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Organic carbon content and mineralization characteristics of soil in a subtropical *Pinus massoniana* forest

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ABSTRACT

Soils were collected from a broad leaf-Pinus massoniana mixed forest, a Chinese fir (Cunninghamialan ceolata)-Pinus massoniana mixed forest, and a pure Pinus massoniana subtropical forest for subsequent analyses to compare characteristics of soil organic carbon and microbial biomass carbon content. Soil organic carbon mineralization characteristics were further modeled using a double exponential equation. The soil organic carbon and active carbon content displayed obvious surface accumulation and decreased with increasing soil depth in all three forest types. Soil microbial carbon in the two mixed forests was primarily concentrated at depths of 0-20 cm, and significant differences were found between the topsoil and subsoil. However, soil microbial carbon in the pure forest exhibited a gradual vertical change without significant differences between soil layers. Soil organic carbon mineralization characteristics in each layer could be well represented using a double exponential equation, with similar fitting results displaying a strong initial reaction intensity followed by a gradual decrease at later stages in all three forest types. Soil organic carbon mineralization reactions at depths of 0-10 cm were always strong due to high levels of soil organic carbon, active carbon content, and greater microbial activity; however, there were no significant differences among layers below 10 cm. More intensive soil organic carbon mineralization processes were observed in mixed forests compared with the pure forest.

Key words: *Pinus massoniana* forests; soil organic carbon; mineralization process; double exponential equation

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INTRODUCTION

The study of mineralization processes involves effectively learning about and understanding the characteristics and transformations of organic soil carbon. Certain scholars have used this perspective as a basis for many relevant studies[1-13]. For example, Ribeiro *et al.* studied the effects of organic fertilizers on the mineralization kinetics of soil organic carbon[1]. C. Tarnocai *et al*. have put forward a new carbon cool estimates that based on the research of the permafrost area soil carbon cool[2].Van Hemelryck *et al.* assessed the impact of soil redistribution on the mineralization of soil organic carbon[3]. Arevalo *et al.* conducted research addressing the mineralization potential and temperature sensitivity of soil organic carbon under different land use patterns[4]. Weng *et al.* studied the effects of the application of nitrogen fertilizers on soil organic carbon mineralization in citrus orchards[5]. To better understand the characteristics of soil organic carbon mineralization, various types of equations, such as exponential, double exponential, exponential-plus-linear, exponential-plus-constant, and hyperbolic equations, have been introduced into studies of soil organic carbon mineralization processes. For example, Paul *et al.* fitted single exponential, double exponential, and exponential-linear equations to the mineralization processes of soil active carbon and assessed the fitting results[6]. Similarly, Alvarez *et al*. evaluated the results obtained from fitting various types of equations, including single exponential, double exponential, exponential-constant, and exponential-linear equations, to soil organic carbon mineralization processes in regions subjected to different management and tillage

practices[7]. In addition, Yang *et al*. used a double exponential model to predict dynamic variations in soil organic carbon mineralization in different Chinese forest belts[8].

China has 8,676,500 hectares of natural *Pinus massoniana* forest, which represents 7.51% of the total area of natural forests in China[14]. These natural *P. massoniana* forests are not only important forest resources but also an important contributor to the forest soil carbon cycle. To date, few studies have examined soil organic carbon mineralization processes in natural *P. massoniana* forests. In this study, soil from a broadleaf-*P.massoniana* mixed forest, a Chinese fir (*Cunninghamialanceolata*)-*P. massoniana* mixed forest, and a pure *P. massoniana* forest were examined. Based on analyses and comparisons of the organic carbon content characteristics of these soils, double exponential equations were utilized to further describe soil organic carbon mineralization processes, thereby providing a theoretical basis for future in-depth studies of decomposition and transformation processes of soil organic carbon in *P. massoniana* forests.

EXPERIMENTAL SECTION

2.1 Overview of study areas

The study areas for this investigation were located at the following sites in Jiangxi Province: the Dagang Mountain National Forest Ecosystem Research Station in Fenyi County (27°30'-27 °50' N, 114°30'-114°40' E), Gannan Arboretum in Shangyou County (25°5'-25°51' N, 114°02'-114°04' E), and the Changling Forest Farm in Xiajiang County (27°27'-27°45' N, 114°53'-115°31' E). These sites, which have Kandiudult , experience a subtropical humid monsoon climate with an annual average temperature of 16.8°C-18.5°C and annual precipitation of approximately 1500 mm.

2.2 Sample plots

A broadleaf -*P. massoniana* mixed forest, a Chinese fir-*P. massoniana* mixed forest, and a pure *P.massoniana* forest in representative regions of the three study areas were selected for examination in this study. Nine sample plots were established; a basic overview of these plots is provided in Table 1.

Table 1 General characteristicS of the experimental sites

Study area	Forest type	Average elevation (m)	Slope (°)	Average diameter at breast height (cm)	Average tree height (m)	Canopy density (%)
I	Broadleaf-pine mixed forest	260	34	27	20	67
II	Fir-pine mixed forest	260	25	22	25	70
III	Pure*Pinus massoniana* forest	67	5	18	20	70

Other species and major understory vegetation:

Broadleaf-pine mixed forest: *Loropetalum chinensis*(R. Br.) Oliv, *Symplocos caudata*, *Eurya matsudai* Hayata, *Castanopsisrargesn*, *Machiluspauhoi* Kaneh, *Camellia oleifera* Abel, *Cyclobalanopsis glauca*(Thunb.) Oerst, and *Schima superba*, among other species.

Fir-pine mixed forest: *Cunninghamia lanceolata*, *Mytilarialaosensis*(Hamamelidaceae), *Daphniphyllum calycinum* Benth, and *Ficus simplicissima* Lour. var. hirta (Vahl.) Migo, among other species.
Pure *P. massoniana* forest: *Elatostemamacintyrei* Dunn, Radix Linderae, *Quercusfabri* Hance, *Viburnum dilatatum* Thunb, and *Adinandra millettii* (Hook. Et Arn) Benth. Et Hook. F, among other species.

Note: Study areas I, II, and III were located in Fenyi County, Shangyou County, and Xiajiang County, respectively. Throughout the paper, broadleaf-pine mixed forest refers to a broadleaf-P. massoniana mixed forest; fir-pine mixed forest refers to a C. lanceolata-P. massoniana mixed forest; pure forest refers to a pure P. massoniana forest; and the metrics of average diameter at breast height and tree height refer to measurements of P. massoniana.

2.3 Sample collection and analysis

2.3.1 Sample collection

Three 20 m × 20 m sample plots were established at each sampling site. Five soil profiles were excavated using an S-shaped sampling approach, and composite soil samples were collected from depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, and 60-100 cm. Samples were air dried and sieved in accordance with the procedures outlined in "Forest soil analysis methods"[15] and used for the determination of soil organic carbon content and CO_2 emissions during the mineralization process. Other fresh soil samples were stored at -4°C for determination of microbial carbon content.

2.3.2 Determination methods

The soil organic carbon content was determined by the volumetric addition of potassium dichromate followed by external heating[16]. The microbial carbon content was determined using the chloroform fumigation-extraction method[17]. CO_2 emissions during soil organic carbon mineralization processes were determined by the alkaline solution absorption approach, using samples incubated indoors at a constant temperature for 100 days[18].

2.4 The fitted equation for soil organic carbon mineralization processes

The Boyle and Paul double exponential model [19] may be expressed as follows:

$$C_{min} = Co(1-e^{-kot}) + C_S(1-e^{-kst})$$

where C_{min} is the quantity of CO_2 emitted by the soil after a time t ($g \cdot kg^{-1}$); Co is the active organic carbon content of soil ($g \cdot kg^{-1}$); k_o is the turnover rate of the active organic carbon pool (d^{-1}); C_S is the slow-release organic carbon content of the soil ($g \cdot kg^{-1}$); and k_s is the turnover rate for slow-release organic carbon (d^{-1}).

2.5 Data processing

The SPSS 17.0 software package (SPSS Inc., Chicago, IL, USA) was used to conduct analyses of variance on the experimental data, and the Origin 8.6 software package (Origin Lab Corp., Northampton, MA, USA) was used for the fitting of equations describing soil organic carbon mineralization processes.

RESULTS AND ANALYSIS

3.1 Characteristics of changes in soil organic carbon content

The organic carbon content of soils from *P. massoniana* forests tended to decrease as the soil depth increased, with a marked enrichment in the organic carbon content in the top soil layers. Specifically, the organic carbon content of the 0-10 cm soil samples ranged from 19.0-33.6 $g \cdot kg^{-1}$, which was approximately twice the organic carbon content of the 10-20 cm soil samples; this difference was significant at the 0.05 level. A certain degree of organic carbon enrichment was also observed in the 10-20 cm soil samples, which had significantly greater organic carbon content than subsoil samples (Table 2).

There was large vertical variation in the organic carbon content in all three types of forests, with coefficients of variation of 69.97%, 70.79% and 108.82% in broadleaf-pine mixed forests, fir-pine mixed forests and pure pine forests, respectively. Although variability in the organic carbon content within the same soil layer was observed, this variation was of relatively small magnitude, with coefficients of variation ranging from 27.34-38.32% (Table 2).

The organic carbon content of the 0-20 cm soil samples was higher in the two types of mixed forests than in the pure forest (Figure 1), indicating that more concentrated enrichment of organic carbon occurred in the mixed forests. However, different patterns were observed for soil layers below 20 cm. In these layers, the organic carbon content of soils in the broadleaf-pine mixed forest remained at a relatively high level, whereas there were no significant differences between pine-fir mixed forest and pure forest soil samples with respect to organic carbon content.

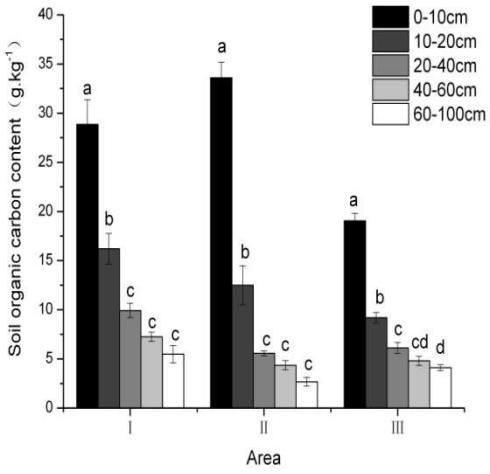

Figure 1 Soil organic carbon content of the different forest types

Table 2 Soil organic carbon content (g·kg^{-1}) and coefficients of variation

Soil depth (cm)	Broadleaf-pine mixed forest	Fir-pine mixed forest	Pure forest	Coefficient of variation (%)
0-10	28.8±4.33aA	33.6±2.72aA	19.0±1.33aB	27.34
10-20	16.2±2.69bA	12.5±3.45bA	7.11±0.91bB	38.32
20-40	9.93±1.28cA	5.57±0.42cB	6.11±0.98cB	33.00
40-60	7.25±0.82cA	4.36±0.82cB	4.8±0.80cdB	28.47
60-100	5.49±1.50cA	2.68±0.78cB	4.1±0.53dAB	34.30
Coefficient of variation (%)	69.97	108.82	70.79	

3.2 Variation in soil microbial carbon content

Soil samples from all three forest types exhibited decreases in the microbial carbon content as the soil depth increased, although the variation in microbial carbon content differed for the different forest types. In the broadleaf-pine mixed forest, the soil microbial carbon content was primarily concentrated in the 0-20 cm soil layers, which exhibited significantly greater microbial carbon content than subsoil layers. In the fir-pine mixed forest, the soil microbial carbon content varied greatly among layers, with significant differences between the 0-10 cm, 10-20 cm, 20-40 cm, and >40 cm soil layers. In the pure forest, the soil microbial carbon content exhibited a gradual vertical gradation, with no significant differences in microbial carbon content between adjacent soil layers (Table 3). The greatest vertical variation in soil microbial carbon content was observed in the broadleaf-pine mixed forest, with a coefficient of variation of 42.75%, followed by the fir-pine mixed forest (32.26%) and the pure forest (29.84%). For all three forest types, these vertical coefficients of variation were greater than the coefficients of variation within the same soil layer (7.15-29.29%) (Table 3).

Table 3 Soil microbial carbon content (g·kg^{-1}) and coefficients of variation

Soil depth (cm)	Broadleaf-pine mixed forest	Fir-pine mixed forest	Pure forest	Coefficient of variation (%)
0-10	0.69±0.27aA	0.52±0.03aA	0.38±0.15aB	29.29
10-20	0.48±0.16aA	0.47±0.01bA	0.38±0.05aA	12.42
20-40	0.38±0.06bA	0.39±0.02cA	0.34±0.08abA	7.15
40-60	0.28±0.08bA	0.27±0.01dA	0.21±0.04bA	14.94
60-100	0.25±0.01bA	0.24±0.03dA	0.20±0.06bA	11.50
Coefficient of variation (%)	42.75	32.26	29.84	

3.3 Soil organic carbon mineralization characteristics

The double exponential equation fit the measured data well, with correlation coefficients (R^2) as high as 0.96-1.00. Thus, soil organic carbon mineralization processes in the examined *P. massoniana* forests could be well described by the examined equations (Figure 2, Table 4).

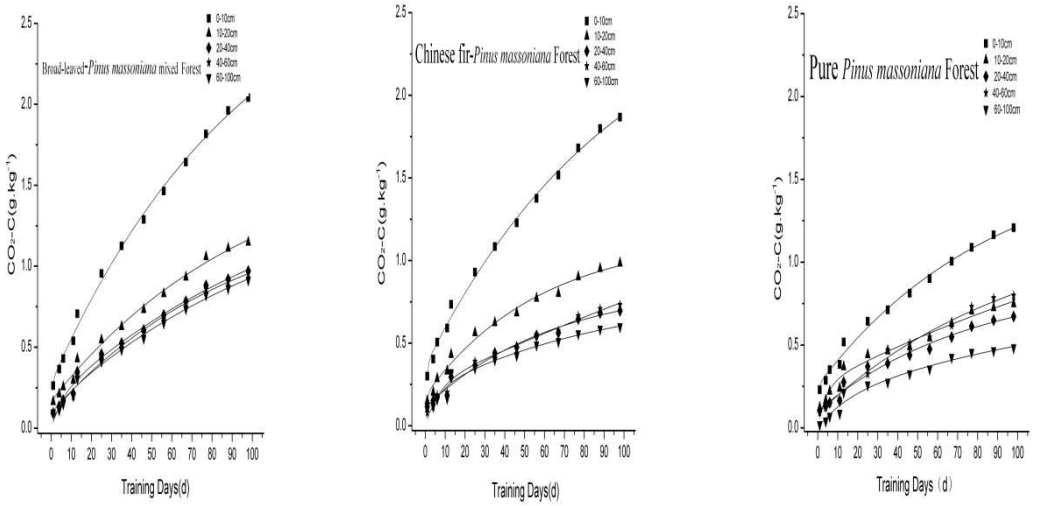

Figure 2 Double exponential equation curves fit to soil organic carbon mineralization data

In the three types of forests, soil organic carbon mineralization in the examined soil layers exhibited the same trend, with a rapid increase in cumulative CO_2-C emissions during initial reaction stages that gradually leveled off at later stages, when the magnitude of increases in cumulative emissions declined (Figure 2). The fitting results demonstrated that the soil active carbon (C_0) was primarily concentrated in the 0-10 cm soil layer and gradually

decreased as the soil depth increased. Organic carbon mineralization intensities in the examined soil layers also exhibited the same type of vertical variation. In particular, the mineralization intensity was greatest in the 0-10 cm soil layer; for this layer, cumulative CO_2-C emissions over 100 days reached 2.04 g·kg^{-1}, 1.87 g·kg^{-1}, and 1.21 g·kg^{-1} for the three forest types, with cumulative CO_2-C emissions decreasing with the soil layer depth (Figure 2, Table 4). Further analyses demonstrated that during the course of a 100-day mineralization process, the cumulative CO_2-C emissions from the 0-10 cm soil layer were lower than the active carbon content of this soil layer for all three forest types; C/C_0 values for the three forest types were 0.73, 0.79, and 0.86, which were all less than 1. Certain variations in the C/C_0 ratio were found in soil layers at depths of greater than 10 cm. In these layers, cumulative CO_2-C emissions exceeded the active carbon content in soil samples from the fir-pine mixed forest, with C/C_0 ratios of 1.03-1.10; for the other two forest types, the C/C_0 ratios remained less than 1 (Table 4).

Table4 Characteristics of soil organic carbon mineralization

Forest type	Soil depth (cm)	C (g·kg^{-1})	C_0 (g·kg^{-1})	C/C_0	R^2
Broadleaf-pine mixed forest	0-10	2.04±0.16aA	2.81	0.73	1.00
	10-20	1.48±0.57bA	1.60	0.93	0.99
	20-40	0.97±0.08bcA	1.52	0.64	0.99
	40-60	0.95±0.07cA	1.32	0.72	0.99
	60-100	0.92±0.20cA	1.44	0.64	0.99
Fir-pine mixed forest	0-10	1.87±0.26aA	2.38	0.79	1.00
	10-20	1.12±0.25bA	1.09	1.03	0.98
	20-40	0.82±0.22bA	0.80	1.03	0.98
	40-60	0.90±0.29bA	0.84	1.07	0.98
	60-100	0.77±0.31bA	0.70	1.10	0.96
Pure *Pinus massoniana* forest	0-10	1.21±0.3aB	1.41	0.86	0.99
	10-20	1.02±0.13abA	1.07	0.95	0.99
	20-40	0.69±0.18bcA	0.85	0.81	0.98
	40-60	0.66±0.14cA	0.84	0.79	0.98
	60-100	0.54±0.10cA	0.82	0.66	0.99

Note: C: cumulative CO_2-C emissions over 100 days of mineralization; C_0: active carbon content derived from the fitted equation; R^2: the fitting correlation coefficient; a, b, c: vertical differences in C levels ($P<0.05$); A, B: differences in C levels between soil layers at the same depth ($P<0.05$).

CONCLUSION AND DISCUSSION

4.1 For all three forest types, the organic carbon content and active carbon content of soil layers gradually decreased with the increase in soil depth and were relatively enriched in the surface layers. Previous research indicated that 47.53-71.73% of the fine roots of *P. massoniana* were concentrated within the 0-20 cm soil layer, with a decreasing trend in biomass with increasing soil depth. Large quantities of dead fine roots jointly decompose with surface litter, providing a rich carbon source for the topsoil and thereby directly affecting the vertical distribution of soil organic carbon[20,21]. These effects are also manifested in the vertical distribution of active carbon in soil layers because the aforementioned root and litter properties cause the active carbon content to be higher in the 0-20 cm soil layer compared with subsoil layers and produce the same vertical variation in the active carbon content as that observed for the soil organic carbon content (Table 4).

4.2 The three forest types exhibited differences in vertical variation in the soil microbial carbon content. In mixed forests, the microbial carbon content was primarily concentrated in the 0-20 cm soil layer, which contained significantly higher levels of microbial carbon content than subsoil layers. However, in pure *P. massoniana* forest samples, the soil microbial carbon content exhibited a gradual vertical change, with no significant interlayer differences. The distribution of the microbial carbon content may be affected by distributions of litter and roots. In particular, mixed forests can generate many types of litter. In combination with fine root distribution characteristics, the diverse litter found in these forests promotes the aggregation of soil microbes in surface soil layers. In contrast, microbial carbon distributions in pure forests may be more strongly influenced by root distribution.

4.3 Similar organic carbon mineralization characteristics were observed for each soil layer in the examined *P. massoniana* forests. In particular, the mineralization intensity was initially strong but decreased over the course of the reaction period. A study by Collins et al. suggested that during the early stages of mineralization, monosaccharides and other readily decomposed active organic carbon-based compounds in soils undergo rapid decomposition. As these compounds are decomposed and consumed, by the later stages of mineralization, microbes are forced to break down organic carbon compounds that are difficult to decompose, resulting in a gradual decrease in decomposition rates and an accompanying reduction in CO_2 emissions[22]. A second explanation for the observed mineralization characteristics is that mineralization reactions will perpetually appear to be more rapid in the 0-10 cm topsoil layer than at other layers because this topsoil layer not only contains the highest concentrations of active organic carbon compounds in the soil but also exhibits stronger microbial activity than other soil layers (Tables 3

and 4). Soil layers deeper than 10 cm contain relatively low levels of active organic carbon compounds and exhibit relatively weak microbial activity; as a result, these layers exhibit low mineralization reaction intensities, without significant interlayer differences in mineralization (Tables 3 and 4).

4.4 There were no significant differences between the two types of mixed forests with respect toorganic carbon mineralization intensities at the same soil depth (Table 4). However, further analyses revealed significant differences in the characteristics of the mineralization reactions in these two types of forest at soil layers deeper than 10 cm. In the broadleaf-pine forest, after 100 days of mineralization, a considerable quantity of residual active carbon remained present in soil layers deeper than 10 cm (C/C_0 = 0.64-0.93). In these layers, soil mineralization reactions involving the decomposition of readily processed active organic carbon-based compounds continued for a certain time period, and the mineralization intensity remained at high levels. In the fir-pine mixed forest, the active carbon in soil layers deeper than 10 cm had essentially completely decomposed by the conclusion of 100 days of mineralization (C/C_0 = 1.03-1.10); thus, organic carbon compounds that were relatively difficult to break down had become major reactants in the decomposition process, causing a gradual decrease in mineralization intensity. Differences between the two types of mixed forests with respect to soil mineralization intensity should be closely related to the types of litter and microbial activity found in each forest. Notably, a greater variety of litter types exist in the broadleaf-pine mixed forest than in the fir-pine mixed forest; this variety of litter types not only produces large quantities of active carbon in soil layers (Table 4) but also provides a relatively hospitable environment for microbial survival and activity. As a result, relative to the fir-pine mixed forest, the broadleaf-pine mixed forest exhibited a higher microbial carbon content in the examined soil layers (Table 3). This high carbon content ensured that soil organic carbon mineralization reactions remained at a high intensity for a relatively long time period.

In the pure forest, the 100-day cumulative CO_2 emissions from mineralization in the 0-10 cm soil layer were 1.21 g·kg-1, and organic carbon mineralization intensities were significantly lower than the organic carbon mineralization intensities of the mixed forests, although certain quantities of active carbon remained in soil layers after the 100-day period had elapsed (Table 4). The pure forest exhibited relatively homogeneous litter that was unfavorable to microbial activity; as a result, the soil microbial carbon content was significantly lower in the pure forest than in the mixed forests (Table 3), causing the pure forest to exhibit slower active carbon decomposition and lower levels of mineralization intensity.

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