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Research Article

Application of Two Exponential Equations in the Study of Soil Organic Carbon Mineralization in Natural Forests

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Abstract: This study respective using the exponential equation and double exponential equation which are widely used were fitted *Pinus massoniana*, evergreen broad leaved forest, deciduous oak forest, pine-oak forest, *Pinus koraiensis* and *Pinus tabulaeformis* and other six kinds of typical natural forest soil organic carbon mineralization process, it also by fitting curves and cumulative release of CO_2 mineralization process analysis and correlation of inert carbon content of soil measured and fitted values of t-test analysis, the two exponential equations in natural forest soil organic carbon mineralization process the application results were evaluated. The results show that the double exponential equation on soil organic carbon mineralization has a better fitting description effect can be more realistically reflect the changes in soil organic carbon mineralization characteristics of the fitting results of insert soil carbon content and measured values a significant difference is not level, the soil can be more accurately reflect the changes of the inert carbon.

Keywords: Exponential equation, mineralization process, natural forest soil, resistant carbon

INTRODUCTION

The classification of Soil Organic Carbon (SOC) composition is an important basis for in-depth studies of the characteristics of SOC. However, the method for the composition classification varies according to different objectives. Based on the ease of decomposition, the SOC component can be divided into three categories: activated carbon, slow-release carbon and inert carbon (Parton *et al*., 1988). Since the 20th century, a number of scholars have attempted to investigate SOC components using a fitted SOC mineralization process with exponential or double exponential equations, particularly the characteristics of activated carbons in the soil (Bonde and Rosswall, 1987; Yang *et al*., 2006a). For example, Jones (1984) examined the concentration and variation pattern of activated organic carbon in soil. Juma *et al*. (1984) compared the fitting performance of single exponential, double exponential, exponential and linear equations in the investigation of soil activated carbon mineralization in pastures and farmlands. Wedin and Pastor (1993) applied an exponential model to fit the soil mineralization of grassland. Fernández *et al*. (1999) also investigated the impact of fire on the dynamics of the carbon mineralization process in forest soil. In China, a number of scholars have performed relevant studies of farmland and grassland soils. However, the specific drawbacks of current studies remain. First, the unique characteristics of the SOC composition of forest soils, especially natural forest soils, which are produced by different growing environments, are rarely addressed in the relevant literature (Wu *et al*., 2004; Yang *et al*., 2008; Yang *et al*., 2006b; Dou *et al*., 2009). Second, the majority of studies is too simple and direct in terms of the selection of the fitted equations and lack preliminary judgment of the applicability of the selected equations. Third, the studies lack authenticity analyses of the fitted data regarding the concentration of organic carbon components. In this study, we investigated the soil in six representative types of natural forests, i.e., the subtropical *Pinus massoniana* forest, the evergreen broadleaf forest, the deciduous broadleaf forest, the mixed broadleaf-conifer forest, the temperate Korean pine forest and the Chinese pine forest. By applying the commonly used exponential equation and double exponential equation to fit the mineralization process of SOC in each layer, we evaluate their data fitting performance in the study of SOC mineralization in natural forests. We compare the measured values of the soil inert carbon concentration with the difference between the fitted values and investigate the authenticity of the fitted data for the concentration of organic carbon components. Our results provide reliable evidence and an applicable method for future studies of SOC mineralization and the soil composition characteristics of natural forests.

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STUDY METHODS

Sample plot overview and soil sample collection: The six study areas include three sample plots, including the natural *Pinus massoniana* forest of the Dagangshan National Ecological Station in Jiangxi Province, the evergreen broadleaf forest of the Lushan Ecological Station in Jiangxi Province, the deciduous broadleaf forest and the mixed conifer-broadleaf forest of the Jigongshan Ecological Station in Xinyang of Henan Province, the Korean pine forest in the Baishilizi National Natural Preservation Area and the Chinese pine forest of the Yiwulushan National Natural Preservation Area in Liaoning Province. The general data for these sample plots are shown in Table 1. Three standard sites contained sample plots with dimensions of 20×20 m for each plot. Using an "S"-shaped sampling approach, we collected mixed soil samples from layers in the depth ranges of 0-10, 10-20, 20-40, 40-60 and 60-100 cm, respectively. After each soil sample was dried, it was filtered with 2 and 0.149 mm sieves (State Forestry Bureau, 1999) to measure the quantities of total organic carbon and inert carbon, as well as the cumulative CO_2 emissions during soil mineralization.

Measurement methods: The total organic carbon content in the soil was measured using the potassium dichromate volumetric method-external heating method (Bao, 2000).

The quantity of inert carbon in the soil was measured using an acid hydrolysis method (Leavitt *et al*., 1997).

The cumulative quantity of CO_2-C emissions during the SOC mineralization was measured with an approach that combines indoor cultivation under constant temperature and alkali absorption (Zou *et al*., 2005) with a cultivation period of 100 days.

The fitted equation for soil organic carbon mineralization:

The double exponential equation used in this study: The Boyle and Paul (1989) double exponential equation can be expressed as:

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

where

- C_{min} : The cumulative quantity of CO_2-C emitted by the soil after time t (g/kg)
- Co : The size of the activated organic carbon pool in the soil (g/kg)
- ko : The turnover rate of the activated organic carbon pool (d^{-1})
- C_S : The slow-release organic carbon pool in the soil (g/kg)
- ks : The turnover rate of the slow-release organic carbon pool (d^{-1})

Table 1: Overview of the sample plots

Forest type	Avg. elevation/m	Dominant tree species	Stand age/year	Avg. tree height/m	Avg. breast-height diameter/cm	Canopy density/%	Soil type
Pinus massoniana forest	255	*Pinus massoniana*	50	25	22	80	Red-yellow soil
Evergreen broadleaf forest	221	*Quercus sclerophylla*, *Cinnamomum porrectum* (Roxb.) *Kosterm*	45	14.8	31.8	63	Red-yellow soil
Deciduous broadleaf forest	211	*Quercus*	55	22/22	33/28	90	Yellow-brown soil
Mixed broadleaf-conifer forest	215	*Pinus massoniana*, *Quercus*	55	19/17	26/25	90	Yellow-brown soil
Korean pine forest	845	*Korean pine*	95	20	25.4	60	Dark brown soil
Chinese pine forest	433	*Chinese pine*	60	15.3	20.8	75	Dark brown soil

Other wood species and the primary understory vegetation are as follows:

Pinus massoniana forest consists of *Syzygium buxifolium* Hook. *etArn* and *Cinnamomum porrectum* (Roxb.) *Kosterm*; its main understory vegetation consists of *Phyllostac hysheterocycla* (Carr.), *Viburnum dilatatum* thunb, *Elatostema macintyrei* dunn, *Nephrolepis auriculata* trimen and *Lophatherum gracile* brongn.

The evergreen broadleaf forest consists of *Castanopsis sclerophylla*, *Cinnamomum porrectum* (Roxb.) *kosterm*, *Liquidambar formosana*; its main understory vegetation consists of *Alangium chinense*, *Quercus fabri*, *Syzygium buxifolium* Hook. *etArn*, *Woodwardia japonica* and *Rubus corchorifolius*.

The deciduous broadleaf forest consists of *Quercus variabilis*, *Quercus acutissima* and *Liquidambar formosana*; its main understory vegetation consists of *Lindera glauca*, *Symplocos paniculata*, *Pteris nervosa* and *Achyranthes longifolia*.

The mixed broadleaf-conifer forest consists of *Quercus variabilis*, *Quercus acutissima* and *Liquidambar formosana*; its main understory vegetation consists of *Celtis bungeana*, *Pistacia chinensis*, *Ampelopsis sinica* and *Hedera helix*.

The Korean pine forest consists of pure forest and the main understory vegetation consists of *Rhododendron dauricum*, *Radix acanthopanacis* senticosi, *Carex rigescens*, *Convallaria majalis* and *Aegopodium alpestre*.

The Chinese pine forest consists of *Populus davidiana*, *Quercus wutaishanica*; its main understory vegetation consists of *Lespedeza bicolor* turcz, *Rosa xanthina* lindl, *Pennisetum centrasiaticum* tzvel and *Glycyrrhizae*.

Avg.: Average

According to the measured data of the quantity of total SOC and the fitted Co and C_S, we calculate the soil inert carbon pool Cr, namely Cr = SOC-(Co+Cs).

Exponential equation: The first-order kinetic equation of Stanford and Smith (1972) is expressed as:

$$C_{min} = C_0 (1-e^{-kt})$$

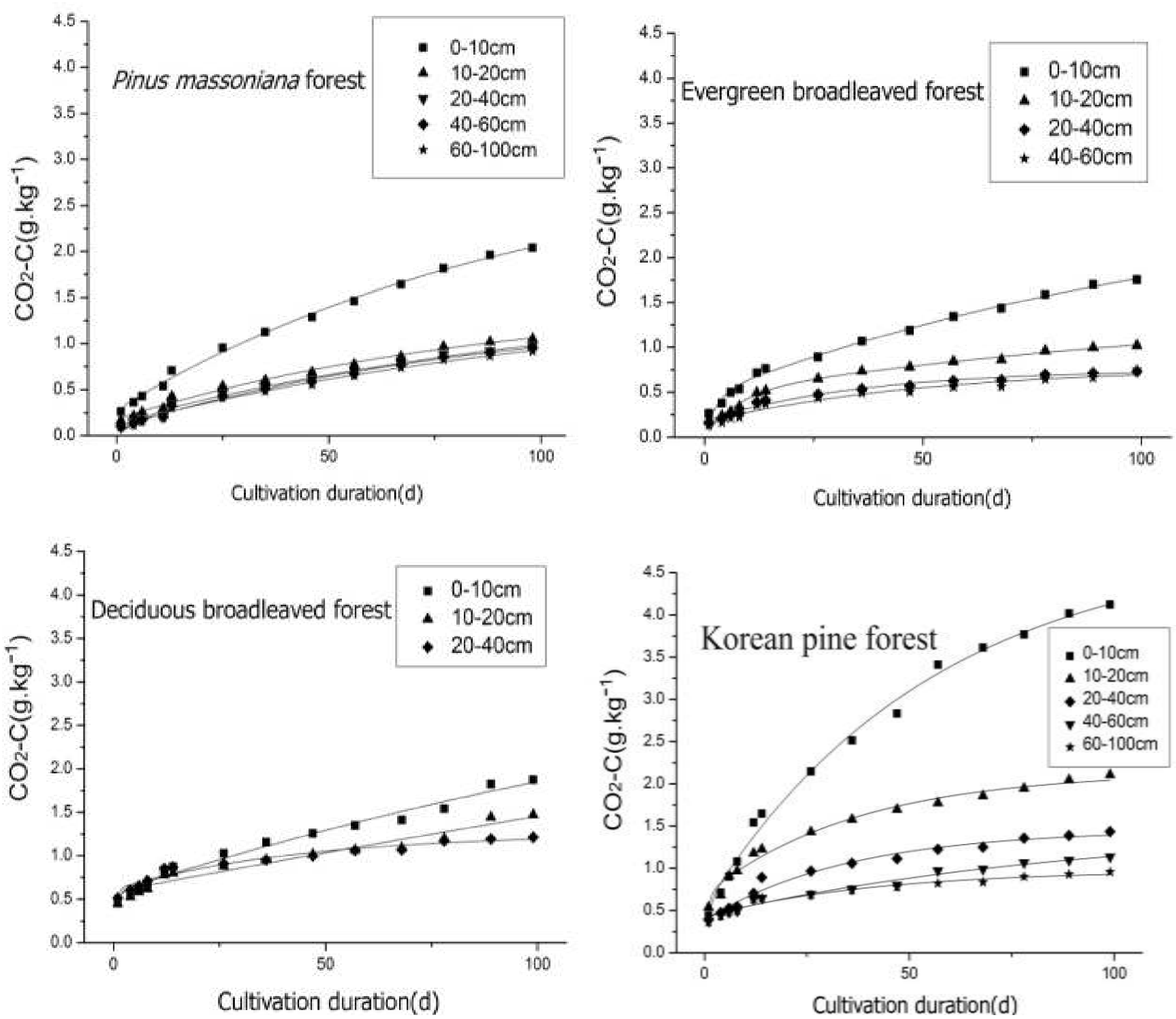
where,

C_{min} = The cumulative quantity of CO_2-C emitted by the soil after time *t* (g/kg)
C_0 = The size of the activated organic carbon pool (g/kg) in the soil
k = The turnover rate of the activated organic carbon pool (d^{-1})

Data processing: The software Excel 2007 and SPSS 17.0 were employed for the statistical analysis and data processing in this study. The analyses of variance and correlation analysis were performed for the data comparison and the determination of the significance of differences. The Origin 8.6 software was used to fit the equations that describe the SOC mineralization processes.

RESULTS AND ANALYSIS

Comparison of data fitting results with two exponential equations: The fitted curves derived from two exponential equations (Fig. 1 and 2) indicated that the trend line fitted with the double exponential equation corresponds with the measured data and accurately reflects the characteristics of organic carbon mineralization. According to Table 2, the curves fitted with the double exponential equation exhibit high correlation coefficients, which indicate a close correlation. The R^2 values for all 24 curves exceed 0.96, with a maximum of 1, which indicates satisfactory fitting results. The trend line fitted with the exponential equation reflects the reaction features of organic carbon mineralization and exhibits some correlation with the



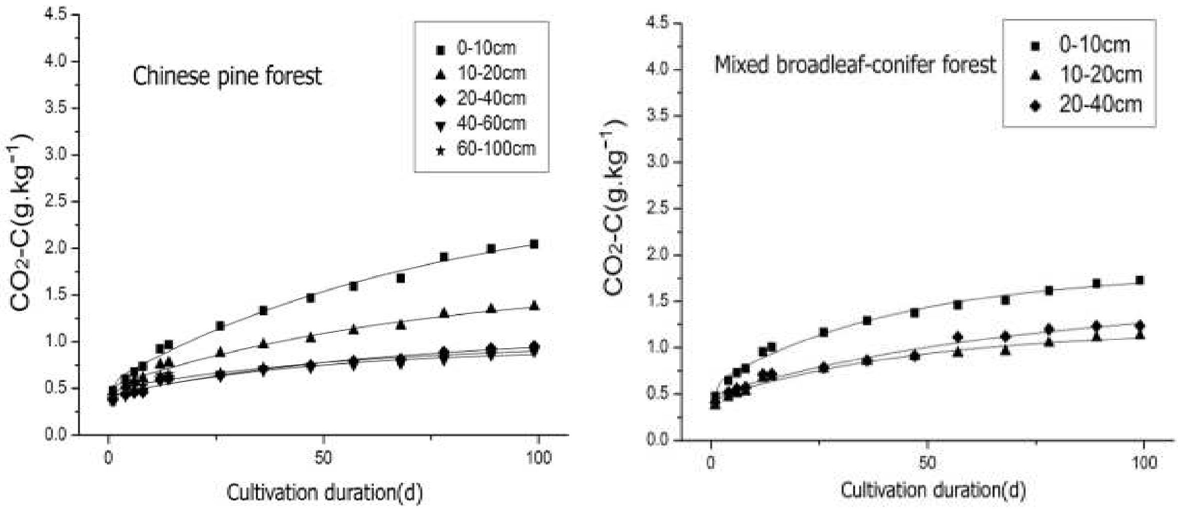
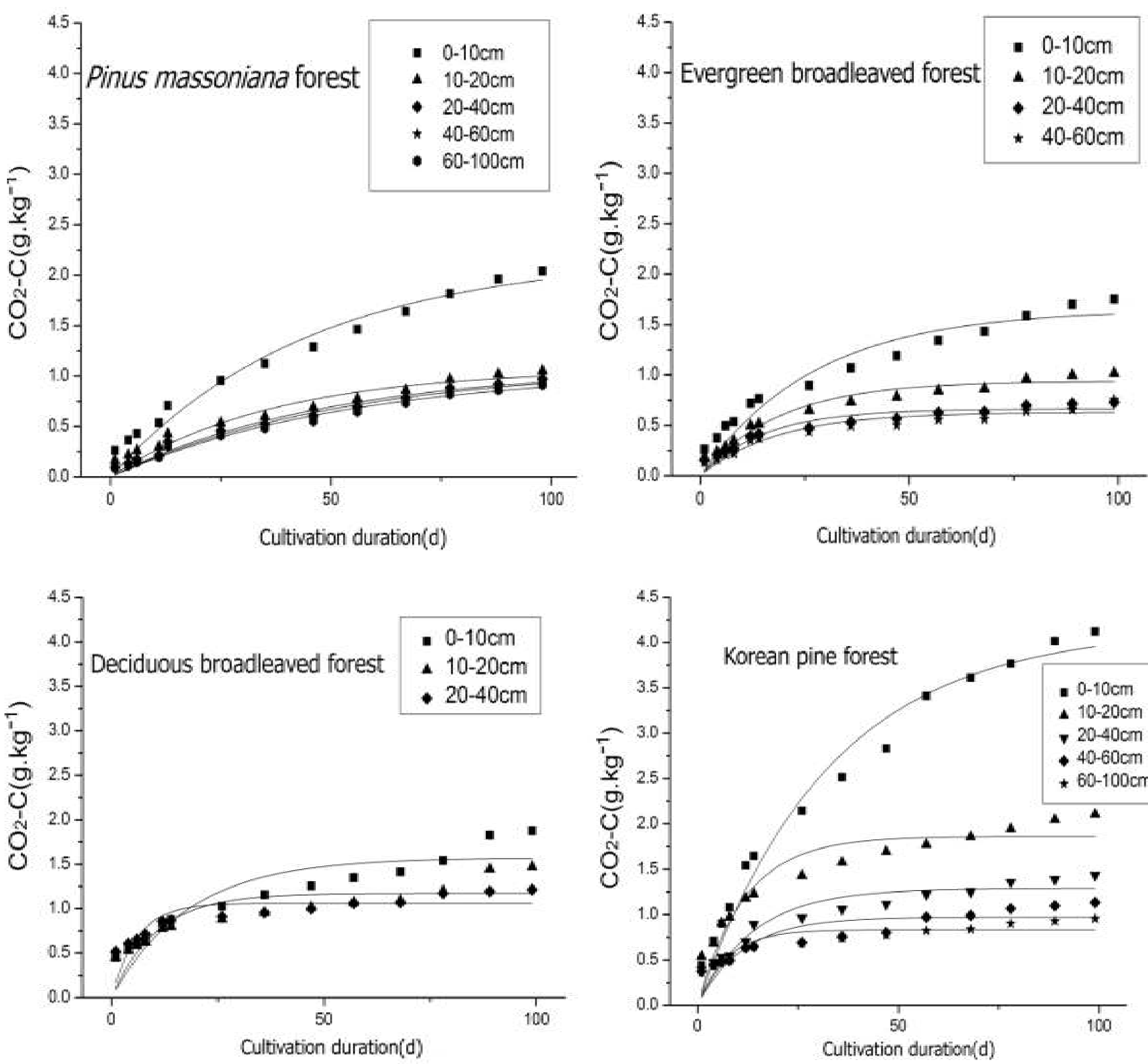


Fig. 1: Fitting results of the double exponential equation for the CO_2-C emission during the SOC mineralization process
"." Indicates the measured cumulative quantity of CO_2-C emitted by the soil after time t; "-" Indicates the fitted curve of the cumulative quantity of CO_2-C emitted by the soil after time t



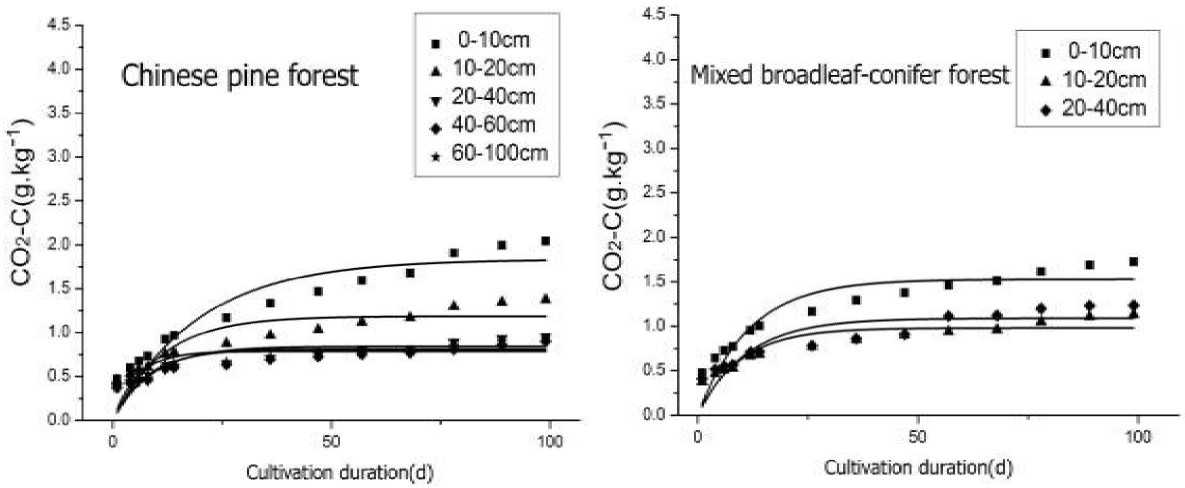


Fig. 2: Fitting results of the exponential equation on the CO_2-C emission during the SOC mineralization process
"." Indicates the measured cumulative quantity of CO_2-C emitted by the soil after time t; "-" Indicates the fitted curve of cumulative quantity of CO_2-C emitted by the soil after time t

Table 2: R^2 of the fitted curve and the C_r and C_R values for SOC mineralization

		Double exponential equation				Exponential equation
Forest type	Soil depth/cm	C_r/g/kg	C_R/g/kg	Amplitude of change/g/kg	R^2	R^2
Pinus massoniana forest	0-10	30.42	26.62	3.80	1.00	0.93
	10-20	12.14	8.12	4.02	0.98	0.87
	20-40	4.32	3.77	0.55	0.99	0.84
	40-60	3.39	3.26	0.13	0.99	0.89
	60-100	1.60	1.53	0.07	0.97	0.85
Evergreen broadleaf forest	0-10	21.70	18.64	3.06	0.99	0.92
	10-20	10.12	6.66	3.46	0.98	0.95
	20-40	7.44	4.04	3.40	0.98	0.92
	40-60	5.85	2.48	3.37	0.96	0.90
Deciduous broadleaf forest	0-10	12.69	9.74	2.95	0.98	0.80
	10-20	2.18	4.39	-2.21	0.96	0.68
	20-40	2.28	2.42	-0.14	0.96	0.64
Mixed broadleaf-conifer forest	0-10	33.83	26.42	7.41	0.99	0.85
	10-20	10.55	6.13	4.42	0.98	0.77
	20-40	5.40	2.02	3.38	0.98	0.72
Korean pine forest	0-10	133.48	110.71	22.77	0.99	0.97
	10-20	34.46	29.95	4.51	0.99	0.88
	20-40	17.21	14.83	2.38	0.98	0.88
	40-60	14.85	12.92	1.93	0.98	0.71
	60-100	8.06	6.74	1.32	0.97	0.72
Chinese pine forest	0-10	40.37	36.64	3.73	0.99	0.87
	10-20	11.65	9.77	1.88	0.99	0.73
	20-40	4.29	3.12	1.17	0.98	0.63
	40-60	3.96	1.78	2.18	0.97	0.63
	60-100	2.53	1.68	0.15	0.97	0.64
Average					0.98	0.85

C_R: The actual measured value of the inert carbon content; C_r: The fitted value of the inert carbon content and the amplitude of change is the difference between C_r and C_R

measured data with an average correlation coefficient of 0.85 (Table 2). However, the fitted curves and measured data for the samples from some layers exhibited slight dispersion, particularly, the 0-10 cm soil layer range of mixed broadleaf-conifer forest, deciduous broadleaf forest and Chinese pine forest. Although the organic carbon mineralization remained in the stage characterized by rapid CO_2-C emissions and accelerated mineralization during the late stage of cultivation, the fitted trend line demonstrated a decreased growth rate and a mild stage, which revealed a different pattern from the actual mineralization process. The analysis of the correlation coefficients fitted with the exponential equation revealed similar results; the minimum correlation coefficient, R^2, for 24 fitted curves was only 0.63. Only one curve of the Korean pine forest for the 0-10 cm soil layer range exhibited an R^2 value higher than 0.96. The R^2 values

Table 3: The t-test between the measured values and the fitted values for the soil inert carbon

Forest type	d	S_d	v	t	$t_{0.05}$	$t_{0.01}$
Pinus massoniana forest	4.49	3.00	14	1.50	1.76	2.62
Evergreen broadleaf forest	13.40	5.51	10	2.43	1.81	2.76
Deciduous broadleaf forest	3.71	2.16	8	1.72	1.86	2.90
Mixed broadleaf-conifer forest	6.43	3.29	8	1.93	1.86	2.90
Korean pine forest	15.76	11.51	13	1.37	1.77	2.65
Chinese pine forest	2.63	1.34	13	1.96	1.77	2.65

d: Average of the difference; S_d: Standard deviation of d; v: Degree of freedom; t: t-test value; $t_{0.05}$: Threshold of the t-test when $\alpha = 0.05$; $t_{0.01}$: Threshold of the t-test when $\alpha = 0.01$

for the remaining curves were all lower than the minimum correlation coefficient when fitted by the double exponential equation.

Compared with the fitting results of the exponential equation, the double exponential equation yielded a more accurate reflection of the characteristics of SOC mineralization in natural forests.

Analysis on the applicability of the double exponential equation: Because the double exponential equation showed superior fitting results, we compared the difference between the fitted values (Cr) of the inert carbon concentration derived from the fitting calculation with the equation and the measured values (CR). The results indicated that the Cr and CR for the soils of different forest types were equivalent. The values were highest in the 0-10 cm soil layer range but gradually decreased with deeper soil layers. The comparison of the fitted data with the measured data in each layer also indicated that the Cr value was higher than CR in various soil layers, which demonstrated some deviation. Higher organic carbon content and inert carbon content corresponded to greater deviation. The maximum deviation of 22.77 g/kg in the 0-10 cm soil layer range of the Korean pine forest was the most distinct and varied in the range of 4-7 g/kg for the 0-10 cm soil layer range in other types of forests. For the soil below 20 cm, the deviation was relatively small, with a minimum of 0.07 g/kg, which was detected in the 60-100 cm soil layer range of the *Pinus massoniana* forest (Table 2). However, despite the difference between the fitted values and the measured values for the quantity of soil inert carbon in all forest types, a t-test (Table 3) revealed that the t values of all soil layers in three types of forest (*Pinus massoniana* forest, deciduous broadleaf forest and Korean fine forest) were smaller than $t_{0.05}$, which indicates an insignificant difference. For the soil in the remaining three types of forest, the t values were also smaller than $t_{0.05}$, which indicated a difference at the 95% confidence level. However, at the 99% confidence level, the t values were not located in the rejection region; thus, the original assumption was accepted. Consequently, no significant differences were observed between the measured values and the fitted values of the inert carbon concentration in the soils of the six forest types at the 95 or 99% confidence levels.

DISCUSSION AND CONCLUSION

- **SOC consists of three components:** Activated carbon, slow-release carbon and inert carbon. During the early stage of mineralization, the activated organic carbon substances that are readily decomposed (such as monosaccharides) can decompose rapidly, which produces a relatively intense reaction and a rapid increase in CO_2 emissions. With the decomposition and consumption of activated organic carbon sources during the late stage of mineralization, the organic carbons that are difficult to decompose also begin to undergo decomposition, which results in a gradually reduced decomposition rate, a reduction in CO_2 emissions and a weakened reaction (Collins *et al*., 1992). In this study, the organic carbon mineralization process in the various soil layers of six types of natural forests exhibit this pattern and display reasonable characteristics associated with the mineralization reaction.
- The mineralization curves derived from fitting with exponential and double exponential equations are relatively consistent with the actual measured data and reflect the SOC mineralization process and characteristics. However, when using the exponential equation for the fitting, the relatively low correlation coefficients between the fitting values and the measured values indicate a relatively high degree of dispersion, which will affect the determination and investigation of the changing trend and characteristics of the SOC mineralization process, e.g., the 0-10 cm soil layer range in the mixed broadleaf-conifer forest, the deciduous broadleaf forest and the Chinese pine forest. Therefore, the double exponential equation exhibits superior fitting performance in the study of SOC mineralization in natural forests, which is consistent with the results obtained by Juma *et al*. (1984) and Boyle and Paul (1989).
- Regarding the characteristics and changing trend of the cross-sectional vertical distribution and inter-forest horizontal distribution of inert carbon, the fitting results were consistent with the measured data (Table 2), exhibiting a satisfactory fitting performance. The fitting values were generally smaller than the measured values, indicating discrepancies, particularly for the 0-10 cm soil

layer range with high organic carbon content. However, because these differences fell within the confidence interval of t<0.05 or t<0.01, the differences were insignificant. The fitting data accurately reflect the variational characteristics of the soil inert carbon concentration.

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