Soil & Tillage Research 261 (2026) 107195

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

# Conservation tillage promotes soil organic carbon sequestration in warm and semi-humid regions of Northeast China

Jianyu Tao [a,*], Xiaoyuan Liu [b], Shuai Liu [c], Fahui Jiang [d], Yongqi Qian [a], Zhongbin Zhang [a], Xinhua Peng [a,*]

[a] State Key Laboratory of Efficient Utilization of Arable Land in China, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[b] School of Geography and Planning, Chizhou University, Chizhou, Anhui 247000, China
[c] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing 210008, China
[d] Soil and Fertilizer Institute, Anhui Academy of Agricultural Sciences, Anhui Provincial Key Laboratory of Nutrient Cycling and Arable Land Conservation, Hefei 230031, China

ARTICLE INFO

*Keywords:*
Soil C sequestration
Conservation tillage
Zero tillage
Subsoil

ABSTRACT

Zero tillage with straw mulching (ZT) is a widely adopted conservation tillage practice for enhancing soil organic carbon (SOC) storage. Nevertheless, its impact on SOC stocks in Northeast China remains uncertain. Here, a regional meta-analysis was conducted to evaluate the effects of different tillage regimes on SOC stocks in Northeast China. The meta-analysis confirmed that ZT generally increased SOC and total nitrogen (TN) stocks in the topsoil (0–20 cm) but exhibited no significant effects on subsoil SOC and TN stocks (20–40 cm) compared to other tillage regimes (i.e., deep and conventional tillage). Nevertheless, the overall SOC and TN stocks within the 0–40 cm soil profile still increased under ZT. Random forest (RF) model and Shapley additive explanations (SHAP) further revealed that experimental duration, straw management, and mean annual temperature (MAT) were key factors influencing the effects of tillage regimes on topsoil SOC stocks. SHAP dependence analyses indicated that ZT tended to store more SOC in the topsoil than other tillage regimes when the experimental duration exceeded 6.3 years or MAT ranged from 2.9 to 7.5 °C. In addition, subsoil SOC stock change ratios were mainly controlled by initial soil C:N ratio, SOC content, and tillage regime. SOC stocks may decline under ZT when the initial soil C:N ratio exceeded 11.8 or SOC was above 15.6 g $kg^{-1}$. Predictions via RF models suggested that subsoil SOC stocks determined the direction of SOC stock dynamics in the 0–40 cm soil layer across tillage regimes. ZT inclined to enhance 0–40 cm SOC stocks in warm and semi-humid areas compared to other tillage regimes. Collectively, these findings quantify the SOC sequestration potential of long-term ZT application in Northeast China, which provides scientific evidence to policymakers for soil reclamation.

## 1. Introduction

Zero tillage with straw return (ZT) is a typical conservation tillage practice that is frequently adopted to reduce soil erosion (Akplo et al., 2022), improve soil structure (Marahatta et al., 2025), and enhance SOC accumulation (Pramanick et al., 2024). In contrast, deep and rotary tillage impose intensive physical disturbance, which degrades soil structure and may reduce SOC stocks (Li et al., 2021). The effectiveness of tillage practices on SOC stocks is influenced by multiple factors, including climatic conditions and soil properties. Previous studies have indicated that SOC accumulation decreases with increasing temperature and precipitation (Kirschbaum, 2000; Márton, 2008), likely as a result of enhanced soil microbial activity and accelerated SOC decomposition (Chen et al., 2020). Tillage practices may alter soil temperature and moisture (Jiang et al., 2025), with effects that vary across climatic zones and ultimately influence SOC storage. A 20-year field experiment conducted by Zhang et al. (2023) indicated that ploughing with straw return enhanced SOC sequestration more effectively than ZT in warm and humid regions. However, the meta-analysis by Ul Islam et al. (2023) demonstrated that ZT generally outperformed deep tillage with straw return (DP) in enhancing topsoil SOC stocks under warm and dry climatic conditions. Hermle et al. (2008) reported no significant

* Corresponding authors.
*E-mail addresses:* taojianyu@caas.cn (J. Tao), pengxinhua@caas.cn (X. Peng).

https://doi.org/10.1016/j.still.2026.107195
Received 29 January 2026; Received in revised form 19 March 2026; Accepted 23 March 2026
Available online 26 March 2026

differences in SOC stocks among deep ploughing, shallow tillage, and zero tillage under moist, cold-temperate climatic conditions. These findings suggest that the effects of tillage regimes on SOC stocks under different climatic conditions remain insufficiently understood, despite numerous existing studies. The region of Northeast China spans humid, semi-humid, semi-arid, and arid climatic zones; therefore, the applicability of different tillage regimes in this region warrants more comprehensive investigation.

Soil organic C storage potential is limited and can be modified by agricultural management practices, such as tillage and straw management (tillage regimes). SOC stocks tend to stabilize once a new equilibrium is established following the continuous application of a given tillage regime (Lu et al., 2009; West and Six, 2007). Deep tillage exerts negligible effects on SOC stocks when initial SOC contents exceed 15 g $kg^{-1}$ (Wang et al., 2023), whereas zero tillage enhances SOC accumulation when initial SOC levels are below 20 g $kg^{-1}$ (Huang et al., 2025). However, other studies have reported that ZT and DP can also promote SOC retention under high initial SOC contents (Chen et al., 2026; Liu et al., 2025). In addition, studies have indicated that nutrient limitations constrain the replenishing effect of straw return on SOC stocks (Mo et al., 2024; Cao et al., 2022). High N availability may accelerate the decomposition of straw and soil organic matter, thereby reducing the extent of SOC accumulation under straw return (Wang et al., 2024). In contrast, a high level of available P may suppress microbial mining of SOC for P acquisition (Fang et al., 2019), consequently inhibiting SOC decomposition following straw return. Moreover, tillage practices physically disturb the distribution of soil nutrients and straw, which reshapes the habitats of soil microorganisms and the amount of SOC accumulated.

Soil organic matter decomposition rate is generally slower in fine-textured soils (i.e., those rich in clay) due to oxygen limitation, clay mineral adsorption, and physical protection within aggregates (FAO, 2004). ZT causes minimal soil disturbance and preserves soil aggregate structure. Thus, the positive effects of ZT on SOC sequestration are generally more pronounced in fine-textured soils than in medium- and coarse-textured soils (Bregaglio et al., 2022). Studies have indicated that ZT increases topsoil SOC stocks more effectively than conventional tillage in coarse-textured soils (Bhattacharyya et al., 2009; Mina et al., 2008). However, Qiang et al. (2022) reported that DP significantly increased SOC stocks in coarse-textured soils compared to ZT. In addition, soil pH is widely recognized as a critical regulator of SOC dynamics. Limousin and Tessier (2007) found that ZT reduced the pH of 0–5 cm topsoil, probably due to organic acids released during straw decomposition (Liang et al., 2023). Soil acidification caused by straw return is more pronounced under high initial soil pH conditions (Limousin and Tessier, 2007). Meanwhile, straw-induced SOC accumulations are relatively higher in alkaline soils than in acidic or neutral soils (Zhu et al., 2023). However, Li et al. (2023a) observed no significant differences in SOC stocks among acidic, neutral, and alkaline soils under straw return. Moreover, subsoil exhibits considerable potential for storing SOC despite its relatively low SOC content (Rumpel et al., 2012). SOC stratification under ZT may hinder the formation of subsoil SOC pools, thereby reducing the SOC sequestration potential of the soil profile. Conflicting findings have been reported regarding the effect of deep tillage on subsoil SOC stocks, with studies documenting both increases (Wang et al., 2023) and decreases (Tian et al., 2016). In summary, it is essential to examine the effects of tillage regimes on SOC stocks under varying climatic conditions, soil properties, and soil layers.

Given the vast heterogeneity of climatic and edaphic conditions across Northeast China, evaluating the effects of different tillage regimes on regulating SOC dynamics is urgent. In this study, a regional meta-analysis of 92 published studies was conducted to (1) compare the effects of tillage regimes on SOC stocks in both topsoil and subsoil layers, (2) identify the key environmental drivers of SOC stocks in Northeast China, and (3) estimate the differences in SOC stocks between ZT and other tillage regimes across Northeast China.

## 2. Materials and methods

### 2.1. Data collection

The literature search for peer-reviewed publications was conducted in *ISI Web of Science* (http://apps.webofknowledge.com/), *ScienceDirect* (https://www.sciencedirect.com/), and *China Knowledge Resource Integrated Database* (CNKI; http://www.cnki.net/), using search terms listed in Table S1. All the publications were screened and selected according to the following criteria: (1) only field experiments conducted in the agroecosystems of Northeast China were included, whereas pot and incubation studies were excluded; (2) each study must include conservation tillage (zero tillage with straw return) and at least one additional tillage practice (e.g., rotary tillage, ploughing, and subsoiling); (3) treatments combining tillage with amendments (e.g., biochar and compost) were excluded; (4) multiple observations from a single study were analyzed as independent paired data points for different treatments, and only measurements from the final sampling time were included in the analysis. Same experimental results reported across various publications were considered only once. However, observations derived from the same long-term experiment but reported in different publications were treated as independent paired data points only when the final sampling times differed by at least five years. Following this screening procedure, 92 peer-reviewed publications were included in the meta-analysis database (Fig. S1; Supplementary Note S2). Following the data processing method of Watson et al., (2020)), we updated the dataset with the latest unpublished data from the networked field experiments conducted by the authors' research group. Detailed experimental design is described in Jiang et al. (2025). The experimental durations of the dataset ranged from 1 to 37 years. SOC, TN, TP, AN, AP, AK, BD, pH, microbial biomass carbon (MBC), and crop yield were extracted from the topsoil (0–20 cm) and subsoil layers (20–40 cm). Means (M), standard deviations (SD), and sample sizes (n) were obtained directly from tables or indirectly from figures using the WebPlotDigitizer tool. Standard error (SE) was converted to SD using the following formula $SD=SE\times\sqrt{n}$. For studies lacking both SD and SE, the average coefficient of variation (CV) of the available observations was calculated, and the missing SD values were estimated by multiplying the corresponding mean with the average CV (Yang et al., 2015). Geographic features (latitude and longitude) were collected from the original publication or retrieved from other publications by the same authors (Fig. S2). For each study, we also extracted the following data: climatic conditions (i.e., mean annual temperature, mean annual precipitation, and aridity index), inorganic fertilization amounts, and initial soil properties which included soil texture, pH, SOC, total nitrogen (TN), available nitrogen (AN), total phosphorus (TP), and available phosphorus (AP). Missing climatic data were supplemented by averaging the 30-year climate data (1970–2020) from WorldClim v2.1 (https://www.worldclim.org/) based on the geographic coordinates of the experimental sites. The HSWD 2.0 database (https://gaez.fao.org/pages/hwsd) was used to fill the missing soil texture and pH values based on the geographic coordinates. Soil bulk density (BD) was estimated using SOC content (Eq.1) when it was not reported in the publications (Mo et al., 2024; Song et al., 2005). The estimated BD values were used to calculate SOC stocks, whereas the meta-analysis was conducted using the originally reported BD values. An equivalent soil mass (ESM) method was applied to calculate the stocks of soil organic C and other elements (N, P, and K), where the lowest mineral soil mass was used as the baseline in each site. The stocks were interpolated via a linear model (Peng et al., 2024; Supplementary Note S1).

$$Estimated\mathrm{BD} = 1.377 \times \mathrm{Exp}(-0.0048 \times \mathrm{SOC}) \quad (1)$$

### 2.2. Classification and data analysis

Tillage regimes were classified according to straw management and tillage practices. Straw management included straw return (SR) and removal (nR), while tillage practices were subgrouped into conventional tillage (CT; <25 cm), deep tillage (DT; >25 cm), and zero tillage. Zero tillage was consistently accompanied by straw return across all the collected publications; therefore, zero-tillage with straw return was denoted by ZT. In total, five tillage regimes were identified: CTSR, CTnR, DTSR, DTnR, and ZT. In addition, conventional tillage was further divided into shallow ploughing (PL) and rotary tillage (RT), while deep tillage was classified into deep ploughing (DP) and subsoiling (SS). Soil layers were classified as topsoil (0–20 cm) and subsoil (20–40 cm) based on the sampling depths. Soils were classified as acidic (< 6.5), neutral (6.5–7.5), and alkaline (>7.5) based on pH thresholds. A soil clay content of 27% was adopted to subgroup the dataset as it is the threshold for loamy soils (Fig. S3).

The effect size of each response variable was calculated as the natural logarithm of the response ratio (lnRR), where ZT was chosen as the control (Eq. 2). The variance of lnRR was calculated using Eq. 3. The standard workflow of meta-analysis was followed to ensure the robustness of the results. Briefly, a mixed-effects model was employed to pool effect sizes, which accounted for both between-study and within-study heterogeneity. For better interpretation, effect sizes were converted to the change ratios of the variables between ZT and other tillage regimes using Eq. 4. Funnel plots and Begg's tests were used to assess for potential publication bias. A leave-one-out sensitivity analysis was performed to evaluate the influence of individual observations on the meta-analysis. Furthermore, meta-regression analyses were conducted by introducing continuous moderators (explanatory variables) into the mixed-effects model. Experimental duration was incorporated into the model as a weighting factor in the meta-regression analyses. All meta-analyses were conducted using the "metafor" package in R.

$$\ln RR = \ln\left(\frac{x_e}{x_c}\right) \tag{2}$$

$$Var - \ln RR = \frac{(SD_e)^2}{n_e(x_e)^2} + \frac{(SD_c)^2}{n_c(x_c)^2} \tag{3}$$

$$ChangeratiooftheVar = \left(\frac{1}{\exp(\ln RR)} - 1\right) \times 100\% \tag{4}$$

where $x$, $n$, and $SD$ represent the mean, sample size, and standard deviation of the response variables under different tillage regimes. Subscripts $e$ and $c$ denote tillage treatments (CTSR, CTnR, DTSR, and DTnR) and the control (ZT).

### 2.3. Random forest model with Shapley additive explanations

Random forest (RF) models were fitted to investigate the effects of climatic and soil properties on SOC stocks under different tillage regimes. SOC stock change ratio (converted from lnRR) was used as the response variable in the RF model. A 5-fold cross-validation method was applied to tune the RF models for SOC stocks in the topsoil and subsoil layers respectively. One hundred RF models were simulated with identical parameters but different random seeds (1−100) to select the best model. Meanwhile, the overall importance of explanatory variables was estimated by averaging the increases in mean square error (MSE) of these models. Coefficient of determination ($R^2$; Eq. 5) and root mean square error (RMSE; Eq. 6) were used to select the optimal RF model. Moreover, Shapley additive explanations (SHAP) were employed to interpret the contributions of explanatory variables in the RF model. SHAP values were computed using the "kernelshap" package in R. A positive SHAP value indicates a positive effect of the feature on the response variable. The absolute value of SHAP represents the importance of a feature in the model (Dong et al., 2025). SHAP dependence plots were constructed to examine the effects of explanatory variables on the response variables (SOC stock). General additive models (GAM) were used to simulate the non-linear relationships between SHAP values and explanatory variables. Differences in SOC stocks between ZT and other tillage practices were estimated via the RF models for 0–20 and 20–40 cm. Climatic information and edaphic properties were obtained from WorldClim v2.1 and the dataset provided by Shi and Shangguan (2024).

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{6}$$

where $y_i$, $\hat{y}_i$, and $\bar{y}$ represent the observed, predicted, and mean values of the response variables, respectively.

## 3. Results

### 3.1. Tillage regimes and straw management

Zero tillage with straw mulching (ZT) significantly decreased soil pH but increased BD in the topsoil compared to other tillage regimes (Fig. 1). Topsoil SOC and TN stocks were generally higher under ZT than those under other tillage regimes, whereas no significant differences were observed between tillage regimes for all soil properties in the subsoil. Although the overall 95% CIs of the subsoil AP stock change ratios were below zero, our sensitivity analysis demonstrated that this result may not be robust (Fig. S4). As for the 0–40 cm soil profile, SOC and TN stocks under ZT were significantly higher than those under other tillage regimes, with mean increases by 5.4% and 3.5%, respectively (Fig. 1a c). Moreover, ZT generally had no obvious effect on crop yields compared to other tillage regimes (Fig. 1h).

ZT effectively enhanced SOC accumulation in the topsoil than other tillage practices with straw removal, except for subsoiling (SS; Fig. 2a). Specifically, ZT increased topsoil SOC stocks by 14.47%, 15.03% and 9.40% relative to shallow ploughing (PL), rotary tillage (RT), and deep tillage (DT), respectively. However, ZT exhibited no significant differences in SOC stocks compared to other tillage practices combined with straw return across all soil layers (Fig. 2), except for DT in the 0–20 cm soil layer which was primarily attributed to the positive effect sizes of deep ploughing (DP; Fig. 2a).

In the topsoil, TN stock change ratios were positively correlated with SOC stock change ratios across different tillage regimes (Fig. 3a), indicating that tillage regimes concurrently influenced SOC and TN stocks. A significant positive linear relationship was observed between the change ratios of MBC and SOC under DTnR and CTnR in the subsoil layer (Fig. 3f). In addition, SOC stock change ratios decreased linearly with increasing soil pH change ratios under DTnR and CTnR in the topsoil layer (Fig. 3c). According to the Begg's test, no potential publication bias was detected in our meta-analysis (Fig. S5).

### 3.2. Environmental variables

Experimental duration had a pivotal effect on SOC stocks under different tillage regimes, especially in the topsoil (Fig. 4, S6). ZT increased SOC stocks in 0–20 and 0–40 cm soil layers by 22.2% and 12.2%, respectively, when the experimental duration was longer than 10 years (Fig. 4a c). SOC change ratios between ZT and other tillage regimes demonstrated opposite trends in 0–20 and 20–40 cm soil layers under different initial SOC contents and varying C:N and C:P ratios. Further meta-regression analyses revealed that the effect sizes (lnRR) of subsoil SOC stocks were positively related to initial SOC contents and soil C:N ratios under straw return conditions ($p < 0.05$; Table S2). This result indicated that ZT tended to reduce subsoil SOC stocks compared to other tillage regimes with increasing initial SOC contents or soil C:N ratios. In addition, ZT increased topsoil SOC stocks by 6.8% and 10.9%

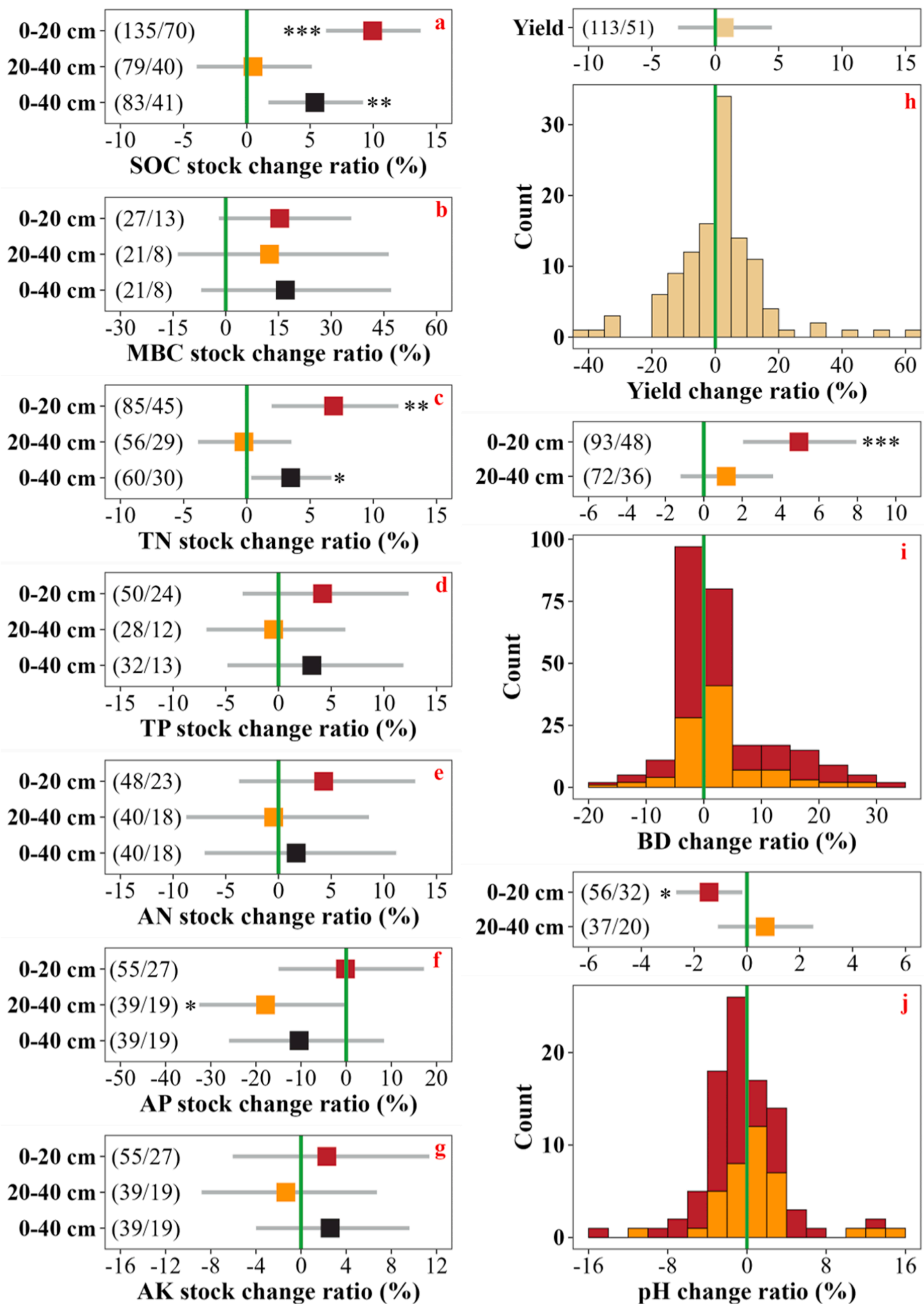


**Fig. 1.** Change ratios of soil organic carbon (SOC), microbial biomass carbon (MBC), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), available phosphorus (AP), and available potassium (AK) stocks, bulk density (BD), pH, and crop yield between zero tillage and other tillage regimes across different soil layers. Bars with 95% confidence intervals that exclude zero are considered statistically significant (*, $P < 0.05$, **, $P < 0.01$, ***, $P < 0.001$).

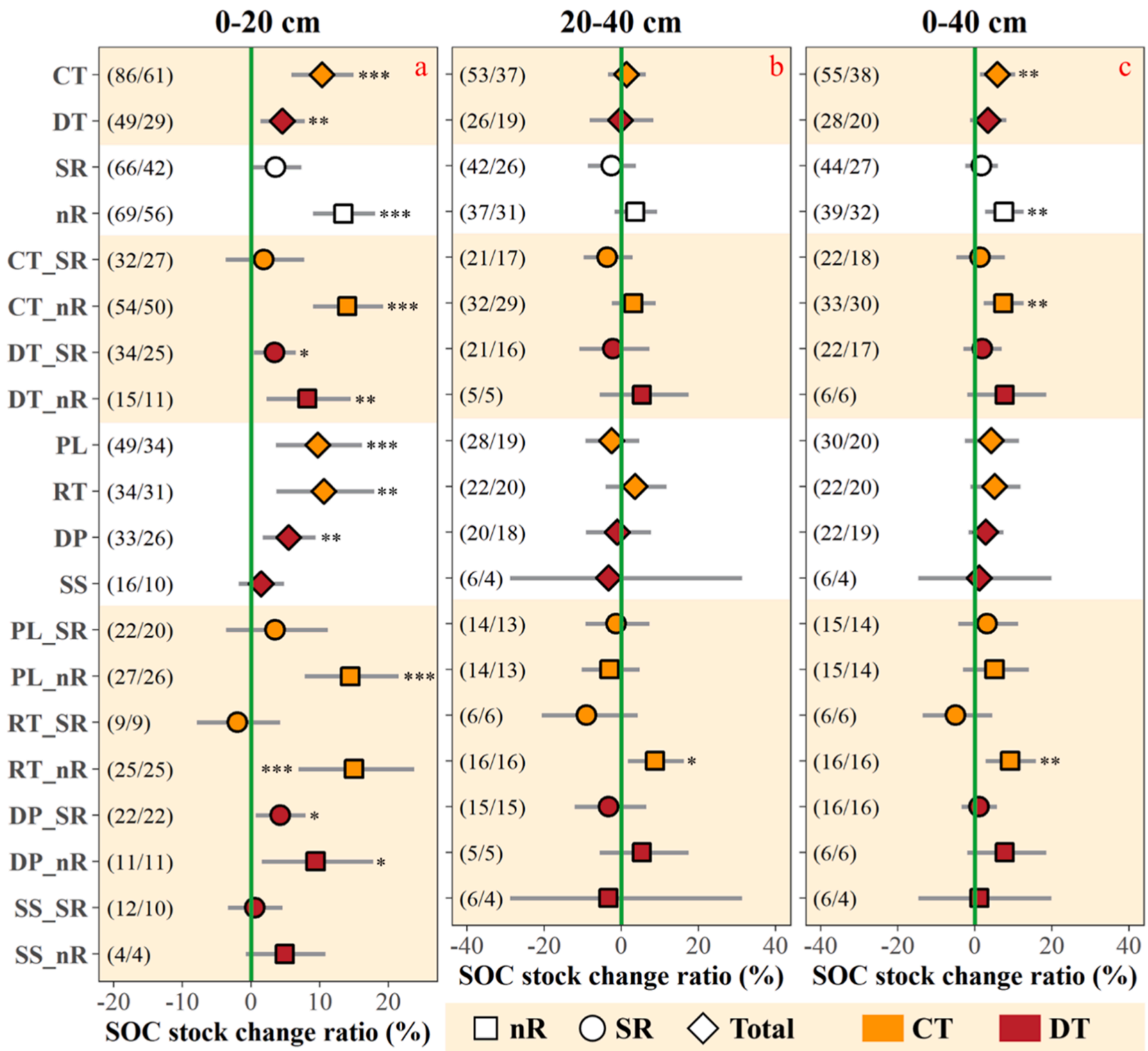


**Fig. 2.** Effects of tillage regimes on SOC stock change ratios across different soil layers. CT and DT represent conventional and deep tillage, respectively. SR and nR represent straw return and removal, respectively. PL, RT, DP, and SS represent shallow ploughing, rotary tillage, deep ploughing, and subsoiling, respectively. Numbers adjacent to each bar are the sample sizes. Bars with 95% confidence intervals that exclude zero are considered statistically significant (*, $P < 0.05$, **, $P < 0.01$, ***, $P < 0.001$).

compared to other tillage regimes in regions with MAT below 4 ℃ and above 4 ℃, respectively (Fig. 4a). ZT significantly increased topsoil SOC stocks in regions with MAP ranging from 400 to 600 mm, whereas its negative effects on subsoil SOC stocks occurred in regions with MAP exceeding 600 mm. The effects of ZT on topsoil SOC stocks were generally insensitive to aridity index (Fig. 4). However, significant negative relationships were observed between the effect sizes (lnRR) of topsoil SOC stocks and both the aridity index and MAP under straw removal conditions ($p < 0.05$; Table S3). Inorganic fertilization (N and P) exerted no obvious effects on SOC stocks between ZT and other tillage regimes, although a potential reduction was noticed when P fertilization was lower than 40 kg P $ha^{-1}$ $yr^{-1}$ (Fig. 4b). ZT was more conducive to enhancing SOC stocks in acidic soils across all soil depths, although no significant differences were found. Moreover, crop yields under ZT decreased relative to other tillage regimes with straw incorporation as straw return amounts increased ($p < 0.05$; Table S2).

### 3.3. Random forest models and Shapley additive explanations

Experimental duration, straw management, and MAT were the top three most influential factors regulating topsoil SOC stock change ratios between ZT and other tillage regimes (Fig. 5a, S7a). In the subsoil, initial soil C:N ratio, initial SOC, tillage practices (CT and DT), and silt content were identified as the most important regulators of SOC stock change ratios (Fig. 6a, S7b).

In the topsoil, SHAP values increased almost linearly with increasing experimental durations, exhibiting a threshold of 6.3 years (Fig. 5b). Straw return (SR) and removal (nR) posed completely opposite effects on SOC change ratios between ZT and other tillage practices, which may be influenced by soil clay content. Specifically, low soil clay content may narrow down the differences between straw return and removal (Fig. 5c). Positive SHAP values were observed in soils with clay content above 30.6% (Fig. 5f). In addition, SHAP values initially increased and subsequently decreased with increasing MAT, with positive SHAP values observed in the range from 2.9 to 7.5 ℃ (Fig. 5d). SHAP values were prevailingly positive under DT but negative under CT, whereas the SHAP values of CT and DT were relatively similar under straw removal conditions (Fig. 5g). Moreover, low soil C:N ratios may expand the differences in SHAP values between CT and DT (Fig. 5h). The effects of initial soil C:N ratio on SOC change ratios were highly dynamic, with a crucial inflection point of 12.9 identified from the simulated GAM curve (Fig. 5e).

In the subsoil, SHAP values of straw management exhibited a similar trend to those in the topsoil (Figs. 5c, 6f), whereas SHAP values of tillage

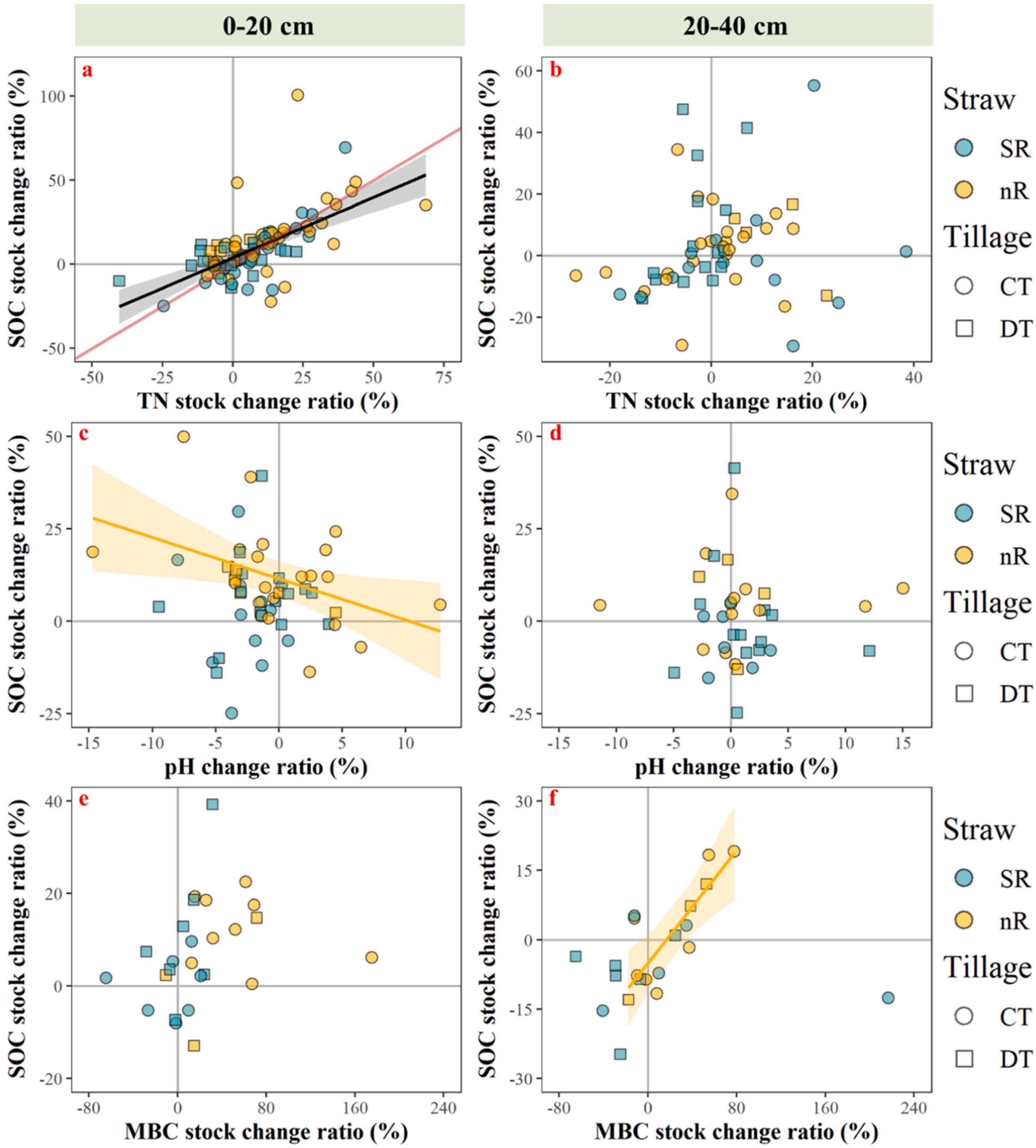


**Fig. 3.** Relationships between the change ratios of SOC stock and other experimental variables in the 0–20 and 20–40 cm soil layers. CT and DT represent conventional and deep tillage, respectively. SR and nR represent straw return and removal, respectively. The black line and grey shaded area in plot (a) are the regression line and its 95% confidence area for all the data points, while the red line indicates the line y = x. Yellow lines and shaded areas in plot (c) and (f) indicates the linear regression lines and 95% confidence areas for data points under straw removal (nR).

practices differed significantly from those in the topsoil (Figs. 5g, 6d). However, the interactive effects between soil C:N ratio and tillage practices on SHAP values were more pronounced in the subsoil compared to those in the topsoil. SHAP values under DT became negative at high soil C:N ratios, while an opposite trend was observed under CT. Moreover, SHAP values exhibited nonlinear negative relationships with initial soil C:N ratio, SOC content, and pH (Fig. 6b e g), with thresholds of 11.8, 15.6 g $kg^{-1}$, and 7.7, respectively. SHAP values remained stable and negative when silt contents were below 44.6%, after which they increased sharply (Fig. 6d).

Ten-year ZT had overwhelmingly positive effects on topsoil SOC stocks in northeast China compared to other tillage regimes, since all SOC stock change ratios were above zero (Fig. 7, 8, S8, S9). Notably, 80% of the topsoil SOC change ratios between ZT and CTSR were below zero after one year (Fig. 7a). Moreover, subsoil SOC stocks under ZT were generally lower than those under CTSR and DTSR even after 10 years, since 85.9% and 80.2% of the SOC stock change ratios remained negative, respectively (Figs. 7f, 8f). These results also directly reflected that subsoil SOC stocks were insensitive to experimental duration across tillage regimes. Collectively, prevailing SOC stock accruals were observed within the 0–40 cm soil profile under ZT compared with other tillage regimes with straw removal (CTnR and DTnR, Fig. S8, S9). In contrast, ZT enhanced 0–40 cm SOC stocks in warm and semi-humid areas compared to CTSR and DTSR after 10 years (Figs. 7i, 8i), accounting for 65.3% and 67% of the total area.

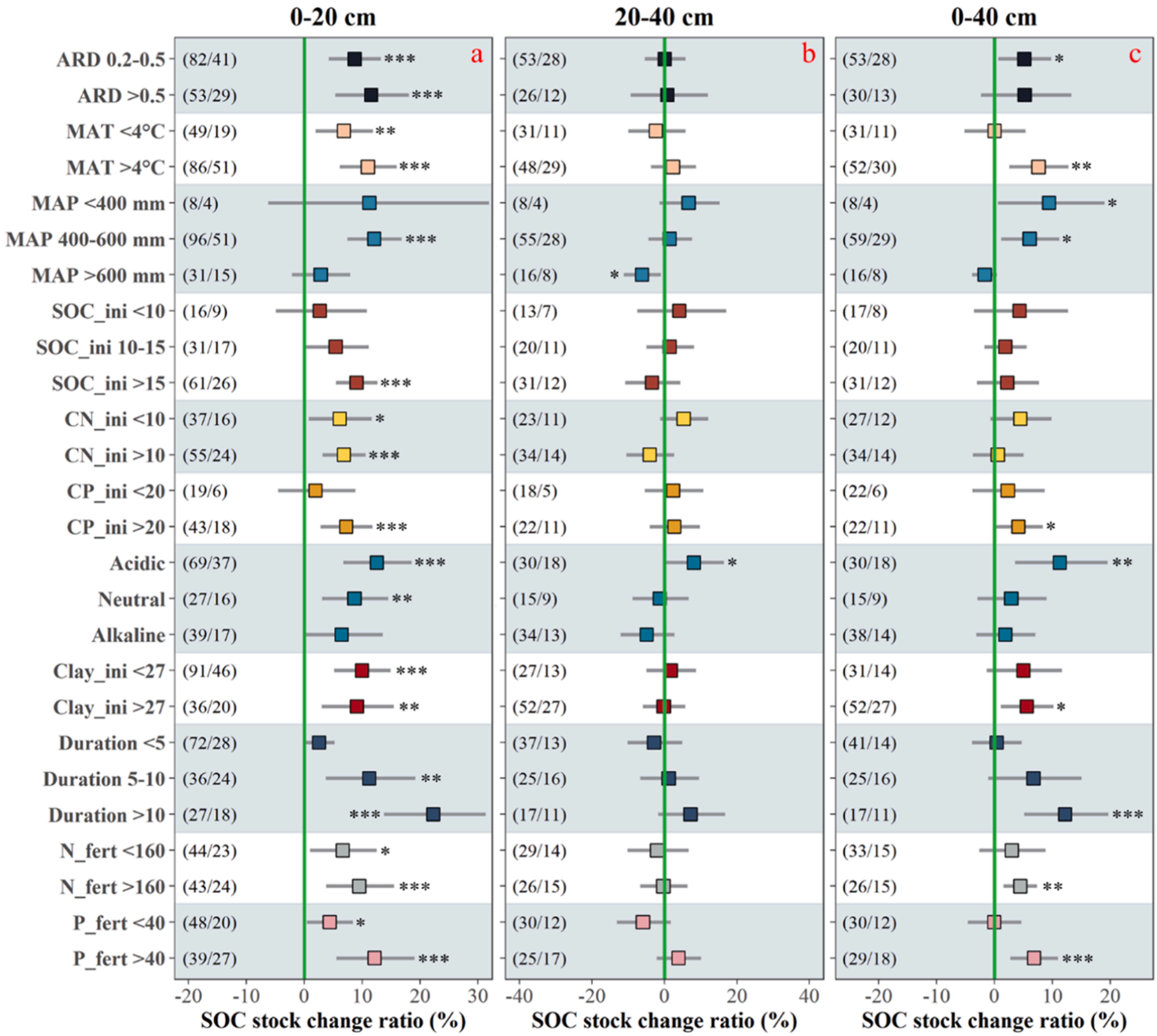


**Fig. 4.** Effects of environmental variables on SOC stock change ratios between zero tillage and other tillage regimes across different soil layers. ARD, MAT, and MAP represent the aridity index, mean annual temperature, and mean annual precipitation, respectively. SOC_ini, CN_ini, CP_ini, and Clay_ini represent the initial values of soil organic carbon, the carbon-to-nitrogen ratio, the carbon-to-phosphorus ratio, and clay content, respectively. N_fert and P_fert represent the application amounts of nitrogen and phosphorus fertilizers, respectively. Numbers adjacent to each bar are the sample sizes. Bars with 95% confidence intervals that exclude zero are considered statistically significant (*, $P < 0.05$, **, $P < 0.01$, ***, $P < 0.001$).

## 4. Discussion

### 4.1. Tillage regimes and climatic conditions

Zero tillage with straw mulching (ZT) is widely implemented to minimize disruption of soil aggregates and mitigate soil erosion (Döring et al., 2005; Song et al., 2016), which facilitates SOC accumulation. Thus, ZT is commonly recognized for promoting SOC stocks in the topsoil. Our meta-analysis confirms this perspective and further demonstrates that increases in SOC are accompanied by concurrent gains in TN stocks (Figs. 1, 3). These findings corroborate the concerns that the positive effects of ZT are limited only to the topsoil. However, the positive effects are not immediately evident in the short term (Figs. 7, 8), mainly due to the slow decomposition of straw applied on the soil surface (Wang et al., 2021), which delays the conversion of residues into stable soil organic matter. Fresh C inputs may stimulate microbial activity and trigger a priming effect (Wu et al., 2019), thereby diminishing the net increase in SOC stocks. In contrast, long-term ZT (> 10 years) enhances microbial C use efficiency and increases physical SOC protection by improving soil structure (Ma et al., 2024; Cooper et al., 2021), thereby promoting the accumulation and stability of topsoil SOC stocks. In addition, long-term ZT decreases SOC stocks in the 20–40 cm soil layer while increasing total SOC stocks within the 0–40 cm soil profile relative to other tillage practices in warm and semi-humid regions (Figs. 7, 8). This pattern demonstrates the surface accumulation effect of ZT on SOC, which may contribute to SOC sequestration within the 0–40 cm soil profile. Moreover, several studies have reported that deep ploughing with straw incorporation leads to greater SOC accumulation in the subsoil than ZT, mainly due to the increase in C inputs (Mary et al., 2020; López-Fando and Pardo, 2011). Another major issue of deep tillage lies in the intensive disruption of soil structure, which may accelerate the decomposition of aggregate-protected SOC. This

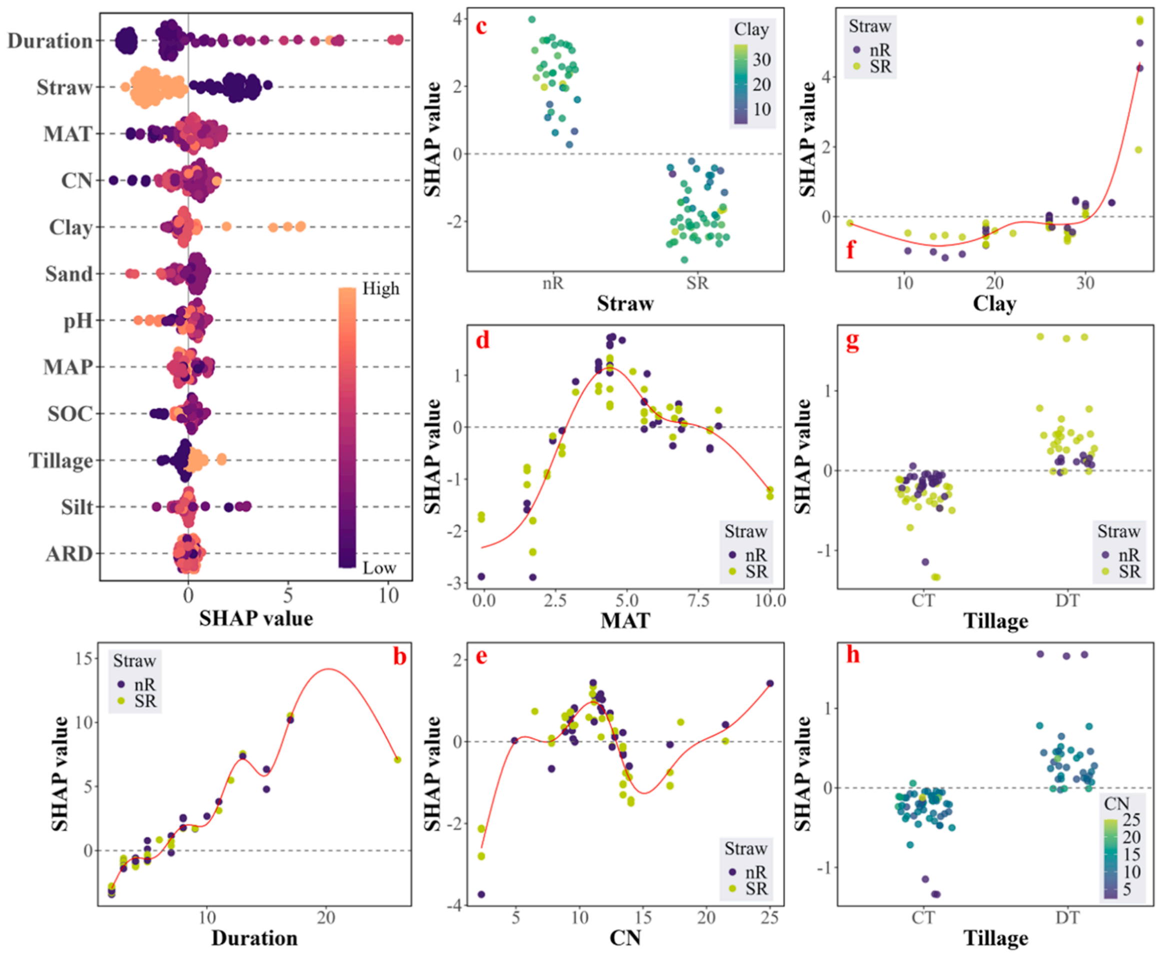


**Fig. 5.** Influences of climatic conditions, soil properties, straw management, and tillage regimes on topsoil SOC stock change ratios derived from a random forest model with SHAP values. Tillage regimes consist of conventional (CT) and deep (DT) tillage, while straw management includes straw return (SR) and removal (nR). SOC stock change ratios are chosen as the response variables. Variable importance (a) and dependence plots (b-h) are simulated based on SHAP values. Variable importance is sorted in descending order. ARD, MAT, and MAP represent the aridity index, mean annual temperature, and mean annual precipitation, respectively. The color legend in plot (a) indicates the range of values for each variable. High and Low represent the maximum and minimum values of each variable, respectively.

drawback may be exacerbated in Northeast China due to frequent freeze-thaw cycles (Fu et al., 2019), thus promoting SOC losses associated with deep ploughing (Fig. 2). In addition, ZT presents no superior positive effect on SOC stock accumulation compared to straw-incorporating conventional tillage (CTSR) and subsoiling in both topsoil and subsoil layers (Fig. 2). One possible explanation is that the responses of SOC stock to tillage regimes require longer experimental periods to become evident (Figs. 5, 7; Dimassi et al., 2014). More importantly, the insignificant differences among tillage regimes may be attributed to regional variations in climatic and edaphic conditions.

Climatic conditions fundamentally determine the net primary C input of agroecosystems by regulating plant growth and biomass accumulation. Previous study has shown that soil microbial C decomposition can exceed plant-derived C inputs when annual precipitation increases in a semi-arid prairie (Maillard et al., 2018). Our findings reveal that ZT generally enhances SOC stock accumulation in humid regions but leads to declines in arid regions within the 0–40 cm soil layer after 10 years (Figs. 7, 8). ZT is more conducive to enhancing soil water use efficiency and sustaining plant productivity compared to other tillage practices (Phogat et al., 2020), which contributes to increased organic matter inputs from crop residues and root biomass in humid regions. Concurrently, ZT reduces SOC decomposition by enhancing aggregate stability, thus mitigating SOC losses (Six et al., 2000). In contrast, DTSR and CTSR can concurrently increase the soil labile C pool and soil microbial activities within the 0–40 cm soil layer, potentially inducing strong priming effects and SOC losses (Tao and Liu, 2025; Ndzelu et al., 2020; Li et al., 2023b). Consequently, C losses may offset the gains from C input under CTSR and DTSR in humid regions over decadal timescales. Liu et al. (2022) reported that precipitation primarily governs SOC accumulation in Northwest China. However, our results indicate that mean annual temperature (MAT) plays a more critical role than mean annual precipitation (MAP) in regulating topsoil SOC stocks in Northeast China (Fig. 5). This is probably because elevated temperature is beneficial for maize germination, growth, and biomass accumulation in Northeast China (Chen et al., 2011; Jiang et al., 2025). ZT reduces soil temperature compared to other tillage regimes, which exacerbates thermal limitations during the early stage of maize growth (Jiang et al., 2024), particularly in regions with low MAT. In addition, thermal limitations under ZT reduce root-derived C inputs and inhibits microbial decomposition of straw (Zhu et al., 2015), accounting for the relatively low topsoil SOC stocks compared to other tillage regimes in low MAT regions (Figs. 4, 5). Nevertheless, it is important to note that collinearity between MAT and MAP may exist along regional climatic gradients (Quetin and Swann, 2017), and regional differences in agricultural productivity as well as straw return rates may further influence SOC dynamics. Therefore, the apparent dominance of MAT over MAP may partly arise from their interrelated spatial variability rather than solely from independent climatic controls.

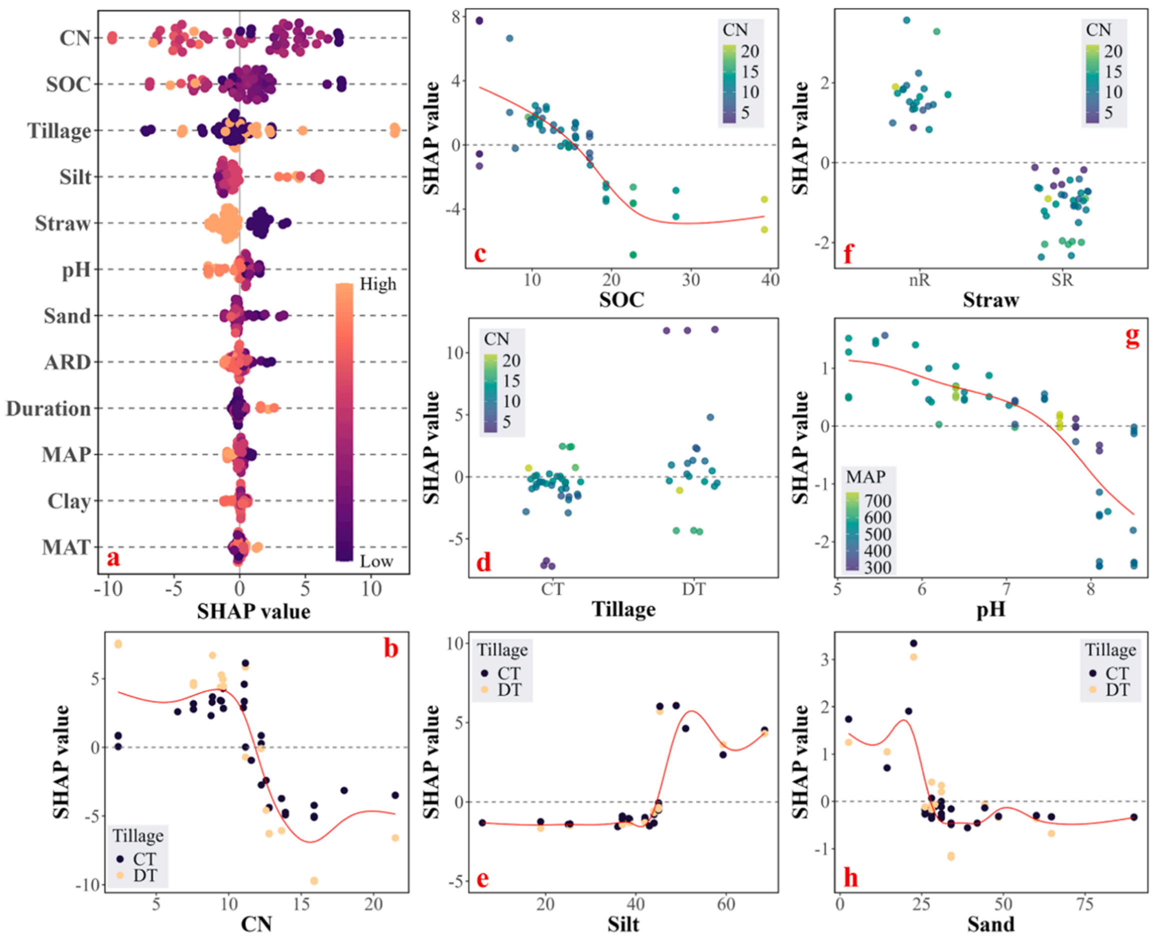


**Fig. 6.** Influences of climatic conditions, soil properties, straw management, and tillage regimes on subsoil SOC stock change ratios derived from a random forest model with SHAP values. Tillage regimes consist of conventional (CT) and deep tillage (DT), while straw management includes straw return (SR) and removal (nR). SOC stock change ratios are chosen as the response variables. Variable importance (a) and dependence plots (b-h) are simulated based on SHAP values. Variable importance is sorted in descending order. ARD, MAT, and MAP represent the aridity index, mean annual temperature, and mean annual precipitation, respectively. The color legend in plot (a) indicates the range of values for each variable. High and Low represent the maximum and minimum values of each variable, respectively.

### 4.2. Soil properties and practical implications

Numerous studies have revealed that soil nutrient condition and stoichiometry play a crucial role in mediating soil C dynamics. In this study, ZT leads to higher subsoil SOC stocks than other tillage regimes under low soil C:N ratios (Figs. 4, 6). These phenomena may be explained by the interactive effects of tillage practices, straw-induced changes in soil C:N ratio, and associated variations in microbial activity. ZT predominantly increases SOC contents in the 0–5 cm layer (Xue et al., 2015) but has limited effects on the C:N ratio and microbial activity of the remaining soil. In contrast, straw incorporation under CT and DT accrues the C:N ratio and microbial activities in the 20–40 cm soil layer. Previous studies have indicated that the application of exogenous substances to soils with a relatively low initial C:N ratio is generally associated with a high SOC decomposition rate (Tao and Liu, 2025; Ge et al., 2013). High initial soil N enhances microbial capacity to decompose soil organic matter, thereby inducing a positive C priming effect that ultimately contributes to soil C losses. Therefore, the positive effects of CTSR and DTSR on subsoil SOC stock increases are moderated under low initial soil C:N ratios (Figs. 4, 6f). In addition, straw incorporation intensifies soil nutrient limitation under high soil C:N ratios since the C:N ratio of maize straw far exceeds that of the soil. Such conditions may constrain microbial biomass accumulation and reduce the priming of native SOC (Tao and Liu, 2025; Coonan et al., 2020). In addition, abundant oligotrophic microorganisms in the subsoil are more conducive to decompose recalcitrant and complex C (Tian et al., 2023), thus promoting the stabilization of straw in the subsoil. Therefore, CTSR and DTSR lead to a higher net increase in the subsoil C pool than ZT in soils with a relatively high C:N ratio (4, Fig. 6). Importantly, our results suggest that ZT may be more suitable in soils with a C:N ratio below 11.8 in Northeast China.

Our results indicate that ZT is more effective in increasing topsoil SOC stocks than other tillage regimes in soils with clay content exceeding 30.6% by facilitating clay mineral-mediated SOC stabilization processes (Fig. 5f). Minimal soil disturbance under ZT maintains aggregate integrity and clay adsorption sites (Nandan et al., 2019), while straw mulching improves soil moisture and thermal stability, potentially supporting microbial biomass accumulation and mineral-associated OC formation (Sushko et al., 2026). However, high soil pH may decrease the adsorption of SOC onto clay mineral surfaces because of the increased negative surface charge (Appel and Ma, 2002). Moreover, alkaline conditions favor the complexation and flocculation of dissolved organic carbon derived from straw with soil $Ca^{2+}$ (Römkens et al., 1996), and this process occurs primarily in surface or near-surface layers under ZT. Therefore, ZT may result in lower subsoil SOC stocks than CT and DT in soils with relatively high pH (Figs. 4, 6).

The application of ZT reduces energy consumption and operational costs (e.g., machinery operation and fuel) while promoting more efficient use of available agricultural resources compared with other tillage practices (Knowler and Bradshaw, 2007; FAO, 2001). Our findings

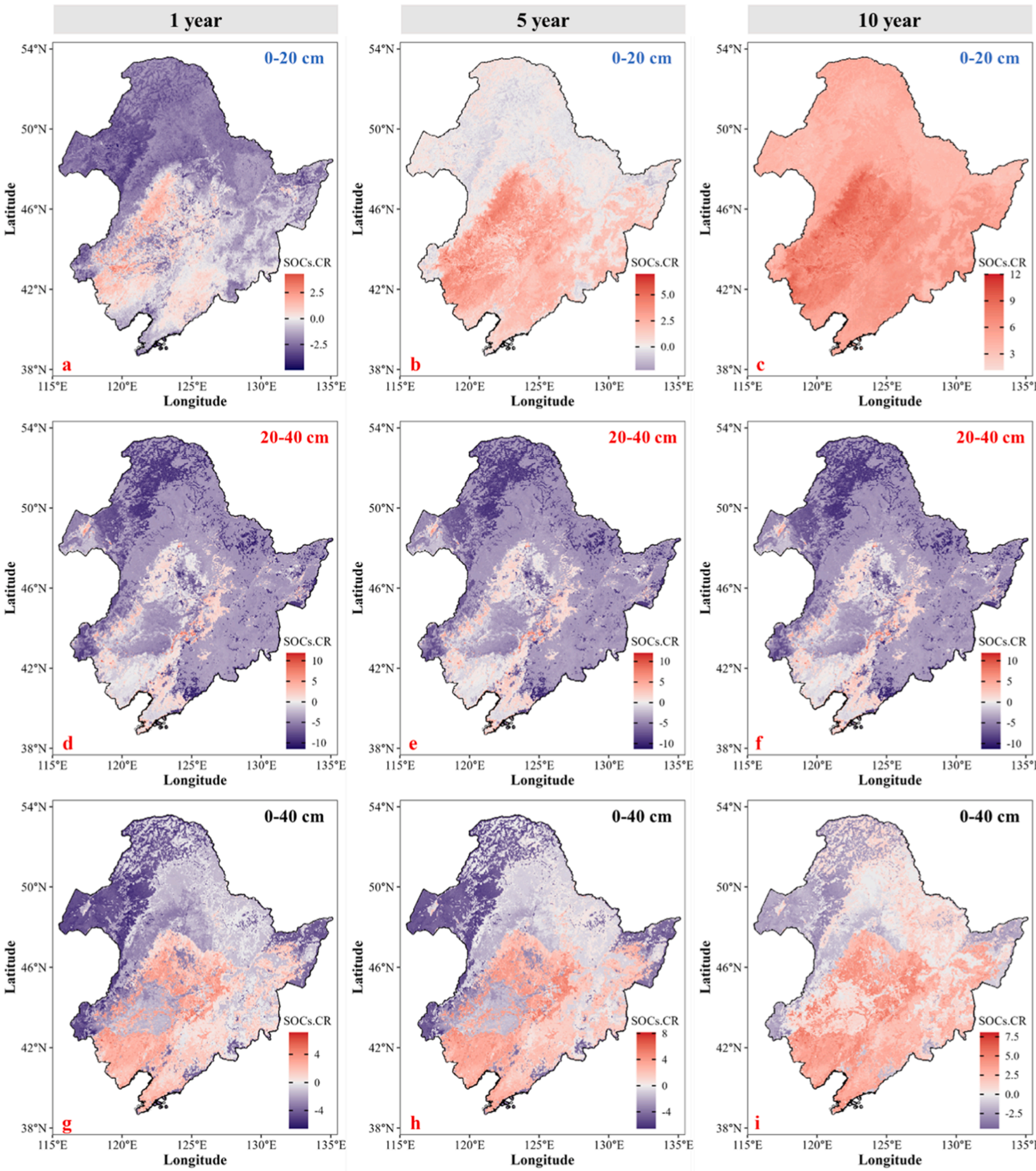


**Fig. 7.** Soil organic carbon stock change ratios (SOCs.CR) between conservation (zero) and conventional tillage with straw return simulated by random forest models. Three experimental durations are chosen for the modelling.

indicate that long-term ZT sustains crop yields comparable to other tillage practices while progressively enhancing SOC stocks across the 0–40 cm soil profile. Nevertheless, adopting ZT may involve short-term trade-offs. In some cases, crop productivity may temporarily decline during the initial years of implementation (Song et al., 2026; Pittelkow et al., 2015), which may exacerbate financial pressures on resource-poor farmers. Therefore, supportive policies and incentives during the transition period may facilitate broader adoption of ZT in Northeast China.

## 5. Conclusion

This study conducts a regional meta-analysis to evaluate the effects of different tillage regimes on SOC stocks in Northeast China. Our

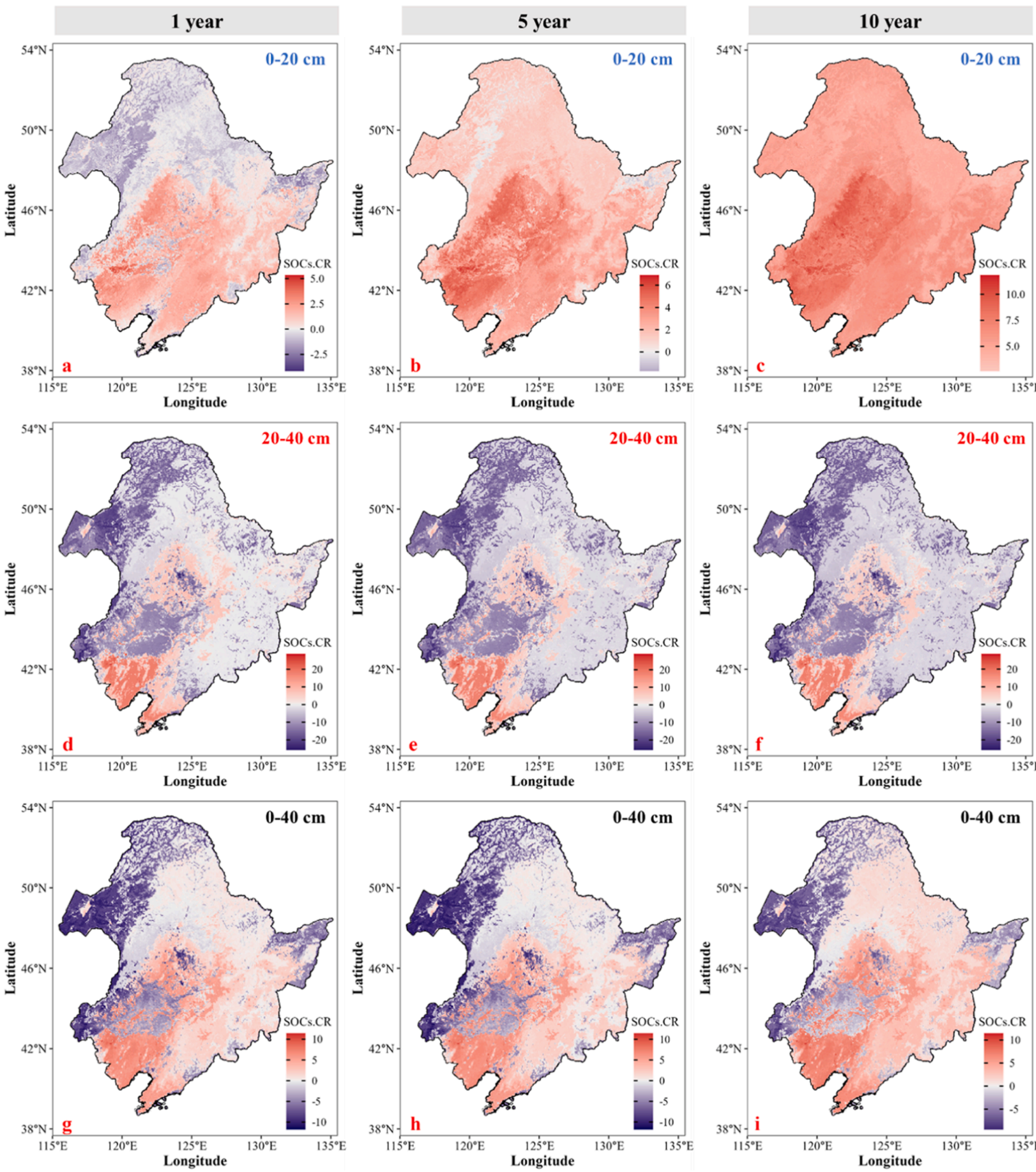


**Fig. 8.** Soil organic carbon stock change ratios (SOCs.CR) between conservation (zero) and deep tillage with straw return simulated by random forest models. Three experimental durations are chosen for the modelling.

findings indicate that climatic and edaphic conditions strongly regulate the effects of tillage regimes on SOC stocks. According to the SOC stocks estimated from random forest models, ten years of ZT application has prevailing positive effects on topsoil SOC stocks compared to other tillage regimes combined with straw return, while reductions in subsoil SOC stocks limit the applicability of ZT in Northeast China. However, reductions in subsoil SOC stocks under ZT are offset by increases in the topsoil, resulting in overall SOC stock gains within the 0–40 cm soil profile. Thus, long-term ZT accrues SOC stocks in warm and semi-humid areas relative to other tillage regimes combined with straw return. These results suggest that environmental factors interactively regulate SOC dynamics under different tillage regimes in Northeast China. However, the thresholds for different environmental variables (e.g., soil C:N = 11.8; SOC = 15.6 g $kg^{-1}$) were derived from SHAP dependence analyses based on RF models, which may be indicative. Thus, further long-term field experiments are needed to verify the generalizability of these thresholds and to better elucidate the mechanisms underlying the observed patterns.

## CRediT authorship contribution statement

**Zhongbin Zhang:** Writing – review & editing. **Xinhua Peng:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Jianyu Tao:** Writing – original draft, Software, Formal analysis, Data curation, Conceptualization. **Xiaoyuan Liu:** Writing – review & editing. **Shuai Liu:** Writing – review & editing. **Fahui Jiang:** Data curation. **Yongqi Qian:** Data curation.

## 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.

## Acknowledgement

This study was supported by the National Natural Science Foundation of China (U23A20222). The authors would like to thank Baoyu Chen, Yuxian Wang, Ying Jiang, Xiangwei Gong, Xinwei Xue, and Hao Zhang for their help in the field experiments.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2026.107195.

## Data availability

Data will be made available on request.

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