Effects of Meso- and Micronutrient Addition on Mineralization Characteristics and Soil Organic Carbon Fractions in Aeolian Sandy Soil (Postprint)

Authors: Liu Jiayue, Kou Wei, Yuan Jianqiang, Xue Shaoqi, Wang Xudong(1)

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Abstract

To investigate the mineralization characteristics of organic fertilizer amended with medium and trace elements in sandy soil and its effects on soil organic carbon fractions, laboratory incubation and field experiments were conducted to examine the decomposition and residual rates of organic fertilizer and organic fertilizer amended with medium and trace elements, as well as the impacts of different application rates on soil organic carbon, labile organic carbon, particulate organic carbon, mineral-associated organic carbon, microbial biomass carbon, and the contents of glucosamine, galactosamine, and muramic acid. The results demonstrated that, compared with the application of organic fertilizer alone, the addition of medium and trace elements to organic fertilizer reduced the mineralization amount of soil organic carbon under laboratory incubation conditions. Under field conditions, organic fertilizer amended with medium and trace elements further increased the contents of labile organic carbon (1.79%~1.99%), less labile organic carbon (2.20%~4.91%), mineral-associated organic carbon (3.89%~7.95%), and microbial biomass carbon (1.71%~8.10%); concurrently elevated the contents of soil glucosamine (3.46%~6.32%), galactosamine (1.21%~13.32%), muramic acid (2.41%~6.14%), and microbial necromass carbon (2.70%~4.99%); and decreased the contents of highly labile organic carbon (0.71%~1.48%) and particulate organic carbon (4.91%~5.86%); however, these differences were not statistically significant. These findings indicate that organic fertilizer amended with medium and trace elements can, to a certain extent, mitigate the mineralization of organic fertilizer in sandy soil, enhance the contents of labile organic carbon, less labile organic carbon, mineral-associated organic carbon, and microbial biomass carbon, and facilitate the turnover and sequestration of organic carbon.

Full Text

Effects of Medium and Trace Element Addition on Mineralization Characteristics and Soil Organic Carbon Fractions in Aeolian Sandy Soil

LIU Jiayue[1], **KOU Wei**[1], **YUAN Jianqiang**[2], **XUE Shaoqi**[1], **WANG Xudong**[1]

[1]College of Resources and Environment, Northwest A&F University, Yangling, Shaanxi 712100, China
[2]Hongliulin Mining Company, Binhe New District, Shenmu City, Yulin City, Shaanxi Province, Shenmu, Shaanxi 719300, China

Abstract

To investigate the mineralization characteristics of organic fertilizer combined with medium and trace elements and its effects on soil organic carbon fractions in aeolian sandy soil, we conducted laboratory incubation experiments and field trials. We examined the decomposition and residual rates of organic fertilizer with and without medium/trace element addition, as well as the impacts of different application rates on soil organic carbon, active organic carbon, particulate organic carbon, mineral-associated organic carbon, microbial biomass carbon, and the contents of amino sugars (glucosamine, galactosamine, and muramic acid). Results showed that compared with organic fertilizer alone, the addition of medium and trace elements reduced soil organic carbon mineralization in the incubation experiment. In field trials, this addition further increased active organic carbon (1.79%-1.99%), low-activity organic carbon (2.20%-4.91%), mineral-associated organic carbon (3.89%-7.95%), microbial biomass carbon (1.21%-13.32%), muramic acid (2.41%-6.14%), and galactosamine (0.71%-1.48%) contents, while also enhancing amino sugar content (3.46%-6.32%). However, it decreased high-activity organic carbon (1.71%-8.10%) and particulate organic carbon (4.91%-5.86%) contents, though differences were not significant. These findings indicate that adding medium and trace elements to organic fertilizer can slow mineralization of organic fertilizer in aeolian sandy soil, increase the contents of active organic carbon, low-activity organic carbon, mineral-associated organic carbon, and microbial biomass carbon, and promote organic carbon turnover and sequestration.

Keywords: organic fertilizer; mineralization; organic carbon; aeolian sandy soil; medium and trace elements; organic carbon fractions

Introduction

The soil carbon pool represents the largest terrestrial carbon reservoir, directly influencing global terrestrial ecosystem carbon balance and playing a crucial role in soil quality. Soil organic carbon (SOC) constitutes an important component of the soil carbon pool, exerting significant effects on ecosystem resilience and productivity. Mineralization represents the primary pathway for carbon release from soil carbon pools to the atmosphere. Under global climate change, strengthening SOC research and management not only helps mitigate climate change but also promotes healthy soil ecosystem development and sustainable agriculture.

Soil organic carbon fractions include active organic carbon, particulate organic carbon, microbial biomass carbon, and mineral-associated organic carbon, which respond more rapidly to agricultural management practices and thus enable quick assessment of overall organic carbon accumulation and stability. Microbial residues constitute a major source of soil organic carbon, with soil amino sugars serving as important components of microbial cell walls that persist long-term in soil matrices after microbial death. Changes in amino sugar quantity and composition can be used to evaluate the contribution of microbial residue carbon to SOC.

China' s soils commonly suffer from low fertility. According to statistics, the national aeolian sandy soil area reached 17.58% of total land area in 2020, with approximately 6.84$\times10^{6}$ km^2 of desertified land distributed across northern China. Aeolian sandy soils, characterized by low clay content, high porosity, low fertility, and insufficient organic carbon, significantly impact agricultural ecological environments and sustainable development. Previous studies have improved aeolian sandy soils through organic fertilizer, biochar, and natural mineral applications. Organic fertilizer application represents the most direct method for increasing SOC content and fractions, and is considered an effective approach for improving soil quality. However, due to good soil aeration in aeolian sandy soil regions, exogenous organic materials such as straw and organic fertilizer readily mineralize, resulting in low humification coefficients and slow organic carbon enhancement.

Medium and trace elements such as calcium, manganese, zinc, and iron are essential plant nutrients involved in various life processes. Current research indicates that adding appropriate amounts of medium and trace elements to organic fertilizer can increase soil soluble trace element content, improve bioavailability of exchangeable cations, and facilitate plant uptake. These added elements can also strongly adsorb to soil components, exchange on soil surfaces, and form complexes with organic carbon, thereby inhibiting organic carbon decomposition and benefiting SOC sequestration.

Therefore, this study employed incubation and field experiments to investigate the mineralization characteristics of organic fertilizer with added medium and trace elements and its effects on SOC fractions in aeolian sandy soil, providing theoretical support for addressing issues of low fertility and rapid organic carbon mineralization in these soils.

Materials and Methods

1.1 Study Site and Soil Properties Soil samples were collected from Shenmu City in northern Shaanxi Province (109°40 -110°54 E, 38°13 -39°27 N). The region has a temperate semi-arid continental climate with an average annual temperature of 8.5°C, annual precipitation of 423.2 mm, and average annual sunshine duration of 2876 hours. The experimental soil was aeolian sandy soil with light loam texture, containing 6.0 $g \cdot kg^{-1}$ organic carbon, 0.48 $g \cdot kg^{-1}$ total nitrogen, 0.28 $g \cdot kg^{-1}$ total phosphorus, and 21.14 $g \cdot kg^{-1}$ total potassium. Available nutrients included 8.52 $mg \cdot kg^{-1}$ available phosphorus and 165.67 $mg \cdot kg^{-1}$ available potassium, with pH 8.59. The cropping system was annual single-crop maize (variety DF899).

1.2 Experimental Design 1.2.1 Experimental Materials

Two organic fertilizer materials were used: (1) OF (organic fertilizer) composed of fermented and decomposed crop straw; and (2) OF+ME (organic fertilizer with medium and trace elements) composed of sheep manure supplemented with medium and trace elements. The medium/trace element addition included calcium nitrate, manganese sulfate, ferrous sulfate, and zinc sulfate at specific ratios. All fertilizers were provided by Inner Mongolia Hengsheng Environmental Protection Technology Engineering Co., Ltd., with main nutrient contents shown in .

1.2.2 Experimental Methods

Incubation Experiment: Air-dried soil samples (500 g, <2 mm) were placed in 500 mL plastic bottles. Treatments included: (1) control (no organic fertilizer), (2) OF (organic fertilizer), and (3) OF+ME (organic fertilizer with medium and trace elements), each replicated three times. Organic fertilizers were mixed into the soil at 6 $g \cdot kg^{-1}$ (soil basis) based on equal organic carbon content. Soil moisture was adjusted to 60% of field water holding capacity, and bottles were capped with ventilated lids and incubated at 25°C for 360 days. Moisture was replenished every 5 days by weight, and destructive sampling was performed at 30, 60, 90, 120, 150, 180, 240, and 360 days to determine SOC content and calculate decomposition and residual rates.

Field Experiment: Conducted in aeolian sandy soil with two organic fertilizers applied at four rates: 7.5 $t \cdot hm^{-2}$ (OF1, OF1+ME), 15 $t \cdot hm^{-2}$ (OF2, OF2+ME), 22.5 $t \cdot hm^{-2}$ (OF3, OF3+ME), and 30 $t \cdot hm^{-2}$ (OF4, OF4+ME), plus a no-fertilizer control (CK). The experiment used a randomized block design with plot size 10 m × 66.7 m (667 m^2). Fertilizers were applied as base fertilizer before sowing on April 28, 2022, with soil samples collected post-harvest on October 5, 2022. Samples were air-dried and sieved for SOC and fraction analysis.

1.2.3 Soil Sample Analysis

Soil organic carbon was determined by $K_2Cr_2O_7$-H_2SO_4 heating method. Active organic carbon, the readily oxidizable fraction, was extracted using three $KMnO_4$ concentrations (33, 167, and 333 mmol·L^{-1}) and measured at 565 nm, dividing it into high-activity, medium-activity, and low-activity fractions. Particulate organic carbon (>53 m) and mineral-associated organic carbon (<53 m) were separated by sodium hexametaphosphate dispersion. Microbial biomass carbon was measured by chloroform fumigation extraction. Amino sugars were determined by gas chromatography of aldononitrile acetate derivatives after acid hydrolysis, following Zhang and Amelung (1996), yielding three amino monosaccharides: glucosamine, galactosamine, and muramic acid.

1.3 Calculations and Data Analysis The residual rate of organic carbon from organic materials after time-scale mineralization was calculated as:

$$CX = (g_1C/gC - g_2C/gC) \times 100$$

where CX is the organic carbon residual rate (%), g_1C/gC is SOC content after soil-organic fertilizer mixture incubation (g·kg^{-1}), g_2C/gC is SOC content after control soil incubation (g·kg^{-1}), and gC is the initial organic carbon content of added organic fertilizer (g·kg^{-1}). Corrections were made for SOC decomposition in control soil and mineralization-induced mass loss.

Amino sugars were used as biomarkers for fungal and bacterial residues:

Bacterial necromass carbon (BNC) = 45 × MurA-C
Fungal necromass carbon (FNC) = (GluN-C/179 - 2 × MurA-C/251) × 179 × 9

where GluN-C is glucosamine carbon, MurA-C is muramic acid carbon (mg·kg^{-1}), and 45 and 9 are conversion factors to bacterial and fungal necromass carbon, respectively. Microbial necromass carbon is the sum of bacterial and fungal necromass carbon.

Data were analyzed using Microsoft Office Excel 2016 and SPSS 25.0 for variance analysis and significance testing ($\alpha = 0.05$).

Results

2.1 Organic Carbon Residual Rate Under Different Organic Fertilizer Treatments in Incubation Compared with organic fertilizer alone, adding medium and trace elements increased the residual rate of organic carbon. As shown in [Figure 1: see original paper], both organic fertilizer treatments exhibited rapid initial decomposition followed by slower decomposition. Decomposition rates were similar during the first 180 days; after 180 days, the OF+ME treatment showed slower decomposition with increasing time. At 360 days, the residual rates for OF and OF+ME were 4.86% and 8.33%, respectively, with OF+ME showing a 2.99% increase ($P < 0.05$). The decomposition rate of OF+ME was significantly reduced by 1.50% at 180 days and by 1.22% at 240 days compared with OF, though not significantly at 360 days (0.87% reduction) [Figure 2: see original paper].

2.2 Changes in Soil Organic Carbon Content Under Different Organic Fertilizer Application Rates in Field Trials Organic fertilizer with medium and trace elements increased SOC content compared with organic fertilizer alone. As shown in [Figure 3: see original paper], SOC content increased significantly with increasing fertilizer rate for both treatments, rising by 25.45% under OF4+ME ($P < 0.05$). At the same application rate, OF+ME increased SOC content by 0.44% compared with OF. The enhancement effect was most pronounced at OF4+ME, increasing SOC by 27.33% compared with CK ($P < 0.05$).

2.3 Changes in Soil Active Organic Carbon Under Different Organic Fertilizer Application Rates Adding medium and trace elements to organic fertilizer increased soil active organic carbon content while decreasing high-activity organic carbon content, though differences were not significant. As shown in [Figure 4: see original paper], active organic carbon fractions across all treatments followed the order: low-activity > medium-activity > high-activity. Both organic fertilizer treatments increased all three active fractions with increasing application rate ($P < 0.05$). At the same rate, OF+ME increased medium-activity organic carbon by 1.98% and low-activity organic carbon by 2.72% compared with OF, while high-activity organic carbon decreased by 1.79%–1.99% (not significant).

2.4 Changes in Particulate Organic Carbon, Mineral-Associated Organic Carbon, and Microbial Biomass Carbon Organic fertilizer with medium and trace elements increased mineral-associated organic carbon (MAOC) and microbial biomass carbon (MBC) while decreasing particulate organic carbon (POC). As shown in [Figure 5: see original paper], POC and MAOC contents increased with fertilizer rate, with MAOC increasing significantly by 13.75% under OF4+ME ($P < 0.05$). MBC content increased significantly by 10.42%–16.67% across all fertilization levels ($P < 0.05$). Compared with OF, OF+ME further increased MBC by 7.95% and MAOC by 5.86% at the same application rate, though POC differences were not significant.

The proportion of SOC fractions changed accordingly: MAOC/SOC increased significantly by 0.51%–6.99%, while POC/SOC decreased by 4.45%–26.18% ($P < 0.05$). MBC/SOC increased by 5.51%–7.20% .

2.5 Changes in Soil Amino Sugars Under Different Organic Fertilizer Application Rates Organic fertilizer with medium and trace elements increased total amino sugars and individual amino monosaccharides. As shown in [Figure 6: see original paper], total amino sugars and all three monosaccharides increased significantly with fertilization ($P < 0.05$). Compared with OF, OF+ME further increased total amino sugars by 3.46%–6.32%, with the most significant increase under OF2+ME (6.32%, $P < 0.05$). Glucosamine increased by 1.21%–13.32% (most significant under OF4+ME, 13.32%, $P < 0.05$), galactosamine by 2.41%-6.14% (most significant under OF3+ME and OF4+ME, 6.14% and 5.12%, respectively, $P < 0.05$), and muramic acid by 3.61%-6.62% (most significant under OF2+ME, 6.62%, $P < 0.05$).

2.6 Contribution of Amino Sugars to Soil Organic Carbon Total amino sugar carbon, bacterial necromass carbon (BNC), fungal necromass carbon (FNC), and microbial necromass carbon (MNC) all increased significantly compared with CK ($P < 0.05$) [Figure 7: see original paper]. Compared with OF, OF+ME further increased total amino sugar carbon by 2.41%-6.14% and MNC by 2.70%-4.99%. The contribution of MNC to SOC increased by 3.81% across treatments, with significant differences observed.

Discussion

3.1 Effects of Medium and Trace Element Addition on Organic Fertilizer Mineralization Under Incubation Conditions Numerous studies have shown that exogenous organic matter type affects mineralization rates. Metal (oxyhydr)oxides are key factors controlling SOC stabilization. In this study, both organic fertilizers exhibited rapid initial decomposition followed by slower decomposition, consistent with findings in red paddy soils under long-term fertilization. This pattern likely reflects a shift in microbial substrate utilization from labile to recalcitrant organic carbon as incubation progresses, resulting in relatively stable mineralization rates. Compared with OF alone, OF+ME alleviated SOC mineralization and increased residual rates, possibly because the added elements supplemented soil nutrients and formed oxides that bound with SOC, inhibiting mineralization. Iron, calcium, zinc, and manganese can inhibit decomposition through adsorption or complexation, affecting SOC turnover and enhancing sequestration.

3.2 Effects of Medium and Trace Element Addition on Active Organic Carbon in Field Trials Incorporating straw and applying organic fertilizer are important measures for increasing SOC. This study found that both organic fertilizers significantly increased SOC and all active organic carbon fractions compared with CK, consistent with previous research in red soils. The more pronounced increase in medium- and low-activity organic carbon under OF+ME may be attributed to the nutrient-rich composition of decomposed sheep manure, which stimulates microbial growth and adds newly decomposed materials to the active carbon pool, thereby improving soil fertility and quality. The enrichment of organic substances also increases cation exchange capacity, enhancing adsorption of element cations. High-activity organic carbon, being readily oxidizable, may adsorb or chelate with medium and trace elements, leading to its decreased content.

3.3 Effects of Medium and Trace Element Addition on Organic Carbon Fractions in Field Trials Adding medium and trace elements to organic fertilizer increased SOC, total amino sugars, individual amino monosaccharides, and microbial necromass carbon. This may occur because organic fertilizer provides nutrients and energy for microbes, altering microbial activity and stimulating metabolism, which promotes necromass accumulation. Medium and trace element inputs further promote microbial necromass accumulation, which can be physically protected by soil aggregates and chemically protected through interactions with iron oxides and minerals, transforming into stable SOC. The increased MAOC/SOC and decreased POC/SOC ratios under OF+ME likely result from enhanced substrate availability and element composition, promoting formation of soil micro-aggregates that increase microbial abundance and diversity, thereby boosting biological activity, growth rates, and microbial product quantities. Fungal necromass carbon contributed more to SOC than bacterial necromass carbon, indicating fungal dominance, possibly because fungal residues decompose slowly and their strong chemical adsorption with soil minerals facilitates long-term SOC retention. The decrease in POC may reflect its lack of physicochemical protection, making it susceptible to microbial decomposition and transformation from particulate to mineral-associated forms.

Conclusions

This study investigated the effects of organic fertilizer with added medium and trace elements on mineralization characteristics and SOC fractions in aeolian sandy soil, yielding the following main conclusions:

1. Adding medium and trace elements to organic fertilizer can reduce mineralization rate of organic fertilizer in aeolian sandy soil and increase soil organic carbon content.

2. The addition increases microbial biomass carbon, glucosamine, galactosamine, muramic acid, microbial necromass carbon content, and the proportion of mineral-associated organic carbon, facilitating complexation of newly formed humus with soil minerals to form stable SOC and promote carbon sequestration.

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