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ORIGINAL PAPER

Forest-type shift and subsequent intensive management affected soil organic carbon and microbial community in southeastern China

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Abstract In this study, we investigated the effect of forest types changes (from coniferous and broadleaf mixed forest (CBMF) to plantation forests of bamboo (*Phyllostachys pubescens* forest, MBF) and hickory (*Carya cathayensis* forest, CHF)) combined with intensive management on soil organic carbon (SOC) and microbial community structure, using the ^{13}C-nuclear magnetic resonance (NMR) and phospholipid fatty acid (PLFA). The results indicated that soil organic carbon significantly decreased by 30.7 and 28.5% in MBF and CHF, respectively. The aromatic C and aromaticity also significantly decreased in MBF and CHF ($P < 0.05$), while alkyl, *O*-alkyl and carbonyl C contents increased ($P > 0.05$). Significant changes of the soil microbial community were found after the forest type changed from CBMF to MBF and CHF. Total soil microbial PLFAs, soil bacteria PLFAs, fungus PLFAs, actinobacteria PLFAs, arbuscular mycorrhizal fungi PLFAs and protozoan PLFAs ranked as follows: CBMF > CHF > MBF ($P < 0.05$). The ratio of soil fungus to bacteria was in the order of MBF (0.78) > CHF (0.66) > CBMF (0.49) ($P < 0.05$), while an opposite order was found for ratio of G+/G− values (CBMF > CHF > MBF, $P < 0.05$). The converting CBMF into MBF and CHF combined with fertilization and tillage significantly changed the SOC and microbial community. Therefore, necessary measures should be taken to improve the SOC and soil fertility in the MBF and CHF.

Keywords Coniferous and broadleaf mixed forest · Chinese hickory forest · Moso bamboo forest · Phospholipid-derived fatty acids · Soil organic carbon · ^{13}C-NMR

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Introduction

The conifer-broadleaf mixed forest (CBMF) is one of the most widely distributed forests in subtropical China (Ma et al. 2014). However, due to pursuing high economic profits by local foresters, large areas of CBMF were changed to commercial plantations, such as moso bamboo (*Phyllostachys pubescens,* Mazel ex Houzeau de Lehaie) and Chinese hickory (*Carya cathayensis* Sarg.) stands in southern China. Moso bamboo forest (MBF) is one of the most important plantations in China, with a total area of 3.87 million hectares (Mha), accounting for about 25% of the global bamboo forest areas. The MBF area is increasing, at a rate of about 1% per year (Wang et al. 2009), because of its well-developed underground root system. Chinese hickory forest (CHF) is a traditional Chinese high-quality woody nut and oil tree species. It is mainly

distributed on Tianmu Mountain at the boundary of Zhejiang and Anhui provinces in China (Wu et al. 2014a). Currently, the total area of CHF is 8.93×10^5 ha in China, which is 2 times larger than that in the 1980s. In order to improve the yields of moso bamboo and hickory, intensive management referred to deep plow, heavy application of fertilizer and complete clearing of ground vegetation (herbaceous grass and shrub) was taken. In addition, large amounts of herbicides have been applied, which leads to a decrease in plant diversity, and to increasing water loss and soil erosion (Wang et al. 2011; Bai et al. 2012).

Soil organic carbon (SOC) is an important factor in maintaining soil fertility and plant growth (Chang and Chiu 2015). The content and structure of SOC could reflect the spatial distribution of above-ground species, vegetation succession and human disturbance (Su et al. 2005). The soil microbial community is a vital component of the soil biological system, which can be used for monitoring the change of soil quality (Zhang et al. 2013a, b). Forest-type shifts have resulted in forest ecosystem changes, which could further affect soil organic carbon, microbial communities and other physic-chemical properties (Ushio et al. 2010). This was probably related to the forest species differences in total forest litter amount and quality, root exudates, and nutrient uptake and transportation (Lucas-Borja et al. 2012). The litter chemistry effected by initial litter quality, is generally regarded to be closely associated with the structure and stability of soil organic matter during the long-term litter decomposition process (Kogel-Knabner 2002; Schmidt et al. 2011).

The ^{13}C nuclear magnetic resonance spectroscopy with cross-polarization and magic-angle spinning (CPMAS NMR) has been popularly uses to investigate the SOM chemical structure (Simpson et al. 2011). The relative ratios of different organic C functional groups, such as alkyl C, *O*-alkyl C, aromatic C from the NMR spectrum of the soil samples could be investigated. Li et al. (2014) studied the soil C pool variation using NMR technology after the conversion of vegetation from the native shrub forests to Chinese chestnut plantations. Some researchers also studied the relationship between SOC chemical composition and labile organic C pools such as microbial bacterial C (Webster et al. 2001; Chen et al. 2004).

However, previous research mostly focused on above-ground change and plantation cultivation after land-use change (Wang et al. 2011; Chen et al. 2014) in subtropical forest region. There are few studies about the accompanying changes in underground soil organic carbon and microbial diversity in this area of China. The objective of this study was to investigate the effects of converting CBMF to intensively managed MBF and CHF on SOC concentrations, the chemical composition of SOC and microbial community structure by ^{13}C-nuclear magnetic resonance (NMR) and PLFA techniques. We aimed to understand how the extension of bamboo and hickory forests stimulates the change of soil organic carbon and microorganisms. It is expected that the results can be used to guide sustainable forest management in subtropical region.

Materials and methods

Site description

The study site was located in Lin'an County (119°06′–119°15′E, 27°46′–27°58′N), northwest Zhejiang Province, China. Under a monsoonal subtropical climate with four distinct seasons, the study area has an average annual temperature of 16.4 °C, an average annual precipitation of 1628 mm. The average annual day-light hours are about 1774 h, with 235 frost-free days. The elevation of the study area ranges from 100 to 150 m above the sea level, and the soils were classified as Ferralsols in FAO soil classification system (WRB 2006).

Before the land use change, the study area was uniformly distributed by CBMF. The original tree species of the area were *Cyclobalanopsis glauca* (50%), *Pinus massioniana* (40%), *Liquidamba formosana* and *Taxus maire* (10%). In 1989, in order to set up the experiment, the previous natural forest was harvested. Then, three different forest stands have been formed in the study area (Table 1). Ten hectares remained as CBMF through natural regeneration. Ten hectares of the original CBMF were changed to MBF, and 10 hectares of CBMF were converted to CHF through artificial stimulation of natural regeneration. No further anthropogenic measures were taken to manage the CBMF since 1989. The MBF and CHF were managed by annual application of inorganic fertilizer, deep tillage and removal of understory vegetation. In April of each year, NPK compound fertilizer was broadcast applied to the plantations (450 kg N ha^{-1}, 450 kg P_2O_5 ha^{-1}, and 450 kg K_2O ha^{-1}, respectively). The understory vegetation including shrub and grass was removed in the MBF and CHF in order to reduce the competition for nutrients and water.

Soil sampling

Three 20 m × 20 m sample plots were set up by random design within each of forest type stand in March 2014, giving a total of 9 sample plots. Soil samples were taken using a soil sampler (10 cm Ø) from four corners and the middle position of each plot (0–20 cm deep) and thoroughly mixed to form a composite sample. The soil samples were preserved in the ice box after being sealed in plastic bags. Half of each soil sample was passed through a

Table 1 Basic information of the selected forest stands

Forest type	Stand density (plant ha^{-1})	Age (year)	Average DBH (cm)	Average height (m)	Canopy density (%)	Altitude (m)	Aspect	Slope (°)	Rock type	Forest litter (t ha^{-1} $year^{-1}$)	Forest litter carbon (Kg m^2)	Soil sampling depth (cm)
CBMF	1950	25	18.6	13.0	80	440	Southwest	25	Limestone	4.76	0.22	20
MBF	3150	25	10.2	11.0	80	430	Southwest	24	Limestone	2.16	0.08	20
CHF	375	25	15.1	8.0	80	430	Southwest	23	Limestone	3.62	0.15	20

CBMF stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest, *DBH* stands for diameter at breast height

2-mm nylon mesh and saved at −20 °C in cryogenic refrigerator for analysis of microbial community structure. The remaining half of the mixed samples were air-dried and sieved with a 0.25-mm nylon mesh for analysis of soil organic carbon content, structure and other soil properties.

Chemical and microbial community structure analysis

Soil pH was analyzed with a pH meter using an aqueous suspension (soil-to-water ration of 1:2, W:V). Organic carbon was determined by the wet oxidation using concentrated H_2SO_4 and $K_2Cr_2O_7$, and titrating with $Fe(NH_4)_2(SO_4)_2{\cdot}6H_2O$ and total N was measured by a semi-micro Kjeldahl method. Available P and K were determined by the $NaHCO_3$ extraction-colorimetry and NH_4OAc extraction-flame photometry method, respectively. All the methods described above followed Lu (2000).

Soil samples were further analyzed with cross-polarization magic-angle-spinning (CPMAS) solid-state NMR spectroscopy. Soil samples were pretreated with hydrogen fluoride (HF) solution to increase the signal-to-noise ratio of the spectrum. The HF pretreatment was recommended by Mathers et al. (2000). The HF treated soil samples were subjected to ^{13}C NMR analysis by a Bruker (Spectrospin, Rheinstetten, Germany) Avance 600 MHz NMR spectrometer. The experiments were carried out using a 7 mm CPMAS probe, at a carbon frequency of 75.5 MHz, MAS spinning frequency at 5000 Hz, with a contact time of 2 ms, and recycle delay time of 2.5 s. The NMR spectra were divided into the following seven resonance regions representing different chemical environments of a ^{13}C nucleus: alkyl C (0–50 ppm), *O*-alkyl C (50–110 ppm), aromatic C (110–160 ppm) and carbonyl C (165–220 ppm) (Huang et al. 2008). The area under the curve in each region was calculated by integration, and the relative contents of different C fractions were obtained. There were two indices of SOC stability which were included: (1) Alkyl C to *O*-alkyl C ratio (A/*O*-A) = $C_{0-50\ ppm}/C_{50-110\ ppm}$ (Huang et al. 2008) and (2) aromaticity = $C_{110-165\ ppm}/C_{0-165\ ppm}$ (Zhang et al. 2013a, b).

The extraction and analysis of PLFAs were realized as described by Frostegård et al. (1993). Citrate buffer (3.2 ml, 0.15 M), chloroform (4 ml), and methanol (8 ml) were mixed to extract soil lipids. The phospholipid fatty acid (PLFA) was methyl esterificated after being separated using silicic acid chromatography. The compositions of the PLFA samples were analyzed by gas chromatograph (Agilent, 6890 N, USA) with an HP-5MS column (25.0 m × 200 μm × 0.33 μm). Sample volume was 1 μL, diversion ratio was 10:1, and carrier gas (N_2) velocity was 0.8 ml min^{-1}. The column temperature in second-order procedure was increased from 170 to 260 °C (5 °C min^{-1}), and then increased to 310 °C at a rate of 40 °C min^{-1}, and maintained for 1.5 min. The compositions of PLFA were analyzed by MIDI Sherlock microbial identification system (Version 4.5, MI-DI, Inc., Newark, DE). Then the obtained PLFAs were used to calculate the microbial biomass and the richness of each community.

The unit to express the amount of fatty acids was nmol g^{-1} water-free soil. Meanwhile, the relative abundance of the PLFA was expressed in mol %. In this research, the communities of $Gram^+$ bacteria were characterized by PLFA i14:0, i15:0, a15:0, i16:0, i17:0 and a17:0. $Gram^-$ bacteria were characterized by 16:1ω7c, cy17:0, 18:1ω7c and cy19:0 (Zogg et al. 2006). Bacteria were characterized by i14:0, i15:0, a15:0, 15:0, i16:0, 16:1ω7c, 17:0, i17:0, a17:0, cy17:0, 18:1ω7c, cy19:0 (Frostegård and Bååth 1996). Fungi were characterized by 18:1ω9c and 18:2ω6c (Federle 1986). Arbuscular mycorrhizal fungi were represented by 16:1ω5c (Olsson 1999). Actinobacteria were indicated by Me16:0, Me17:0 and Me18:0. Protozoans were characterized by 20:4w6, 9, 12 and 15c (Yu et al. 2003). The ratios of fungi and bacteria were included in the data analysis. The same was done with the ratios of Gram-positive bacteria (G+) and Gram-negative bacteria (G−).

Statistical analyses

The data presented in this research are the average of three replications [average ± standard deviation (SD)]. The one-way analysis of variance (ANOVA) was applied to test the

forest-stand change effects on the physical and chemical properties, organic C chemical composition and microbial community, based on the Duncan's multiple comparison method ($\alpha = 0.05$). Before performing the ANOVA analysis, the normality and homogeneity of raw data were tested and data were log-transformed if homogeneity of the variance was not met. The principal component analysis (PCA) was performed by R statistical package (version 3.3.3). Other statistical analyses were carried out with SPSS® for windows (version 18.0).

Results

Soil chemical and physical properties

The highest soil pH, SOC, and C/N ratio and lowest total N, available P and K were found in the CBMF soil samples (Table 2). 25 years after the forest type changed from CBMF to the MBF and CHF, the pH, SOC content and C/N ratio significantly decreased. There was no significant difference between the MBF and CHF soils in these factors.

Soil organic content structure

The solid-state ^{13}C NMR spectrogram of SOC includes 4 obvious resonance areas and corresponding organic C fractions: alkyl C (0–50 ppm), *O*-alkyl C (50–110 ppm), aromatic C (110–160 ppm), carbonyl C (160–220 ppm) (Fig. 1). Integration over the major areas of ^{13}C resonance to find areas under the curve provided the ratios of different organic carbon groups to total organic carbon. Overall, the *O*-alkyl C (37.2–38.2%) dominated the SOC in all the three forest stands. However, the forest-type shift changed the signal intensity of different C fractions in the SOC (Table 3). The alkyl, *O*-alkyl and carbonyl C contents increased, while aromatic C significantly decreased by converting CBMF to MBF and CHF. The alkyl to *O*-alkyl C ratios did not significantly change. The aromaticity significantly decreased by forest-type shift.

PLFA analyses

Total PLFA concentration, as an indicator of active soil microbial biomass, was highest in the CBMF soil samples (Fig. 2). Meanwhile, soil bacteria PLFAs, fungus PLFAs, actinobacteria PLFAs, arbuscular mycorrhizal fungi (AMF) PLFAs and protozoan PLFAs ranked as follows: CBMF > CHF > MBF. The differences between them were significant ($P < 0.05$).

The soil microbial community significantly changed 25 years after the forest-type conversion from CBMF to the MBF and CHF (Figs. 3, 4). The relative abundance analysis of PLFA showed that bacteria dominated in the soils, while the second most abundant component was the fungus and actinobacteria. Arbuscular mycorrhizal fungi and protozoans were less abundant in the soil. The relative abundance of soil G− bacteria biomass ranked as follows: CBMF > MBF > CHF ($P < 0.05$). But the relative abundance of soil G+ bacteria biomass ranked as follows: CBMF > CHF > MBF ($P < 0.05$). The relative abundance of fungus and arbuscular mycorrhizal fungi (AMF) between the three forest types did not show a significant change. The relative abundance of soil actinobacteria in the bamboo forest was significantly lower than that in the other forest types. The relative abundance of protozoan biomass in the CBMF was significantly higher than that in MBF and CHF. 25 years after the forest type changed from CBMF to the plantation forests of bamboo and hickory, the ratio of soil fungus to bacteria showed a significant rise, while the ratio of G+ bacteria to G− bacterium declined significantly (Fig. 4).

Soil communities, analyzed by PCA of PLFA levels, significantly differed among different vegetation types (Fig. 5). The PLFA levels in the soil could be divided into clear three clusters, CBMF, CHF and MBF soils. The first and second principle component (PC1, PC2) accounted for 93.7% of the variation in PLFA levels (Fig. 5). PC1 differentiated the CBMF soil from other plantation soils, whereas PC2 had positive loading and differentiate MBF from CHF soil.

Table 2 Changes in soil properties of different forest types

Forest types	pH	Soil organic carbon (g kg^{-1})	Soil organic carbon density (Kg m^2)	Total N (g kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	C/N
CBMF	6.2 ± 0.2a	19.24 ± 2.31a	4.62 ± 0.38a	1.08 ± 0.17a	2.4 ± 0.3b	114.7 ± 12.4a	17.8 ± 1.2a
MBF	5.4 ± 0.3b	13.34 ± 1.87b	3.20 ± 0.27b	1.27 ± 0.18a	5.8 ± 0.5a	123.6 ± 14.5a	10.5 ± 1.3b
CHF	5.5 ± 0.2b	13.76 ± 2.06b	3.30 ± 0.28b	1.36 ± 0.19a	6.3 ± 0.7a	145.3 ± 15.8a	10.1 ± 1.1b

CBMF stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest

Different letters in the same column indicate values are significantly different at $P = 0.05$ level according to Tukey's HSD multiple range test

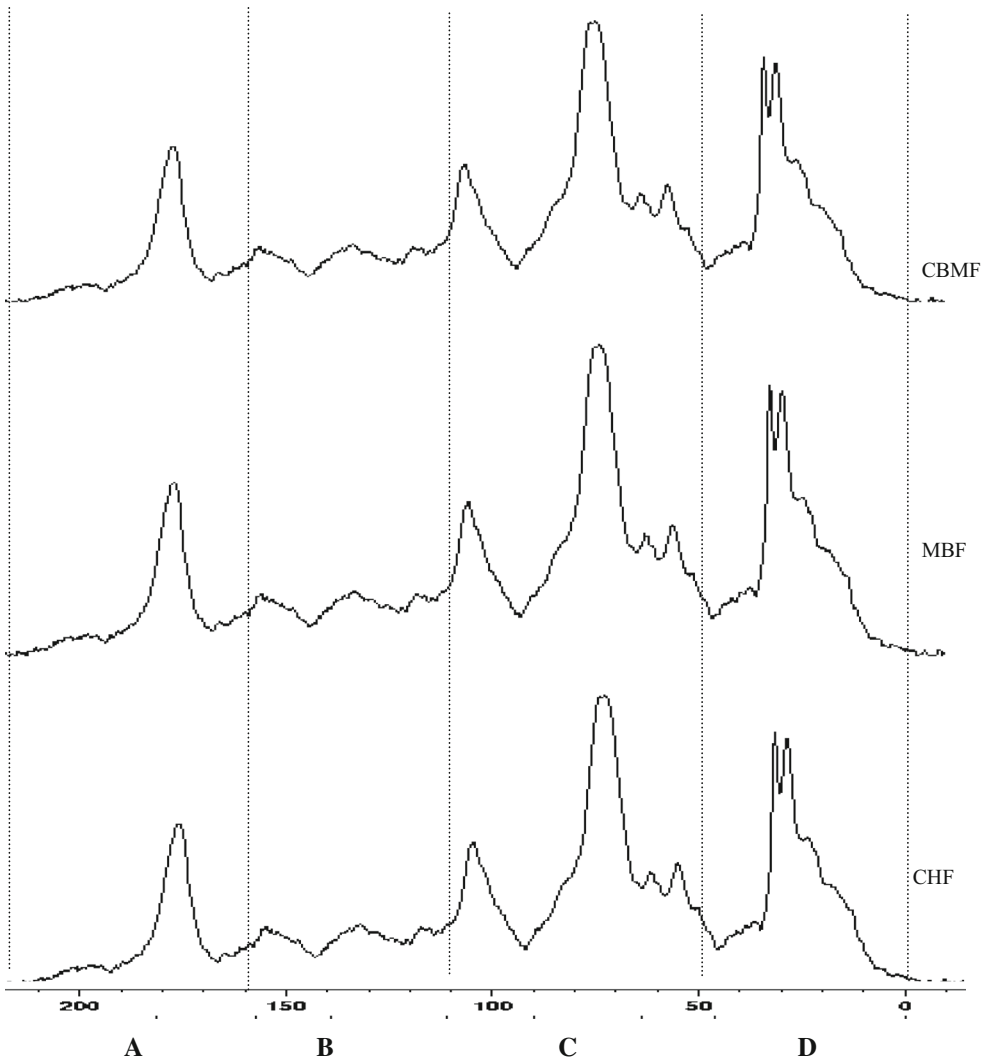

Fig. 1 Solid-state ^{13}C NMR spectrogram of SOC includes 4 obvious resonance areas. *A* Carbonyl C; *B* Aromatic C; *C* *O*-alkyl C; *D* Alkyl C. *CBMF* stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest

Table 3 Distributions of different chemical shift ranges in total signal intensity (%) for ^{13}C NMR in organic carbon of different forests

Forest type	Alkyl C (0–50 ppm)	*O*-alkyl C (50–110 ppm)	Aromatic C (110–160 ppm)	Carbonyl C (160–220 ppm)	Alkyl C/*O*-alkyl C	AC (%)
CBMF	24.8 ± 3.5a	37.2 ± 2.3a	24.8 ± 1.8a	13.2 ± 1.4a	0.67 ± 0.1a	28.6 ± 2.7a
MBF	26.3 ± 2.5a	38.2 ± 1.4a	20.2 ± 1.2b	15.3 ± 1.6a	0.69 ± 0.1a	23.8 ± 2.5b
CHF	26.1 ± 3.2a	37.8 ± 1.5a	20.3 ± 1.2b	15.7 ± 1.2a	0.69 ± 0.1a	24.7 ± 2.3b

CBMF stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest

Alkyl C/*O*-alkyl C = $(C_{0–50\ ppm})/(C_{50–110\ ppm})$; AC = Aromaticity = $[(C_{110–165\ ppm})/(C_{0–165\ ppm})] \times 100\%$

Different letters in the same column indicate values are significantly different at $P = 0.05$ level

Discussion

The effect of forest-type change on soil organic carbon and its chemical composition

In this study, 25 years after converting CBMF into MBF and CHF, the SOC in top soils (0–20 cm) significantly decreased (Table 2), which was similar to the findings of Wu et al. (2014b) who reported that converting natural ever-green broad-leafed forests to plantations (Chestnut forest and CHF) reduced SOC in subtropical China. The possible mechanisms for the decrease in SOC in the MBF and CHF soils samples include: (1) there is less human disturbance in CBMF and its arbor-shrub-grass multiple layered forest ecosystem provides a large amount of litter-fall input to the soils (4.76 t ha^{-1} $year^{-1}$ for CBMF, only

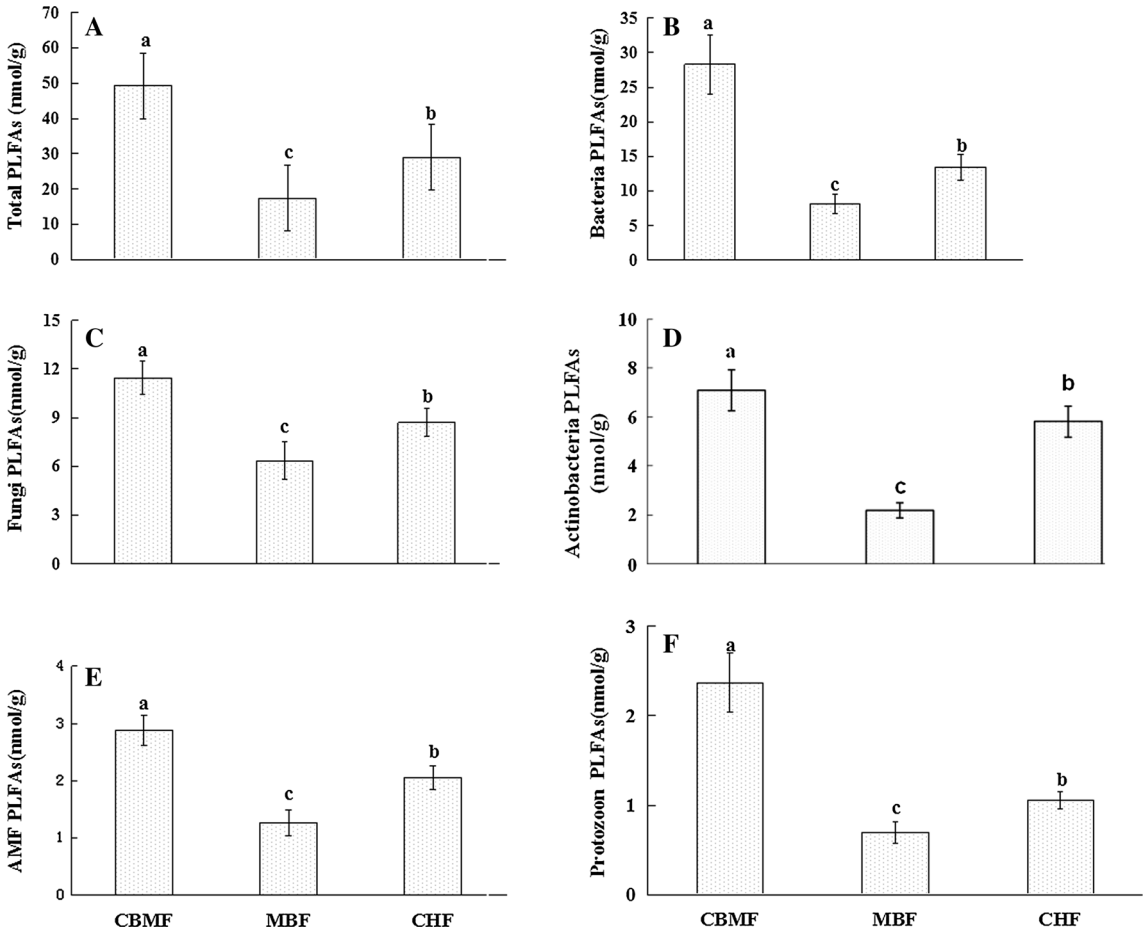

Fig. 2 Soil microbial PLFAs under different forest stands: **a** total PLFAs; **b** bacteria PLFAs; **c** fungi PLFAs; **d** actinobacteria PLFAs; **e** AMF PLFAs; **f** protozoan PLFAs AMF is arbuscular mycorrhizal fungi; *Different letters* in the same column indicate values are significantly different at $P = 0.05$ level. *CBMF* stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest

2.16 and 3.62 t ha^{-1} year^{-1} for MBF and CHF, respectively, Table 1), which affects the incorporation of litter into the soil (Wiesmeier et al. 2009); (2) the simple forest structures and relatively high soil temperatures in MBF and CHF could accelerate decomposition rate of soil organic matter (Li et al. 2014); (3) serious soil erosion in plantations caused a huge loss of soil organic carbon (Wu et al. 2014a); (4) the fertilizer application in MBF and CHF accelerates the decomposition of organic matter (Mancinelli et al. 2010). Our results demonstrate that SOC concentrations in MBF and CHF are being depleted, and necessary measures should be taken to maintain soil fertility.

Solid-state ^{13}C CPMAS NMR has been extensively used to investigate the response of chemical composition of SOC to different management practices. Significant differences in the ratios of C fractions to total SOC were found among different studies (Chen et al. 2004; Huang et al. 2008; Li et al. 2014), due to different forest and soil types. In this study, *O*-alkyl C dominated the SOC regardless of forest-type change, which was consistent with the findings of Chung et al. (2012) in a natural Hinoki cypress (*Chamaecyparis obtusa*) forest in Taiwan and Li et al., (2014) in Chestnut plantation soils in subtropical China. However, Ussiri and Johnson (2007) found that the alkyl C predominated in the SOC in Bh horizon of a hardwood forest soil. Fertilization and tillage could play an important role in the chemical composition of SOC (Huang et al. 2011). It was reported that long-term fertilization increased the alkyl C content and the A/O-A ratio in the top soil of a second rotation *Pinus radiate* D (Huang et al. 2011). In our study, alkyl C and *O*-alkyl C content increased, but aromatic C content and aromaticity decreased after converting CBMF into MBF and CHF with long-term fertilization. This finding is similar to the results of Zhang et al. (2013a, b) who found that the aromaticity significantly decreased in a MBF under a long-term intensive management, compared to the natural forest stand. However, Shang et al. (2012) reported that after conversion of natural shrub into

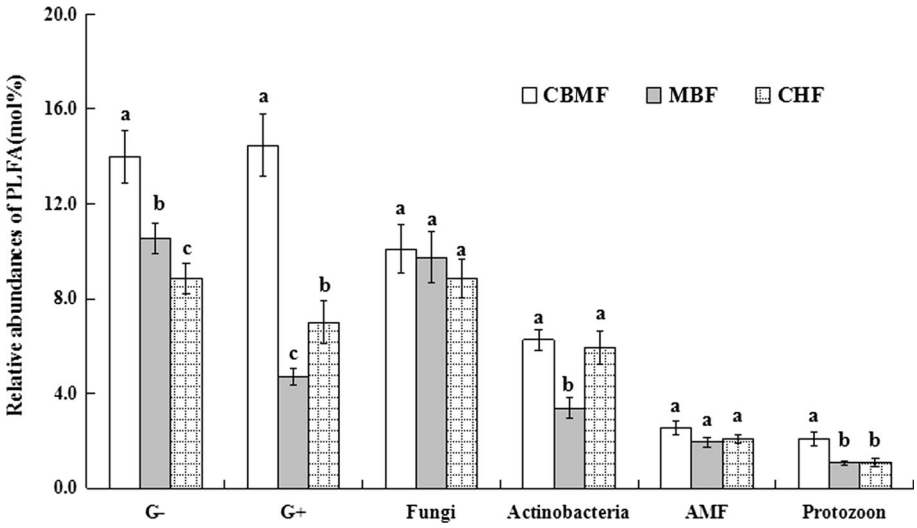

Fig. 3 Relative abundance of forest soil microbial PLFAs. *CBMF* stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest. *Different letters* in the same column indicate values are significantly different at $P = 0.05$ level

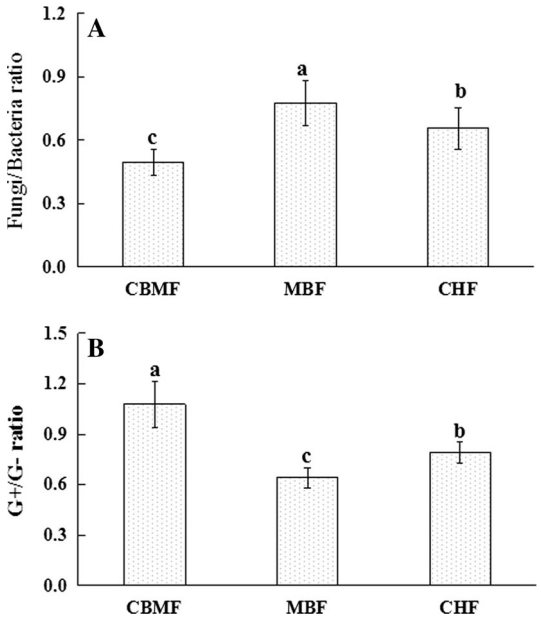

Fig. 4 **A** Ratio of soil fungus to bacteria, **B** the ratio of G+/G− bacteria. *CBMF* stands for conifer-broadleaf mixed forest, *MBF* stands for moso bamboo forest, *CHF* stands for Chinese hickory forest. *Different letters* in the same column indicate values are significantly different at $P = 0.05$ level

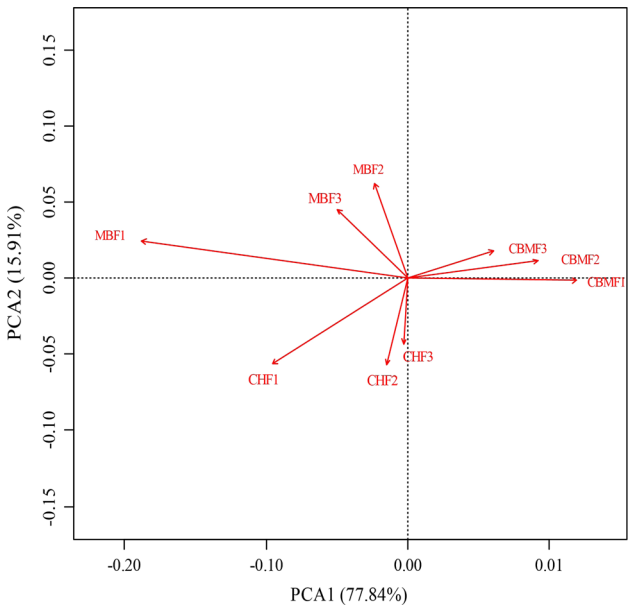

Fig. 5 Plots of the two main principal components (PCs) from principal component analysis of the mol % of microbial phospholipid fatty acid content in soil samples from different forest types

chestnut forest and 20 years of intensive management, the stability of SOC increased significantly. On the other hand, some studies showed that fertilization and tillage did not impact the chemical composition of SOC (González Pérez et al. 2004). The differences among the above studies are probably related to the variations in soil type, plant species, and environmental factors (Wang et al. 2010), while the contribution of each factor to the change in the chemical composition of SOC in the converting CBMF to MBF and CHF needs to be investigated in the future.

The effect of forest-type change on soil microbial community structure

The composition of the soil microbial community changed significantly 25 years after conversion from CBMF into MBF and CHF (Figs. 3, 4). Since the location and site condition are almost the same in this research, forest types and management practices are considered to be the main factors that caused the significant differences in microbial community. The type and amount of litter, as well as root system secretions, could have selective stimulating effect on the growth of the edaphon, so as to affect microbial community characteristics (Waid 1999).

Chang and Chiu (2015) found the bamboo rhizome system reduces opportunities for the growth of other plants and further reduces seedling abundance and species under a bamboo canopy. Additionally, different management practices affect soil microbial community structure by changing the soil environment (Bi et al. 2010; Chen et al. 2013).

Studies have shown that the composition of the soil microbial community is influenced by soil pH, and soil nutrient and carbon recycling efficiency (Fierer et al. 2007; Högberg et al. 2007). In our study, the value of soil pH was significantly correlated with the PLFAs in forest soil ($R = 0.81$–0.92, $P < 0.05$, not shown). After conversion of CBMF into MBF, the both soil pH and the PLFAs decreased. The significant reductions of relative abundance of bacterial PLFAs, which are greater than the PLFAs of fungi, resulted in significant growth of the ratio of fungi to bacteria (Figs. 3, 4), and the ratios are as follows: CBMF (0.49) < CHF (0.66) < MBF (0.78). This is similar to the result of Bardgett's research (Bardgett et al. 1993), namely the richness of total fungi in forest soil would increase with the enhancement of soil acid, and the bacterial PLFAs would decrease with the reduction in soil pH. The ratio of G+/G− bacteria indicated the quality of SOM; a low ratio of G+/G− may be due to induced growth of G− bacteria under substrate-rich conditions (Margesin et al. 2009; Chang and Chiu 2015), which results in high levels of G− bacteria in plantation soils. Low rations of G+/G− in the MBF and CHF agreed with low AC values (Table 3), indicating easily decomposable organic matter in their soils. Chang and Chiu (2015) found that the ratio of G+/G− decreased in MBF, compared to the adjacent Japanese Cedar forest, revealing an increase in easily decomposable organic matter in the moso plantation.

Conclusions

The SOC content decreased significantly 25 years after the conversion of CBMF into MBF and CHF. In addition to the less input of forest litter in MBF and CHF, long-term fertilizer application also led to the SOC decrease in their soils. Compared to the CBMF, the stability of SOC pool in MBF and CHF significantly decreased ($P < 0.05$) and so does the PLFAs. Converting the CBMF to MBF and CHF, the ratio of soil fungus to bacteria showed a significant rise, while the ratio of G+/G− bacteria decreased significantly. Therefore, necessary measures such as less intensive management and more organic manure application should be carried out to improve the soil fertility and quality in the MBF and CHF, in order to maintain a sustainable development in the forest industry.

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