

Article

The Effect of Deep Tillage Combined with Organic Amendments on Soil Organic Carbon and Nitrogen Stocks in Northeast China

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Abstract

Soil organic carbon (SOC) and total nitrogen (TN) are fundamental indicators of soil fertility and long-term agricultural sustainability. However, intensive cultivation, residue removal, and imbalanced fertilization have resulted in substantial declines in SOC and TN across many agroecosystems, particularly in Northeast China. This study investigated SOC and TN dynamics within the 0–35 cm profile of four representative soils in Northeast China under a continuous maize cropping system. Five treatments were assessed: conventional tillage (CT), deep tillage (DT), deep tillage with straw (SDT), deep tillage with organic fertilizer (MDT), and deep tillage combined with straw and organic fertilizer (SMDT). Compared with DT, organic amendment treatments increased SOC and TN contents in the 0–20 cm layer by 9.41–57.57% and 5.29–60.76%, respectively. The SMDT treatment achieved the highest SOC and TN stocks (65.03 Mg ha^{−1} and 7.91 Mg ha^{−1}) and enhanced nutrient accumulation in the 20–35 cm layer. In the subsoil, the ratio of soil C and N (C/N) under SMDT increased by 3.11%, 11.08%, 2.10%, and −7.01% across the four soils, indicating improved C–N balance and reduced nutrient stratification. SOC and TN stocks were linearly correlated with cumulative C input, confirming that organic amendments were among the main drivers of C and N sequestration. Mantel and path analyses further revealed that clay content and mean annual precipitation enhanced SOC and TN storage by improving soil structure and C–N balance through increased C input and reduced bulk density. Overall, deep tillage combined with amendments strengthened C–N coupling, improved soil fertility, and provided a mechanistic basis for reconstructing fertile tillage layers and sustaining productivity in Northeast China.

Keywords: carbon and nitrogen sequestration; cumulative carbon input; deep application of organic amendments; environment factor; soil texture



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1. Introduction

Soil organic carbon (SOC) and total nitrogen (TN) are among the important factors that influence soil fertility and environmental quality. Soil can store approximately 1500 Pg SOC [1] and 140 Pg TN in up to 100 cm of soil [2]. Maintaining an appropriate level of SOC and TN is not only important for sustaining agricultural production but also for reducing soil degradation and the impact of climate change. However, many agricultural systems have poor soil structure, low microbial activity, and nutrient imbalance due to the

decline of SOC and TN over a long period caused by intensive tillage, residue removal, and the excessive use of chemical fertilizers [3]. Long-term inappropriate soil management practices result in soil degradation, thereby reducing crop productivity to varying degrees. Therefore, improving the C and N sequestration capacity is very important for increasing soil fertility and maintaining crop production [4].

Incorporating organic amendments such as straw and organic fertilizers is an efficient approach to restore SOC and TN contents [5,6]. Straw incorporation increases SOC by enhancing the accumulation of stable C fractions [7], while organic fertilizers provide readily labile substrates and nutrients to enhance microbial proliferation and mineral-associated organic C [8]. However, conventional incorporation practices confine organic inputs to the topsoil (0–20 cm), thereby limiting the improvement of subsoil fertility and stimulating nutrient stratification and mineralization losses [9]. Consequently, the stabilization of soil organic matter (SOM) in the subsoil is limited. In contrast, deep tillage that evenly mixes crushed straw and decomposed organic fertilizer into the 0–35 cm soil profile enhances soil physical structure, promotes C and N sequestration in the plow layer, and improves nutrient utilization [10–12]. Several studies have reported that deep tillage increases the proportion of large pores by disrupting compacted layers, which enhances oxygen diffusion into deeper soil horizons and stimulates the activity of subsurface microorganisms [13,14]. Meanwhile, the mixing of surface C-enriched materials with the deeper mineral matrix increases the number of mineral adsorption sites, thereby facilitating the downward migration and stabilization of SOC and TN [15]. In addition to external organic inputs, driving from roots, root systems, and rhizosphere deposits also affect inputs of soil C into the pedosphere, changing the composition and dynamics of SOM [16]. These C sources differ in their turnover rates and stabilization efficiencies, and affect the sequestration SOC and TN in different soil types. Because of the close relationship between SOC and TN, the ratio of soil C and N (C/N) is a key indicator of soil quality. Distinct differences were observed in the effects of soil management practices and the return depth of organic amendments on the C/N ratio. In the 0–5 cm soil layer, rotation tillage generally results in a higher C/N ratio than no tillage, whereas under straw returning conditions, no tillage increases the C/N ratio in the 0–5 cm layer but decreases it in the 5–20 cm layer. Soil texture is also an important factor influencing the accumulation of SOC and TN. Soils with high clay content typically accumulate more SOM and support greater microbial biomass, both of which protect SOC and TN from microbial decomposition and enhance their adsorption capacity [17]. However, a meta-analysis reported that mineral soils with naturally high SOM content may inhibit the sorption of newly added C [18]. As clay content increases, smaller pores account for a greater proportion of total porosity and provide more favorable habitats for soil microorganisms [19], thereby accelerating the decomposition of SOM. However, the responses of SOC and TN to deep tillage combined with organic amendments across different soil textures remain poorly understood.

The Northeast China is the nation's major grain production base and is characterized by high-fertility soils [20]. However, decades of intensive cultivation have induced cloddy plow pans, low SOC and TN contents, and thus threaten sustainable grain production [21,22]. Restoring tillage depth, enhancing SOC and TN stocks, and reconstructing fertile arable layers have become key priorities for soil conservation. Therefore, this study was based on the field experiments of deep tillage with organic amendments and focused on four typical soil types in Northeast China: black soil, dark brown soil, albic soil and chernozem. The objectives were to (i) determine the changes in SOC and TN content and stocks; (ii) characterize the vertical distributions in 0–20 cm and 20–35 cm; and (iii) identify the main environmental and soil factors affecting SOC and TN accumulation in different soil types. By integrating organic amendments inputs with improved soil physical

conditions through deep tillage, this study aims to elucidate the mechanisms of SOC and TN accumulation across contrasting soil types, thereby providing a scientific basis for soil fertility restoration and sustainable management of soils in Northeast China.

2. Materials and Methods

2.1. Site Description and Experimental Design

This study was conducted across four representative soil types in Northeast China. The experimental sites were located in Suihua (SH, central region), Heihe (HH, northern region), Fujin (FJ, eastern region), and Longjiang (LJ, western region). The corresponding soil types were black soil, dark brown soil, albic soil, and chernozem [23]. The areas of the four soil types at the site were 105.09, 446.67, 140.94, and 109.32 hm², respectively. Detailed site characteristics are presented in Figure 1 and Table 1.

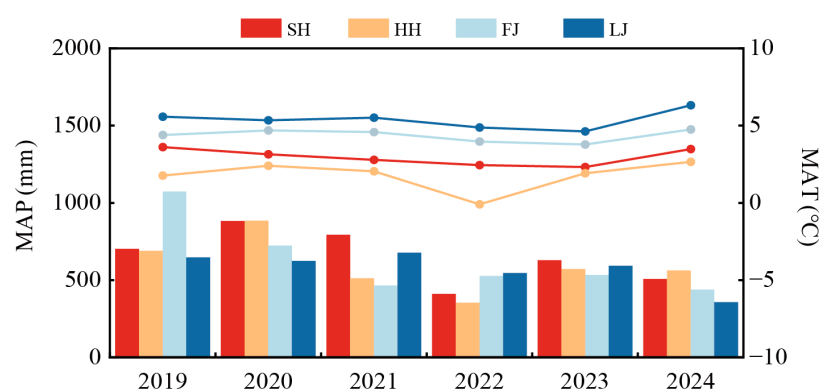


Figure 1. Annual average precipitation (MAP) and annual average temperature (MAT) at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ) from 2019 to 2024.

Table 1. Basic information of Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ).

Site	Location	Experiment Starting Year	Annual Active Accumulated Temperature ($\geq 10^{\circ}\text{C}$)	Digital Elevation Model (m)	Soil Type
SH	46°35' N, 126°47' E	2021	2200–2400	179	Black soil
HH	50°15' N, 127°27' E	2019	2100–2300	161	Dark brown soil
FJ	47°03' N, 132°16' E	2019	2600–2800	75	Albic soil
LJ	47°22' N, 123°15' E	2019	2400–2700	177	Chernozems

Each experimental site has maintained a continuous maize cropping system since the beginning of the trial. The experiment includes five treatments with four replicates arranged in a randomized block design. Maize is sown in early May and harvested in early October, following an annual cropping cycle. Maize was sown in early May and harvested in early October. The specific treatments included: (1) Conventional tillage (CT), straw was not incorporated to the field, and the tillage depth was 20 cm; (2) Deep tillage (DT), straw was removed, and the tillage depth was 35 cm; (3) Deep tillage with straw (SDT), crushed straw was incorporated into the 35 cm soil layer; (4) Deep tillage with organic fertilizer (MDT), straw was removed, and decomposed cow dung was evenly applied and incorporated into the soil to a depth of 35 cm; (5) Deep tillage combined with straw and organic fertilizer (SMDT), crushed straw and decomposed cow dung were evenly spread on the topsoil and mixed into the 0–35 cm soil layer. The crop residue used in the experiment was maize straw, and the organic fertilizer was decomposed cow dung. Before application, 10,000 kg ha^{−1} of dry straw, chopped to less than 5 cm, is evenly spread on the soil surface.

Subsequently, 30,000 kg ha⁻¹ (on a dry weight basis) of decomposed organic fertilizer is incorporated into the soil. The nutrient composition of maize straw was as follows: 40.7 g C kg⁻¹; 0.62 g N kg⁻¹; 0.08 g P kg⁻¹; and 0.79 g K kg⁻¹. The decomposed cow dung contained 30.3 g C kg⁻¹, 2.33 g N kg⁻¹, 0.87 g P kg⁻¹, and 1.21 g K kg⁻¹ [24]. Irrigation, weeding, and other field management practices were conducted according to local routines at all sites; however, the rates of chemical fertilizer application differed significantly among the sites. In accordance with local agronomic practices, the annual fertilizer application rates for the chemical fertilizer are 135, 120, 160 and 180 kg N ha⁻¹, 69, 70, 69 and 70 kg P₂O₅ ha⁻¹ and 60, 60, 46 and 60 kg K₂O ha⁻¹.

2.2. Soil Sampling and Determination of Related Indicators

Soil sampling was conducted from July to August 2024. For each plot, five sampling points were selected and combined to form a composite sample. The areas of the four sites were 24, 24, 21, and 13 m², respectively. Soil samples from the 0–20 cm tillage layer and the 20–35 cm subsoil layer were collected separately using a shovel. The samples were transported to the laboratory, air-dried at room temperature, and sieved after removing visible debris such as gravel and plant residues. SOC and TN contents were determined using an elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The contents of available nitrogen (AN), available phosphorus (AP) and available potassium (AK) were measured as described by Taylor and Francis [25]. The determination of soil mechanical composition followed the method as described [26]. Soil bulk density (BD) was measured using the ring-knife method [27]. Undisturbed soil cores were collected, sealed, and oven-dried at 105 °C for measurement. Organic C input was divided into four components: straw, root stubble, roots (0–20 cm), and rhizosphere C exudates. Root stubble and root biomass were estimated based on the stubble-to-grain and root-to-grain ratios, which were 0.13 and 0.26, respectively [28]. The C contents of straw, root stubble, and roots were described as per Hao et al. [16]. The formula for calculating SOC stock is as follows [16]:

$$\text{SOC stock} = H \times B \times \text{SOC} / 10$$

where SOC stock represents SOC stock (Mg ha⁻¹); H is the soil layer thickness (cm); B is the BD (g cm⁻³); and SOC denotes the SOC content (g kg⁻¹). TN stock was calculated in the same manner.

The initial physical and chemical properties of the soil were determined by Zou et al. [29], and the sampling time was in October of the year of the experiment. The data on average annual temperature (AAT), digital elevation model (DEM), drought index (AI), and humidity index (MI) were obtained from the Nanjing Institute of Soil Science, Chinese Academy of Sciences.

2.3. Statistical Analysis

Microsoft Excel 2016 was used for data processing, and Origin 2021 was used for plotting. Analysis of variance (ANOVA) was performed using JMP 16, and the vegan package in R was employed to conduct the Mantel correlation analysis. The Partial Least Squares Path Modeling (PLS-PM) method was implemented in R (version 4.3.3).

3. Results

3.1. Organic C Input and Initial Soil Properties

Significant differences in cumulative C input were observed among treatments under deep tillage combined with organic amendments (Table 2). Compared with CT and DT, SMDT significantly increased cumulative C input ($p < 0.05$). The cumulative C input from applied organic amendments, roots, and root stubble ranged from 5.60 to 15.57 Mg ha⁻¹

across treatments. When the same amount of organic material was applied, cumulative C input among soil types followed the order: albic soil > black soil > chernozem > dark brown soil. Compared with MDT, SMDT increased cumulative C input by 36.56%, 38.35%, 36.01% and 37.16% in black soil, dark brown soil, chernozem, and albic soil, respectively. These findings indicate that SMDT substantially enhances C input, facilitates C pool accumulation, and provides a material basis for subsequent C and N transformations.

Table 2. Cumulative carbon (C) inputs under different treatments at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ). Treatments are conventional tillage (CT), deep tillage (DT), deep tillage with straw (SDT), deep tillage with organic fertilizer (MDT), and deep tillage combined with straw and organic fertilizer (SMDT). Different lowercase letters indicate significant differences among treatments according to Tukey's multiple comparison test ($p < 0.05$). Values are means $\pm$ standard deviation ($n = 4$).

Site	Treatment	Organic Amendments (Mg ha ⁻¹)	Root (Mg ha ⁻¹)	Stubble (Mg ha ⁻¹)	Cumulative C Input (Mg ha ⁻¹)
SH	CT	0	1.32 $\pm$ 0.07 a	0.65 $\pm$ 0.04 a	1.98 $\pm$ 0.11 d
	DT	0	1.26 $\pm$ 0.05 a	0.62 $\pm$ 0.02 a	1.88 $\pm$ 0.07 d
	SDT	4070	1.34 $\pm$ 0.06 a	0.66 $\pm$ 0.03 a	6.07 $\pm$ 0.08 c
	MDT	9090	1.43 $\pm$ 0.15 a	0.70 $\pm$ 0.08 a	11.22 $\pm$ 0.23 b
	SMDT	13,160	1.44 $\pm$ 0.04 a	0.71 $\pm$ 0.02 a	15.30 $\pm$ 0.06 a
HH	CT	0	0.88 $\pm$ 0.05 b	0.44 $\pm$ 0.02 b	1.32 $\pm$ 0.07 d
	DT	0	0.99 $\pm$ 0.06 ab	0.49 $\pm$ 0.03 ab	1.47 $\pm$ 0.09 d
	SDT	4070	1.03 $\pm$ 0.09 ab	0.51 $\pm$ 0.05 ab	5.60 $\pm$ 0.14 c
	MDT	9090	1.10 $\pm$ 0.03 a	0.54 $\pm$ 0.01 a	10.73 $\pm$ 0.04 b
	SMDT	13,160	1.13 $\pm$ 0.11 a	0.56 $\pm$ 0.05 a	14.85 $\pm$ 0.16 a
FJ	CT	0	1.10 $\pm$ 0.05 c	0.54 $\pm$ 0.02 c	1.65 $\pm$ 0.07 e
	DT	0	1.36 $\pm$ 0.06 b	0.67 $\pm$ 0.03 b	2.03 $\pm$ 0.08 d
	SDT	4070	1.42 $\pm$ 0.11 b	0.70 $\pm$ 0.06 b	6.20 $\pm$ 0.17 c
	MDT	9090	1.61 $\pm$ 0.07 a	0.79 $\pm$ 0.03 a	11.49 $\pm$ 0.10 b
	SMDT	13,160	1.62 $\pm$ 0.09 a	0.80 $\pm$ 0.04 a	15.57 $\pm$ 0.13 a
LJ	CT	0	1.00 $\pm$ 0.08 b	0.49 $\pm$ 0.04 b	1.50 $\pm$ 0.21 d
	DT	0	0.96 $\pm$ 0.07 b	0.48 $\pm$ 0.04 b	1.44 $\pm$ 0.11 d
	SDT	4070	1.17 $\pm$ 0.08 ab	0.58 $\pm$ 0.04 ab	5.82 $\pm$ 0.13 c
	MDT	9090	1.29 $\pm$ 0.08 a	0.64 $\pm$ 0.04 a	11.02 $\pm$ 0.12 b
	SMDT	13,160	1.30 $\pm$ 0.09 a	0.64 $\pm$ 0.04 a	15.10 $\pm$ 0.13 a

The initial soil physical and chemical properties of the four soil types showed distinct differences (Table 3). Among them, dark brown soil exhibited the highest SOC and TN contents, reaching 25.4 g kg⁻¹ and 2.15 g kg⁻¹ in the 0–20 cm soil layer, respectively. Black soil contained higher available nutrient contents than the other soil types, while chernozem was the only alkaline soil, with a pH of 7.81. Regarding soil mechanical composition, chernozem had the highest sand content, whereas dark brown soil had the lowest; conversely, the clay content showed the opposite pattern.

3.2. Effects of Tillage and Organic Material Return on SOC and TN Content and BD

Compared with the CT and DT, the incorporation of organic amendments significantly increased SOC content ($p < 0.05$) in the 0–20 cm soil layer, with the dark brown soil reaching up to 31.33 g kg⁻¹ (Figure 2a). Due to the high N content in organic fertilizers, TN content was significantly higher under the MDT and SMDT ($p < 0.05$). In chernozem, TN content reached 3.86 g kg⁻¹, indicating the greatest increase among all soil types (Figure 2b). C/N ratios also differed significantly among treatments and soil layers (Figure 2c). In the 0–20 cm layer, the DT slightly increased the C/N ratio, while SDT significantly increased it in dark

brown, albic, and chernozem soils ($p < 0.05$). In the 20–35 cm layer, significant differences were observed only in dark brown soil, where the C/N ratios were 10.16, 9.89, and 9.98 under SDT, MDT, and SMDT, respectively. Across all soil types, deep tillage markedly reduced BD (Figure 2d). The BD in the 20–35 cm layer of dark brown soil was slightly higher than in other soil types, likely due to its greater clay content.

Table 3. Initial physicochemical and mechanical properties in soil layers of 0–20 cm and 20–35 cm at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ). Properties are soil organic carbon (SOC), soil total nitrogen (TN), soil available nitrogen (AN), soil available phosphorus (AP), and soil available potassium (AK). Different lowercase letters indicate significant differences among treatments according to Tukey’s multiple comparison test ($p < 0.05$). Values are means $\pm$ standard deviation ($n = 4$).

Soil Layer (cm)	Site	SOC (g kg ^{−1})	TN (g kg ^{−1})	AN (mg kg ^{−1})	AP (mg kg ^{−1})	AK (mg kg ^{−1})	pH	Sand (%)	Silt (%)	Clay (%)
0–20	SH	20.37 $\pm$ 2.67 b	1.55 $\pm$ 0.19 a	251.70 $\pm$ 29.60 a	39.30 $\pm$ 3.30 a	198 $\pm$ 26 a	5.61 $\pm$ 0.09 c	29.49 $\pm$ 4.22 c	28.51 $\pm$ 2.85 ab	42.00 $\pm$ 4.66 a
		25.40 $\pm$ 2.33 a	2.15 $\pm$ 0.30 a	114.70 $\pm$ 9.40 b	18.50 $\pm$ 2.00 b	119 $\pm$ 15 b	6.11 $\pm$ 0.09 b	26.17 $\pm$ 2.58 c	31.64 $\pm$ 3.51 a	42.19 $\pm$ 4.37 a
	HH	18.45 $\pm$ 1.76 b	1.51 $\pm$ 0.20 a	120.70 $\pm$ 11.10 b	19.90 $\pm$ 2.00 b	79 $\pm$ 11 c	6.04 $\pm$ 0.12 b	39.24 $\pm$ 4.81 b	25.73 $\pm$ 3.14 bc	35.04 $\pm$ 3.02 b
		20.71 $\pm$ 2.39 ab	1.82 $\pm$ 0.21 a	251.10 $\pm$ 26.50 a	12.40 $\pm$ 1.50 c	128 $\pm$ 17 b	7.81 $\pm$ 0.13 a	49.27 $\pm$ 6.20 a	24.82 $\pm$ 3.11 c	25.92 $\pm$ 3.03 c
	FJ	20.35 $\pm$ 2.34 a	1.31 $\pm$ 0.17 a	205.20 $\pm$ 22.20 b	24.60 $\pm$ 2.90 a	176 $\pm$ 25 a	6.67 $\pm$ 0.11 b	27.54 $\pm$ 3.32 b	27.00 $\pm$ 2.80 ab	45.46 $\pm$ 4.40 a
		17.16 $\pm$ 2.20 a	1.48 $\pm$ 0.19 a	49.30 $\pm$ 5.90 d	10.10 $\pm$ 1.10 bc	64 $\pm$ 8 b	6.04 $\pm$ 0.11 c	16.19 $\pm$ 2.02 c	35.04 $\pm$ 4.50 a	48.77 $\pm$ 4.65 a
	LJ	7.54 $\pm$ 0.99 b	0.62 $\pm$ 0.08 b	68.70 $\pm$ 7.50 c	12.50 $\pm$ 1.50 b	49 $\pm$ 7 b	6.49 $\pm$ 0.08 b	37.80 $\pm$ 4.51 a	25.47 $\pm$ 3.12 b	36.73 $\pm$ 4.01 b
		15.6 $\pm$ 1.91 a	1.38 $\pm$ 0.17 a	222.10 $\pm$ 24.80 a	7.00 $\pm$ 0.90 c	68 $\pm$ 8 b	8.12 $\pm$ 0.19 a	40.97 $\pm$ 4.16 a	24.89 $\pm$ 3.19 b	34.14 $\pm$ 2.92 b

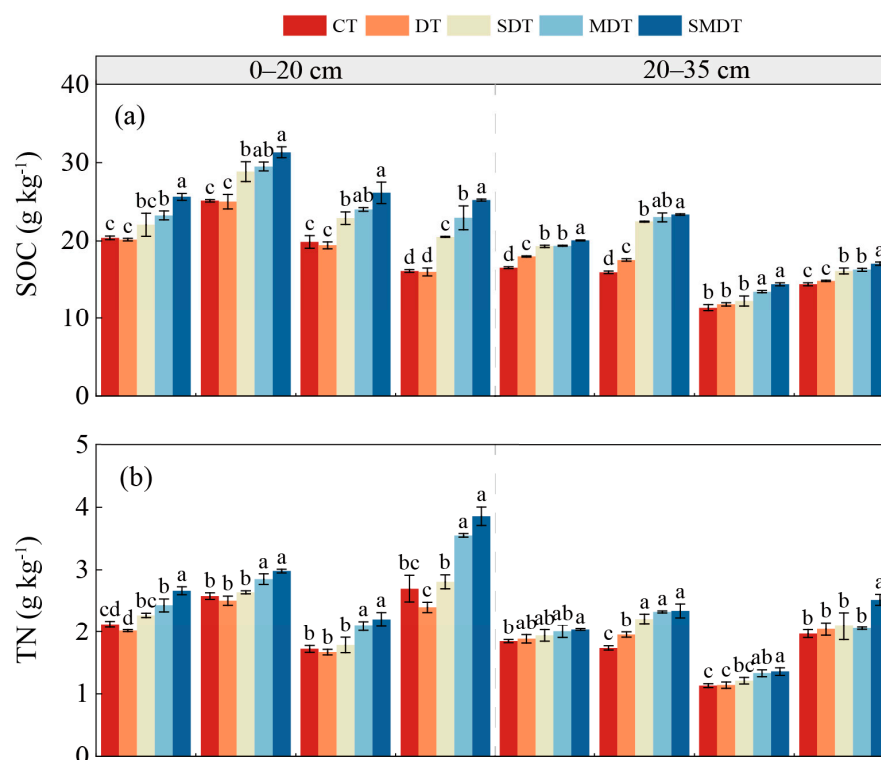


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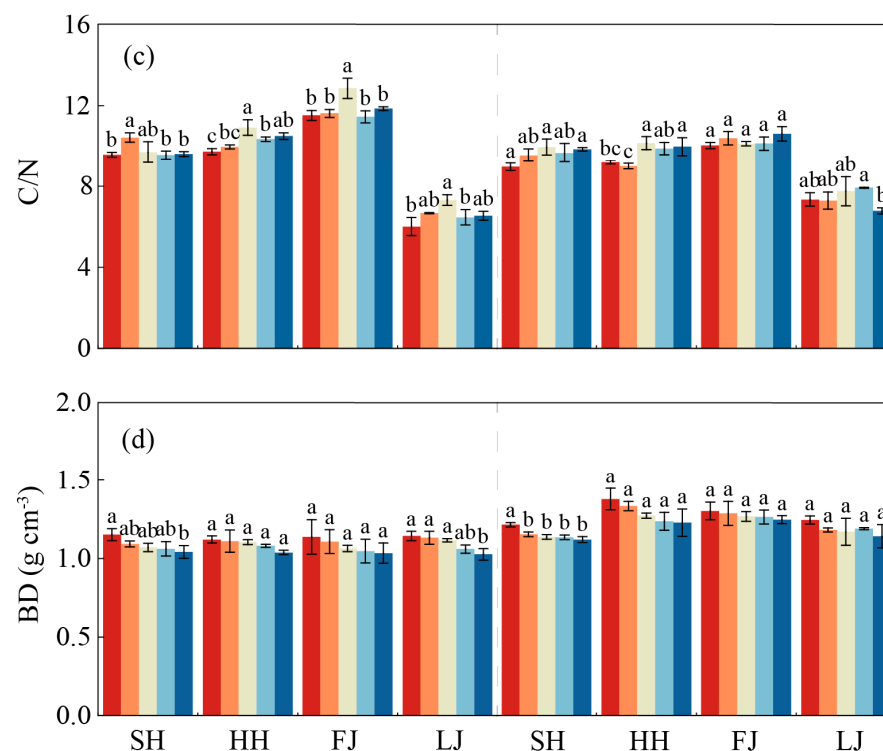


Figure 2. Soil organic carbon (SOC), total nitrogen (TN) content, C/N ratio, and soil bulk density (BD) in soil layers of 0–20 cm and 20–35 cm at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ). (a) SOC content, (b) TN content, (c) C/N ratio, and (d) BD for conventional tillage (CT), deep tillage (DT), deep tillage with straw (SDT), deep tillage with organic fertilizer (MDT), and deep tillage combined with straw and organic fertilizer (SMDT). Different lowercase letters indicate significant differences among treatments according to Tukey’s multiple comparison test ($p < 0.05$). Values are means $\pm$ standard deviation ($n = 4$).

3.3. The Effect of Deep Tillage Combined with Organic Amendments on SOC and TN Stocks

Organic material addition significantly increased SOC and TN stocks across all soil types (Figure 3). In the 0–20 cm layer, SOC stocks followed the order SMDT > MDT > SDT > CT > DT, reaching 53.39–65.03 Mg ha⁻¹ under SMDT. SOC stocks declined more sharply with depth in albic soil than in the other soils. In the same layer, TN stocks ranked as chernozem > dark brown soil > black soil > albic soil and were significantly higher under SMDT than under CT and DT ($p < 0.05$). In the 20–35 cm layer, TN stocks in chernozem decreased markedly, following the order dark brown soil > chernozem > black soil > albic soil. Deep tillage combined with organic amendments altered the vertical distribution of SOC and TN stocks (Figure 4). Only chernozem exhibited a significantly higher SOC stock ratio than DT, while the TN stock ratio increased significantly only in black soil. CT maintained the highest SOC to TN stock ratio (SOC: 1.03–1.52; TN: 1.09–1.33) because its soil layers remained undisturbed.

The regression analysis indicated that SOC and TN stocks were significantly and positively correlated with cumulative C input in the 0–35 cm soil layer across the four soil types (Figure 5, $p < 0.05$). Compared with TN stocks, SOC stocks showed stronger coupling among soil types.

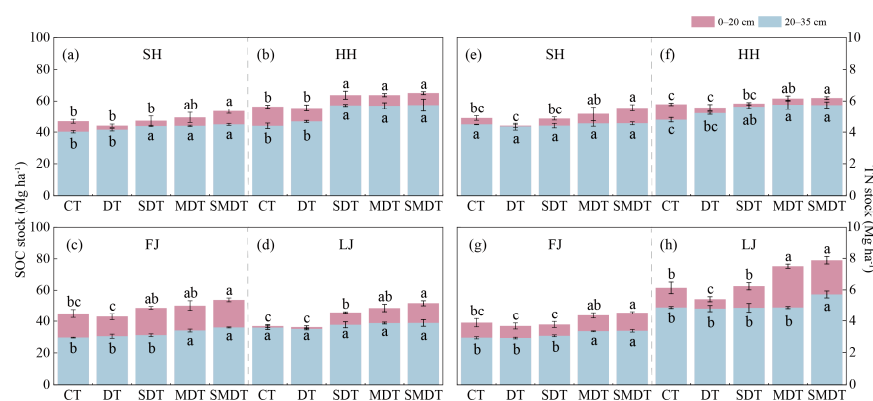


Figure 3. Soil organic carbon (SOC) and total nitrogen (TN) stocks in 0–20 cm and 20–35 cm soil layers at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ). (a–d) SOC stocks and (e–h) TN stocks for conventional tillage (CT), deep tillage (DT), deep tillage with straw (SDT), deep tillage with organic fertilizer (MDT), and deep tillage combined with straw and organic fertilizer (SMDT). Different lowercase letters indicate significant differences among treatments according to Tukey’s multiple comparison test ($p < 0.05$). Values are means $\pm$ standard deviation ($n = 4$).

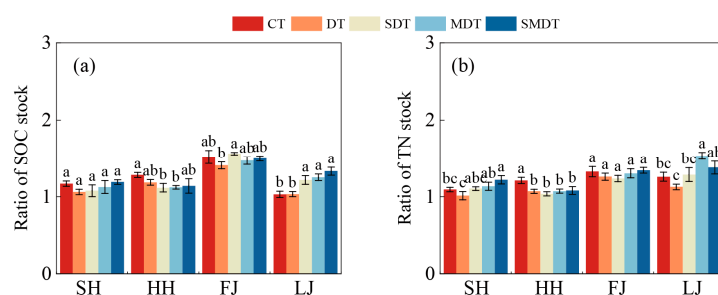


Figure 4. Ratios of soil organic carbon (SOC) and total nitrogen (TN) stocks of 0–20 cm and 20–35 cm soil layers at Suihua (SH), Heihe (HH), Fujin (FJ), and Longjiang (LJ). (a) Ratios of SOC stock and (b) ratios of TN stock for conventional tillage (CT), deep tillage (DT), deep tillage with straw (SDT), deep tillage with organic fertilizer (MDT), and deep tillage combined with straw and organic fertilizer (SMDT). Different lowercase letters indicate significant differences among treatments according to Tukey’s multiple comparison test ($p < 0.05$). Values are means $\pm$ standard deviation ($n = 4$).

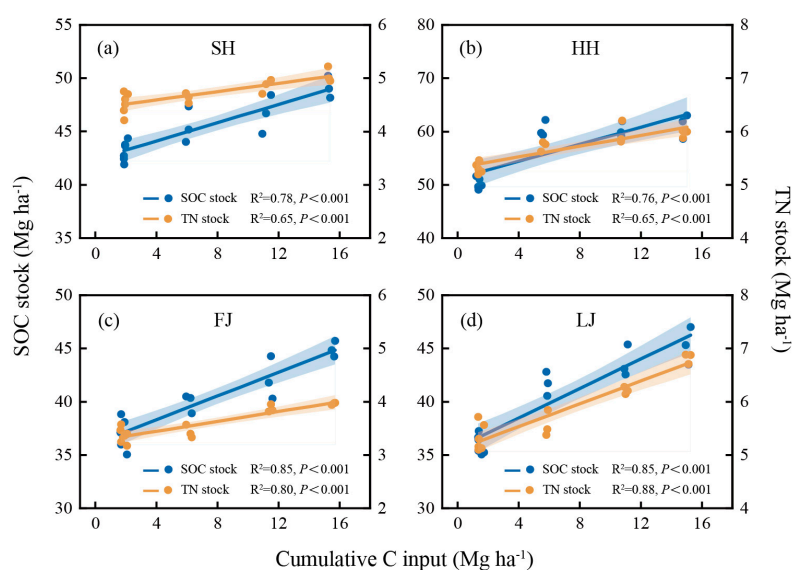


Figure 5. The relationship between soil organic carbon (SOC) and total nitrogen (TN) stocks and cumulative carbon (C) inputs at (a) Suihua (SH), (b) Heihe (HH), (c) Fujin (FJ), and (d) Longjiang (LJ). Lines represent ordinary least-squares linear regressions and shaded bands represent 95% confidence intervals.

3.4. Relationship Between SOC and TN, Soil Texture, and Environmental Factors

The Mantel analysis revealed that clay content, MAP, and cumulative C input were significantly and positively correlated with the soil C/N ratio (Figure 6a, $p < 0.05$). SOC and TN stocks were also positively associated with most environmental variables, suggesting that their accumulation was jointly regulated by climatic and textural factors. MAP and clay content were the key determinants controlling SOM decomposition and stabilization, thereby influencing the spatial distribution of SOC and TN. The random forest analysis further identified SOC, TN content, and the C/N ratio as the dominant predictors of SOC and TN stocks (Figure 6b,c). Under deep tillage combined with organic amendments, SOC and TN properties, together with soil texture and environmental variables, jointly explained 91.15% and 93.28% of the variation in SOC and TN stocks, respectively. The partial least squares path model (PLS-PM) demonstrated that organic amendments input indirectly enhanced SOC and TN stocks by improving soil structure and increasing C input (Figure 7). Environmental factors were negatively related to soil texture and SOC stocks but showed no significant association with TN stocks.

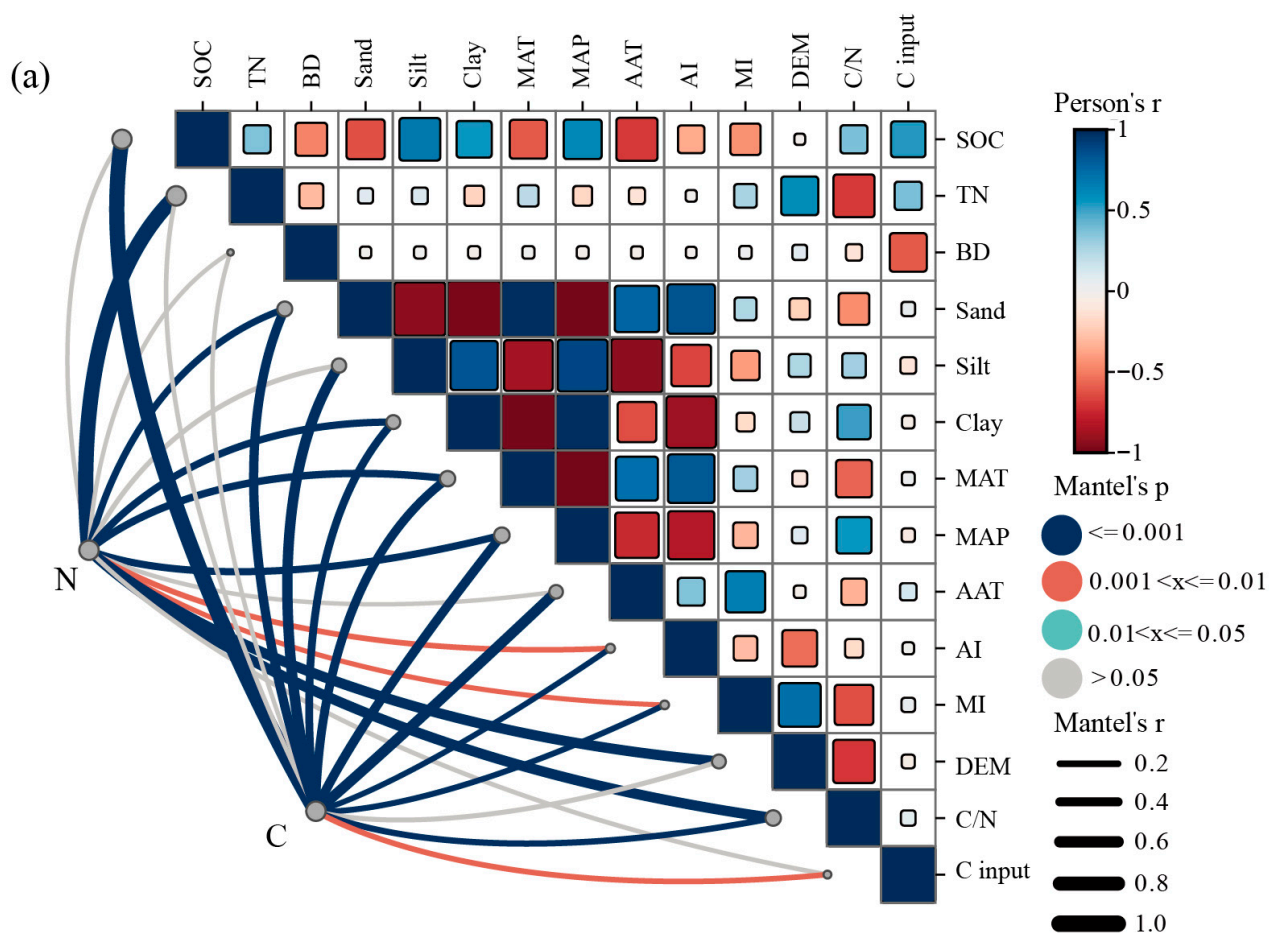


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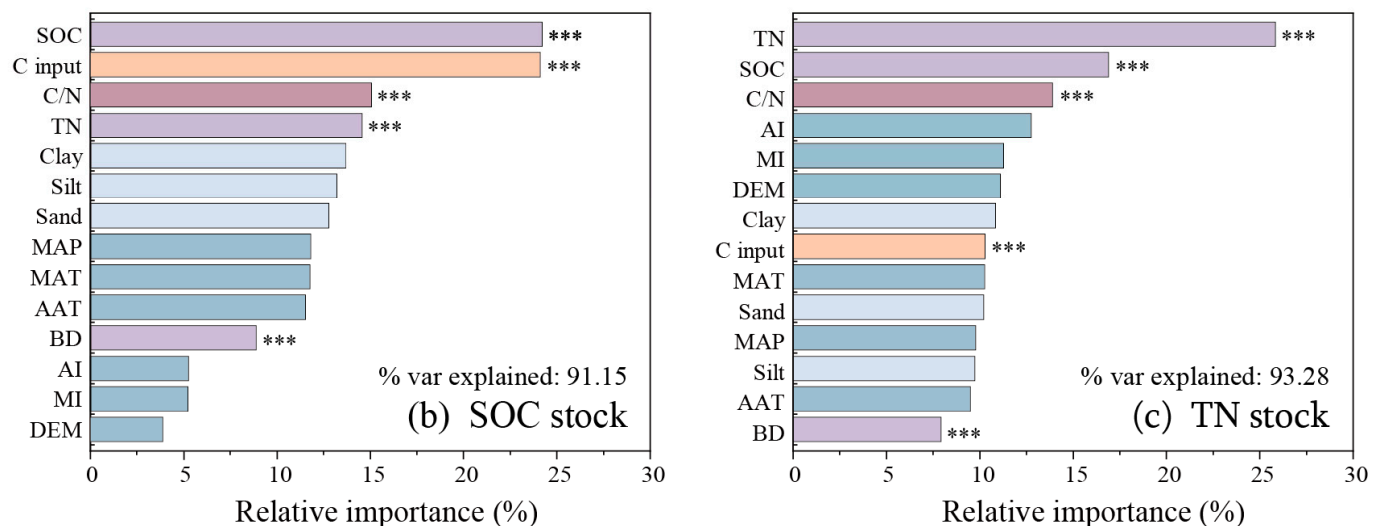


Figure 6. Relationships between soil organic carbon (SOC) and total nitrogen (TN) stocks, soil texture, and environmental variables based on (a) Mantel analysis and (b,c) random forest model. Relevant indicators are soil organic carbon content (SOC), total nitrogen content (TN), bulk density (BD), cumulative carbon inputs (C input), ratio of soil carbon and nitrogen (C/N), average annual temperature (MAT), average annual precipitation (MAP), accumulated temperature (AAT), drought index (AI), humidity index (MI), and digital elevation model (DEM). C represents SOC stock and ratios of SOC stock. N represents TN stocks and ratios of TN stock. *** represents significance level of $p < 0.05$.

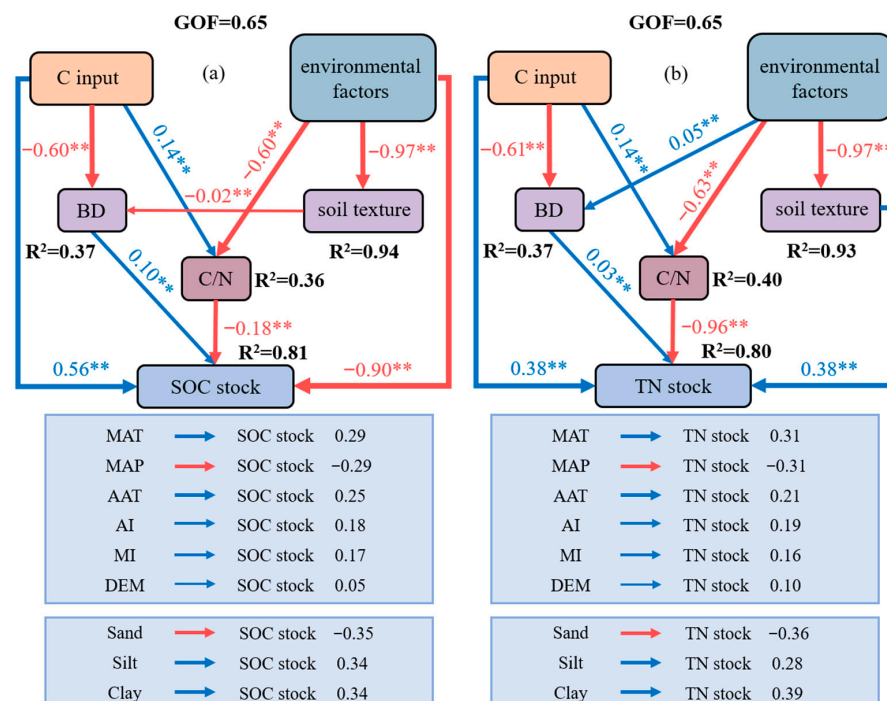


Figure 7. Partial least squares pathway model (PLS-PM) showing the direct or indirect effects of anthropogenic and environmental conditions on (a) soil organic carbon (SOC) stock, and (b) total nitrogen stock. Relevant indicators are bulk density (BD), cumulative carbon inputs (C input), ratio of soil carbon and nitrogen (C/N), average annual temperature (MAT), average annual precipitation (MAP), accumulated temperature (AAT), drought index (AI), humidity index (MI), and digital elevation model (DEM). The width of the arrows is proportional to the strength of the pathway coefficients. Blue and red arrows indicate positive and negative causality. ** represents significance level of $p < 0.05$.

4. Discussion

4.1. Main Driving Mechanisms of SOC and TN Accumulation Under Deep Tillage Combined with Organic Amendments

Deep tillage combined with organic amendments significantly enhanced SOC and TN contents and stocks in black, dark brown, albic, and chernozem soils (Figures 2 and 3), with the SMDT treatment exhibiting the most pronounced effect. This integrated practice promotes SOC and TN accumulation through multiple synergistic mechanisms, including enhanced organic inputs, improved soil structure, and biochemical regulation [30].

The incorporation of exogenous organic inputs is the basis for SOC and TN accumulation [31]. The incorporation of straw increases the return of root exudates and residues, providing a continuous C source for soil microorganisms, while organic fertilizer provides available N that enhances the microbial assimilation process and accelerates the transformation of SOM. However, competition for N between soil microorganisms and crops will weaken the decomposition of straw and decrease long-term accumulation of SOC [32,33]. In contrast, the application of organic fertilizer alleviates N limitation, promoting the decomposition of straw and the transformation of SOM. The C input cumulative under SMDT was significantly greater than that under straw only (SDT) or organic fertilizer only (MDT) (Table 2). This finding highlights the synergistic effect of combined organic amendments, which sustain continuous C input and N supplementation, thereby providing a solid foundation for the stabilization of SOC and TN [34]. Similar results were observed by Gao et al. [35], who found that deep tillage combined with straw and manure increased SOM throughout the 0–35 cm profile and promoted C stabilization in the subsoil.

DT also improved soil structure and the physical conditions, creating favorable environments for SOM retention. DT can ensure the uniform distribution of organic amendments in the 0–35 cm layer, decrease mineralization losses of SOM at the soil surface, decrease BD, and increase porosity and soil aggregate stability, which can prolong the residence time of C [36,37]. In soils with weak structural stability, including albic and dark brown soils, the effects of deep tillage with organic amendments were more evident [38]. DT could effectively relieve the compaction of the plow layer, improve soil aeration and water content, and form a good physical environment for the stable accumulation of SOC and TN [39].

In addition to its physical regulatory role, the soil C/N ratio acts as an intrinsic biochemical driver that links C and N transformations [40]. High C/N indicated that the microbial decomposition of SOM was limited by N input, which would slow down the C turnover and decrease the mineralization [41,42]. While low C/N enhanced the N remineralization and SOC release, which affected the equilibrium of SOC and TN accumulation [43]. The C/N ratio of MDT and SMDT remained relatively stable (Figure 4), which is consistent with the findings of Wang et al. [44], indicating that N from organic fertilizer could maintain the balance of SOC and TN and avoid the desynchronization of C and N decomposition process (Figure 5). Continuous inputs of C increase microbial N demand and promote the reincorporation of N into organic matter. These changes may indirectly contribute to C stabilization by improving microbial metabolic balance, thereby supporting microbially mediated interactions between C and N [45]. Soluble C derived from straw stimulates microbial activity, whereas manure—derived N promotes ammonification and N assimilation [46]. Thus, regulation of the C/N ratio represents a key internal mechanism driving long-term SOC and TN stabilization under deep tillage with organic amendments.

4.2. Response Characteristics and Influencing Factors of SOC and TN Under Different Soil Types

Our research demonstrated that deep tillage combined with organic amendments significantly increased SOC and TN stocks across different soil types, with the magnitude of response influenced by soil texture (Figures 6 and 7). Black and dark brown soils, characterized by high clay content, large specific surface area, and strong cation exchange capacity, effectively retained SOC and TN through mechanisms such as clay adsorption and aggregate encapsulation, thereby promoting higher SOC and TN storage [47,48]. Previous studies have shown that DT in dark brown soils can significantly reduce soil BD, increase total porosity [49], enhance saturated water content, and raise the proportion of water-stable aggregates > 0.25 mm, thereby improving SOC sequestration efficiency and crop C input utilization. Similarly, the findings conducted in the Sanjiang Plain indicate that soil texture is a key intrinsic factor driving regional differences in SOC and TN storage [50]. Albic and chernozem soils, characterized by a high sand fraction, loose structure, weak SOM adsorption capacity, low baseline SOC and TN contents, and rapid C and N mineralization rates, exhibited relatively low SOC and TN storage. Chen et al. [24] reported that in sandy brown soil, SOC stock in the 15–35 cm layer increased when straw and decomposed pig manure were incorporated through deep plowing, which markedly improved the structure and fertility of the cultivated layer.

However, the spatial distribution of TN stocks did not correspond to the pattern observed for SOC (Figure 3). In albic soils with high sand content, N was more susceptible to leaching through water movement. In contrast, the 0–20 cm layer of chernozem soils maintained higher TN stocks than other soil types, likely because their higher pH and strong cation—fixation capacity enhanced inorganic N retention. A similar trend was observed in the chernozem region of Daqing [51], where TN density was closely associated with BD, pH, and C inputs. Overall, these results suggest that in Northeast China, climatic factors regulate crop productivity and organic matter inputs, while texture—dependent stabilization mechanisms jointly determine the spatial differentiation of SOC and TN storage.

4.3. Environmental Controls on SOC and TN Accumulation

Clay content and MAP were the primary external factors influencing SOC and TN storage across different soil types at the regional scale [52]. Mantel analysis showed that both clay content and MAP were significantly positively correlated with C/N ratio (Figure 5). When clay content is high and MAP is moderate, C–N coupling tends to be more stable [53,54]. This indicates that external environmental conditions not only directly influence SOC and TN accumulation but also regulate the internal biochemical balance of the soil by affecting the C/N ratio.

Climatic factors exert a decisive influence on the spatial distribution of SOC and TN storage [55]. In Northeast China, the MAT gradually decreases from southwest to northeast, while the MAP increases along the same gradient. Lower temperatures inhibit organic matter decomposition, whereas higher precipitation promotes biomass accumulation and root C inputs [56]. In this study, the SOC stocks of dark brown soil and albic soil were significantly higher than those of black soil and chernozem soil (Figure 3b,c). Zhang et al. [57] reported that climatic factors accounted for 68% of the variation in surface SOC stock, with the influence of temperature diminishing with depth, whereas pH and clay proportion became increasingly important in explaining deep SOC storage. This pattern indicates that climate mainly regulates surface C inputs and decomposition, while soil physical properties control C sequestration and stabilization in deeper layers.

The interaction between soil texture and climate further determines the mechanisms governing SOC and TN stability (Figure 7). Some studies have found that the accumulations of SOC in heavy rainfall areas were shown to have been largely regulated by clay

minerals [58], whereas some studies showed that SOC was weakly related to clay particles in semi-arid sandy regions [59,60]. Goebel et al. [61] partly attributed this effect to soil water repellency, which may aggravate runoff flow and erosion and ultimately result in the loss of SOM. In addition, sandy soils have a limited capacity to stabilize organic compounds on mineral surfaces compared with clay-rich soils, thereby constraining their potential for SOC and TN storage and slowing their turnover rates. Consequently, environmental factors directly control SOM stability through moisture and textural conditions, while indirectly influencing the maintenance of the C/N balance and the long-term stability of SOC and TN.

5. Conclusions

Deep tillage combined with organic amendments significantly increased the accumulation of SOC and TN within the 0–35 cm layer across four soil types in Northeast China. Among all treatments, SMDT achieved the highest SOC and TN stocks, improved subsoil fertility, and alleviated nutrient stratification. This practice enhanced C input, optimized soil structure, and maintained a balanced C/N ratio, thereby strengthening C–N coupling and promoting long-term nutrient retention. SOC and TN stocks were strongly correlated with cumulative C input, indicating that organic amendment incorporation was the main driver of C and N sequestration. Mantel analysis and PLS–PM further revealed that clay content and MAP regulated SOC and TN accumulation through their effects on C input and soil physical properties. Overall, deep tillage combined with organic amendments effectively enhanced SOC and TN sequestration, improved soil structure and fertility, and provided a feasible management strategy for sustainable agricultural production in Northeast China, offering practical guidance for farmers, land management practitioners, and regional policymakers.

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