EFFECTS OF NATURAL FOREST TYPES ON SOIL CARBON FRACTIONS IN NORTH-EAST CHINA

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WANG D, WANG B & NIU X. 2014. Effects of natural forest types on soil carbon fractions in north-east China. Tree species have strong influence on soil carbon storage but the interactions are not well understood. Using the path analysis method, the response of soil carbon pool to changes in tree species were studied by comparing soil organic carbon quantity and quality in primary mixed broadleaved Korean pine (*Pinus koraiensis* and *Quercus mongolica*), natural Korean larch (*Larix olgensis*) and natural Chinese pine (*Pinus tabulaeformis*) forests in north-east China. Results showed that the effects of tree species on soil total organic carbon, recalcitrant organic carbon and microbial biomass carbon occurred at 0–40 cm depth. The mixed forest increased organic carbon and carbon fraction concentration over pure Korean larch and Chinese pine stands. Path analyses suggested that the effects of tree species on soil organic carbon mostly passed through direct effects on recalcitrant organic carbon and indirect effects on microbial biomass carbon but not through water-soluble organic carbon. Microbial biomass carbon may be used as a sensitive indicator of changes in soil organic carbon. Moreover, the response of recalcitrant organic carbon to forest conversion will also determine the magnitude of feedback of soil carbon to forest type due to its large storage in soil.

Keywords: Recalcitrant organic carbon, microbial biomass carbon, water-soluble organic carbon, forest conversion

INTRODUCTION

Forest ecosystems play a significant role in sequestering carbon in biomass and soil. The influence of tree species on forest soil carbon pool has long been discussed (Resh et al. 2002, Pérez-Cruzado et al. 2012). Labial fractions of organic matter such as light fraction carbon, microbial biomass carbon and water-soluble organic carbon can respond rapidly to changes in carbon supply (Haynes 2000). Such components have, therefore, been suggested as early indicators of the effects of management practices and cropping systems on soil organic matter quality (Ghani et al. 2003). However, most researches on effects of tree species on soil carbon pool are currently focused on the change in total soil organic carbon rather than soil carbon subpools (Neff et al. 2002).

Temperate and boreal forests act as major sinks for atmospheric carbon dioxide (CO_2), especially soil carbon pool (Lorenz & Lal 2010). North-east China possesses all the major forest types in northern East Asia. Forest types change from deciduous broadleaved, needle leaved and broadleaved mixed forests to boreal forest with increasing latitude in the region. The region is one of the biggest natural forest regions in China and possesses 24.79 M ha well-protected natural forests. Natural forests have high biodiversity and are of great value in silviculture, where they represent model systems for studying processes which are important for the implementation of sustainable forest management. Soil in a natural forest ecosystem has high carbon sink (Lal 2005). However, there are very few studies on effects of natural forest on levels of labile and recalcitrant carbon fractions as well as distribution of carbon fractions through soil profile depth in this region.

In this study, we focused on a primary mixed broadleaved Korean pine (*Pinus koraiensis* and *Quercus mongolica*) forest and two pure natural forests of Korean larch (*Larix olgensis*) and Chinese pine (*Pinus tabulaeformis*) forests to estimate effects of forest types on soil organic carbon quantity and quality. Relationships

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between recalcitrant organic carbon, microbial biomass carbon, water-soluble organic carbon and total organic carbon were also investigated. To obtain better understanding of carbon fraction response to forest types, we used path analysis to quantify direct and indirect interactions of carbon fractions with tree species.

MATERIALS AND METHODS

Study area

This research was carried out in a primary mixed broadleaved and Korean pine forests and two pure natural forests, Korean larch forest and Chinese pine forest, which are typical forest types in north-east China. The locations are in the Baishilazi Forest Ecological Research Station, Yiwulu Mountain Natural Reserve and Jinchang Forestry Farm, Wangqing Country of Jilin Province (40° 47'–43° 18' N, 121° 11'–130° 33' E). Annual average precipitation in the study areas ranges from 570 to 1400 mm and annual mean temperature ranges from 3.9 to 8.2 °C. The climate is characterised by cold weather during long winter and short cool summer. A large portion of the area is original mature forest. The average age of the three forests is over 60 years. The soil in these areas is dark brown earth (Cryumbreps in American Soil Taxonomy). Average soil pH of the horizon is 5.8. Soil bulk density and texture did not significantly differ among natural forests in 2011 (Figure 1).

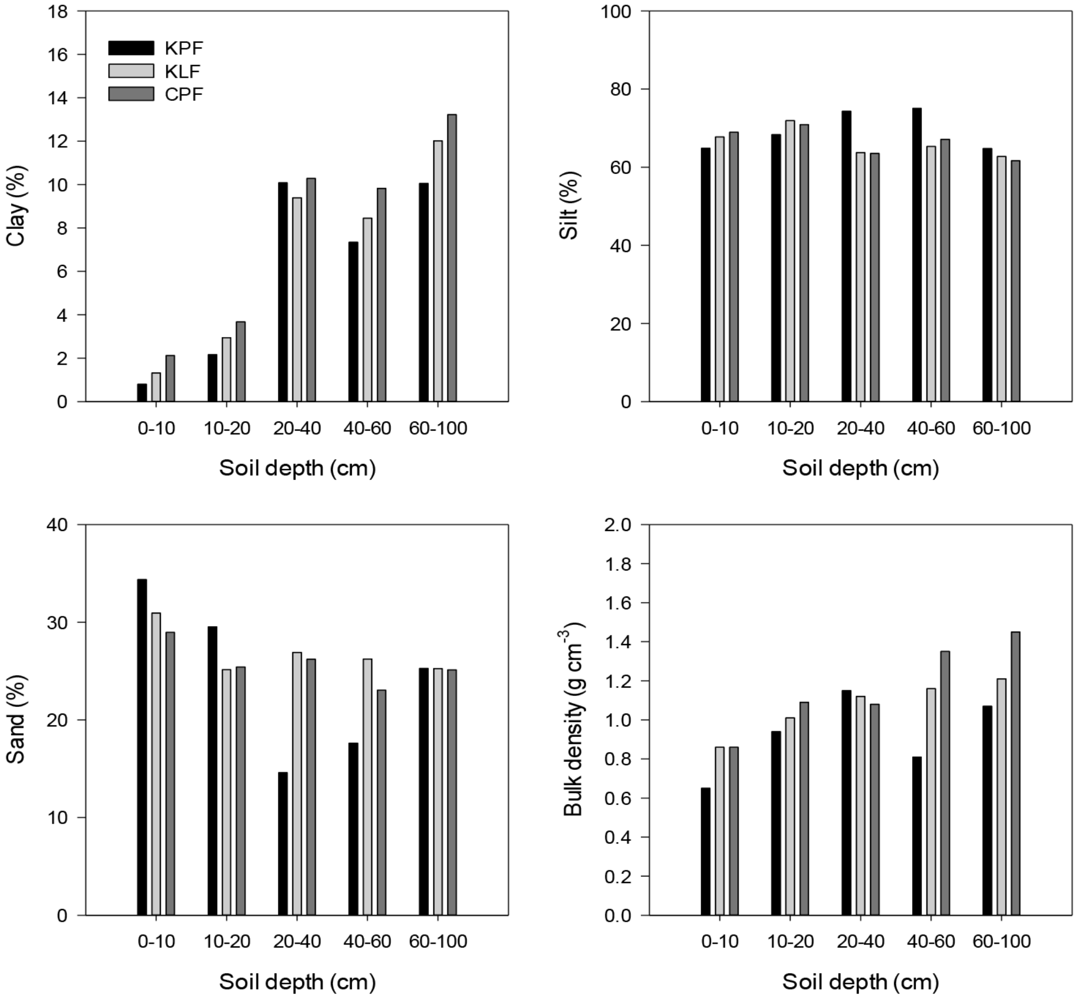

Figure 1 Texture and soil bulk density at different depths collected from mixed broadleaved Korean pine forest (KPF), Korean larch forest (KLF) and Chinese pine forest (CPF)

Soil sampling and analysis

In July 2011, three 20 m × 20 m plots for each ecosystem were established on the representative sites. Five soil profiles were randomly chosen in each plot. Four or five soil samples (> 200 g) at each depth of 0–10, 10–20, 20–40, 40–60 and 60–100 cm were collected from each profile (Wang et al. 2011). The soil samples were divided into two parts. One was immediately sieved through a 2-mm mesh and stored at 4 °C until the analyses for microbial biomass carbon and water-soluble organic carbon. The other part was also sieved through a 2-mm mesh and subsequently air dried for total organic carbon and recalcitrant organic carbon.

Fresh soil samples were analysed for microbial biomass carbon by fumigation extraction method (Vance et al. 1987). In brief, 25 g fresh soil was fumigated with chloroform for 24 hours and then extracted with 0.5 M K_2SO_4 for 2 hours on a shaker. The extracts were centrifuged and filtered (Whatman 42). Similar sets of non-fumigated samples were extracted by the same way. Microbial biomass carbon was calculated using the equation by Wu et al. (1990):

$$\text{Biomass carbon} = (F - C)/K_c$$

where F and C = the carbon concentrations in the extracts of fumigated and non-fumigated soils respectively and K_c = conversion factor, 0.45. Water-soluble organic carbon was extracted from 30 g of fresh soil with an addition of 60 ml of distilled water (Xu et al. 2010). The mixture was shaken for 30 min on a shaker at 250 rpm and at 20 °C, centrifuged for 20 min at 3500 rpm and the supernatant liquid was filtered through 0.45-µm cellulose nitrate membrane filter. Recalcitrant organic carbon was determined using acid hydrolysis technique (Leavitt et al. 1996). This was measured by refluxing 2 g soil in 6 M HCl at 116 °C for 18 hours. Refluxed residues were washed three times with deionised water, dried at 55 °C and ground to pass through a 180-µm screen (Collins et al. 2000). Total organic carbon was also measured. Carbon content was analysed using a total organic carbon analyser. Soil texture was analysed by pipette method and bulk density by soil core method. Soil pH was measured on a soil–water suspension (1:2.5).

Statistical analyses

All comparisons were performed using analysis of variance. Significance levels were set at $p < 0.05$ in all statistical analyses. Direct influence of independent variable (recalcitrant organic carbon, microbial biomass carbon or water-soluble organic carbon) upon dependent variable (total organic carbon) and indirect influence of one independent variable through another were measured with path coefficients. Path coefficients were calculated using Sigmastat package according to Dewey and Lu (1959). Residual effect (e_y) was calculated using the formula by Smith et al. (1997):

$$e_y = \sqrt{1 - R^2}$$

where R^2 = R squared in regression analyses.

RESULTS

Changes in quantity and quality of soil organic carbon

The concentration of total organic carbon decreased with increasing soil depth and about 70% of total organic carbon was stored at the top 40-cm soil. Carbon concentration of mixed broadleaved Korean pine forest was higher than that of Korean larch and Chinese pine forests at all depths (Figure 2). However, statistically significant differences were only found at 0–10, 0–20 and 40–60 cm depths.

Three fractions of recalcitrant organic carbon, microbial biomass carbon and water-soluble organic carbon behaved differently (Figure 2). The fractions also decreased with depth, especially at 0–10, 10–20 and 20–40 cm depths. Recalcitrant organic carbon accounted for 30–90% of the total organic carbon at all depths and they were highest in the mixed broadleaved Korean pine forest and lowest in the Chinese pine forest. Microbial biomass carbon accounted for just 0.3–3.0% but they were also significantly reduced with total organic carbon, i.e. in the order mixed broadleaved Korean pine forest > Korean larch forest > Chinese pine forest. The proportion of water-soluble organic carbon was smallest in natural forest soil, in particular in the mixed broadleaved Korean pine forest.

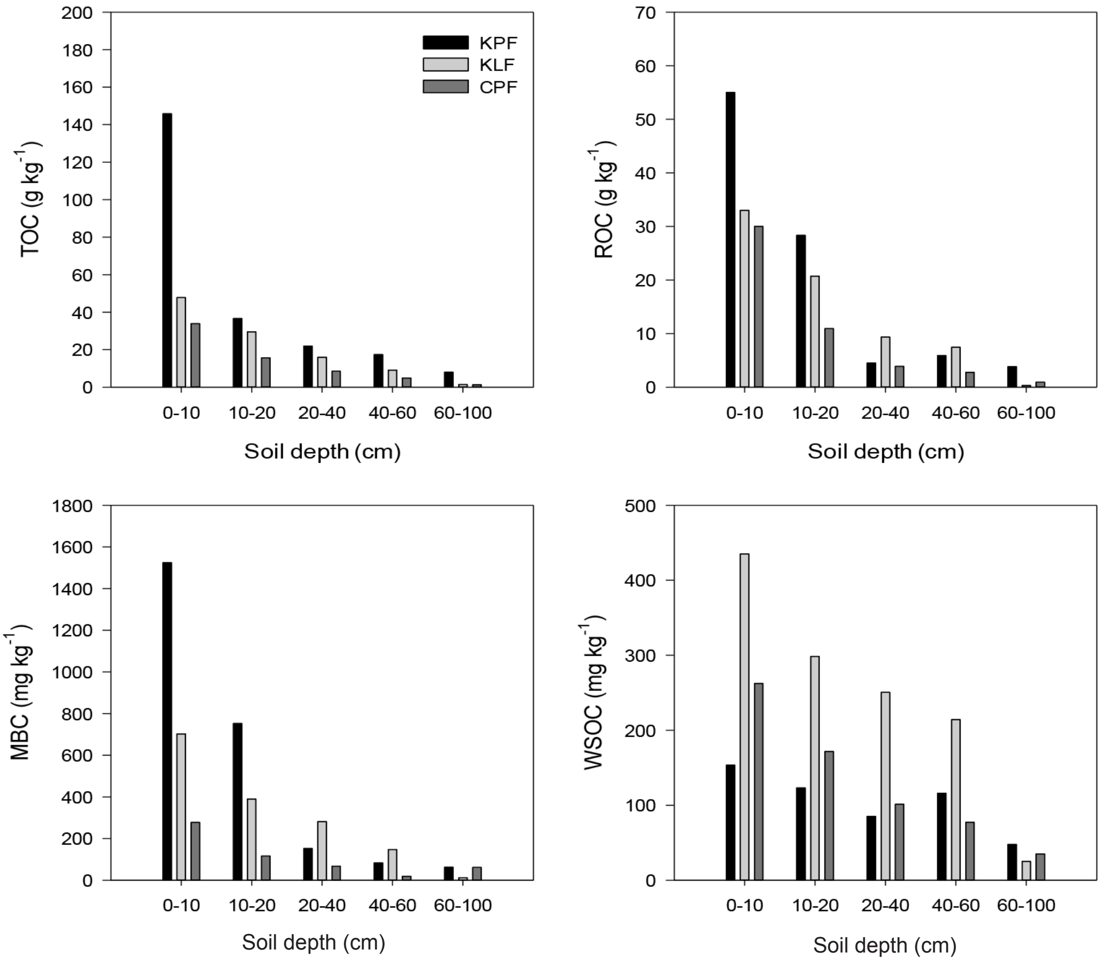

Figure 2 Total organic carbon (TOC), recalcitrant organic carbon (ROC), microbial biomass carbon (MBC) and water-soluble organic carbon (WSOC) obtained in mixed broadleaved Korean pine forest (KPF), Korean larch forest (KLF) and Chinese pine forest (CPF) for several soil depths

There was no significant difference in tree species for water-soluble organic carbon, although the fraction in the Korean larch forest was higher than that of the mixed broadleaved Korean pine and Chinese pine forests.

Contributions of microbial biomass carbon, recalcitrant organic carbon and water-soluble organic carbon to total organic carbon

There was highly significant correlation between total organic carbon and microbial biomass carbon or recalcitrant organic carbon (Table 1) in mixed broadleaved Korean pine, Korean larch and Chinese pine forests. Microbial biomass carbon showed highly significant correlation with recalcitrant organic carbon in all three forests at the same time (Table 1). Both microbial biomass carbon and recalcitrant organic carbon played essential roles in the sensitivity of tree species. The strongest correlations between recalcitrant organic carbon and total organic carbon in mixed broadleaved Korean pine forest, Korean larch forest and Chinese pine forest (r_{YX_3} = 0.954, 0.913, 0.985 respectively) were based almost entirely on the direct path (Tables 2 and 3). Effects of microbial biomass carbon on total organic carbon were due mostly to the indirect effect via recalcitrant organic carbon ($r_{X_1X_2} P_{YX_2}$ = 0.790, 0.525, 0.798 respectively). However, correlations between water-soluble organic carbon and total organic carbon (r_{YX_2}= 0.508, 0.545, 0.778 respectively) were lower and they were attributed to indirect effects of recalcitrant organic carbon ($r_{X_3X_2} P_{YX_2}$ = 0.504, 0.457, 0.685 respectively).

Table 1 Linear correlation coefficients between different carbon fractions and total organic carbon in mixed broadleaved Korean pine forest (KPF), Korean larch forest (KLF) and Chinese pine forest (CPF)

Forest type	Fraction	TOC	MBC	ROC	WSOC
KPF	MBC	0.910**	-	0.933**	0.583*
	ROC	0.954**	0.933**	-	0.595**
	WSOC	0.508*	0.583*	0.595*	-
KLF	MBC	0.947**	-	0.860**	0.585*
	ROC	0.913**	0.860**	-	0.750**
	WSOC	0.546*	0.585*	0.750**	-
CPF	MBC	0.948**	-	0.941**	0.730*
	ROC	0.984**	0.941**	-	0.808**
	WSOC	0.778**	0.730**	0.808**	-

*, ** significant at $p < 0.05$ and $p < 0.01$ respectively; TOC = total organic carbon, MBC = microbial biomass carbon, ROC = recalcitrant organic carbon and WSOC = water-soluble organic carbon

Table 2 Path analysis of the direct and indirect effects of the different carbon fractions on total organic carbon in mixed broadleaved Korean pine forest (KPF), Korean larch forest (KLF) and Chinese pine forest (CPF)

Forest type	Fraction	Direct effect	Indirect effect		
			MBC	ROC	WSOC
KPF	MBC	0.179	-	0.790	-0.058
	ROC	0.847	0.167	-	-0.060
	WSOC	-0.100	0.104	0.504	-
KLF	MBC	0.565	-	0.525	-0.142
	ROC	0.610	0.486	-	-0.182
	WSOC	-0.243	0.331	0.458	-
CPF	MBC	0.176	-	0.798	-0.026
	ROC	0.848	0.166	-	-0.028
	WSOC	-0.035	0.128	0.685	-

MBC = microbial biomass carbon, ROC = recalcitrant organic carbon, WSOC = water-soluble organic carbon

DISCUSSION

General patterns of soil organic carbon

Natural forest type affected soil carbon pool and its vertical distribution in the profile. The effects were mostly obvious in the upper 40-cm soil in these forests, which were consistent with the results of Yang et al. (2005) and Wang et al. (2008) who found that 60% of soil carbon storage was in the 0–40 cm soil layer for evergreen broadleaved forest, Chinese fir plantation and mixed plantations in China.

Microbial biomass carbon and water-soluble organic carbon displayed a clear decline with soil depth in the three natural forests, as also shown by findings in evergreen broadleaved and coniferous forests (Xu et al. 2010). Recalcitrant organic carbon decreased with increasing soil depth in the current study. Rovira and Vallejo (2007) showed that the decreasing content of recalcitrant organic carbon could be due to decreasing fine roots as soil depth increased, and the limited mobility of recalcitrant organic carbon from the surface to the deep soil horizons. In addition, our results showed

Table 3 Path equation of the effects of the different carbon fractions on total organic carbon in mixed broadleaved Korean pine forest (KPF), Korean larch forest (KLF) and Chinese pine forest (CPF)

Forest type	Carbon fraction	Path equation	e_y
KPF	X_1	0.910 = 0.179 – 0.0583 + 0.790	0.283
	X_2	0.954 = 0.847 + 0.167 – 0.0595	
	X_3	0.508 = -0.100 + 0.104 + 0.504	
KLF	X_1	0.947 = 0.565 – 0.142 + 0.524	0.202
	X_2	0.913 = 0.610 + 0.485 – 0.182	
	X_3	0.545 = -0.243 + 0.330 + 0.457	
CPF	X_1	0.948 = 0.176 – 0.0255 + 0.797	0.161
	X_2	0.985 = 0.848 + 0.165 – 0.0282	
	X_3	0.778 = -0.0350 + 0.128 + 0.685	

X_1, X_2, X_3 = microbial biomass carbon, water-soluble organic carbon and recalcitrant organic carbon respectively; decomposition of overall correlations between microbial biomass carbon and total organic carbon = $r_{YX_1} = P_{YX_1} + r_{X_1X_2} P_{YX_2} + r_{X_1X_3} P_{YX_3}$, $r_{YX_2} = P_{YX_2} + r_{X_2X_1} P_{YX_1} + r_{X_2X_3} P_{YX_3}$, $r_{YX_3} = P_{YX_3} + r_{X_3X_1} P_{YX_1} + r_{X_3X_2} P_{YX_2}$ where r_{YX_1}, r_{YX_2} and r_{YX_3} = correlation coefficients between different carbon fractions and total organic carbon, P_{YX_1}, P_{YX_2} and P_{YX_3} = the direct effect of microbial biomass carbon, water-soluble organic carbon and recalcitrant organic carbon respectively on total organic carbon, $r_{X_2X_1} P_{YX_1}$ and $r_{X_3X_1} P_{YX_1}$ = the indirect effect via microbial biomass carbon, $r_{X_1X_2} P_{YX_2}$ and $r_{X_3X_2} P_{YX_2}$ = indirect effect via water-soluble organic carbon, and $r_{X_1X_3} P_{YX_3}$ and $r_{X_2X_3} P_{YX_3}$ = indirect effect via recalcitrant organic carbon, e_y = residual variation due to unknown factors not included in the path equation

that there was significant correlation between recalcitrant organic carbon and microbial biomass carbon. This suggests that soil microbe is another important effect on recalcitrant organic carbon (Cheng et al. 2007).

Effects of tree species on soil organic carbon

Mixed-species forests had improved the amount of carbon sequestration in soil, which was the same trend observed by Resh et al. (2002). Total organic carbon and recalcitrant organic carbon in the top 20-cm soil were significantly higher in the mixed broadleaved Korean pine forest than that in the Korean larch and Chinese pine forests, but there was no significant difference between Korean larch and Chinese pine forests. Thus, higher carbon stocks in the mixed forest could be due to the presence of the broadleaved species rather than to the mixture per se. Water-soluble organic carbon at all depths did not show significant difference between the three tree species, while microbial biomass carbon was significantly different at depth 0–40 cm. Changes in these carbon fractions indicated that environment sensitivity of microbial biomass carbon was greater than that of recalcitrant organic carbon and water-soluble organic carbon. In addition, path analysis showed that recalcitrant organic carbon had the highest direct effects on total organic carbon in these forests. The effects may be because the proportion of recalcitrant organic carbon in total organic carbon was higher. Also, recalcitrant organic carbon, especially in the form of lignin, is beneficial for soil carbon sequestration because of its long residence time in soil due to the specificity of lignin-degradation enzymes and limited occurrence of the soil fungi (Zak et al. 2006). Thus, the response of recalcitrant organic carbon to forest types will also determine the magnitude of the effect of soil carbon on forest type due to its large storage in soil. Effects of microbial biomass carbon on total organic carbon were attributed to indirect effects. This suggested that effects of microbial biomass carbon on total organic carbon had resulted from the biological processes associated with microbial biomass, rather than from microbial biomass carbon. Microbial biomass, which is the most labile carbon fraction of soil organic carbon, is responsible for residue decomposition process (Powlson et al. 1987) and has been promoted as indicator of changes in soil organic carbon status (Haynes 2000), as shown in this study. Water-soluble organic carbon is commonly used as soil quality indicator in soil organic carbon change resulting from landuse change (Ghani et al. 2003). However, our results demonstrated that water-soluble organic carbon cannot be used as indicator of changes for soil organic carbon quality brought about by the tree species in forest soils. Only a small proportion of total labile carbon pool is extracted for water-soluble organic carbon (Balesdent 1996). Thus, there is limitation for using single-pool approach to investigate soil carbon responses towards changing environmental conditions (Neff et al. 2002).

Dominant species in tropical plantations and natural forests have been shown to increase or decrease carbon storage, depending on their functional characteristics (Ruiz-Jaen & Potvin 2010). Our results showed that types of forest affected not only total organic carbon content but also carbon fractions, as shown by Yang et al. (2009). Since most carbon is returned to the soil through litter, litter production and decomposition rates are estimated to predict carbon input from vegetation to soil (Zhang & Wang 2012). Litter decomposition rate is influenced by tree characteristics such as hardness, shape, soil N stock, C:N ratio and leaf longevity and quality, which in turn are dependent on tree species (Gower & Son 1992, Wang et al. 2013b). Compared with broadleaved litter, conifer litter contains more components that are difficult to decompose, resulting in litter accumulation in the forest floor and less carbon incorporation into the mineral soil (Berg 2000). Broadleaved forest contained higher microbial biomass carbon and water-soluble organic carbon than coniferous forest (Smolander & Kitunen 2002). Litter production could also be related to aboveground biomass, in particular leaf biomass (Nakane 1995, Wang et al. 2010). It has been reported that mixed Korean pine forest had higher biomass and net primary production than Korean larch and Chinese pine forests (Jiang et al. 1999).

Fine root is another important source of soil organic carbon. Microbial biomass carbon is strongly related to root carbon inputs (Gale et al. 2000). Fine roots may result in vertical distribution of carbon concentrations and fractions in the profile. Fine roots usually accumulate in upper layers, but in the horizons the characteristics of soil organic matter are also greatly affected by the more humified soil organic matter coming from H horizons while in B horizons, fine roots may constitute the main source of soil organic matter (Rovira & Vallejo 2002, 2007). Site environment and initial litter quality in regulating decomposition of fine roots played more critical roles than that of leaf litter (Wang et al. 2013a). Broadleaved trees may allocate more biomass in their roots, which can transfer more root detritus to the soil (Jandl et al. 2007).

Soil biota (e.g. fungi, bacteria and fauna) can transform organic material from the forest floor into mineral soils and strongly affect soil carbon dynamics (Fox et al. 2006). Soil microorganisms, especially fungi, affect decomposing beech leaves and water-soluble organic carbon fraction quality (Møller et al. 1999). In the current study, microbial biomass carbon in the mixed broadleaved Korean pine forest was significantly higher than those in Korean larch and Chinese pine forests. Microbial biomass carbon was significantly lower in coniferous plantation soil than in native broadleaved forest (Wang et al. 2007). Tree species affected soil fauna densities and abundance, which were higher in mixed stands than pure stands (Zou 1993). In the pure stand, soil pH and soil fauna activity were lower, which decreased the amount of organic material incorporated into mineral soils (Thuille & Schulze 2006). Therefore, these results could explain the higher organic carbon concentration in the primary mixed broadleaved Korean pine forest than natural Korean larch and Chinese pine forests.

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