Composition and mineralization of soil organic carbon pools in four single-tree species forest soils

Qingkui Wang & Micai Zhong

Journal of Forestry Research

ISSN 1007-662X
Volume 27
Number 6

J. For. Res. (2016) 27:1277-1285
DOI 10.1007/s11676-016-0244-z

Springer

Your article is protected by copyright and all rights are held exclusively by Northeast Forestry University and Springer-Verlag Berlin Heidelberg. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your article, please use the accepted manuscript version for posting on your own website. You may further deposit the accepted manuscript version in any repository, provided it is only made publicly available 12 months after official publication or later and provided acknowledgement is given to the original source of publication and a link is inserted to the published article on Springer's website. The link must be accompanied by the following text: "The final publication is available at link.springer.com".

Author's personal copy

J. For. Res. (2016) 27(6):1277–1285
DOI 10.1007/s11676-016-0244-z

ORIGINAL PAPER

Composition and mineralization of soil organic carbon pools in four single-tree species forest soils

Qingkui Wang[1,2] · **Micai Zhong**[3]

Received: 11 February 2015 / Accepted: 10 March 2015 / Published online: 17 May 2016
© Northeast Forestry University and Springer-Verlag Berlin Heidelberg 2016

Abstract Forest soil carbon (C) is an important component of the global C cycle. However, the mechanism by which tree species influence soil organic C (SOC) pool composition and mineralization is poorly understood. To understand the effect of tree species on soil C cycling, we assessed total, labile, and recalcitrant SOC pools, SOC chemical composition by ^{13}C nuclear magnetic resonance spectroscopy, and SOC mineralization in four monoculture plantations. Labile and recalcitrant SOC pools in surface (0–10 cm) and deep (40–60 cm) soils in the four forests contained similar content. In contrast, these SOC pools exhibited differences in the subsurface soil (from 10 to 20 cm and from 20 to 40 cm). The alkyl C and *O*-alkyl C intensities of SOC were higher in *Schima superba* and *Michelia macclurei* forests than in *Cunninghamia lanceolata* and *Pinus massoniana* forests. In surface soil, *S. superba* and *M. macclurei* forests exhibited higher SOC mineralization rates than did *P. massoniana* and *C. lanceolata* forests. The slope of the straight line between C_{60} and labile SOC was steeper than that between C_{60} and total SOC. Our results suggest that roots affected the composition of SOC pools. Labile SOC pools also affected SOC mineralization to a greater extent than total SOC pools.

Keywords ^{13}C nuclear magnetic resonance · Labile soil organic carbon · Monoculture plantation · Soil organic carbon mineralization · Tree species

Introduction

Carbon (C) stock in global forest ecosystems is estimated as 861 Pg C with approximately 383 Pg C (44 %) stored in soil (depth of 1 m), which plays an important role in the global C cycle (Pan et al. 2011). Soil organic C (SOC) is heterogeneous and composed of different functional and biological pools (von Lutzöw et al. 2006). SOC can be divided into labile and recalcitrant SOC pools (Rovira and Vallejo 2002). Labile SOC pool is more sensitive to changes in tree species and management practices than is the total SOC pool because the former exhibits a higher turnover rate and lower residence time than the latter (von Lutzöw et al. 2006). Moreover, the composition of SOC pools shows large spatial variations in different forest ecosystems (Giardina et al. 2001; Kiikkilä et al. 2005; Wang and Wang 2011).

Tree species can influence the composition of SOC pools because of the differences in quantity and quality of tree litter that penetrates the soil (Guo and Gifford 2002; Fissore et al. 2008). On the one hand, a portion of C entering the soil is rapidly decomposed; on the other hand, a large stock accumulates in soil and then becomes

Project founding: This study was supported by the National Natural Science Foundation of China (Grant No. 31570466) and the National Basic Research Program of China (Grant no. 2012CB416905).

The online version is available at http://www.springerlink.com

Corresponding editor: Chai Ruihai

✉ Qingkui Wang
wqkui@163.com

[1] Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China

[2] Huitong National Research Station of Forest Ecosystem, Huitong 418307, People's Republic of China

[3] Kunming Institute of Botany, Chinese Academy of Sciences, Kunming 650201, People's Republic of China

Author's personal copy

recalcitrant (Fissore et al. 2008). Some studies have found that higher amounts of recalcitrant SOC have accumulated in hardwood forests than in pine forests (Fissore et al. 2008), whereas lower labile SOC pools [e.g., dissolved organic C (DOC) and soil microbial biomass C (MBC)] are found in hardwood forests (Yano et al. 2000; Giardina et al. 2001). In other studies, higher MBC and DOC pools are found in broad-leaved forests than in coniferous forests (Smolander et al. 2005; Wang and Wang 2011). Labile SOC pools in the surface soils of three monoculture forests showed no differences (Lu et al. 2012; Wang et al. 2013a). These results indicate that the effects of tree species vary on SOC pool composition. Further studies on forest ecosystems are needed to gain insights into the influence of tree species on SOC pool composition.

Tree species can affect SOC chemical composition (Quideau et al. 2001; Chen et al. 2004; Hannam et al. 2004; Wang et al. 2010, 2013b). Solid-state ^{13}C nuclear magnetic resonance (NMR) spectroscopy can aid understanding of the influence of tree species on SOC chemical composition because it can be employed to divide SOC into several functional C groups (Wang et al. 2010). For example, O-alkyl C is a labile form of SOC; alkyl and aromatic C are recalcitrant forms (Quideau et al. 2001; Chen et al. 2004). Soils in broad-leaved forests contain higher percentages of *O*-alkyl C, lower percentages of alkyl C, and lower alkyl C/*O*-alkyl C ratios than do soils in *Pinus massoniana* forests (Wang et al. 2010, 2013b). Quideau et al. (2001) reported that alkyl C is dominant in soils under coniferous vegetation. In many terrestrial ecosystem models, high quality litter can form high quality SOC (Giardina et al. 2001; Gentile et al. 2011). However, the relationship between the initial quality of litter and SOC chemical composition remains poorly understood (Quideau et al. 2001; Smolander et al. 2005). Thus, we performed ^{13}C NMR spectroscopy of SOC to investigate the mechanism by which tree species and litter quality affect SOC chemical composition.

SOC mineralization (i.e., heterotrophic respiration) is a primary part of soil CO_2 efflux in which 80–100 Pg C a^{-1} is released into the atmosphere (Bond-Lamberty and Thomson 2010). SOC mineralization varies across forest ecosystem types, as demonstrated by extensive investigation (Raich and Tufekcioglu 2000; Subke et al. 2006; Borken et al. 2002; Berger et al. 2010; Fanin et al. 2011; García-Palacios et al. 2013). This could be partly attributed to differences in tree species. Broad-leaved forests exhibit higher respiration rates than coniferous forests (Borken and Beese 2005; Berger et al. 2010) but soil respiration in broad-leaved forests is similar to that in coniferous forests (Borken et al. 2002; Ladegaard-Pederson et al. 2005; Subke et al. 2006; Vesterdal et al. 2012). These conflicting results can be attributed to the differences in the quality and quantity of litter derived from different tree species. Additional study of the impact of tree species on SOC mineralization is needed to improve our understanding of the effect of litter quality on soil C cycling.

This study aimed to determine whether tree species influence the variability of SOC composition and mineralization in forest ecosystems. We would determine the total, labile, and recalcitrant SOC pools and SOC chemical composition by ^{13}C NMR spectroscopy. We also investigated the SOC mineralization in four subtropical forests, including two broad-leaved forests and two coniferous forests. Furthermore, we qualitatively analyzed the relationship between SOC mineralization and different fractions of SOC pools. We hypothesized that: (1) soils in broad-leaved forests with nutrient-rich litters would contain higher labile SOC pools and SOC mineralization rates than soils in coniferous forests and (2) labile SOC pool would also elicits greater effects on SOC mineralization than other SOC pools.

Materials and methods

Site description and experimental design

The experimental site was located at the Huitong National Research Station of Forest Ecosystems (26°50′N, 109°36′E). This region lies in a transition zone that extends from the Yungui Plateau to the lower mountains and hills along the southern bank of the Yangtze River. This region is characterized by a humid mid-subtropical monsoon climate with annual mean temperature of 16.5 °C and precipitation of 1200 mm. The four study forests were located at 540–570 m elevation. The underlying bedrock was mainly composed of grayish green slate of the Sinian Period. The soil in this region was relatively deep silt-like clay, which is classified as an Ultisol according to the United States Department of Agriculture soil taxonomy.

The experiment was based on a completely randomized block design consisting of four treatments with three replicates (3 blocks). One of the three blocks was located 100-200 m away from another block. Each block was divided into four plots (30 × 20 m). Each plot in every block randomly planted one species seedlings of *Cunninghamia lanceolata*, *P. massoniana*, *Schima superba* and *Michelia macclurei* in spring 1983 and 1985. Stand density was 2500 trees·ha^{-1} (spacing of 2 × 2 m) when the plantation was established, but these stands were thinned in 1994 and 2004. Stand density was approximately 1200 trees ha^{-1} in 2011. No fertilizer or lime was applied before or after the seedlings were planted. Leaf litters from the monoculture forests were of contrasting qualities (Table 1).

Author's personal copy

Table 1 Chemical property of leaf litters collected from *S. superba*, *M. macclurei*, *C. lanceolata* and *P. massoniana* forests

	C (g kg^{-1})	N (g kg^{-1})	C/N	P (g kg^{-1})	C/P	Lignin (g kg^{-1})	Lignin/N	Ca (g kg^{-1})
S. superba	465.2	10.73	43.4	0.896	519	403.5	37.6	8.08
M. macclurei	464.1	12.47	37.2	0.634	732	212.6	17.0	5.85
C. lanceolata	465.5	9.35	49.8	0.461	1010	371.2	39.7	3.87
P. massoniana	485.0	7.22	67.2	0.340	1427	442.4	61.3	4.37
P value	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Soil sampling and analyses

Mineral soil samples were collected using a stainless cylinder (diameter = 45 mm) after organic materials were removed from this layer. In each plot, five soil cores were randomly obtained from each of four soil layers: 0 to 10; 10 to 20; 20 to 40 cm; and 40 to 60 cm. The five soil cores of each layer from each plot were pooled into a composite sample. All of the soil samples were immediately transported to the laboratory and then sieved using a 2 mm mesh to remove rocks and plant residues. Some of the soil samples were stored at 3 °C to determine SOC mineralization; other samples were air-dried to determine the soil chemical properties and the different fractions of SOC pools. The remaining samples were subjected to solid-state ^{13}C NMR spectroscopy.

C and N concentrations in the soil and litter samples were determined with an element analyzer (Elementar Vario EL II, Germany). SOC mineralization was defined as the evolution of CO_2 at field moisture level by using laboratory incubation instruments. This procedure is more relevant than actual in situ soil respiration, which can be affected by differences in environmental conditions of different tree species. Approximately 100 g of fresh soil was placed in 500 mL airtight mason jars, where moisture was adjusted to 60 % of water holding capacity. The jars were then incubated in a growth chamber under dark conditions at 25 °C and 100 % humidity. Microcosms were randomized weekly to avoid the potential effects of subtle temperature and moisture gradients within the growth chamber. The released CO_2 was absorbed by 0.1 mol L^{-1} NaOH solution and determined by titrating with 0.05 mol L^{-1} HCl. The CO_2–C output from the soil was expressed in mg C kg^{-1} dry soil day^{-1}. Cumulative amounts of mineralized C were fitted in the following negative exponential model (Côté et al. 2000): $C_t = C_0$ [1 − exp (−kt)], where C_t is the cumulative amount of C mineralized at time t (d), C_0 is the potential mineralizable C, and k is the constant mineralization rate of a particular pool. The half-life ($t_{1/2}$) of potentially mineralizable C was calculated using the following equation: $t_{1/2} = \ln 2/k$.

Labile and recalcitrant C pools were determined by the acid hydrolysis method (Rovira and Vallejo 2002). Approximately 500 mg of soil samples was hydrolyzed with 20 mL of 2.5 mol L^{-1} H_2SO_4 for 30 min at 105 °C in sealed tubes. These tubes were then centrifuged. The remaining residues were hydrolyzed again overnight with 2 mL of 13 mol L^{-1} H_2SO_4 at room temperature. Deionized water was added to dilute the acid to 1 mol L^{-1} H_2SO_4 and then hydrolyzed for 3 h at 105 °C with occasional shaking. Afterward, these tubes were centrifuged again. The remaining non-hydrolyzable residue was washed twice with deionized water and dried at 60 °C. This fraction was used as the recalcitrant pool. C concentrations were also determined using an element analyzer (Elementar Vario EL II, Germany).

To obtain the solid-state ^{13}C NMR spectra, we repeatedly treated the soil samples with 10 % hydrofluoric acid and washed with deionized water as described by Wang et al. (2013b). These soil samples were then freeze-dried. The solid-state ^{13}C NMR spectra were obtained using a Bruker Avance III 400 WB spectrometer equipped with a 4 mm standard bore CP/MAS probehead. HF-treated soil samples were packed in ZrO_2 rotor closed with Kel-F caps and spun at a rate of 5 kHz. The experiments were conducted with a contact time of 2 ms. A total of 10,000 scans were recorded with a recycle delay of 3 s for each sample. ^{13}C CP/MAS chemical shifts were referenced to the resonances of the adamantane ($C_{10}H_{16}$) standard ($dCH_2 = 38.5$). Chemical groups from the ^{13}C NMR spectra were categorized into four regions according to the divisions of the spectra (Wang et al. 2013a): 0 ppm to 45 ppm alkyl C (lipids, cutin, and suberin); 45–110 ppm *O*-alkyl C (carbohydrates, cellulose, hemicellulose, and methoxyl C); 110–160 ppm aromatic C (lignin, tannin, olefins, and aromatic compounds); and 160–210 ppm carboxyl C (carboxylic acid, amide and ketone groups). Integration peaks in each region were used to calculate the relative distribution (%) of each chemical group within the measured sample. Alkyl C/*O*-alkyl C ratios (A/OA) were then calculated for each soil fraction as an indicator of microbial transformation. Aromaticity index was calculated using the following equation: aromaticity aromaticity (%) = aromatic C intensity/(alkyl + *O*-alkyl + aromatic) C intensity × 100.

Author's personal copy

Statistical analyses

The total N, total SOC pool, labile SOC pool, recalcitrant SOC pool, functional C groups, and SOC mineralization rates of each soil layer under the four monoculture forests were compared by ANOVA in SPSS version 17.0 for Windows. The assumptions of normality and the homogeneity of variances were verified. Dependent variables were then transformed with natural logarithm when necessary. Tukey's significant difference test was performed post hoc to separate the means where differences were significant. Pearson's linear correlation was calculated to assess the relationships between the cumulative mineralized C at 60 d (C_{60}) and the total, labile, and recalcitrant SOC pools in mineral soils. Significance levels were set at $P < 0.05$.

Results

Total, labile, and recalcitrant SOC pools

Surface (0–10 cm) soils in the four forests were similar in total SOC concentration but other soil layers differed (Table 2). In the 10–20 cm soil layer, *P. massoniana* forest yielded a lower total SOC concentration than did *M. macclurei* forest. In the 20–40 cm and the 40–60 cm soil layers, total SOC concentrations were higher in *P. massoniana* forest than in *M. macclurei* forest. Total soil N concentration in the 0–10 cm and 20–40 cm soil layers differed significantly among the four forests. The lowest values were observed in *P. massoniana* and *C. lanceolata* forests.

Labile and recalcitrant SOC in the 10–20 cm and 20–40 cm soil layers differed significantly among the four forests (Fig. 1). In the 10–20 cm soil layer, labile SOC was significantly higher in *S. superba* (by 51.8 %) and *C. lanceolata* (by 46.8 %) forests than in *M. macclurei* forest. In contrast, recalcitrant SOC was significantly lower in *S. superba* forest (by 24.7 %) than in *C. lanceolata* forest. Labile SOC in the 20-40 cm soil layer was significantly higher in *P. massoniana* forest than in *C. lanceolata* (by 27.0 %) and *M. macclurei* (by 24.6 %) forests. Recalcitrant SOC at 20 cm to 40 cm soil layer was significantly higher in *M. macclurei* forest than in *P. massoniana* (by 32.1 %) and *S. superba* (by 35.2 %) forests.

SOC chemical composition

^{13}C NMR relative intensities of SOC varied among the four forests (Table 3). Alkyl C and *O*-alkyl C intensities were greater in *S. superba* and *M. macclurei* forests than in *P. massoniana* and *C. lanceolata* forests. However, aromatic

Table 2 Total SOC and N concentrations in *S. superba* (SS), *M. macclurei* (MM), *C. lanceolata* (CL) and *P. massoniana* (PM) forests

		0–10 cm	10–20 cm	20–40 cm	40–60 cm
Total SOC (g kg^{-1})	SS	24.7 ± 2.3^{a}	13.4 ± 1.3^{a}	5.7 ± 0.4^{ab}	3.3 ± 0.4^{ab}
	MM	22.0 ± 1.2^{a}	10.4 ± 1.5^{ab}	5.0 ± 0.7^{b}	2.7 ± 0.3^{b}
	CL	23.3 ± 1.6^{a}	13.2 ± 0.8^{a}	5.5 ± 0.6^{ab}	3.1 ± 0.3^{ab}
	PM	20.4 ± 2.1^{a}	11.1 ± 0.4^{b}	6.1 ± 0.2^{a}	3.4 ± 0.1^{a}
Total N (g kg^{-1})	SS	2.01 ± 0.13^{a}	1.26 ± 0.06^{a}	0.83 ± 0.01^{b}	0.70 ± 0.05^{a}
	MM	1.87 ± 0.05^{ab}	1.15 ± 0.08^{a}	0.85 ± 0.08^{ab}	0.75 ± 0.03^{a}
	CL	1.77 ± 0.13^{ab}	1.18 ± 0.01^{a}	0.80 ± 0.04^{b}	0.73 ± 0.04^{a}
	PM	1.59 ± 0.10^{b}	1.14 ± 0.05^{a}	0.91 ± 0.02^{a}	0.79 ± 0.03^{a}

Means (±SD) within a row followed by different letters are significantly different. Values (mean ± SD) with different letters in a column at the same soil layer are significantly different at $P < 0.05$

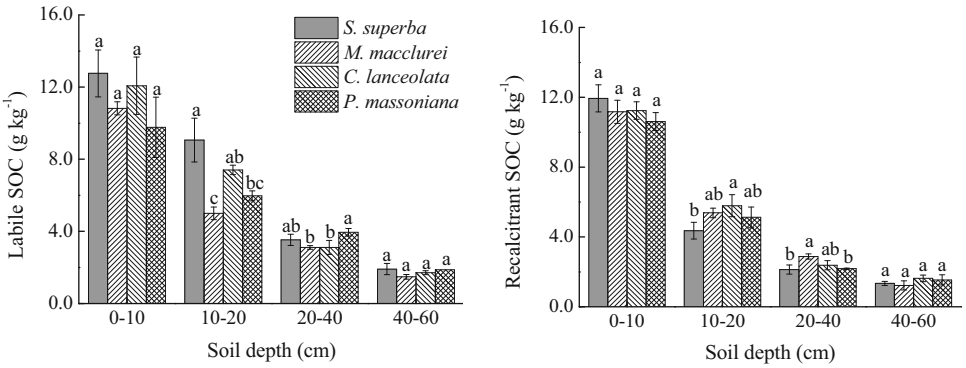

Fig. 1 Labile and recalcitrant soil organic C determined by acid hydrolysis method in *S. superba*, *M. macclurei*, *C. lanceolata*, and *P. massoniana* forests

Author's personal copy

Table 3 Relative intensities (%), alkyl C/*O*-alkyl C (A/OA) ratios and aromaticities derived from the ^{13}C NMR spectra of the surface soil layer (0–10 cm) in *S. superba* (SS), *M. macclurei* (MM), *C. lanceolata* (CL), and *P. massoniana* (PM) forests

	Alkyl C	*O*-alkyl C	Aromatic C	Carboxyl C	A/OA	Aromaticity (%)
SS	19.29 ± 0.57[a]	52.86 ± 1.44[a]	20.0 ± 0.89[c]	7.85 ± 0.53[a]	0.365 ± 0.032[a]	21.7 ± 1.3[c]
MM	19.08 ± 0.43[a]	50.48 ± 1.03[a]	23.1 ± 0.95[b]	7.34 ± 0.51[a]	0.378 ± 0.029[a]	24.9 ± 1.6[b]
CL	18.28 ± 0.38[b]	46.07 ± 0.98[c]	28.5 ± 1.14[a]	7.15 ± 0.42[a]	0.397 ± 0.035[a]	30.7 ± 1.8[a]
PM	16.70 ± 0.41[c]	48.39 ± 1.06[b]	28.0 ± 1.21[a]	6.91 ± 0.39[a]	0.345 ± 0.027[a]	30.1 ± 1.4[a]

Values (mean ± SD) with different letters in a column are significantly different at $P < 0.05$

C intensity and aromaticities showed a reverse trend. The lowest alkyl C intensity was recorded in *P. massoniana* forest and the lowest *O*-alkyl C intensity in *C. lanceolata* forest. The lowest values of aromatic C intensity and aromaticities were recorded in *S. superba* forest. Furthermore, carboxyl C intensity and A/OA ratios of SOC were identical among the four forests.

SOC mineralization

SOC mineralization rates differed significantly among different tree species and soil layers (Fig. 2). Mineralization rates decreased significantly with increasing soil depth and incubation time. During the first 14 days of incubation, the SOC mineralization rate decreased rapidly and then gradually. In the 0–10 cm soil layer, the highest SOC mineralization rate was recorded in *S. superba* forest and then in *M. macclurei* and *P. massoniana* forests. The lowest mineralization rate was recorded for *C. lanceolata* forest. In the 10–20 cm and 20–40 cm soil layers, *C. lanceolata* forest exhibited a significantly lower SOC mineralization rate than other forests; in comparison, no differences in the mineralization rates were observed among *P. massoniana*, *S. superba*, and *M. macclurei* forests. In the 40–60 cm soil layer, *M. macclurei* forest yielded a lower SOC mineralization rate than *P. massoniana* and *S. superba* forests.

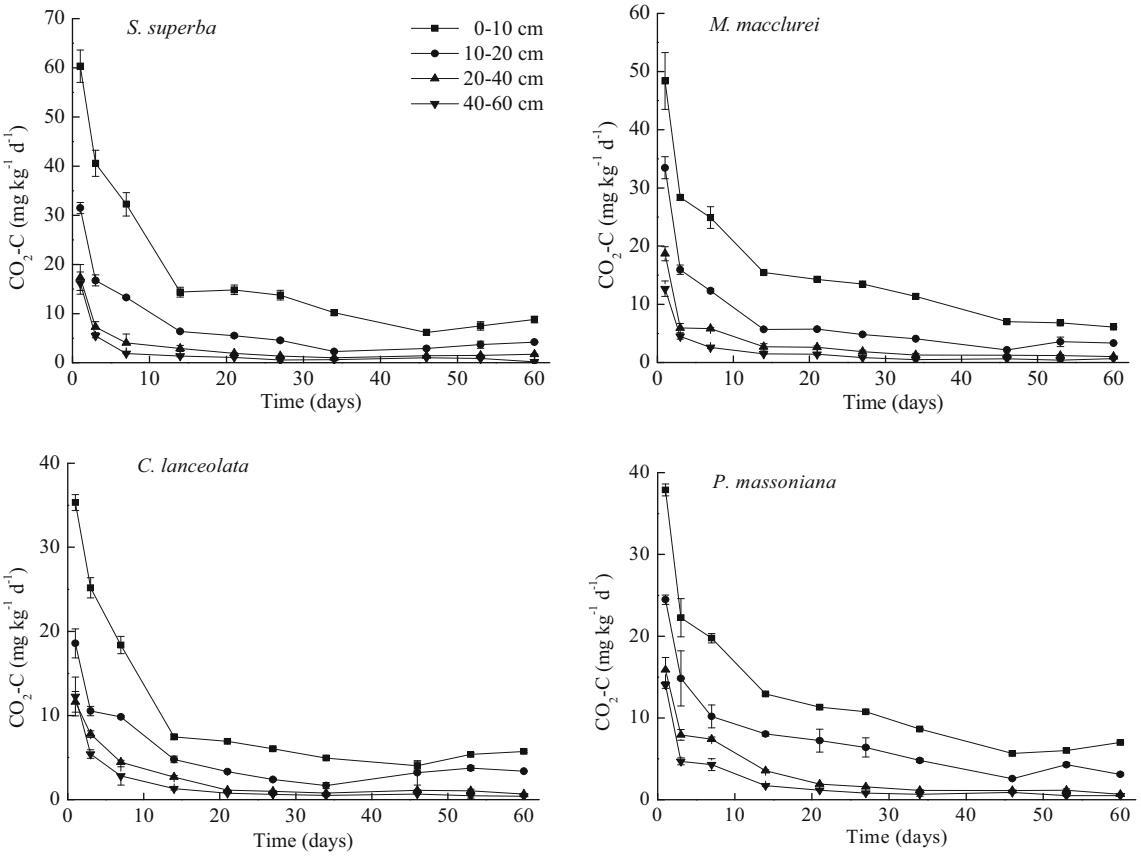

Fig. 2 SOC mineralization rate under laboratory incubation conditions in *S. superba*, *M. macclurei*, *C. lanceolata*, and *P. massoniana* forests

Author's personal copy

Table 4 Soil potentially mineralizable C (C_0), mineralization rate constants (k), ratio of C_0 to total SOC, and half-life ($t_{1/2}$) of C_0 in *S. superba* (SS), *M. macclurei* (MM), *C. lanceolata* (CL), and *P. massoniana* (PM) forests

Soil depth		C_0 (mg CO_2–C kg^{-1})	k ($days^{-1}$)	C_0/SOC (%)	$t_{1/2}$
0–10 cm	SS	894.7 ± 64.5a	0.038 ± 0.004a	3.63 ± 0.09a	18.3 ± 1.7b
	MM	941.0 ± 14.6a	0.028 ± 0.001ab	4.29 ± 0.29a	24.8 ± 0.9a
	CL	502.9 ± 19.2c	0.039 ± 0.001a	2.16 ± 0.12b	17.8 ± 0.5b
	PM	753.1 ± 7.3b	0.026 ± 0.001b	3.72 ± 0.43a	26.7 ± 1.0a
10-20 cm	SS	347.1 ± 9.6ab	0.043 ± 0.001a	2.60 ± 0.28bc	16.1 ± 0.4a
	MM	347.4 ± 12.1ab	0.041 ± 0.001ab	3.40 ± 0.52ab	16.8 ± 0.2a
	CL	306.7 ± 67.4b	0.030 ± 0.009c	2.31 ± 0.36c	25.0 ± 2.4b
	PM	427.3 ± 23.1a	0.031 ± 0.002bc	3.86 ± 0.29a	22.7 ± 1.8b
20-40 cm	SS	143.3 ± 9.0 a	0.048 ± 0.007c	2.54 ± 0.25a	14.7 ± 2.1a
	MM	145.0 ± 3.0a	0.050 ± 0.005bc	3.10 ± 0.86a	13.8 ± 1.2ab
	CL	112.5 ± 1.5b	0.063 ± 0.001ab	2.06 ± 0.16a	11.1 ± 0.1b
	PM	141.8 ± 0.9a	0.064 ± 0.006a	2.32 ± 0.07a	10.9 ± 1.0b
40-60 cm	SS	81.3 ± 4.5a	0.074 ± 0.012ab	2.52 ± 0.18a	9.5 ± 1.4b
	MM	68.9 ± 2.1b	0.057 ± 0.003b	2.56 ± 0.20a	12.3 ± 0.7a
	CL	70.7 ± 5.1b	0.085 ± 0.010a	2.13 ± 0.33a	8.2 ± 0.9b
	PM	83.1 ± 2.3a	0.072 ± 0.008ab	2.44 ± 0.05a	9.7 ± 1.0ab

Values (mean ± SD) with different letters in a column at the same soil layer are significantly different at $P < 0.05$

Potentially mineralizable C parameters showed different patterns in different soil layers (Table 4). The lowest C_0 was observed in *C. lanceolata* forest in each soil layer. However, the highest C_0 in each soil layer was not found in the same forest. In the 0–10 cm soil layer, highest C_0 was observed in *M. macclurei* forest. In other soil layers, highest C_0 was found in *P. massoniana* forest. The proportion of C_0 to total SOC showed a similar C_0—pattern in the four forests, although no differences were observed in the 20–40 cm and 40–60 cm soil layers. $t_{1/2}$ of C_0 in the 0–10 cm soil layer was higher in *P. massoniana* and *M. macclurei* forests than in other forests. In the 10–20 cm and 20–40 cm soil layers, *C. lanceolata* and *P. massoniana* forests exhibited higher $t_{1/2}$ than did other forests. In the 40–60 cm soil layer, *M. macclurei* forest exhibited the highest $t_{1/2}$.

The cumulative C mineralized at 60 d (C_{60}) exhibited a significantly positive linear correlation with total, labile, and recalcitrant SOC (Fig. 3). The slope of the straight line between C_{60} and labile and recalcitrant SOC was steeper than that between C_{60} and total SOC, indicating that SOC mineralization had stronger relation to labile SOC than total SOC. However, the straight line between C_{60} and labile SOC exhibited a slope similar to the straight line between C_{60} and recalcitrant SOC.

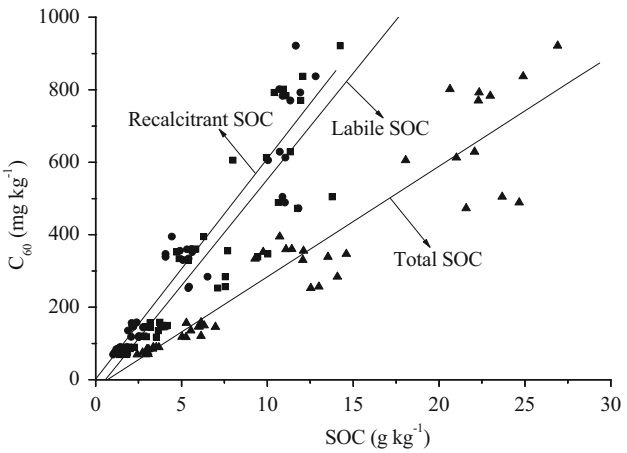

Fig. 3 Pearson's correlation coefficient of the cumulative mineralized C at 60 d (C_{60}) with total ($P < 0.01$, $r = 0.945$), labile ($P < 0.01$, $r = 0.912$), recalcitrant ($P < 0.01$, $r = 0.949$) SOC in mineral soils

Discussion

We expected that tree species influenced the composition of SOC pools by altering the relative abundance of labile and recalcitrant C compounds that return to soil (Giardina et al. 2001; Guo and Gifford 2002; Clemente et al. 2013; Fissore et al. 2008). However, our results differed from our hypothesis. In particular, total, labile, and recalcitrant SOC pools in the surface soil were similar among the four monoculture forests. This finding is consistent with recent observations (Lu et al. 2012; Wang et al. 2013a). These results indicate that aboveground litter slightly influenced the composition of SOC pools in the four forests but differences were insignificant due to the short time (approximately 28 years) of forest establishment. Some studies found that higher recalcitrant SOC accumulates in hardwood forest than in pine forest (Fissore et al. 2008) and

Author's personal copy

DOC and MBC are lower in hardwood forest (Yano et al. 2000; Giardina et al. 2001). In contrast, other studies have noted that labile SOC (e.g., MBC and DOC) is higher in broad-leaved forests than in coniferous forests (Smolander et al. 2005; Jiang and Xu 2006; Wang and Wang 2011). Jiang and Xu (2006) found a lower percentage of labile SOC compared with total SOC in soils under broad-leaved forests than in soils under coniferous forests. In our study, the percentage of labile SOC to total SOC in the surface soils did not differ among the four forests (data not shown).

In contrast to surface soil, subsurface soil layers (at 10–20 cm and 20–40 cm) in the four forests exhibited significant differences in labile and recalcitrant SOC pools. This result suggests that root inputs significantly affected SOC pool composition. Fine root turnover and exudation are important sources of SOC and greatly affect the varieties of SOC pool compositions (Kiikkilä et al. 2005). However, our results did not support our hypothesis that broad-leaved forest soil exhibited higher labile SOC pools and lower recalcitrant SOC pools than coniferous forest soil.

SOC chemical composition is influenced by tree species (Quideau et al. 2001; Hannam et al. 2004; Wang et al. 2010, 2013b). For instance, a high *O*-alkyl C in broad-leaved forests (*S. superba* and *M. macclurei*) is consistent with previous observations (Chen et al. 2004; Hannam et al. 2004). This observation indicated that tree species can influence SOC chemical composition. In contrast to other observations that alkyl C contents are higher in coniferous forests than in broad-leaved forests (Chen et al. 2004; Wang et al. 2010), our findings showed that coniferous forests contained lower alkyl C than broad-leaved forests. The alkyl C/*O*-alkyl C ratio is considered as an index of the extent of decomposition (Baldock and Preston 1995). However, the difference in alkyl C/*O*-alkyl C ratio was not detected in the four forests, and this result is inconsistent with that of Wang et al. (2010). In other words, alkyl C/*O*-alkyl C ratios were not different, indicating that the accumulated amounts of relatively stable C in the four forest soils were similar because of the lack of difference between labile and recalcitrant SOC pools found in surface soils (0–10 cm).

The four forest soils exhibited different SOC mineralization rates, and this result is consistent with that of Berger et al. (2010), who reported that CO_2 effluxes differed among spruces, beeches, and mixed stands at their Molasse site. This difference in SOC mineralization was partly attributed to the different quantities and qualities of litter input to the soil. Studies have also noted that broad-leaved forests yield higher respiration rates than coniferous forests (Borken and Beese 2005; Raich and Tufekcioglu 2000; Berger et al. 2010). In the 0–10 cm soil layer in this study, SOC mineralization rate was higher in *S. superba* and *M. Macclurei* forests than in *P. massoniana* and *C. lanceolata* forests. This result supported our hypothesis that nutrient-rich broad-leaf litter corresponds to a high SOC mineralization rate. By contrast, other studies have not revealed any significant difference in soil respiration rates between broad-leaved and coniferous forests (Borken et al. 2002; Subke et al. 2006; Vesterdal et al. 2012). These conflicting observations indicated that SOC mineralization is controlled by many complex factors and further study is needed.

SOC mineralization is influenced by litter quality (Raich and Tufekcioglu 2000; Berger et al. 2010; Fanin et al. 2011; Laganière et al. 2012; García-Palacios et al. 2013). Higher initial concentrations of N, P, and Ca and lower ratios of C/N and C/P in *S. superba* and *M. Macclurei* litters partly explained the variations in SOC mineralization among the four forests. This result also supported the observations revealed in previous studies, in which high litter quality corresponds to high soil respiration rates (Raich and Tufekcioglu 2000; Berger et al. 2010; Fanin et al. 2011; Vesterdal et al. 2012). We also found that SOC mineralization was positively correlated with initial N and P concentrations in the litters (data not shown). However, the initial N concentration exhibited a smaller positive correlation than did P concentration. This finding supports the results of Bréchet et al. (2009) and Fanin et al. (2011), indicating that P limitation is observed to a greater extent than N limitation in subtropical forest ecosystems. This result is also consistent with that of a previous study, in which added P increased soil microbial biomass in an old-growth tropical forest ecosystem (Liu et al. 2012).

C_{60} was more strongly correlated with recalcitrant and total SOC pools than with the labile SOC pool. This result is consistent with that of Ahn et al. (2009), who stated that higher C mineralization rates are observed in total SOC than in labile SOC, as determined by the acid hydrolysis method that we used in this study. Labile SOC does not guarantee the physical accessibility of C to soil microorganisms (Ahn et al. 2009) and provides limited information regarding the ability of microorganisms to use extracted substrates (Helfrich et al. 2008). Moreover, we documented stronger correlation between C_{60} and labile SOC than between C_{60} and total SOC. This result suggests that the labile SOC pool had greater effects on SOC mineralization than did the total SOC pool. Laganière et al. (2012) demonstrated that labile SOC was considered an important factor in addition to soil temperature as an indicator of soil respiration.

Conclusions

This study elucidated the effects of tree species on labile and recalcitrant SOC pools, SOC chemical composition, and mineralization. Tree species affected labile and recalcitrant SOC pools in subsurface soils (10–20 cm and

Author's personal copy

20–40 cm) but not in surface (0–10 cm) or deep (40–60 cm) soils. This finding suggested that root inputs may have more important effects on SOC pool composition than did aboveground litter. Tree species also affected SOC chemical composition and mineralization rates. Soils in broad-leaved forests had higher alkyl C and *O*-alkyl C intensities than those in coniferous forests, but the ratios of alkyl C to *O*-alkyl C did not differ. Surface soils in broad-leaved forests exhibited higher SOC mineralization rates than those in coniferous forests. A higher slope was found in a straight line between C_{60} and labile SOC than between C_{60} and total SOC. This result suggested that labile SOC pools had greater effects on SOC mineralization than did total SOC pools.

Acknowledgments This study was supported by the National Natural Science Foundation of China (Grant No. 31570466) and the National Basic Research Program of China (Grant no. 2012CB416905). We extend our sincerest gratitude to Xiuyong Zhang, Xiaojun Yu, and Guangbiao Xu for their assistance in collecting and analyzing soil samples.

References

Ahn M-Y, Zimmerman AR, Comerford NB, Sickman JO, Grunwald S (2009) Carbon mineralization and labile organic carbon pools in the sandy soils of a north Florida watershed. Ecosystem 12: 672–685

Baldock JA, Preston CM (1995) Chemistry of carbon decomposition processes in forests as revealed by solid state carbon-13 nuclear magnetic resonance. In: McFee WW, Kelly JM (eds) Carbon forms and functions in forest soils. Soil Sci Soc Am, Madison, WI, pp 89–117

Berger T, Inselsbacher E, Zechmeister-Boltenstern S (2010) Carbon dioxide emissions of soils under pure and mixed stands of beech and spruce, affected by decomposing foliage litter mixtures. Soil Biol Biochem 42:986–997

Bond-Lamberty B, Thomson AM (2010) Temperature-associated increases in the global soil respiration record. Nature 464: 579–582

Borken W, Beese F (2005) Soil respiration in pure and mixed stands of European beech and Norway spruce following removal of organic horizons. Can J Forest Res 35:2756–2764

Borken W, Xu Y, Davidson EA, Beese F (2002) Site and temporal variation of soil respiration in European beech, Norway spruce, and Scots pine forests. Global Change Biol 8:1205–1216

Bréchet L, Ponton S, Roy J, Freycon V, Coûteaux M-M, Bonal D, Epron D (2009) Do tree species characteristics influence soil respiration in tropical forests? A test based on 16 tree species planted in monospecific plots. Plant Soil 319:235–246

Chen CR, Xu ZH, Mathers NJ (2004) Soil carbon pools in adjacent natural and plantation forests of subtropical Australia. Soil Sci Soc Am J 68:282–291

Clemente JS, Simpson MJ, Simpson AJ, Yanni SF, Whalen JK (2013) Comparison of soil organic matter composition after incubation with maize leaves, roots, and stems. Geoderma 192:86–96

Côté L, Brown S, Paré D, Fyles J, Bauhus J (2000) Dynamics of carbon and nitrogen mineralization in relation to stand type, stand age and soil texture in the boreal mixedwood. Soil Biol Biochem 32:1079–1090

Fanin N, Hättenschwiler S, Barantal S, Schimann H, Fromin N (2011) Does variability in litter quality determine soil microbial respiration in an Amazonian rainforest? Soil Biol Biochem 43:1014–1022

Fissore C, Giardina CG, Kolka RK, Trettin KC, King GM, Jurgensen MF, Barton CD, McDowell SD (2008) Temperature and vegetation effects on soil organic carbon quality along a forested mean annual temperature gradient in North America. Global change Biol 14:193–205

García-Palacios P, Milla R, Álvaro-Sánchez M, Martín-Robes N, Maestro M (2013) Application of a high-throughput laboratory method to assess litter decomposition rates in multiple-species experiments. Soil Biol Biochem 57:929–932

Gentile R, Vanlauwe B, Six J (2011) Litter quality impacts short- but not long-term soil carbon dynamics in soil aggregate fractions. Ecol Appl 21:695–703

Giardina CP, Ryan MG, Hubbard RM, Binkley D (2001) Tree species and soil texture controls on carbon and nitrogen mineralization rates. Soil Sci Soc Am J 65:1272–1279

Guo LB, Gifford RM (2002) Soil carbon stock and land use change: a meta analysis. Glob Change Biol 8:345–360

Hannam KD, Quideau SA, Oh S-W, Kishchuk BE, Wasylishen RE (2004) Forest floor composition in aspen- and spruce-dominated stands of the boreal mixedwood forest. Soil Sci Soc Am J 68:1735–1743

Helfrich M, Ludwig B, Potthoff M, Flessa H (2008) Effect of litter quality and soil fungi on macroaggregate dynamics and associated partitioning of litter carbon and nitrogen. Soil Biol Biochem 40:1823–1835

Jiang P, Xu Q (2006) Abundance and dynamics of soil labile carbon pools under different types of forest vegetation. Pedosphere 16:505–511

Kiikkilä O, Kitunen V, Smolander A (2005) Degradability of dissolved soil organic carbon and nitrogen in relation to tree species. FEMS Microbiol Ecol 53:33–40

Ladegaard-Pederson P, Elberling B, Vesterdal L (2005) Soil carbon stocks, mineralization rates, and CO_2 effluxes under 10 tree species on contrasting soil types. Can J For Res 35:1277–1284

Laganière J, Paré D, Bergeron Y, Chen HY (2012) The effect of boreal forest composition on soil respiration is mediated through variations in soil temperature and C quality. Soil Biol Biochem 53:18–27

Liu L, Gundersen P, Zhang T, Mo J (2012) Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. Soil Biol Biochem 44:31–38

Lu S, Chen C, Zhou X, Xu Z, Bacon G, Rui Y, Guo X (2012) Responses of soil dissolved organic matter to long-term plantations of three coniferous tree species. Geoderma 170:136–143

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Pautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Quideau SA, Chadwick OA, Benesi A, Grahama RC, Anderson MA (2001) A direct link between forest vegetation type and soil organic matter composition. Geoderma 104:41–60

Raich JW, Tufekcioglu A (2000) Vegetation and soil respiration: correlations and controls. Biogeochemistry 48:71–90

Rovira P, Vallejo VR (2002) Labile and recalcitrant pools of carbon and nitrogen in organic matter decomposition at different depths in soil: an acid hydrolysis approach. Geoderma 107:109–141

Smolander A, Loponene J, Suominen K, Kitunen V (2005) Organic matter characteristics and C and N transformations in the humus layer under two tree species, *Betula pendula* and *Picea abies*. Soil Biol Biochem 37:1309–1318

Author's personal copy

Subke J-A, Inglima I, Cotrufo MF (2006) Trends and methodological impacts in soil CO_2 efflux partitioning: a meta analytical review. Glob Change Biol 12:921–943

Vesterdal L, Elberling B, Christiansen JR, Callesen I, Schmidt IK (2012) Soil respiration and rates of soil carbon turnover differ among six common European tree species. For Ecol Manag 264:185–196

von Lutzöw M, Kögel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2006) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions—a review. Eur J Soil Sci 57:426–445

Wang Q, Wang S (2011) Response of labile soil organic matter to changes in forest vegetation in subtropical regions. Appl Soil Ecol 47:210–216

Wang H, Liu S, Mo J, Wang J, Makeschin F, Wolff M (2010) Soil organic carbon stock and chemical composition in four plantations of indigenous tree species in subtropical China. Ecol Res 25:1071–1079

Wang Q, Xiao F, He T, Wang S (2013a) Responses of labile soil organic carbon and enzyme activity in mineral soils to forest conversion in the subtropics. Ann For Sci 70:579–587

Wang H, Liu S, Chang S, Wang J, Shi Z, Huang X, Wen Y, Lu L, Cai D (2013b) Stable soil organic carbon is positively linked to microbial-derived compounds in four plantations of subtropical China. Biogeosci Dis 10:18093–18119

Yano Y, McDowell WH, Aber JD (2000) Biodegradable dissolved organic carbon in forest soil solution and effects of chronic nitrogen deposition. Soil Biol Biochem 32:1743–1751