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Stability of soil organic carbon changes in successive rotations of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantations

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Abstract

The importance of soil organic carbon (SOC) under forests in the global carbon cycle depends on the stability of the soil carbon and its availability to soil microbial biomass. We investigated the effects of successive rotations of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantations on the stability of SOC and its availability to microbes by adopting the two-step hydrolysis with H_2SO_4 and density fractionation. The results showed that successive rotations of Chinese fir decreased the quantity of total SOC, recalcitrant fraction, and carbohydrates in Labile Pool I (LP I), and microbial properties evidently, especially at 0–10 cm horizon. However, cellulose included in Labile Pool II (LP II) and the cellulose/total carbohydrates ratio increased in successive rotations of Chinese fir. The non-cellulose of carbohydrates included in LP I maybe highly available to soil microbial biomass. Hence the availability of SOC to microbial biomass declined over the successive rotations. Although there was no significant change in recalcitrance of SOC over the successive rotations of Chinese fir, the percentage of heavy fraction to total SOC increased, suggesting that the degree of physical protection for SOC increased and SOC became more stable over the successive rotations. The degradation of SOC quality in successive rotation soils may be attributed to worse environmental conditions resulted from disturbance that related to “slash and burn” site preparation. Being highly correlated with soil microbial properties, the cellulose/total carbohydrates ratio as an effective indicator of changes in availability of SOC to microbial biomass brought by management practices in forest soils.

Key words: Chinese fir plantation; forest soils; organic carbon; microbial property; biochemical quality; density fractionation

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Introduction

Soil organic carbon (SOC) under forests plays an important role in the global carbon cycle. However, the role of these soils now and in the future strongly depends on the stability of the soil carbon and its availability to the soil microbial biomass.

The capacity of soils to accumulate and stabilize organic carbon (OC) has received great attention in recent years to evaluate how the increase in atmospheric CO_2 content could be affected by management practices. OC accumulates in soil is smaller than the input from litterfall and/or dead roots when the amount lost by microbial activity. Therefore, to properly manage the soils as a sink of OC, it is necessary to understand the reasons in OC losses, in other words, why SOC becomes stable. In addition to chemical processes such as precipitation by Ca^{2+} or Fe^{3+}, there are two main reasons: (1) biochemical recalcitrance, i.e., the content of organic fractions difficult to decompose (recalcitrant OC), and (2) physical protection, which makes the OC partly unavailable for the microflora, namely form the physical barriers between substrates and decomposer organisms (Christensen, 2001; Wang *et al*., 2005a; Lützow *et al*., 2006). Soil microbes are responsible for the decomposition and mineralization of SOC (Brookes, 1995). Biochemical quality of SOC is defined as the capacity of SOC to be utilized by soil microbes as a source of energy (Rovira and Vallejo, 2002). Soil microbial properties, such as microbial biomass carbon (MBC), microbial quotient (MQ), basal respiration (BR) and metabolic quotient ($q\mathrm{CO}_2$), have proved to be powerful indicators of changes in the quantity and quality of SOC (Nannipieri *et al*., 1990; Riffaldi *et al*., 1996; Hernandez *et al*., 1997; Liang *et al*., 1998; Lundquist, 1999; Balota *et al*., 2003). However, the relationship between biochemical quality of SOC and soil microbial properties are still unknown.

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is one of fast growing tree species with most fine timber in subtropical China. Land used for plantation was mostly covered by broadleaf forests that had been cleared, and

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residues were slashed and burned before planting Chinese fir. Chinese fir plantation is usually established with a short rotation time of around 25 years. In addition to planting new areas with Chinese fir, more and more plantations are being established with successive rotations of Chinese fir. In other words, once planted with Chinese fir, the sites are usually retained under Chinese fir for several rotations (Chen and Wang, 2004). It has been proved that human disturbance, such as burning residues during site preparation resulted in the reduction of carbon stocks and soil microbes in successive rotations (Feng *et al*., 1982; Chen and Wang, 2004; Zhang *et al*., 2004; Wang *et al*., 2006). However, there is very little information of any attempt to explore effects of successive rotation of coniferous plantation on the stability of SOC and its availability to soil microbial biomass.

Therefore, the objectives of our studies focused on the following points: (1) how biochemical recalcitrance, physical protection, and soil microbial properties are affected by successive rotations of coniferous plantation; (2) the relationship between biochemical quality of SOC and soil microbial properties.

1 Materials and methods

1.1 Experimental sites

The study was conducted at the forest region of Huitong County in Hunan Province, China. The sites are located at latitude between 26°45′N and 27°02′N, longitude between 109°34′E and 109°52′E, and an altitude of about 300 m above sea level under a humid mid-subtropical monsoon climate. The mean annual precipitation in the range of 1200–1400 mm. The mean temperature is 16.5°C with a mean minimum of 4.9°C in January and a mean maximum of 26.6°C in July. The relative humidity is 80%. The main characteristics of the forest stands soil are shown in Table 1. Soils of all the investigated sites are developed from the similar parent materials (slate and shale), and classified as Oxisols according to U.S. Soil Taxonomy (Chen *et al*., 2000). Thereby, there were similar soil properties among Chinese fir plantations prior to the establishment. Nine plantations of Chinese fir from the first rotation to the third rotation were selected. They all have a similar age (the same growth stage) and stocking density (1200–1600 stems/hm^2), which meant that every rotation contained three available sites as replicates. The situations of each site are shown in Table 2.

Table 2 Status of experimental plots

Site		Altitude (m)	Latitude	Longitude	Aspect	Age (year)
FCF	I	364	26°46′58.7″	109°41′44.6″	NE 40°	17
	II	321	26°46′45.7″	109°39′6.4″	ES 20°	15
	III	336	26°46′49.0″	109°39′12.2″	NW 30°	15
SCF	I	310	26°47′7.4″	109°35′55.6″	EN 25°	18
	II	321	26°47′7.9″	109°35′53.8″	EN 15°	18
	III	431	26°50′55.3″	109°36′29.1″	EN 18°	16
TCF	I	390	26°50′34.4″	109°42′00″	EN 10°	18
	II	390	26°50′20.8″	109°41′41.6″	SE 20°	18
	III	362	26°50′58.5″	109°41′34.3″	SE 20°	15

N: north; E: east; S: south; W: west.

1.2 Soil sampling

Litter horizon was removed before sampling. The soil samples (0–10 cm and 10–20 cm depth) were collected using a stainless cylinder with 3 cm inner diameter in August, 2006. In each site the soil was collected from 15 points randomly, and mixed homogenously. After visible roots and organic residues removed, the mixed soil sample was divided into two parts. One was sieved through a 2-mm mesh immediately and stored at 4°C until analysis for the estimation of MBC and other microbial properties. The other part was also sieved through a 2-mm mesh and subsequently air-dried for OC fractionation and determination of biochemical quality of SOC. The sample was ground through 0.25-mm mesh prior to determine the SOC.

1.3 Analytical procedures

1.3.1 Soil physicochemical analysis

Soil pH was determined by measuring the pH of a soil water suspension (1:2.5 water suspension). The soil texture was analyzed according to pipette method and bulk density according to soil core method (Lu, 2000). Soil total OC (TOC) was determined by potassium dichromate oxidation and total N by the semimicro-Kjeldahl method. Total P was measured colorimetrically and total K by flame emission spectrometry (Liu, 1996).

1.3.2 Biochemical quality of soil organic carbon

To quantify SOC biochemical quality, the two-step hydrolysis with H$_2$SO$_4$ recommended by Oades *et al*. (1970)

Table 1 Physicochemical characteristics of Chinese fir plantation different rotations

Site		pH	Bulk density (g/cm^3)	Total N (g/kg)	Total K (g/kg)	Total P (g/kg)	Sand (%)	Silt (%)	Clay (%)	TOC (g/kg)
FCF	I	4.86	1.03	1.81	11.27	0.128	8.43	41.53	50.04	18.84
	II	4.46	1.15	1.87	12.05	0.137	7.80	39.83	52.37	17.32
	III	4.32	1.27	1.74	11.63	0.144	9.15	34.42	56.43	17.94
SCF	I	4.59	1.25	1.52	11.83	0.122	8.63	42.06	49.31	16.67
	II	4.66	1.19	1.38	10.56	0.115	10.28	43.62	46.10	15.72
	III	4.63	1.25	1.45	10.76	0.117	7.32	47.31	45.37	15.11
TCF	I	4.68	1.32	1.11	9.57	0.094	7.54	44.95	47.51	14.80
	II	4.56	1.30	1.31	10.15	0.119	8.04	41.20	50.76	15.84
	III	4.65	1.27	1.12	10.72	0.104	8.66	38.31	53.03	14.22

FCF: the first rotation of Chinese fir plantation; SCF: the second rotation of Chinese fir plantation; TCF: the third rotation of Chinese fir plantation. I, II, and III are three replicates for the same forest type.

for a maximum release of carbohydrates was applied. About 500 mg of ground soil sample was hydrolyzed with 20 mL of 2.5 mol/L H_2SO_4 in a sealed Pyrex tube, at 105°C for 30 min. The hydrolysate (Labile Pool I, LP I) was recovered by centrifugation. The residue was washed with distilled water and dried. Then, 2 mL of 13 mol/L H_2SO_4 was added, and the tubes were placed on an end-over-end shaker overnight. After diluting the acid with water to 1 mol/L, the residue was hydrolyzed 3 h at 105°C. The hydrolysate (Labile Pool II, LP II) was also recovered by centrifugation. The residue (recalcitrant pool) was washed again, dried at 60°C, and taken as recalcitrant fraction (RF) (Oades *et al.*,1970; Rovira and Vallejo, 2002).

The carbon of the recalcitrant fraction was analyzed through potassium dichromate oxidation. Then, recalcitrancy indices (RI_C, %) was calculated (Rovira and Vallejo, 2002):

$$RI_C = (\text{Recalcitrant carbon}/\text{TOC})\times 100 \quad (1)$$

Carbohydrates in the labile pools were analyzed for total sugars according to the phenol-sulphuric method (Safarik and Santruckova, 1992), using glucose as a standard, after elimination of Fe^{3+} with Na_2CO_3 to avoid interferences (Martens and Frankenberger, 1993). Carbohydrates of LP II correspond to cellulose, whereas those of LP I include polysaccharides of both plant origin (hemicelluloses, starch residues) and microbial origin (microbial cell walls). Therefore, the LP II/(LP I + LP II) ratio for sugars is equivalent to the cellulose-to-total-carbohydrates ratio (Oades *et al.*, 1970).

1.3.3 Soil microbial properties

Soil microbial biomass carbon (MBC) was determined by the chloroform fumigation extraction method (Vance *et al.*, 1987). Soil basal respiration (BR) was determined by measuring CO_2 evolution (Xu and Zhen, 1986). Field-moisture soil sample (equals to 20 g oven-dry soil) was placed in gauze and incubated in 500-mL air-tight glass vessel at 28°C for 24 h. The CO_2 evolved from the soil was absorbed in 15 mL of 0.1 mol/L NaOH and the unconsumed base titrated with 0.05 mol/L HCl following addition of $BaCl_2$. qCO_2 was calculated using dividing the basal respiration rate by the corresponding microbial biomass carbon. The microbial quotient was calculated using dividing MBC by the corresponding TOC.

1.3.4 Organic carbon fractionation

The method of SOC fraction was established according to Golchin *et al.* (1994), with three degrees of physical protection for OC: non-protected (free light, extractable without sonication), occluded (extractable by sonication) and protected (retained in the residue, after sonication). The procedure was as follows: (1) 20 g of sample was placed in a 200-mL centrifuge tube with 100 mL of NaI solution (ρ = 1.8 g/mL), gently shaken by hand, and left standing at room temperature overnight. After centrifugation at 3500 r/min for 15 min, the supernatant was filtered through a membrane filter (0.45 μm) into a millipore vacuum unit. The fraction recovered on the filter was washed with 100 mL of 0.01 mol/L $CaCl_2$ solution and 200 mL of distilled water, and then the fraction was transferred to a pre-weighted 50 mL beaker. The sediment was resuspended in 100 mL NaI, centrifuged, and filtered as described above. The obtained fractions were added to the previous ones. After left standing for 24 h, it was dried at 60°C for about 72 h, weighted, and then was taken as free light fraction (FLF). (2) The sediment was resuspended in 100 mL NaI, shaken and sonicated using a ultrasonic disintegrator for 15 min, at 100 W, and left standing 4 h. The centrifugation and filtration procedure was repeated two times as described above. The fraction recovered from the supernatant was referred to occluded light fraction (OLF). (3) The sediment was resuspended in 100 mL distilled water, shaken for 20 min and centrifuged 20 min at 4000 r/min. The sediment was washed with distilled water at least 3 times, then transferred to a pre-weighted beaker, dried at 60°C to constant weight and weighted. It was taken as heavy fraction (HF). All fractions were ground in an agatha mortar, through a 60 eye mesh, and analyzed for OC content through potassium dichromate oxidation.

1.3.5 Statistical analysis

All data are expressed on oven-dry (105°C) soil weight basis, and statistical analyses were conducted with the SPSS 13.0. One-way ANOVA was used to analyze means, to least significant difference at the 5% level. When significance was observed at the $p < 0.05$ level, LSD test was used to carry out multiple comparisons. If the analyzed data were percentages, they were transformed previously by arcsine square root to ANOVA. Pearson's test was used to determine whether there was significant correlation between measured properties of the soils.

2 Results and discussion

2.1 Changes in the quantity of soil organic carbon

The TOC content under different successive rotations of Chinese fir are shown in Fig. 1. The successive rotation of Chinese fir reduced the concentrations of TOC in 0–20 cm soil, which was consistent with the observations by Wang *et al.* (2005b), Wang and Wang (2007), and Zhang *et al.*

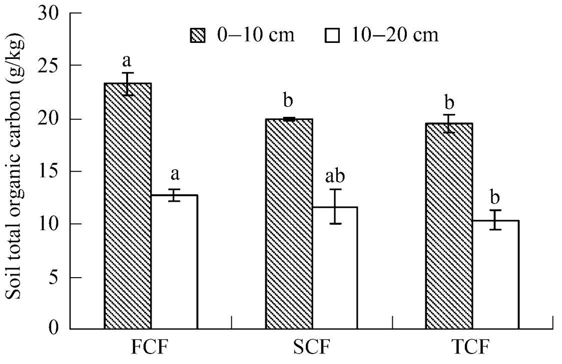

Fig. 1 Comparisons of soil total OC under different rotations of Chinese fir plantations.

(2004). However, there were no significant difference in TOC between the second rotation (SCF) and the third one (TCF). In the deeper soil layer (10–20 cm), the changes of TOC from FCF to SCF were also insignificant. The decline of TOC could be attributed to poor site preparation practices, such as clear-cutting, slash burning, and ploughing the site before replanting, which resulted in rapid and large loss of soil organic matter. Yang *et al*. (2005) reported that clear-cutting and slash burning had caused marked short-term changes in SOC in Chinese fir forest. Ma *et al*. (1997) also found 6.6% of total soil organic matter was lost during slashing and burning, and 10.1% was lost with erosion over the next 4 years after burning.

2.2 Changes of soil microbial properties

Microbial biomass is the most active fraction of soil organic matter (Diaz-Ravina *et al*., 1993). Microbial quotient (MQ, the percentage ratio of MBC to TOC) can reflect the availability of SOC to the soil microbes (Anderson and Domsch, 1986) and this ratio declines significantly as the concentration of available OC decreases (Joergensen and Scheu, 1999; Vance and Chapin, 2001). Basal respiration (BR), the average carbon content mineralized daily per kilogram soil throughout the incubation, is indicative of total microbial activity (Nannipieri *et al*., 1990). In the present study, microbial biomass carbon (MBC) declined over successive rotation of plantations (Table 3). Compared with FCF, the concentrates of MBC under SCF and TCF decreased by 16.8% and 45.0% in 0–10 cm soil, and by 17.6% and 24.3% in 10–20 cm soil, respectively. The change of MBC was no significant between SCF and TCF in 10–20 cm soil. The values of MQ and BR in 0–10 cm soil increased in the order: FCF > SCF > TCF. However, there was no significant difference among them in 10–20 cm soil (Table 3). Similar decreasing patterns have been documented in the literature regarding a variety of microbiological parameters (Wang *et al*., 2005b, 2006). It suggests that the available OC pools decreased and microbial activity declined under successive rotations of Chinese fir, which could be owing to poor litter fall under successive rotations of Chinese fir failing to provide sufficient substrate to sustain the microbial nutrient pools (Feng *et al*., 1982; Huang *et al*., 2004).

The $q\mathrm{CO}_2$ is a sensitive indicator of microbial activity and has been used to assess the process of soil development or degradation (Ren and Stefano, 2000). The more efficiently the microbial function, the greater the fraction of substrate carbon is incorporated into biomass and the less carbon per unit biomass is lost through respiration, which results in a low $q\mathrm{CO}_2$ (Behera and Sahani, 2003). Thus, a high $q\mathrm{CO}_2$ have been associated with ecosystem stresses (Ren and Stefano, 2000). Our results showed that $q\mathrm{CO}_2$ was the highest in TCF soil, although the changes were insignificant in 10–20 cm layer (Table 3), suggesting that the process, the environmental conditions for soil microbes is worse and the ecosystem was in degradation. Intense competition for limited nutritional resources between microbial and root biomass in plantation soils might explain the higher stress existing under SCF and TCF (Agnelli *et al*., 2001; Villar *et al*., 2004; Goberna *et al*., 2006). Under such stressed conditions, much energy would be diverted to maintenance and less to biosynthesis (Islam and Wei, 2000). Furthermore, the rise in the portion of energy required for maintenance in soils of successive rotation of Chinese fir might reflect of the shift in the bacterial/fungal biomass ratio (Goberna *et al*., 2006). This assumption is supported by the result from Feng *et al*. (1982) in Hunan Province and Sheng and Fan (2005) in Fujian Province, who observed that over successive rotation of Chinese fir, the numbers of both bacteria and fungi decreased evidently, but the bacterial/fungal biomass ratio increased. Bacteria produce less biomass but present a higher respiration rate, and hence a decrease in the relative abundance of fungi might provoke an increase in the $q\mathrm{CO}_2$ (Grayston *et al*., 2001).

2.3 Biochemical quality of soil organic carbon

Oades *et al*. (1970) found that LP I comprised non-cellulosic polysaccharides, whereas LP II only consisted of cellulose. The former was either of plant or microbial origin, and the latter was mainly of plant origin. The observation by Rovira and Vallejo (2002) has illustrated that the carbohydrates can transfer from LP II to LP I, probably monosaccharides or oligosaccharides resulting from the degradation of lignocellulose. However, cellulose is the most resistant to biodegradation among carbohydrates (Minderman, 1968). In this study, the amount of carbohydrates in LP I under FCF was significantly higher than under SCF and TCF (Table 4). However, the amount of carbohydrates in LP II and LP II/(LP I + LP II) increased over successive rotations of Chinese fir, and these differences were significant except that between SCF

Table 3 Changes of soil microbial properties in different rotations of Chinese fir plantation

	MBC (mg/kg)	$q\mathrm{CO}_2$ (μg C/(mg·h))	MQ (%)	BR (μg C/(g·d))
0–10 cm depth				
FCF	295.58 ± 19.07 a	0.60 ± 0.08 b	1.31 ± 0.07 a	4.27 ± 0.38 a
SCF	245.88 ± 8.08 b	0.60 ± 0.03 b	1.23 ± 0.04 a	3.54 ± 0.13 b
TCF	162.70 ± 24.65 c	0.84 ± 0.09 a	0.87 ± 0.12 b	3.26 ± 0.38 b
10–20 cm depth				
FCF	170.88 ± 11.66 a	0.74 ± 0.05 a	1.12 ± 0.14 a	3.02 ± 0.20 a
SCF	140.79 ± 21.99 b	0.91 ± 0.16 a	0.99 ± 0.06 a	3.01 ± 0.14 a
TCF	129.42 ± 1.29 b	0.95 ± 0.09 a	1.01 ± 0.08 a	2.96 ± 0.28 a

MBC: microbial biomass carbon; $q\mathrm{CO}_2$: metabolic quotient; MQ: microbial quotient; BR: basal respiration.
Data are expressed as means ± standard deviation, $n = 3$, data with the different letter are significantly different at $p < 0.05$ in the same depth.

Table 4 Biochemical quality of SOC under different rotations of Chinese fir plantations

	LP I (g/kg)	LP II (g/kg)	RF (g/kg)	RI_C (%)	LP II/(LP I+LP II) (%)
0–10 cm depth					
FCF	5.84 ± 0.27 a	1.67 ± 0.10 c	9.87 ± 0.40 a	36.3 ± 0.7 a	23.3 ± 2.1 c
SCF	3.92 ± 0.08 b	2.27 ± 0.01 b	8.39 ± 0.77 b	37.4 ± 0.8 a	36.7 ± 0.6 b
TCF	3.81 ± 0.19 b	2.86 ± 0.16 a	7.98 ± 0.33 b	36.9 ± 0.9 a	42.9 ± 1.9 a
10–20 cm depth					
FCF	3.88 ± 0.31 a	1.62 ± 0.09 b	5.13 ± 0.23 a	32.9 ± 1.5 a	29.5 ± 1.7 b
SCF	3.06 ± 0.21 b	1.85 ± 0.05 a	4.69 ± 0.88 a	33.7 ± 2.2 a	37.7 ± 2.2 a
TCF	2.98 ± 0.06 b	1.91 ± 0.08 a	3.05 ± 0.69 b	33.4 ± 0.9 a	39.1 ± 0.9 a

LP I: Labile Pool I; LP II: Labile Pool II; RF: recalcitrant fraction; RI_C: recalcitrancy indices.

and TCF in 10–20 cm soil. These changes could be attributed to: (1) a smaller quantity of microbial biomass and reduced microbial diversity (Li *et al*., 2005) resulting in the decline of microbial polysaccharides, included in LP I, and (2) the more difficult or slower degradation of cellulose resulting from low microbial activity in soils of successive rotation. On the other hand, the ratio of cellulose to total carbohydrates decreases as decomposition proceeds, and hence a high cellulose/total carbohydrates ratio indicated a relevant presence of fresh plant contributions (Rovira and Vallejo, 2002). In the present study, this ratio increased over successive rotation of Chinese fir (Table 3), suggesting that more organic matter in soil of successive rotations was at the beginning of decomposition or decomposed poorly compared with FCF.

The contents of RF decreased with successive rotation of Chinese fir, which probably was attributed to the accelerated turn of stable organic matter resulting from human practice (Xu and Xu, 2003). In despite of the decline of RF detected in soils of successive rotation, RI_C values in both SCF and TCF soils were maintained at levels similar to those in FCF soils at the same depth. It suggested that plant species could be the dominant factor for maintaining recalcitrance of SOC. This result was consistent with Oyonarte *et al*. (2008), who found that the parameters defining SOC quality were mainly related to the type of vegetation, not to the edaphic environment.

Since SOC is older in deeper horizons, biochemical recalcitrance should increase with depth (Table 4). In this study, however, the values of RI_C were lower in 10–20 cm layer than in 0–10 cm layer, which was consistent with the observations by Goh *et al*. (1984) and Tan *et al*. (2004). The hydrolysate is expected to move down the soil profile more easily than the unhydrolyzable fraction (Goh *et al*., 1984). Therefore, even with the probable partial biodegradation of the hydrolyzable fraction during the process, this would result in the passage of hydrolysable compounds from the surface to the deeper horizon (Rovira and Vallejo, 2007), which resulted in decreased RI_C in the latter under all forest types studied.

2.4 Changes and distribution of OC in the fractions

In general, as the contents of TOC decreased with successive rotation of Chinese fir plantations, the amount of OC in each fraction reduced (Fig. 2), namely there was positive correlation between TOC and OC in fractions (Fig. 3). But for OLF the change was inconsistent and data dispersion resulted in a lack of significance. The correlation between FLF or HF and TOC was significant, and the correlation between OLF and SOC was insignificant. This suggested that the accumulation of TOC was controlled by OC in FLF and HF. In addition, correlation coefficients between TOC and HF was the highest at 0–10 cm horizon, suggesting that change of FLF was very important for changes of TOC at this horizon. At the 10–20 cm horizon, however, the correlation between HF and TOC were the most significant, suggesting that change of HF was more important than FLF at this horizon. It would be explained by the different origins of SOC between the two layers. SOC in the upper layer mainly originates from the

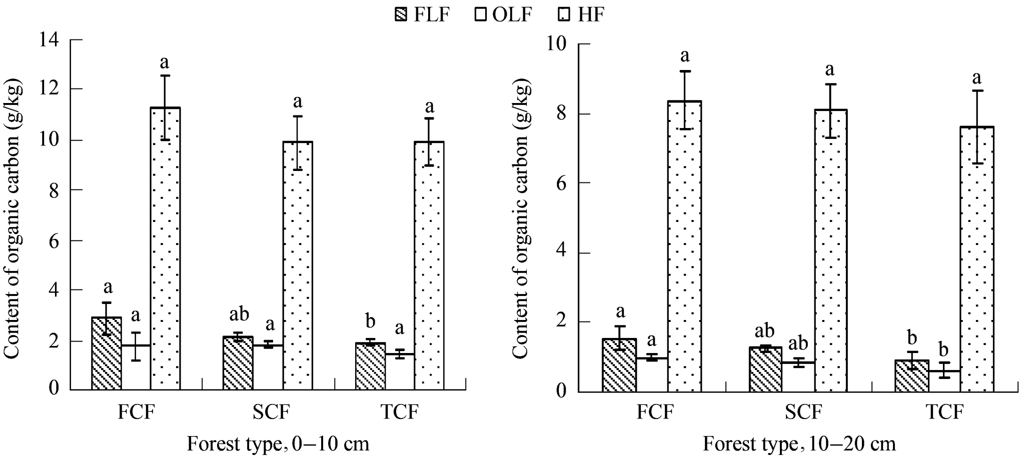

Fig. 2 Changes of OC in the fractions in successive rotations of Chinese fir plantations.

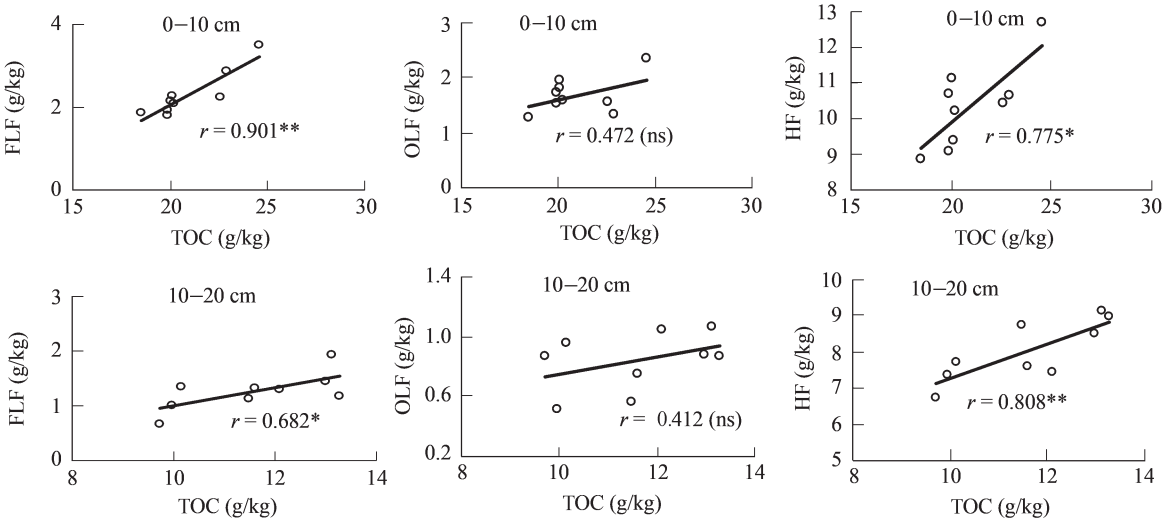

Fig. 3 Changes of OC in the various fractions vs. TOC in different horizon.

decomposed plant litter, which was distributed into FLF at first (Liu, 2007). In the deeper layer, C input occurs mainly through plant roots and leaching of dissolved OC, therefore, physical protection may be the more important ways for stabilization of SOC (Six *et al*., 2002; Rovira and Vallejo, 2007; Lützow *et al*., 2006).

For distribution of OC in the fractions, dominance of the OC decreased in the following order: HF > FLF > OLF (Table 5). Over successive rotations of Chinese fir plantations, the percentage of FLF/TOC reduced significantly ($p < 0.05$) and there was no evident change in OLF/TOC ($p > 0.05$), but HF/SOC increased significantly ($p < 0.05$). This suggested that more proportion of OC in soil of successive rotation of Chinese fir was protected, which could be attributed to lower mineralization rate of HF binding closely with different size fractions into organo-mineral complex (Wu, 2003). In other words, responses of HF to soil management and land use change were slower than those of FLF. In this study, compared with FCF, the OC contents of FLF and HF under SCF were reduced by 26.0% and 12.4% respectively in 0–10 cm layer, and by 17.9% and 3.3% respectively in 10–20 cm layer, respectively. Wu (2003) also found that the decrease of FLF was faster than HF (42 years) after reclamation of nature gray-brown soil, by 91% and 60%, respectively. Therefore, the content of HF can reflect the capacity of soils to protect and stabilize organic carbon.

Table 5 Distribution of OC in the fractions in successive rotations of Chinese fir plantations

	FLF/TOC (%)	OLF/TOC (%)	HF/TOC (%)
0–10 cm depth			
FCF	18.0 ± 1.9 a	11.0 ± 1.8 a	70.9 ± 3.5 b
SCF	15.4 ± 1.5 b	13.2 ± 1.4 a	71.4 ± 2.9 ab
TCF	14.4 ± 0.3 b	11.0 ± 2.0 a	74.6 ± 1.3 a
10–20 cm depth			
FCF	14.2 ± 1.5 a	9.2 ± 1.4 a	76.6 ± 2.7 b
SCF	12.5 ± 3.1 ab	8.4 ± 0.5 a	79.1 ± 3.6 ab
TCF	10.2 ± 2.9 b	7.0 ± 2.1 a	82.8 ± 2.6 a

FLF: free light fraction; OLF: occluded light fraction; HF: heavy fraction.

2.5 Correlation of biochemical quality of SOC and microbial properties

Little information is available on the relationships between biochemical quality of SOC and microbial properties. Soil microbes use the relatively labile carbon pools in soils as the source of energy, and therefore microbial biomass and activity are essentially related to the amount of the labile organic carbon fraction (Francaviglia *et al*., 2004). In the present study, the amount of carbohydrates in LP I was significantly positively correlated with MBC ($p < 0.001$), MQ ($p < 0.01$), and BR ($p < 0.001$), but negatively with $q\mathrm{CO}_2$ ($p < 0.01$) (Table 6). These correlations between the amount of carbohydrates in LP II and MBC, BR, and $q\mathrm{CO}_2$ were insignificant. This result suggested that the carbohydrates in LP I were the main C sources for soil microbes in 0–20 cm layer.

In previously published results, the recalcitrant carbon/total OC ratio ($\mathrm{RI_C}$) has been regarded as an indicator of global OC quality (Oades *et al*., 1970; Rovira and Vallejo, 2002, 2003, 2007; Wang *et al*., 2005a). The higher the biochemical quality is, the lower the value of $\mathrm{RI_C}$ becomes (Wang *et al*., 2005a). However, the insignificant correlations between $\mathrm{RI_C}$ and soil microbial properties were detected in our study (Table 6), suggesting that $\mathrm{RI_C}$ by itself is not sufficient to account for the extreme variation of SOC quality. On the other hand, carbohydrates are the main source of energy for soil microbes (Liang *et al*., 1998). In the present study, the cellulose/total carbohydrates ratio (LP II/(LP I + LP II)) was negatively

Table 6 Correlation coefficients (r) between soil microbial properties and biochemical quality of SOC

	MBC	MQ	BR	$q\mathrm{CO}_2$
LP I	0.875***	0.657**	0.824***	–0.705**
LP II	–0.136	–0.505*	–0.090	0.080
RF	0.822***	0.428	0.752***	–0.656**
$\mathrm{RI_C}$	0.440	0.078	0.364	–0.364
LP II/ (LP I + LP II)	–0.679**	–0.722***	–0.638**	0.593**

*, ** and *** are significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively (two-tailed, $n = 18$).

related to MBC and activity parameters, such as MQ and BR, while significantly positive correlation between LP II/(LP I + LP II) and $q\mathrm{CO}_2$ was detected (Table 6). High resistance of cellulose to biodegradation can account for these relationships. MBC, MQ, BR, and $q\mathrm{CO}_2$ have been promoted as the sensitive indicators of changes in SOC status (Nannipieri *et al*., 1990; Riffaldi *et al*., 1996; Hernandez *et al*., 1997; Liang *et al*., 1998; Balota *et al*., 2003). Therefore, LP II/(LP I + LP II) can be another effective indicator for availability of SOC changes to microbial biomass brought by human disturbance practices in forest soils.

3 Conclusions

Successive rotations of Chinese fir reduced the quantity of TOC, soil microbial biomass, microbial activity and the efficiency of substrate utilization by microbes evidently, especially in the 0–10 cm layer. Microbial properties were closely related to the non-cellulose of carbohydrates included in LP I, thereby it may be highly available to soil microbial biomass. The contents of RF and carbohydrates in LP I were reduced over successive rotation of Chinese fir plantations, while there was no significant change in $\mathrm{RI_C}$. Cellulose included in LP II and the cellulose/total carbohydrates ratio increased in successive rotations of Chinese fir. This suggested that successive rotation of Chinese fir had great effect on the labile carbon pools and their distribution, which resulted in the decline of availability of SOC to microbes, but had no effect on recalcitrance of OC. On the other hand, the percentage of HF to TOC was the highest under TCF and the lowest under FCF, suggesting that the degree of physical protection for SOC increased and SOC became more stable over successive rotations. The degradation of quality and quantity of SOC in successive rotation soils may be attributable to worse environmental conditions resulting from disturbance related to "slash and burn" site preparation. The results implied that successive rotation of pure coniferous plantation can not be considered as a sustainable production pattern under the silvicultural management regime in subtropical China.

Although $\mathrm{RI_C}$ cannot reflect the changes of SOC quality sensitively in current study, the ratio of the cellulose/total carbohydrates was closely correlated with not only soil microbial biomass but also MQ, BR and $q\mathrm{CO}_2$ in the investigated soils. Therefore, the cellulose/total carbohydrates ratio can be used as an effective indicator for changes in availability of SOC to microbial biomass brought by management practices in forest soils.

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