Dynamics of Readily Oxidizable Organic Carbon and Soil Organic Carbon Pools in Cinnamon Soil Under Long-Term Fertilization: Postprint

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Abstract

This study investigated the effects of 24-year long-term fertilization on soil organic carbon (TOC), organic carbon storage (TOCs), net carbon sequestration efficiency (NCSE), and carbon pool management index (CPMI) in cinnamon soil, providing a theoretical basis for evaluating changes and quality of soil carbon pools and scientific fertilization. Using the long-term cinnamon soil fertility and fertilizer experiment as a platform, soil TOC and readily oxidizable organic carbon (ROOC) contents were measured and TOCs, NCSE, CPMI, and related indices were calculated through nine treatments [Group A: no fertilization treatment (N0P0, CK); Group B: single inorganic fertilizer treatment (N1P1, N2P2, N3P3, and N4P4); Group C: combined organic and inorganic fertilizer treatment (N2P1M1, N3P2M3, and N4P2M2); Group D: single high-rate organic fertilizer treatment (M6)]. The results showed that applying higher rates of organic fertilizer combined with inorganic fertilizer and applying high-rate organic fertilizer (N3P2M3, N4P2M2, and M6) could increase TOC and ROOC contents in different soil layers and periods, with the enhancement effect decreasing with increasing soil depth. TOCs, NCSE, and TOC content in the 0-20 cm soil layer showed basically consistent temporal and spatial variation patterns. Applying high-rate organic fertilizer (Groups C and D) could effectively increase TOCs, with mean TOCs in Groups A and B being 76.77% and 17.36% lower than those in Groups C and D, respectively. Long-term fertilization treatments could increase NCSE, especially organic fertilizer treatments which significantly increased NCSE. NCSE followed the order: Group D > Group C > Group A = Group B; NCSE in Group D was 1,152.27 kg · hm ^{2} · a ^{1}, which was 2.51 times that of Group C and 16.20 times that of Group B. Compared with pre-experiment values, CPMI in Groups C and D showed no significant change, and there was no significant difference between Groups C and D, but Groups A and B decreased by 16.38-40.02 compared with pre-experiment values. Compared with Group A (CK), the N1P1 treatment in Group B and treatments in Groups C and D significantly affected CPMI, increasing it by 23.30-45.67. CPMI was significantly positively correlated with ROOC content in the 0-40 cm soil layer, and CPMI could well indicate changes in organic carbon. Therefore, applying high-rate organic fertilizer or combined application of higher-rate organic fertilizer with inorganic fertilizer could extremely significantly increase TOCs, NCSE, and CPMI in cinnamon soil, meaning that applying high-rate organic fertilizer or combined application of higher-rate organic fertilizer with inorganic fertilizer (N3P2M3 and N4P2M2) is beneficial for organic carbon sequestration in cinnamon soil, can reduce inorganic fertilizer application rates, and promotes soil properties developing in a benign direction, thereby improving soil fertility.

Full Text

Characteristics of Readily Oxidizable Organic Carbon and Soil Organic Carbon Pool Under Long-Term Fertilization in Cinnamon Soils

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Abstract: This study examined the effects of 24 years of long-term fertilization on total organic carbon (TOC), total organic carbon storage (TOCs), net carbon sequestration efficiency (NCSE), and carbon pool management index (CPMI) in cinnamon soils to provide a theoretical basis for evaluating soil carbon pool changes and quality and for guiding scientific fertilizer application. Using data from a long-term soil fertility and fertilizer experiment, we analyzed TOC and readily oxidizable organic carbon (ROOC) contents and calculated related indices including TOCs, NCSE, and CPMI across nine treatments: Group A (no fertilization, N0P0, CK), Group B (single inorganic fertilizer applications: N1P1, N2P2, N3P3, N4P4), Group C (combined organic and inorganic fertilizers: N2P1M1, N3P2M3, N4P2M2), and Group D (single high-rate organic fertilizer: M6). Results showed that medium and high organic manure applications (N3P2M3 and N4P2M2) increased TOC and ROOC contents across different soil layers and periods, though this enhancement diminished with soil depth. TOCs, NCSE, and TOC content in the 0–20 cm layer showed similar temporal and spatial variation patterns. High organic fertilizer applications (Groups C and D) effectively increased TOCs, with mean values in Groups A and B being 76.77% and 17.36% lower than those in Groups C and D, respectively. Long-term fertilization improved NCSE, particularly with organic fertilizer applications. NCSE ranked as Group D > Group C > Group A = Group B. Group D' s NCSE reached 1,152.27 kg · hm ^{2} · a ^{1}, which was 2.51 times that of Group C and 16.20 times that of Group B. Compared with pre-experiment values, CPMI in Groups

C and D showed no significant change and did not differ significantly between these two groups, while Groups A and B decreased by 16.38–40.02. Compared with Group A (CK), the low inorganic fertilizer treatment (N1P1) and organic fertilizer treatments (Groups C and D) significantly affected CPMI, increasing it by 23.30–45.67. CPMI showed a significant positive correlation with ROOC content in the 0–40 cm soil layer, indicating that CPMI can effectively indicate organic carbon changes. These findings demonstrate that applying high-rate organic manure or combined high-rate organic-inorganic fertilization (N3P2M3 and N4P2M2) can significantly improve TOCs, NCSE, and CPMI in cinnamon soils, thereby enhancing organic carbon sequestration, reducing inorganic fertilizer requirements, promoting favorable soil development, and improving soil fertility.

Keywords: Long-term fertilization; Organic fertilizer; Total organic carbon storage; Carbon pool management index; Net carbon sequestration efficiency; Soil total organic carbon; Readily oxidizable organic carbon

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Introduction

Soil organic carbon is a crucial component of soil that helps mitigate greenhouse effects while increasing water-holding capacity and nutrient availability, making its sequestration particularly important. Total organic carbon storage (TOCs) and net carbon sequestration efficiency (NCSE) are key indicators of soil carbon sequestration potential that effectively reflect soil organic carbon responses to fertilization practices. These metrics indicate the equilibrium balance among different carbon fractions and are used to evaluate soil quality and management practices. However, soil organic carbon content alone is a capacity indicator that cannot fully reflect intrinsic soil quality changes. Therefore, readily oxidizable organic carbon (ROOC), which can be oxidized by 333 mmol · L^{1} KMnO , has been introduced as an indicator of soil organic matter lability. With a relatively short turnover time, ROOC is closely related to nutrient supply and crop growth, serving as a primary source of plant nutrients and indicating early changes in soil organic matter. Nevertheless, ROOC content alone is insufficient to comprehensively reflect the renewal dynamics of soil organic carbon pools. The carbon pool management index (CPMI) integrates both carbon pool indicators and carbon pool activity under anthropogenic influence, reflecting how external conditions affect both the quantity of soil organic matter and the amount of labile organic matter. This index provides a more comprehensive and dynamic representation of how external conditions influence soil organic matter properties.

Long-term fertilization is a primary method for improving soil fertility and plays a major role in conserving farmland soil nutrients under certain conditions. Previous research has examined changes in soil organic carbon pools under long-term fertilization in black soils of Gongzhuling, Jilin, concluding that long-term application of nitrogen, nitrogen-phosphorus, and nitrogen-phosphorus-potassium fertilizers had no significant effect on soil organic carbon pools. Other studies based on 32-year long-term experiments in yellow mud fields of southern hilly regions found that combining chemical fertilizers with manure or straw return significantly increased soil carbon sequestration rates compared with chemical fertilizer alone. Research on black soils demonstrated that combined organic and chemical fertilization significantly increased soil organic matter, with carbon pool management indices exceeding 100 when using fallow treatment as a reference. Studies across six agricultural soil types (red soil, medium-layer black soil, thick-layer black soil, grey desert soil, black loess soil, and fluvo-aquic soil) showed that different fertilization treatments generally increased the proportion of labile organic carbon, with combined organic fertilizer applications showing the greatest enhancement (44.0%–63.4%). However, domestic research on organic carbon pool dynamics under long-term fertilization has primarily focused on changes in TOC and ROOC contents, without comprehensive correlation analysis incorporating CPMI, NCSE, and TOCs. While previous studies have thoroughly investigated soil organic carbon pool changes under long-term fertilization across various soil types, systematic research on cinnamon soils is lacking. Moreover, the effects of long-term fertilization on soil organic carbon and its readily oxidizable fraction vary under different topographic, environmental, and management conditions. For instance, long-term experiments have shown increased total organic carbon content in fluvo-aquic, red, and other soils, but inconsistent conclusions regarding changes in readily oxidizable organic carbon content.

To address these gaps, this study conducted a 24-year long-term fertilization experiment on cinnamon soils in semi-arid and semi-humid regions, representing typical farmland soils across 34°–40°N, 103°–122°E with distinct soil types, cropping systems, and climatic differences. The research aimed to reveal changes in farmland soil organic carbon pools under long-term combined chemical-organic fertilization, explore relationships among TOCs, NCSE, and CPMI in cinnamon soils, elucidate the effects of long-term fertilization on organic carbon changes and mechanisms for improving farmland soil quality, identify organic carbon pool indicators that best reflect soil fertility and productivity, and provide theoretical support for cinnamon soil fertility improvement, grain yield increase, and greenhouse gas emission reduction.

1. Materials and Methods

1.1 Study Site Description The long-term fertilization experiment was established at Beiping dryland plateau in Zong' ai Village, Shouyang County, Shanxi Province, within the National Dryland Agricultural Science and Technology Research Zone. The experimental site is located at 1,130 m altitude, with a mean annual temperature of 7.6°C, 10°C accumulated temperature of 3,400°C, frost-free period of 135–140 days, mean annual precipitation of 501.1 mm (with high interannual variability), and aridity index of 1.3, classifying it as a semi-humid to semi-arid region. The experimental soil is cinnamon soil (cinnamon-like soil) with light loam texture, deep profile, flat terrain, and groundwater depth exceeding 50 m. Baseline topsoil (0–20 cm) properties before sowing in 1992 were: pH 8.3, organic matter 23.80 g · kg ^{1}, total nitrogen 1.05 g · kg ^{1}, total phosphorus 0.79 g · kg ^{1}, alkaline hydrolyzable nitrogen 106.4 mg · kg ^{1}, available phosphorus 4.84 mg · kg ^{1}, and available potassium 100 mg · kg ^{1}. Fertilizers were applied once annually in autumn during plowing. Nitrogen fertilizer was urea (46% N), phosphorus fertilizer was superphosphate (12%–14% P O), and organic fertilizer was decomposed wet cattle manure (moisture content 49.70%–50.00%). Air-dried decomposed manure contained 90.5–127.3 g · kg ^{1} organic matter, 3.93–4.97 g · kg ^{1} total nitrogen (N), 1.37–1.46 g · kg ^{1} total phosphorus (P O), and 14.1–34.3 g · kg ^{1} total potassium (K O). The cropping system was single-season corn annually. Varieties included 'Yandan 14' (1992–1995), 'Jindan 34' (1996–2002), 'Qiangsheng 31' (2003–2009), and 'Jindan 81' (2010–2015), all at densities of 4.5–7.0 × 10 plants · hm ^{2}. Sowing occurred April 15–28 and harvest September 20–October 10. Field management followed high-yield requirements. No straw return treatments were included in the selected experimental plots; straw was removed after autumn harvest.

1.2 Experimental Design The long-term nitrogen-phosphorus-organic fertilizer experiment began in spring 1992 and had run for 24 years by 2015. The experiment employed a 3-factor (N, P, organic fertilizer) 4-level orthogonal design with additional control and high-rate organic fertilizer treatments, totaling 18 treatments. Plot area was 66.7 m^2 with randomized arrangement and no replications. Nitrogen, phosphorus, and organic fertilizers were applied at different levels. This study selected nine treatments: Group A (no fertilization control, CK, N0P0), Group B (various N and P chemical fertilizer combinations: N1P1, N2P2, N3P3, N4P4), Group C (combined chemical-organic fertilizers: N2P1M1, N3P2M3, N4P2M2), and Group D (single high-rate organic fertilizer: M6). Groups A and B were analyzed for single chemical fertilizer application, Groups A and D for single organic fertilizer application, and Group C represented treatments with higher economic benefits and better soil physicochemical properties in field management. This experiment focused on comprehensive field soil indicators under different fertilization practices, hence Group C was included for analysis. Specific nutrient application rates for each treatment are shown in Table 1 .

1.3 Measurement Methods and Calculations 1.3.1 Measurement Items

This study measured soil organic carbon and readily oxidizable organic carbon contents in baseline samples from 1992 and samples from 1996, 2001, 2006, 2012, and 2015.

1.3.2 Measurement Methods

After annual autumn harvest, soil samples were collected from 0–20 cm, 20–

40 cm, and 40-60 cm layers using soil augers. Each treatment had 6-10 random sampling points for mixed sample preparation (since treatments had no replications, three artificial replicates were created during sampling). Collected soils were air-dried, with one portion passed through a 0.25 mm sieve for TOC measurement and another through a 0.149 mm sieve for ROOC measurement.

Soil TOC content was determined by the potassium dichromate external heating method; soil bulk density by the ring knife method; pH by potentiometry. ROOC content was measured using 333 $\text{mmol} \cdot \text{L}^{1}$ potassium permanganate oxidation method.

1.3.3 Calculation of Total Organic Carbon Storage (TOCs) and Net Carbon Sequestration Efficiency (NCSE)

The formula for TOCs calculation:

$$\text{TOCs} = \sum_{i=1}^{n} C_i \times p_i \times T_i \times 0.1$$

Where: TOCs is soil organic carbon storage at a certain depth ($\text{t} \cdot \text{hm}^{2}$), C_i is TOC content of the ith layer ($\text{g} \cdot \text{kg}^{1}$), p_i is bulk density of the ith layer ($\text{g} \cdot \text{cm}^{3}$), T_i is thickness of the ith layer (cm), and n is the number of soil layers.

The formula for net carbon sequestration efficiency (NCSE):

$$\text{NCSE}_m = \frac{\text{TOCs}_m - \text{TOCs}_{0m}}{n}$$

Where: NCSE_m is carbon sequestration efficiency of the mth layer, TOCs_m is organic carbon storage of the mth layer, TOCs_{0m} is initial organic carbon storage of the mth layer, and n represents the number of years under fertilization treatment (24 years in this experiment).

Net carbon sequestration efficiency NCSE_{my}:

$$\text{NCSE}_{my} = \text{CSE}_{my} - \text{CSE}_{m0}$$

Where: CSE_{my} is net carbon sequestration efficiency of the mth layer for treatment y, and CSE_{m0} is carbon sequestration efficiency of the mth layer for the CK treatment in 2015.

1.3.4 Calculation Method for Carbon Pool Management Index (CPMI)

The carbon pool management index (CPMI) equals 100 times the product of carbon pool index and activity index. The carbon pool index (CPI) is the ratio of sample TOC content to reference soil TOC content (this experiment used 1992 and 2015 0-20 cm soils as reference samples). The activity index (AI) is the ratio of sample carbon pool activity to reference soil carbon pool activity. Carbon pool activity (A) is the ratio of ROOC to (TOC -ROOC).

$$\text{CPMI} = \text{CPI} \times \text{AI} \times 100$$

$$\text{CPI} = \frac{\text{TOC(sample)}}{\text{TOC(reference soil)}}$$

1.4 Data Processing and Statistical Analysis Data analysis and graphing were performed using Microsoft Excel 2010, with variance analysis and correlation analysis conducted using SPSS 17.0 statistical software.

2. Results

2.1 Effects of Long-Term Different Fertilization Treatments on Soil Total Organic Carbon (TOC) Content and Total Organic Carbon Storage (TOCs) 2.1.1 Effects on Inter-Annual Variation Characteristics of TOC Content in the Plough Layer

The effects of different fertilization treatments on inter-annual variation of TOC content in the plough layer (0–20 cm) primarily manifested as enhancement from organic fertilizer application. Compared with pre-experiment values, after 24 years, M6, N3P2M3, and N4P2M2 treatments showed significantly higher TOC contents (14.67–23.15 $g \cdot kg^{1}$), representing increases of 11.56%-67.63%. The N2P1M1 treatment decreased TOC content by 8.83% in 2015 compared with initial values. The N3P2M3 and N4P2M2 treatments showed overall increasing trends year by year, while N2P1M1 remained relatively stable. In contrast, the control (N0P0) and single inorganic fertilizer treatments showed decreasing TOC contents year by year, with reductions of 23.82%-29.04% compared with pre-experiment values (Figure 1 [Figure 1: see original paper]). Comparisons among Groups C, D, B, and A revealed that Groups C and D had significantly higher TOC contents than Groups A and B.

Figure 1 shows that Groups C and D (except N2P1M1 in 2001) had higher TOC contents than Group A with continuing upward trends. In Groups A and B, TOC contents gradually approached and then fell below Group A levels as fertilization years increased.

2.1.2 Effects on Profile Distribution Characteristics of TOC Content

After 24 years of continuous fertilization, significant differences in TOC content developed in the cinnamon soil plough layer (0–20 cm) (Figure 2 [Figure 2: see original paper]). TOC content ranked as Group D > Group C > Groups A and B. Groups A and B had TOC contents of 9.80–10.53 $g \cdot kg^{1}$ (mean 10.14 $g \cdot kg^{1}$) with no significant differences among treatments. Group C had TOC contents of 12.59–15.95 $g \cdot kg^{1}$ (mean 14.40 $g \cdot kg^{1}$), showing highly significant differences from Groups A and B with a 42.01% increase. Group D had a TOC content of

23.15 $g \cdot kg^{1}$, showing extremely significant differences from both Groups A/B and Group C, with increases of 128.30% and 60.76% respectively compared with Group A, and 135.74% compared with Group A.

In the 20–40 cm layer, Groups C and D significantly affected TOC content. In Groups A and B, higher inorganic fertilizer application rates further decreased TOC content in this layer. In the 40–60 cm layer, Group D significantly increased TOC content, while the inorganic fertilizer group (Group B) showed significantly reduced TOC content with no significant differences within the group.

2.1.3 Effects on TOCs

In Figure 3 [Figure 3: see original paper], CK0 represents the TOCs value of the 1992 baseline soil sample. Only Group D showed higher TOCs than CK0, while other treatments decreased, with larger TOCs reductions in treatments with less organic fertilizer application. Groups C and D had significantly higher TOCs than Groups A and B, with increases of 76.77% and 17.36% respectively. The N1P1 treatment had the lowest TOCs, M6 the highest, and N4P4 was significantly higher than other Group B treatments.

2.2 Effects of Long-Term Different Fertilization Treatments on Soil Net Carbon Sequestration Efficiency (NCSE) Table 2 shows NCSE changes in different soil layers after 24 years of fertilization. In the 0–20 cm, 20–40 cm, and 0–40 cm layers, net carbon sequestration efficiency ranked as Group D > Group C > Groups A and B. In the 0–20 cm layer, Group D' s NCSE was 1,152.27 $kg \cdot hm^{2} \cdot a^{1}$, 2.51 times that of Group C and 16.20 times that of Group B, demonstrating that high-rate organic fertilizer application significantly improved soil net carbon sequestration efficiency. Groups A and B, which received no organic fertilizer, showed no significant NCSE differences. In the 20–40 cm layer, Group B showed net carbon release, while Groups C and D (except N4P2M2) showed net carbon fixation. Integrating the 0–40 cm layer, Group B showed average net carbon release, while Groups C and D showed net carbon fixation. The N3P2M3 treatment in Group C and M6 in Group D had better carbon fixation effects, likely due to higher organic manure application rates. The N1P1 and N3P3 treatments in Group B showed the poorest carbon fixation performance with net carbon release, indicating that long-term application of medium-low rates of inorganic fertilizer reduces soil carbon sequestration capacity.

2.3 Effects of Long-Term Different Fertilization Treatments on Soil Readily Oxidizable Organic Carbon (ROOC) Content 2.3.1 Effects on Inter-Annual Variation Characteristics of ROOC Content in the Plough Layer

Figure 4 [Figure 4: see original paper] shows that ROOC content varied from 1.82–4.07 $g \cdot kg^{1}$ between 1992 and 2015. Compared with pre-experiment values, Groups C and D showed initial declines followed by gradual increases in ROOC content, while Group B showed substantial declines with trends approaching Group A levels. In each period, Groups C and D (except N4P2M2 in 1996) had higher ROOC contents than CK, with M6 and N3P2M3 exceeding pre-experiment values for the first time in 2015 and showing continued upward trends. In 2001, Group B treatments (except N3P3) showed increased but still below-pre-experiment ROOC contents. By 2015, ROOC contents for treatments N0P0, N1P1, N2P2, N3P3, N4P4, N2P1M1, N3P2M3, N4P2M2, and M6 had changed by -31.34%, -20.16%, -20.16%, -33.51%, -36.78%, -11.17%, 0.54%, -9.81%, and 10.90% respectively, with higher organic fertilizer rates associated with relatively higher ROOC contents. These results demonstrate that organic fertilizer application promotes ROOC transformation and accumulation, which directly affects soil microbial activity and significantly influences soil minerals and texture.

2.3.2 Effects on Profile Distribution Characteristics of ROOC Content

After 24 years of long-term fertilization, treatments showed highly significant effects on plough layer (0–20 cm) ROOC content (Figure 5 [Figure 5: see original paper]). ROOC content ranked as M6, N3P2M3 > N2P1M1, N4P2M2 > N0P0, N1P1, N2P2, N3P3, N4P4, with mean values of 3.88 $g \cdot kg^{1}$, 3.29 $g \cdot kg^{1}$, and 2.628 $g \cdot kg^{1}$ respectively, representing increases of 53.97%, 30.56%, and 4.29% compared with the control (N0P0). These results indicate that fertilization treatments significantly affected ROOC transformation and fixation in the plough layer.

In the 20–40 cm layer, ROOC response to fertilization followed the pattern Groups C and D (organic fertilizer) > Groups A and B (no organic fertilizer), with mean values of 3.17 $g \cdot kg^{1}$ and 2.28 $g \cdot kg^{1}$, representing increases of 39.76% and 0.53% compared with CK (no fertilizer). This demonstrates that organic fertilizer application had highly significant effects on ROOC content in this layer.

In the 40–60 cm layer, no clear patterns emerged among treatments, though the conventional inorganic fertilizer treatment (N2P2) had the lowest ROOC content (1.59 $g \cdot kg^{1}$) while M6 had the highest (3.17 $g \cdot kg^{1}$), with a significant difference between them. Compared with N0P0, these represented changes of -43.21% and 13.21%, respectively. Thus, long-term application of certain chemical fertilizers reduced 40–60 cm layer ROOC content, while high-rate organic fertilizer application increased it.

2.4 Effects of Long-Term Fertilization on Soil Carbon Pool Management Index (CPMI) Using 1992 0–20 cm TOC content and soil carbon pool activity baseline values as references for significance testing, we calculated CPMI for each treatment in 2015 (designated CPMI). Using 2015 0–20 cm CK treatment TOC content and soil carbon pool activity baseline values as references, we calculated CPMI for each treatment in 2015 (designated CPMI). Results are shown in Table 3 .

Groups A and B and the N2P1M1 treatment showed significant CPI reductions of 8.83%-29.03%. The N3P2M3 and M6 treatments showed significant CPI increases that became more pronounced with higher organic fertilizer rates (15.50%-67.63%). The N4P2M2 treatment showed no difference from pre-experiment values, consistent with TOC content changes. Compared with CK, organic fertilizer application significantly increased CPI values.

Except for N1P1 and N2P2 treatments, which showed no significant differences from pre-experiment values, all other treatments significantly reduced carbon pool activity by 42.00%-0.03%. Compared with CK, low-rate inorganic fertilizer application significantly increased carbon pool activity, while high-rate organic fertilizer application significantly reduced it. Fertilization effects on activity index were consistent with effects on carbon pool activity.

Using 1992 as reference, Groups C and D showed no significant differences in CPMI after organic fertilizer application, maintaining initial levels, with higher organic fertilizer rates approaching initial conditions more closely. Groups A and B showed significant CPMI reductions of 16.38-40.02. Using CK as reference, low-rate inorganic fertilizer treatment (N1P1) and organic fertilizer groups (C and D) significantly affected CPMI , increasing it by 23.30-45.67. In Groups C and D, CPMI increases were related to organic fertilizer application rates. High-rate inorganic fertilizer treatments decreased CPMI by 11.56 compared with CK.

2.5 Correlations Among Soil Organic Carbon (TOC), Readily Oxidizable Organic Carbon (ROOC), and Carbon Pool Management Index (CPMI) Under Long-Term Different Fertilization Treatments Correlation analysis among TOC, ROOC, and CPMI across different soil layers revealed that in the 0-20 cm and 20-40 cm layers, TOC content showed highly significant positive correlations with TOC content in the underlying layer and with ROOC content in the same layer. This indicates that TOC moves downward through the profile and that ROOC can reflect TOC content to some extent, with TOC increases causing ROOC increases. In the 20-40 cm and 40-60 cm layers, TOC content showed significant correlations with underlying layers but no correlation with ROOC content, while ROOC content showed no significant effect on underlying layer ROOC content, suggesting ROOC also moves downward. CPMI showed highly significant positive correlations with 0-20 cm ROOC and significant positive correlations with 20-40 cm ROOC, revealing that ROOC greatly influences CPMI while TOC has less impact. These correlation analyses further demonstrate that ROOC is a sensitive indicator of soil carbon pools that can reflect short-term changes in soil organic carbon pools, and that the CPMI index can effectively indicate soil quality and organic carbon changes.

3. Discussion

3.1 Effects of Long-Term Different Fertilization Treatments on Soil Total Organic Carbon (TOC) Content, Total Organic Carbon Storage (TOCs), and Net Carbon Sequestration Efficiency (NCSE) Fertilization is an important farmland management measure that plays a significant role in increasing TOC. Farmland TOC quantity depends on the balance between organic matter input and decomposition. Soil organic matter inputs primarily come from crop secretions, root residues, litter, and annual organic fertilizer applications. This experiment demonstrated that after 24 years of fertilization, Groups C and D significantly increased TOC content compared with Groups A and B, consistent with previous research findings. Organic fertilizer application supplements soil TOC, increases crop biomass production, and consequently enhances residue and root inputs to soil, substantially increasing organic carbon return and maintaining or improving soil organic matter content, leading to substantial TOC increases. The experimental site had relatively high initial soil organic matter content. Previous studies on black soils have shown that long-term chemical fertilizer application on soils with high organic matter content leads to TOC reduction because organic carbon sources under chemical fertilization are mainly crop root residues. With vigorous crop growth, soil organic carbon inputs cannot meet outputs, making accumulation difficult.

Profile distribution changes in TOC content result from organic fertilizer application increasing soil fertility, which benefits root growth downward and outward, producing more root secretions. Root binding effects help optimize soil structure, increase microbial activity, and improve water and nutrient retention capacity, resulting in higher TOC content in rhizosphere soils with organic fertilizer application.

The consistent temporal and spatial variation patterns among TOCs, NCSE, and TOC content indicate that high-rate organic fertilizer application is optimal for increasing plough layer organic carbon storage and sequestration effects. Therefore, agricultural production should emphasize organic fertilizer application and reduce chemical fertilizer use. Integrating the 0–40 cm layer, Groups A, B, and C showed net carbon release, while Group D showed net carbon fixation. The N3P2M3 treatment in Group C and M6 in Group D had better carbon fixation effects. The N1P1 treatment showed the poorest carbon fixation performance with net carbon release. Previous research indicated optimal effects from combined organic-inorganic fertilization, which differs from this study' s conclusions, possibly because the combined treatments in this experiment used relatively low organic fertilizer rates. This increased soil activity but created an organic matter deficit, preventing accumulation. Future experiments should include high-rate organic fertilizer combined with inorganic fertilizer treatments to explore and compare effects between single high-rate organic and combined high-rate organic-inorganic fertilization.

3.2 Effects of Fertilization on Soil Readily Oxidizable Organic Carbon This study demonstrated that 24 years of organic fertilizer application promoted ROOC transformation and accumulation. Group D showed significant ROOC content increases, Group C treatments with moderate organic fertilizer rates maintained baseline values, while low-rate organic fertilizer and Group C treatments showed ROOC declines, with high-rate inorganic fertilizer treatments showing the greatest reductions. Similar conclusions have been reported in other studies. ROOC content decreased with soil depth, and organic fertilizer application increased 0–40 cm layer ROOC content, consistent with previous research. All these results indicate that high-rate organic fertilizer application significantly enhances ROOC. In this experiment, moderate organic-inorganic combined treatments also maintained or increased ROOC, but without a designed high-rate organic-inorganic combined treatment, we cannot confirm whether high-rate organic-inorganic combined fertilization is more beneficial for ROOC accumulation. Since the crop was single-season corn with minimal tillage disturbance to the 40–60 cm layer, different fertilization treatments had no significant effects on ROOC content in this layer. The high-rate organic fertilizer treatment (Group D) had loose soil texture, good root growth, high permeability, and vigorous microbial activity, resulting in significantly higher ROOC content than other treatments and initial conditions after 24 years of continuous fertilization, though subsequent experiments are needed to verify this hypothesis.

3.3 Effects of Long-Term Fertilization on Soil Carbon Pool Management Index (CPMI) Inorganic fertilizer reduced CPI while organic fertilizer increased it, consistent with their effects on TOC content. The carbon pool activity calculation shows that although organic fertilizer application significantly increased ROOC (labile organic matter) content, the increase in non-labile organic matter content far exceeded the ROOC increase, so carbon pool activity did not substantially improve. Only high-rate organic fertilizer application significantly increased CPI by 67% above initial values. Organic fertilizer application likely increased TOC content because the fertilizer itself contained high organic carbon that entered the soil through application and transformation by soil microorganisms. However, soil carbon pool activity (A) and activity index (AI) did not increase, primarily due to the experimental site' s natural environmental factors (semi-humid to semi-arid region) that limited soil microbial activity and relatively slowed organic matter decomposition.

With anthropogenic disturbance to farmland soil and microenvironments, farmland soil CPMI decreases and soil properties develop unfavorably. However, organic fertilizer application slows or even improves this fertility decline. Using CK as reference, low-rate inorganic fertilizer treatment also increased CPMI because the experimental soil was alkaline, and low-rate inorganic fertilizer application reduced pH to values suitable for microbial activity. Organic fertilizer application significantly increased CPMI, with Groups C and D having CPMI $>$ 1, indicating these treatments not only improved basic soil physicochemical properties and promoted favorable soil development but also effectively enhanced soil nutrient supply capacity to crops and increased crop yields.

3.4 Correlations Among Soil Organic Carbon, Readily Oxidizable Organic Carbon, and Carbon Pool Management Index In the 0–40 cm layer, ROOC content decreased with soil depth and showed highly significant positive correlations with TOC, consistent with findings from other studies on readily oxidizable organic carbon. ROOC content largely depends on TOC storage but also represents an ideal indicator of soil carbon balance and biological fertility, playing a decisive role in soil microbial activity. Soil properties indirectly affect ROOC changes; for example, leaching from the plough layer can cause ROOC loss.

The carbon pool management index (CPMI) showed significant positive correlations with ROOC content in the 0–20 cm and 20–40 cm layers, indicating ROOC content greatly influences CPMI while TOC has less impact. ROOC is a sensitive indicator of soil carbon pools that can reflect short-term changes in soil organic carbon pools, and the CPMI index can effectively indicate soil quality and organic carbon changes.

4. Conclusion

Twenty-four years of long-term fertilization produced different effects on cinnamon soil profile organic carbon, readily oxidizable organic carbon content, and carbon pool management index. After 24 years, medium and high-rate organic fertilizer applications in the plough layer significantly increased both soil organic carbon and readily oxidizable organic carbon contents, while treatments without organic fertilizer showed significant decreases. In the profile, both parameters decreased with soil depth, though readily oxidizable organic carbon content in the 40–60 cm layer was less affected by various fertilization practices. Organic fertilizer application significantly increased carbon pool management index and improved basic soil physicochemical properties. TOCs, NCSE, and TOC content showed essentially consistent temporal and spatial variation patterns, indicating that high-rate organic fertilizer application is optimal for increasing plough layer organic carbon storage and sequestration effects, representing an effective measure for improving soil fertility.

In summary, applying high-rate organic manure or high-rate combined organic-inorganic fertilization can significantly increase soil organic carbon content, readily oxidizable organic carbon content, and carbon pool management index. High-rate organic fertilizer application benefits organic carbon sequestration, reduces chemical fertilizer requirements, promotes favorable soil development, and improves soil fertility.

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Note: Figure translations are in progress. See original paper for figures.