Effects of Bamboo-Tea Intercropping Pattern on Topsoil Organic Carbon Storage and Fractions: Postprint

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Abstract

To investigate the effects of interplanting tea plants under moso bamboo forests on soil organic carbon storage and carbon fractions, this study examined pure moso bamboo forests, bamboo-tea mixed forests, and evergreen broad-leaved forests. Surface soil (0–10 cm) samples were collected from these three forest types to determine soil organic carbon (SOC), carbon fractions, and biotic and abiotic indicators. The results showed that: (1) Understory plant diversity in bamboo-tea mixed forests was significantly lower than in pure moso bamboo forests; however, soil organic carbon density [(22.54\$±2.09)$t\cdot hm^{\{-2\}]andcarbonfractionsshowednosignificantdifferencesfrompurebambooforests(P > 0.05).Mineral - associatedorganiccarbon(}$ 1}], $accountingfor92.66^{\{-1\}], soil16SrRNAabundancerangedfrom[(2.18 5.65)\times 10}$ {10}\$ copies·g^{-1}], carbon fixation gene cbbL abundance ranged from [(0.37~1.10)\$×10^{8}\$ copies · g^{-1}], and soil microbial carbon use efficiency ranged from [0.030~0.28]. However, no significant differences in microbial-related indices were observed among the three forest types (P>0.05). (3) SOC was significantly negatively correlated with soil pH, gravel content, and aboveground litter biomass, and significantly positively correlated with soil clay content, silt content, total nitrogen, C:N ratio, total phosphorus, and ammonium nitrogen content (P<0.05). (4) Regarding different carbon fractions, both particulate organic carbon (POC) and MOC were significantly negatively correlated with soil pH, sand content, and root biomass, and significantly positively correlated with soil water content, clay content, silt content, total nitrogen, C:N ratio, total phosphorus, and ammonium nitrogen content (P<0.05). Based on these findings, conversion to bamboo-tea mixed forests caused a decline in understory vegetation diversity of native pure bamboo forests but did not result in decreased soil carbon storage. Compared with evergreen broad-leaved forests, management practices for moso bamboo need to be improved to enhance its carbon sequestration benefits.

Full Text

Effects of Bamboo-Tea Mixed Model on Surface Soil Organic Carbon Storage and Components

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Abstract: To investigate the effects of interplanting tea trees under Moso bamboo forest on soil organic carbon storage and carbon fractions, this study examined pure Moso bamboo forest, bamboo-tea mixed forest, and evergreen broad-leaved forest. Surface soil (0–10 cm) samples were collected from these three forest types to measure soil organic carbon (SOC), carbon fractions, and biotic and abiotic factors. The results showed that: (1) Understory plant diversity in bamboo-tea mixed forest was significantly lower than in pure bamboo forest, but soil organic carbon density [(22.54\$±2.09)$t \cdot hm^{\{-2\}]andcarbonfractionsshowednosignificantdifferences(P > 0.05).Mineral-associatedorganiccarbon(MOC)inbamboo-teami}$
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Keywords: particulate organic carbon; mineral-associated organic carbon; soil organic carbon density; Moso bamboo forest; bamboo-tea mixed forest

Introduction

With the proposed "carbon neutrality" goal, China will implement more robust policies to reduce carbon emissions and increase carbon sinks over the next 40 years. However, the formulation of effective policies depends on scientific understanding of carbon sequestration and emission reduction. As the largest carbon reservoir on land, soil is considered an effective pathway to achieve carbon neutrality goals through increased soil carbon storage (Yang et al., 2022). The carbon sequestration effects of near-natural afforestation and vegetation restoration have been widely recognized (Dong et al., 2011; Lu et al., 2018), while enhancing soil carbon sequestration benefits in economic forests has become a current research focus (Yang et al., 2021b; Villa et al., 2022).

Moso bamboo (*Phyllostachys edulis*) is a high-value bamboo species widely distributed in mountainous and hilly regions of southern China, accounting for approximately 74% of the national bamboo forest area. Its primary economic value lies in bamboo timber and shoot production (Yang et al., 2020). Due to its importance in economic forest plantations and rapid growth characteristics, the carbon sequestration benefits of Moso bamboo have received considerable attention, with annual aboveground carbon increments reaching (8.13\$±2.15)$Mg \cdot hm$^{-2}\$ (Yen et al., 2011). Current research on Moso bamboo soil carbon pools primarily focuses on two aspects: bamboo invasion and management practices. Compared with evergreen broad-leaved forests, Moso bamboo plantations and invasion often lead to decreased soil carbon storage (Wang et al., 2019; Qi et al., 2021) while causing changes in the content and proportion of particulate organic carbon (POC) and mineral-associated organic carbon (MOC) (Yang et al., 2021b). Different management practices (such as thinning and understory vegetation removal) and mixed models (such as bamboo-Chinese fir mixtures) have varying effects on soil carbon pools in Moso bamboo forests (Qi et al., 2013; Li et al., 2019; Yang et al., 2021a). Yang et al. (2021a) demonstrated in Anji, Zhejiang that extensively managed Moso bamboo forests had higher aggregate stability and organic carbon storage than non-managed and intensively managed forests. The effects of biotic and abiotic factors on Moso bamboo soil carbon pools also vary depending on study region and management practices (Zhang et al., 2019; Yang et al., 2021a).

Currently, the single-income model from Moso bamboo alone can hardly meet farmers' urgent needs for increased income levels. Additionally, the recent downturn in the bamboo processing industry has dampened growers'enthusiasm. Consequently, developing understory economies has become an important measure to increase farmer income and promote sustainable development of the bamboo industry (Cai et al., 2018; Zhang et al., 2019). While focusing on the economic benefits of understory planting in Moso bamboo forests, ecological benefits have also become a research priority, encompassing soil nutrients, microorganisms, and soil and water conservation (Cai et al., 2017; Wang et al., 2020; Cao et al., 2022). Wang et al. (2020) found that low-density Moso bamboo-*Polygonatum* composite models had 13% higher soil organic carbon content than high-density bamboo stands. Cao et al. (2022) reported that soil microbial diversity in Moso bamboo-*Bletilla striata* composite systems gradually increased with intercropping duration. However, research on the ecological benefits of understory composite management in Moso bamboo forests remains limited, with most studies focusing on bamboo-medicinal herb combinations while lacking investigation of the carbon source/sink effects of bamboo-tea composite management. The bamboo-tea planting model represents another important understory economic initiative for enhancing Moso bamboo economic benefits, particularly in bamboo-producing regions with characteristic tea resources. Investigating soil carbon pool changes under bamboo-tea mixed models is crucial for improving understanding of the ecological benefits of this transformation approach and promoting synergistic enhancement of economic and ecological benefits in Moso bamboo forest management.

Currently, research on the effects of bamboo-tea mixed transformation on soil carbon storage and carbon fractions in Moso bamboo forests is relatively scarce. Therefore, this study examined pure Moso bamboo forest, bamboo-tea mixed forest, and natural evergreen broad-leaved forest in the Mao’ er Mountain region of Guangxi to explore the impacts of bamboo-tea mixed models on soil carbon storage in Moso bamboo forests, analyze POC and MOC contents and their proportional changes, and reveal key factors influencing soil carbon storage and fraction variations. Based on assessments of soil carbon storage and fractions, our findings will provide theoretical foundations and technical support for improving understory bamboo-tea transformation in Moso bamboo forests.

1.1 Study Area Overview

The study area is located in Huajiang Yao Autonomous Township, Guilin City, Guangxi (110°27 E, 25°48 N), at an elevation of 300–500 m. The region features a mid-subtropical mountain climate with an average annual temperature of 16.40 °C and annual precipitation exceeding 2,100 mm. The parent material is primarily granite weathering products, with soils dominated by red and yellow soils. Huajiang Yao Autonomous Township is one of China’ s ten major Moso bamboo production bases, with approximately $(1.53\$\times10^{\{4\})hm}\{2\}\$$ of Moso bamboo forest that continues to expand annually. The area is rich in wild medicinal plants and wild tea resources (Yi et al., 2012). In the context of rural revitalization, local communities are undertaking transformation of pure Moso bamboo forests through bamboo-tea composite management based on characteristic tea resources to enhance bamboo economic benefits.

1.2.1 Sample Plot Establishment

This study established three forest type plots: pure bamboo forest (PBF), bamboo-tea mixed forest (BMF), and natural evergreen broad-leaved forest (EBF). Six replicate quadrats (20 m × 20 m) with similar site conditions were established for each forest type, and community surveys were conducted. Evergreen broad-leaved forests were located at the same elevation as Moso bamboo forests. Plots of different forest types were spaced at least 1,000 m apart, with replicate quadrats at least 500 m apart. Selected pure bamboo forest plots had been monoculturally planted with Moso bamboo and underwent periodic thinning and understory vegetation removal annually. Bamboo-tea mixed forest plots had a single-species Moso bamboo canopy layer with annual bamboo thinning; understory tea trees were naturally occurring wild tea without artificial management, though tea leaves were harvested each spring, and tea trees were retained due to their economic value. This naturally occurring bamboo-tea mixed forest served as a reference for pure bamboo forest transformation. Basic information for the three forest type plots is described in Table 1 .

Table 1 Basic information of sample plots

Layer	Forest Type	Simpson Index	DBH (cm)	Density (hm^{-2})	Main Plant Species
Tree layer	Bamboo-tea mixed forest	$±$0.15	$±$0.066b	$±$1.58a	*Phyllostachys edulis*
	Evergreen broad-leaved forest	$±$0.17c	$±$0.085a	$±$2,215.00	*Machilus nanmu*, *Lindera megaphylla*, *Cinnamomum cassia*
Shrub layer	Bamboo-tea mixed forest	$±$0.051a	-	$±$1,518.00a	*Mussaenda pubescens*, *Maesa japonica*, *Mallotus apelta*, *Camellia sinensis*
	Evergreen broad-leaved forest	$±$0.065a	-	$±$354.00c	*Croton tiglium*, *Ilex pubescens*, *Machilus nanmu*
Herbaceous layer	Bamboo-tea mixed forest	-	-	-	*Trachelospermum jasminoides*, *Lophatherum gracile*

Layer	Forest Type	Simpson Index	DBH (cm)	Density (hm^{-2})	Main Plant Species
	Evergreen broad-leaved forest	-	-	-	*Parathelypteris glanduligera*, *Arthraxon hispidus*, *Cibotium barometz*, *Lygodium japonicum*, *Woodwardia japonica*

Note: Different letters indicate significant differences between forest types within the same layer (P<0.05). Data are mean±standard deviation (n=6).

1.2.2 Plot Survey and Sample Collection

Plot surveys and sampling were conducted in November 2021. Survey content included elevation, slope, aspect, plant composition, and management practices. Tree and shrub surveys employed complete enumeration, while herbaceous plants were surveyed using small quadrat methods. Soil samples were collected using soil augers to obtain five 0–10 cm subsamples randomly within each quadrat, which were then mixed to form one composite sample per plot. Concurrently, soil bulk density was measured using the ring knife method, and soil water content was determined using aluminum boxes near each sampling point. Aboveground litter was collected from five randomly placed 50 cm × 50 cm sub-quadrats, and 0–10 cm layer soil roots were collected from five 20 cm × 20 cm sub-quadrats. Collected soil samples were brought to the laboratory, with portions air-dried, portions stored at 4 °C for fresh soil experiments, and portions stored at -80 °C for microbial DNA extraction.

1.2.3 Determination of Soil Physicochemical Properties and Microbial Carbon Metabolism Indicators

Soil total carbon and total nitrogen contents were determined using a carbon-nitrogen elemental analyzer (Elementar Vario EL III, Germany). Soil bulk density was measured using the ring knife method. Soil pH was determined using the potentiometric method (water:soil ratio of 2.5:1). Total phosphorus (TP) content was measured using the molybdenum-antimony-scandium colorimetric method. Available phosphorus (AP) was extracted using 1/2 sulfuric acid digestion followed by molybdenum-antimony colorimetric determination. Ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) contents were extracted with 2 mol/L KCl solution and analyzed using a SKALAR SAN++ continuous flow analyzer. Soil mechanical composition was determined using the hydrometer method: 50 g air-dried soil mixed with dispersant was boiled, filtered into a 1,000 mL settling cylinder, and measured using a hydrometer. The international system was used to classify soil mechanical composition into gravel, silt, and clay fractions. Soil organic carbon content was determined using the concentrated sulfuric acid-potassium dichromate high-temperature external heating oxidation method. Aboveground litter and root biomass were measured using the drying method. Sodium hexametaphosphate dispersion was used to separate particulate and mineral-associated organic carbon. Specifically, air-dried soil samples were mixed with 0.5% sodium hexametaphosphate solution (soil:solution ratio 1:3) and glass beads, then oscillated for full dispersion. A 53 m sieve was used to separate mineral-associated organic matter (<53 m) and particulate organic matter (>53 m). Separated fractions were washed with deionized water and dried at 60 °C for measurement. Soil organic carbon density (SOCD) was calculated using soil layer thickness, bulk density, and other physicochemical properties according to Equation 1:

$$SOCD = SOC \times \rho \times D \times 10 \quad \text{(Equation 1)}$$

where SOC is the average soil organic carbon content $(\mathrm{g \cdot kg^{-1}})$, D is soil layer thickness (cm), and is soil bulk density $(\mathrm{g \cdot cm^{-3}})$.

Soil microbial biomass carbon was determined using the chloroform fumigation method (Wang et al., 2022). 16S rRNA and cbbL genes were quantified using qPCR with primer sequences F515/R907 and K2f/V2f, respectively (Qin et al., 2020). Microbial carbon use efficiency (CUE) was determined using H_2-labeled soil samples following the method of Zheng et al. (2019).

1.2.4 Data Processing and Analysis

Data were organized and analyzed using Excel 2016, SPSS 25, and Origin 2021. One-way ANOVA was used to analyze significant differences among treatment groups. Pearson correlation analysis was employed to examine relationships between variables, and stepwise multiple linear regression models were used to reveal the effects of soil physicochemical and microbial indicators on soil organic carbon. The significance level for all statistics was set at $P<0.05$.

2.1 Differences in Soil Physicochemical Properties Among Forest Types

Significant differences ($P<0.05$) were observed among the three forest types in soil pH, clay and sand contents, total phosphorus, and nitrate nitrogen content. All three forest types had acidic soils, with bamboo-tea mixed forest showing the highest pH. Pure bamboo forest had the lowest soil water content and significantly higher sand content than the other two forest types ($P<0.05$), while its soil nutrient contents (including total phosphorus and nitrate nitrogen) were lower than those of bamboo-tea mixed forest and evergreen broad-leaved forest.

No significant differences were found in root biomass, C:N ratio, total nitrogen, and ammonium nitrogen content between bamboo-tea mixed forest and pure bamboo forest, but both differed significantly from evergreen broad-leaved forest (P<0.05). Root biomass in the former two was significantly higher than in evergreen broad-leaved forest, while other indicators were significantly lower (P<0.05) (Table 2).

Table 2 Soil physicochemical properties of different stand types in the study area

<table>
<tr><th>Index</th><th>Pure Bamboo Forest</th><th>Bamboo-Tea Mixed Forest</th><th>Evergreen Broad-Leaved Forest</th></tr>
<tr><td>Soil pH</td><td colspan="3">4.56$±0.079b|4.68±0.048a|4.28±0.053c||Soilwatercontent(±2.36b|40.44±1.83a|40.65±3.59a||Claypro Nratio|10.21±0.69b|9.42±0.34b|11.64±1.16a||Soiltotalphosphorus(g· kg{-1})|0.15±0.0088c|0.21±0.043b|0.33±0.049a||Soilnitratenitrogen(mg · kg{- 1})|7.48±1.15c|27.88±10.79a|18.14±4.69b||Soilammoniumnitrogen(mg· kg{-1})|1.77±0.77b|1.40±0.14b|5.78±2.13a||Soilavailablephosphorus(mg · kg{- 1})|0.46±0.31a|0.55±0.36a|0.55±0.28a||Abovegroundlitter(kg· m{-2})|1.73±0.17a|2.15±0.74a|1.42±0.33a||Rootbiomass(kg · m{- 2})|0.75±0.24a|0.76±0.14a|0.37±$0.079b</td></tr>
</table>

Note: Different letters indicate significant differences between forest types within the same layer (P<0.05). Data are mean±standard deviation (n=6).

2.2 Characteristics of SOC and SOCD Changes Among Forest Types

Surface SOC in bamboo-tea mixed forest was (22.95$±1.91)g·kg{-1}, showingnosignificantdifferencefrompurebamboofo 1}$ (P<0.05). SOCD across the three forest types ranged from (19.65-44.09) $t \cdot hm^{-2}$. Specifically, surface SOCD in bamboo-tea mixed forest and pure bamboo forest was (22.54$±2.09)t · hm^{-2}$ and (22.60$±2.53)t · hm{-2}, respectively, bothsignificantlylowerthanevergreenbroad − leavedforest(38.31±5.40)t · hm{- 2}$ (P<0.05) (Figure 1 [Figure 1: see original paper]).

Error bars represent standard deviations; different letters indicate significant differences between forest types (P<0.05). The same applies below.

Figure 1 Variation characteristics of SOC (A) and SOCD (B) in different forest types

Soils in all three forest types were dominated by mineral-associated organic carbon, with MOC ranging from (17.98-36.83) $g \cdot kg^{-1}$ and contributing 90.19%-94.40% to SOC; the remaining contribution came from POC. No significant differences in POC and MOC contributions to SOC were observed among forest types (P>0.05). Correlation analysis (Table 3) revealed that SOC was extremely significantly positively correlated with POC and MOC, with correlation coefficients of 0.95 and 0.97, respectively (P<0.05). Evergreen broad-leaved forest had soil POC and MOC of (3.14$±0.42)$g \cdot kg^{-1}$ and (32.09$±3.54)$g \cdot kg^{\text{-1}, respectively, both significantly higher than pure bamboo forest and bamboo-tea mixed forest} (P < 0.05). Bamboo-tea mixed forest$ 1}$ and (20.13$±1.83)$g \cdot kg^{-1}$, respectively, showing no significant differences from pure bamboo forest (P>0.05) (Figure 2 [Figure 2: see original paper]).

Figure 2 Variation characteristics of POC (A) and MOC (B) in different forest types

Table 3 Correlation between SOC and MBC, POC, and MOC

Type	Correlation Coefficient
SOC-POC	0.95**
SOC-MOC	0.97**

Note: and ** indicate significant correlations at the 0.05 and 0.01 levels, respectively.*

Soil microbial biomass carbon across the three forest types ranged from (0.58–3.08) g · kg^{-1} and showed no significant correlation with SOC (P>0.05) (Table 3). No significant differences in microbial biomass carbon content were observed among forest types (P>0.05), with bamboo-tea mixed forest having (1.47$±0.34)$g \cdot kg^{\text{-1}. 16S rRNA gene abundance in bamboo-tea mixed forest averaged} (3.91 \times 10$ {10})$copies \cdot g^{\text{-1}, while cbbL gene abundance was} (0.76 \times 10$ {8})$copies \cdot g^{-1}$, accounting for 0.21% of total bacterial abundance. No significant differences in 16S rRNA and cbbL gene abundances were found among bamboo-tea mixed forest, pure bamboo forest, and evergreen broad-leaved forest (P>0.05). Microbial carbon use efficiency across the three forest types ranged from 0.030–0.28, with no significant differences observed (P>0.05) (Table 4).

Table 4 Changes in microbial carbon metabolism processes in different forest types

Index	Pure Bamboo Forest	Bamboo-Tea Mixed Forest	Evergreen Broad-Leaved Forest
Microbial biomass carbon (g · kg^{-1})	1.54$±0.82a\|1.47±[illegible] copies · g^{-1})	[illegible] copies · g^{-1})	[illegible] cbbL : 16SrRNAratio|0.17±0.048a|0.21±0.074a|0.17±$0.067a

Note: Different letters indicate significant differences between forest types (P<0.05).

2.5 Correlations Between Organic Carbon Fractions and Environmental Factors

Correlation analysis (Table 5) revealed that SOC was significantly negatively correlated with soil pH, gravel content, and aboveground litter biomass, and significantly positively correlated with soil clay content, silt content, total nitrogen, C:N ratio, total phosphorus, and ammonium nitrogen content ($P<0.05$). Regarding different carbon fractions, both POC and MOC were significantly negatively correlated with soil pH, sand content, and root biomass, and significantly positively correlated with soil water content, clay content, silt content, total nitrogen, C:N ratio, total phosphorus, and ammonium nitrogen content ($P<0.05$) (Table 5). Multiple linear regression analysis showed that soil total nitrogen content and C:N ratio were key factors predicting soil carbon density, explaining 97% of soil carbon density variation (Equation 2):

$$y = -22.12 + 11.66N + 1.81C/N \quad (R^2 = 0.97, P < 0.01) \quad \text{(Equation 2)}$$

where y is soil carbon density ($\mathrm{t \cdot hm^{-2}}$), N is total nitrogen content ($\mathrm{g \cdot kg^{-1}}$), and C/N is the carbon-to-nitrogen mass ratio.

Table 5 Correlations between SOC, POC, MOC and soil physicochemical indexes of different stand types

Index	SOC	POC	MOC
Soil pH	-0.83**	-0.85**	-0.85**
Soil water content (%)	0.84**	0.75**	0.49*
Clay proportion (%)	0.85**	0.78**	0.49*
Silt proportion (%)	0.88**	0.76**	0.85**
Sand proportion (%)	-0.86**	-0.88**	-0.89**
Soil total nitrogen (%)	0.96**	0.89**	0.80**
C:N ratio	0.83**	0.74**	0.95**
Soil total phosphorus ($\mathrm{g \cdot kg^{-1}}$)	0.86**	0.95**	0.79**
Soil nitrate nitrogen ($\mathrm{mg \cdot kg^{-1}}$)	0.80**	0.87**	0.81**
Soil ammonium nitrogen ($\mathrm{mg \cdot kg^{-1}}$)	0.96**	0.83**	0.86**
Soil available phosphorus ($\mathrm{mg \cdot kg^{-1}}$)	0.13$±0.0\|0.11±0.0\|0.14±0.\|\|Abovegroundlitter(kg· m{-2})\|−0.70∗∗\|−0.73∗∗\|−0.71∗∗\|\|Rootbiomass(kg·m{-2}$)		

Note: and ** indicate significant correlations at the 0.05 and 0.01 levels, respectively.*

3.1 Effects of Moso Bamboo Forest Transformation on Soil Carbon Storage and Fractions

In the study area, long-term transformation of pure Moso bamboo forest to bamboo-tea mixed model did not cause decreased soil organic carbon storage, although the transformation resulted in loss of understory shrub layer diversity. The results showed no significant difference in SOCD between pure bamboo forest and bamboo-tea mixed forest. Previous studies on tree species and understory vegetation diversity mostly indicated positive correlations between species diversity and soil carbon storage (Zhao et al., 2014; Chen et al., 2020). This discrepancy may be attributed to carbon cycling in both pure bamboo forest and bamboo-tea mixed forest being dominated by Moso bamboo. Both forest types have only Moso bamboo in the canopy layer, and Moso bamboo's well-developed root system occupies the surface soil, influencing soil organic carbon and nutrient cycling. Research has shown that fine root biomass in Moso bamboo forests is 5.86 times that of evergreen broad-leaved forests (Liu et al., 2013). Although bamboo-tea transformation reduced Moso bamboo stand density by approximately 20%, no significant difference in surface soil root biomass was observed between the two forest types (Tables 1, 2). The underground space created by bamboo-tea transformation was rapidly occupied by other Moso bamboo roots. Additionally, growers clear understory vegetation during bamboo harvesting, and this periodic renewal also weakens plant-derived SOC input and accumulation in pure bamboo forests. Li et al. (2019) found no significant difference in SOC between Moso bamboo forests with understory vegetation removal and control plots after two years. Under the dominant position of Moso bamboo and current management practices, bamboo-tea mixed transformation has limited impact on surface soil carbon storage in pure bamboo forests.

Although understory transformation of Moso bamboo forests does not reduce soil carbon storage, this planting model is not conducive to SOC sequestration. This study revealed that SOCD in pure bamboo forest and bamboo-tea mixed forest was 41.15% and 41.00% lower, respectively, than in evergreen broad-leaved forest ($P<0.05$). This indicates that converting evergreen broad-leaved forest to pure bamboo forest or bamboo-tea mixed forest causes soil carbon storage loss, consistent with findings from other regions (Lin et al., 2018; Wang et al., 2019; Qi et al., 2021). Lin et al. (2018) demonstrated that converting natural evergreen broad-leaved forest to intensively managed Moso bamboo plantations reduced soil carbon storage in the 0–40 cm layer by 12%. Differences in Moso bamboo management practices, tree layer species composition, and resulting soil physicochemical properties are the main reasons for soil carbon storage differences among pure bamboo forest, bamboo-tea mixed forest, and evergreen broad-leaved forest. Therefore, exploring methods to increase soil organic carbon storage during bamboo-tea mixed transformation is essential.

This study also indicates that bamboo-tea mixed transformation does not cause significant changes in soil organic carbon fraction contents or proportions. All three forest types were dominated by mineral-associated organic carbon, with

MOC accounting for over 90% of total organic carbon. This suggests that soil organic carbon pools in these forests are dominated by stable carbon but also indicates that POC is difficult to retain. Plants annually release carbon sources to soil through above- and belowground litter and root exudates, which are decomposed into POC. However, POC proportion is minimal across all three forest types, indicating that most newly input carbon cannot be immediately transformed into stable MOC and is likely lost. POC loss may be caused by abundant rainfall in the region. Heavy precipitation can wash away plant litter, reducing its potential for in-situ transformation into POC, while also removing unstable POC through runoff. Dong et al. (2020) similarly found that POC accounted for only 1.26%-14.44% of total organic carbon in evergreen broad-leaved forests at similar elevations in Mao' er Mountain. Therefore, carbon tracing studies are necessary in this region to reveal carbon transformation and fate.

3.2 Main Factors Influencing Soil Organic Carbon and Its Component Changes

Soil organic carbon transformation and accumulation are closely related to biotic and abiotic factors. In this study, soil organic carbon and its fractions were extremely significantly positively correlated with total nitrogen, C:N ratio, total phosphorus, and ammonium nitrogen content ($P<0.01$). Regression analysis identified total nitrogen as the most critical factor affecting organic carbon and its fractions. Microbial growth requires nitrogen sources, and when nitrogen is deficient, microbes degrade litter and organic matter to obtain nitrogen, leading to decreased organic carbon content (Frey et al., 2014; Lu et al., 2021). Therefore, adequate nitrogen sources facilitate SOC accumulation. Several studies have similarly found positive correlations between soil total nitrogen and inorganic nitrogen contents and organic carbon content (Li, 2010; Yang et al., 2021b). Li (2010) found that soil total nitrogen was the most important factor affecting soil organic carbon variation in Moso bamboo forests in Jiangxi' s Dagang Mountain, with a positive correlation between them. Therefore, appropriate nitrogen fertilization could be applied in Moso bamboo management to alter the phenomenon of low soil organic carbon and enhance soil carbon sequestration capacity.

Overall, SOC and its fractions were extremely significantly negatively correlated with soil pH across the three forest types ($P<0.01$), indicating that lower pH favors soil organic carbon accumulation. Soil pH affects organic carbon decomposition and transformation by influencing microbial community structure and activity. Both excessively high and low pH are unfavorable for microbial growth and activity, thereby inhibiting organic carbon decomposition and transformation (Zhang et al., 2019). Zhang et al. (2019) observed the same phenomenon in their study of soil organic carbon characteristics and influencing factors along altitudinal gradients in Wuyi Mountain Moso bamboo forests. This study also found extremely significant positive correlations between SOC and its fractions and soil clay and silt contents (P<0.01), primarily because silt and clay protect SOC, reducing carbon mineralization and loss (Lehmann et al., 2015; Kasmerchak et al., 2018). However, bamboo-tea mixed forest had higher clay and silt contents than pure bamboo forest without significant differences in SOCD, suggesting that clay and silt contents may need to reach a certain threshold to affect organic carbon accumulation, or that other key factors offset the contribution of clay and silt to organic carbon accumulation in bamboo-tea mixed forest. Understory tea planting in Moso bamboo forests can at least improve soil mechanical composition, moving it in a direction favorable for organic carbon accumulation.

Soil microorganisms are key factors affecting soil carbon cycling, participating in both SOC accumulation and decomposition. However, analysis of soil microbial biomass carbon content, carbon fixation gene abundance, and carbon use efficiency indicators showed that microbial activity was not the decisive factor affecting soil organic carbon storage variation in this study area. Some studies have similarly found no significant differences in soil microbial biomass between Moso bamboo forests and evergreen broad-leaved forests (Wang et al., 2020). Furthermore, Bai et al. (2016) found that Moso bamboo invasion into broad-leaved forests caused SOC storage decline but increased microbial biomass carbon. Therefore, dynamic and multi-seasonal studies are needed to reveal microbial impacts on soil carbon pools.

Conclusion

This study demonstrates that compared with pure Moso bamboo forest, understory tea planting in Moso bamboo forests significantly increases soil pH, water content, clay and silt contents, total phosphorus, and nitrate nitrogen content. Tea planting in Moso bamboo forests reduces understory shrub layer plant diversity but does not decrease soil organic carbon density or alter organic carbon fraction proportions. Soil organic carbon storage in both pure bamboo forest and bamboo-tea mixed forest is significantly lower than in evergreen broad-leaved forest. Carbon fractions in all three forest types are dominated by mineral-associated organic carbon. Therefore, current management practices for pure bamboo forest and bamboo-tea mixed forest need improvement to promote synergistic development of economic and carbon sequestration benefits. Additionally, this study reflects ecological benefits from the perspective of soil carbon sequestration, which has both representativeness and limitations. Future research should conduct more comprehensive ecological benefit assessments to reveal the impacts of bamboo-tea transformation on ecosystem functions in pure Moso bamboo forests, thereby providing scientific foundations and guidance for bamboo-tea transformation models.

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