. This process replenishes carbon lost through agricultural practices and supplies essential nutrients—such as lignin, hemicellulose, neutral sugars, and lipids—via microbial decomposition and mineralization (Doetterl et al., 2015; Panettieri et al., 2017; Huang et al., 2022). With increasing global concern over soil degradation and food security, effective straw returning strategies are increasingly critical for enhancing soil fertility and crop productivity (Guan et al., 2020). Our findings showed that straw returning significantly improved SOC, SOCS, and overall soil quality ($p < 0.05$, Fig. 1). This improvement is primarily due to the release of key—nitrogen, phosphorus, and potassium—during straw decomposition, which helps replenish soil fertility (Yan et al., 2019). As such, future agricultural practices should aim to enhance crop yields while promoting SOC sequestration and reducing carbon emissions.

Our analysis shows that all four straw returning depths increased crop yields by 8.4–11.2 % (Fig. 6a)—comparable to yield gains (~10 %) reported for straw mulching and straw burial (Huang et al., 2021). These improvements are likely attributable to enhanced SOC levels and improved soil biophysical and physicochemical conditions (Fig. 1) (Liu et al., 2014). SOC is essential for regulating nutrient dynamics and maintaining chemical balance in the soil (Lal, 2020b), influencing fertility, water retention, and ultimately crop yield (Feng et al., 2020). The positive correlations between crop yield and both topsoil and subsoil SOCS further support this relationship ($p < 0.05$, Fig. 6). Increased SOC also reduced nitrogen leaching, boosted nutrient availability, stimulated microbial activity, and improved TN and AK levels in topsoil and subsoil ($p < 0.05$, Fig. 5), thereby improving soil health and supporting sustainable agricultural production (Oldfield et al., 2019; Lal, 2020b; Kane et al., 2021).

However, the yield benefits varied with straw returning depth, with RD_0 having the least pronounced effect, while $RD_{0–20}$ and $RD_{20–30}$ had the greatest impact (Fig. 6a). The mechanisms driving these yield increases differed by depth. For RD_0—where straw was left on the surface—yield improvements were associated with higher topsoil SOCS ($p < 0.05$, Fig. 6c, e). In contrast, whereas $RD_{30–60}$ was associated with increased subsoil SOCS ($p < 0.05$, Fig. 6e), building a deeper nutrient reservoir for crop use. RD_0 was especially effective under loam soils and for SAR $< 8000\ kg\cdot ha^{-1}$ (Figs. 2 and 3). Surprisingly, while $RD_{0–20}$ increased topsoil and subsoil SOCS, these changes did not translate into higher yields (Fig. 6c and e). This trend could be due to (1) over-fertilization, which may have saturated the 0–20 cm soil layer, diminishing the yield benefits of increased SOCS (Liu et al., 2023a), or (2) intensified nutrient competition between soil microorganisms and crops due to high straw-derived carbon in the surface layer (Yang et al., 2019a). Moreover, $RD_{0–20}$ had the smallest effect on subsoil SOCS (6.1 %) and the weakest impact on yield. Nonetheless, $RD_{0–20}$ was most effective for increasing topsoil SOCS under specific conditions: AAT $\le 14\ °C$, AAP ≤ 800 mm, $SOC_i \ge 10\ g\cdot kg^{-1}$, long straw returning duration ($\ge$ 3 years), single cropping systems, upland regions, clay loam soils, and maize straw returning (Figs. 2 and 3). In contrast, $RD_{20–30}$ showed strong positive associations between crop yield and topsoil and subsoil SOCS ($p < 0.05$, Fig. 6). This depth supported subsoil root decomposition (Liu et al., 2021a), creating an independent nutrient pool below the 20 cm layer. This stratified nutrient availability and suppression of soil-borne fungal pathogens improved crop yields (Yang et al., 2020). Higher SOC at $RD_{20–30}$ also likely improved soil structure, water retention, and nutrient content, further supporting crop growth (Lal, 2020a; Kane et al., 2021). Additionally, better soil quality soil at this depth may help buffer crops against climate variability (Qiao et al., 2022). Since $RD_{20–30}$ is also more energy-efficient than $RD_{30–60}$, its consistent yield efts make it an attractive option. It is especially suitable in areas with AAT $> 14°C$, AAP > 800 mm, $SOC_i < 10\ g\cdot kg^{-1}$, $TN_i \ge 1\ g\cdot kg^{-1}$, straw C: N ratio ≤ 75, NAR $\le 200\ kg\cdot ha^{-1}$, PAR $> 90\ kg\cdot ha^{-1}$, KAR $\le 75\ kg\cdot ha^{-1}$, double cropping systems, paddy and paddy-upland soils, and wheat and rice straw returning (Figs. 2 and 3). Site-specific environmental and management factors must be carefully considered across different regions in China to optimize the benefits of straw returning and maximize carbon sequestration.

5. Conclusions

This meta-analysis assessed the effects of varying straw returning depths on topsoil and subsoil SOCS and crop yield, supporting our initial hypotheses. Different incorporation depths enhanced SOC and SOCS to varying degrees in both topsoil and subsoil and contributed positively to crop productivity. Among the tested treatments, $RD_{20–30}$ had the most significant positive impact on topsoil SOCS, SOC, and NO_3^--N, and was second only to $RD_{30–60}$ in enhancing subsoil SOCS, SOC, TN, and AK. However, the effectiveness of each depth was influenced by environmental and management factors, as expected. Specifically, RD_0 was most effective at increasing SOCS in loam soils and with SAR $< 8000\ kg\cdot ha^{-1}$. $RD_{0–20}$ was optimal for lower temperature and precipitation regions, longer treatment durations ($\ge$ 3 years), single cropping systems, upland regions, and maize straw returning. $RD_{20–30}$ performed best in areas with higher temperatures, greater precipitation, higher TN_i and PAR, and lower straw C: N ratios, NAR, and KAR. These findings highlight the importance of tailoring straw returning strategies to local environmental conditions and management practices to maximize topsoil and subsoil carbon sequestration, ultimately supporting sustainable and productive cropland systems.

CRediT authorship contribution statement

Miaomiao Zhang: Writing - original draft, Methodology, Investigation, Formal analysis, Data curation. **Ning Yang:** Writing - original draft, Methodology, Formal analysis, Data curation. **Xiaoqing Han:** Writing - review & editing. **Rattan Lal:** Writing - review & editing. **Tiantian Huang:** Writing - review & editing. **Pengfei Dang:** Writing-review & editing. **Jiquan Xue:** Supervision, Conceptualization. **Xiaoliang Qin:** Supervision, Funding acquisition, Conceptualization. **Kadambot H. M. Siddique:** Writing-review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109799.

Data availability

Data will be made available on request.

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