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Soil soluble organic carbon and nitrogen pools under mono- and mixed species forest ecosystems in subtropical China

Yumei M. Jiang · Chengrong R. Chen · Yuanqiu Q. Liu · Zhihong H. Xu

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Abstract
Purpose The objective of the present study was to assess the differences in soil total C and N, microbial biomass C and N, soil soluble organic C and N among eight mono- and mixed species forest ecosystems (18-year-old restoration) in subtropical China.
Materials and methods Soil samples were taken at the 0–10 and 10–20-cm depths from each of the eight forest ecosystems: Masson pine (CP1); Pitch pine (CP2); mixed Slash pine and Sweetgum (CBMP1); mixed Slash pine and Camphortree (CBMP2); mixed Masson pine, Sweetgum, and Chinese Gugertree (CBMP3); mixed Sweetgum and Chinese Gugertree (BMP); Chinese Gugertree (BP1); and Sweetgum (BP2). Soil soluble organic C and N pools were measured using hot water and KCl extraction methods. Microbial biomass C (MBC) and N (MBN) were measured by fumigation-extraction method. Soil total C and N were determined using an isotope ratio mass spectrometer.
Results and discussion Concentrations of soil soluble organic N (SON) extracted by KCl solution (35.1–116.9 and 11.2–78.2 mg kg^{-1}) were greater than those by hot water (20.7–72.8 and 8.4–30.6 mg kg^{-1}) in the 0–10 and 10–20-cm soils, while concentrations of soluble organic C (SOC) extracted by KCl solution were lower than those extracted by hot water in the 0–10 cm. Soil soluble C and N pools extracted by both hot water and KCl solution and the MBC and MBN were greatest under the broadleaf forest ecosystems, followed by the mixed conifer–broadleaf forest ecosystems, and then the conifer forest ecosystems.
Conclusions Different restored forest ecosystems had significant impacts on soil SOC and SON, and MBC and MBN. The broadleaf forest ecosystems could be a better choice for the restoration of red soil chemical and biological properities than the conifer–broadleaf forest ecosystem and coniferous forest ecosystems. A further study is necessary to sample over seasons in order to understand whether the significant impacts on soil properties are related to the sample time. In addition, soil microbial community composition and microbial activity should be measured in such studies to understand mechanisms involved in the dynamics of soil SOC and SON pools.

Keywords Forest ecosystems · Soil microbial biomass C (MBC) and N (MBN) · Soluble organic C (SOC) and N (SON) · Subtropical China

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1 Introduction

Concentrations of soil soluble organic matter (SOM) are relatively small with about 1% of total soil organic matter (Jiang and Xu 2006). However, SOM plays an important role in biogeochemical cycling processes in terrestrial ecosystems, and it is an essential source of available C

and N for soil microorganisms and plants (Qualls and Haines 1991; Marschner and Kalbitz 2003; Neff et al. 2003; Jones et al. 2004; Chen and Xu 2008; Scaglia and Adani 2009). Considerable results confirmed that some plants are able to directly utilize and generally prefer amino acid over inorganic N (Chen and Xu 2008). It has been suggested that transformation of soil organic matter into soluble organic N (SON), rather than the conversion of SON to NH_4^+/NO_3^-, may be the rate-limiting step which regulates the overall N cycling in N-limited forest ecosystems (Chen and Xu 2008). Soil SON can be measured by a number of extraction methods, such as water, hot water, 2 M KCl, and 0.5 M K_2SO_4 (Zhong and Makeschin 2003; Chen et al. 2005a; Burton et al. 2007; Huang et al. 2008a, b). Recent findings have indicated that the pool size and the chemical and biological nature of SON varied with climate zones, forest ecosystems, and management practices (Burton et al. 2007; Chen and Xu 2008; Song et al. 2008; Xu et al. 2008a, b; Scaglia and Adani 2009; Xu et al. 2009). Most of these studies have been carried out in subarctic forest (Jones and Kielland 2002) and temperate forest ecosystems (e.g. Hannam and Prescott 2003; Zhong and Makeschin 2003; Zhu and Carreiro 2004; Berthrong and Finzi 2006; Ghani et al. 2007; Kranabetter et al. 2007). Smolander and Kitunen (2002) and Ghani et al. (2007) have reported that concentrations of SON in soil under birch (*Betula pendula* Roth.) and Norway spruce (*Picea abies* (L.)) were higher than those under Scots pine (*Pinus sylvestris* (L.)). Burton et al. (2007) have found that concentrations of soil SON under hoop pine plantations are lower than those under native forests. Few studies have focused on the impact of monospecies (coniferous or broadleaf) and mixed species (coniferous and/or broadleaf species) forest ecosystems composed of coniferous, mixed conifer–broadleaf species, mixed broadleaf species, and broadleaf species forest ecosystems on SOC and SON, and the factors controlling the sizes of soil SOC and SON pools in the forest ecosystems are poorly understood. In particularly, the information for linking the microbially mediated C and N transformation processes and SON pools under different forest ecosystems is limited.

Red soil covers 2.2×10^6 km^2 of ten provinces in the Southern China (Zhao 2002) and is subject to severe soil erosion, high weathering, excessive leaching, and degradation resulting from improper practices (such as frequent cultivation, vegetation clear-cut) (Zhao et al. 2007). Its inherent adverse characteristics, such as low nutrient availability, high acidity, and pollution, have impeded its sustainable use. To date, it is an urgent and long-term task to improve red soil quality and its nutrient status, which would enhance its productivity and help to restore its ecological functions. Restoration has been suggested to be an important measure for reducing soil and water erosion, increasing soil fertility and improving forest ecosystem function (Liu et al. 2008). Numerous studies have reported that red soil quality could be efficiently enhanced after forest restoration by increasing soil microbial diversity, soil enzyme activities, and nutrient contents (Liu et al. 2002, 2003; Zhao et al. 2007; Liu et al. 2008).

In this study, eight different forest ecosystems (18-year-old, either monospecies or various combinations of different coniferous and broadleaf tree species) were selected to examine the impacts of different forest ecosystems on the soil total C and N, soil microbial biomass C and N, and soil soluble organic C and N pools. Our main objectives were to (1) determine the variations in SOC and SON pools under the different forest ecosystems, (2) examine relationships between SOC and SON pools and microbial biomass C and N, and (3) provide guidance for the reclamation of eroded red soils in subtropical China. It was hypothesized that (a) plantations of different mono- and mixed coniferous and broadleaf tree species would lead to the significant difference of the restoration of red soil quality and quantity, and (b) the shift in the availability of SOC and SON pools would be mediated by soil microbial processes.

2 Materials and methods

2.1 Site description and soil sampling

The site is located at the Taihe County, an important part of Jitai Basin, which lies in the middle district of Jiangxi Province in Southern China (26°44′ N, 115°04′ E). The soil has been previously described as Ferralsols (FAO/Unesco) developed from red clay of the quaternary. Due to the adverse environmental conditions and inherent low fertility in the red soil, it has been difficult to establish forest vegetations in this area. Majority vegetations prior to the restoration are compose of only some native grass and shrub species (i.e., *Imperata koenigii*, *Cymbopogon goeringii*, *Setaria viridis*, *Arundinella anomala*, *Heteropogon contortus*, and *Cynodon dactylon*). In 1991, under the support of Jiangxi Forestry Policy, a research group and the local government department had worked in the seriously degraded red soil regions of Taihe County and rehabilitated more than 640 ha with different rehabilitation forest ecosystems. The elevation is from 74.7 to 131.3 m above sea level. It has the subtropical moist monsoon climate, with a cool, wet winter, and a warm, dry summer. Annual rainfall is 1,726 mm, and 49% of the total rainfall occurs from April to June. Atmospheric temperature ranges from –6 to 40.7°C (mean annul temperature 18.6°C), and the average temperature is 6.5°C in January (winter) and 29.7°C in July (summer). Eight different forest ecosystems were selected from the rehabilitated area for soil sampling in this

study. These include (1) Masson pine (*Pinus massoniana* Lamb; designated as coniferous plantation 1, CP1); (2) Pitch pine (*Pinus rigida* Mill. var. serotina (Michx.) Loud.ex Hoopes; designated as coniferous plantation 2, CP2); (3) Slash pine (*Pinus elliottii* Englem) and Sweetgum (*Liquidambar fomosana* Hance; designated as coniferous–broadleaf mixed plantation 1, CBMP1); (4) Slash pine and Camphortree (*Cinnamomum camphora* (L.) Presl.; designated as coniferous–broadleaf mixed plantation 2, CBMP2); (5) Masson pine and Sweetgum and Chinese Gugertree (*Schima superba* Gardn. et Champ; designated as coniferous–broadleaf mixed plantation 3, CBMP3); (6) Sweetgum and Chinese Gugertree (designated as broadleaf mixed plantation, BMP); (7) Chinese Gugertree (designated as broadleaf plantation 1, BP1); and (8) Sweetgum (designated as broadleaf plantation 2, BP2). Study areas for the eight forest ecosystems ranged from 7 to 30 ha, depending upon the previous studies on this site, which mainly focused on the soil physical traits, enzyme activities, and microbial compositions (Liu et al. 2002, 2003). In this study, three replicated sampling subplots were established for CP1, CP2, CBMP2, CBMP3, and BMP, while six subplots for CBMP1, BP1, and BP2 (each of these three forest ecosystems were planted in two sample areas, and three subplots were sampled for each sample area; thus, one of these three forest ecosystems has six subplots, and data were combined from the same two forest ecosystems for analysis of the spatial heterogeneity). The plot size was 10×20 m^2 for CP1, CP2, CBMP1, BMP, BP1, and BP2 treatments, while 10×10 m^2 for CBMP2 and CBMP3 treatments. A total of ten soil cores at the 0–10 and 10–20-cm depths were collected according to the stratified 'S' from each subplot by using a 7.5-cm diameter auger and bulked (well mixed) in November 2008. All samples were packed in plastic bags and transported to the laboratory in a cold container. The field-moist soil samples were sieved (<2 mm) with fine roots and large debris removed. Samples were then separated into two subsamples including air-dried samples and fresh soil samples. The air-dried samples were finely ground (<150 μm) and stored at room temperature prior to analysis of soil chemical properties, and the fresh soil samples were kept at 4°C prior to the analysis of soil biological properties.

2.2 Soil analysis

Soil bulk density was determined by the coring method. Soil pH was determined in 1:5 (*v*/*v*) soil/water extracts using a combination glass electrode and moisture by drying at 105°C for 24 h. Soil total C and N were determined using an isotope ratio mass spectrometer with a Eurovector Elemental Analyzer (Isoprime-EuroEA 3000, Milan, Italy) as reported by Xu et al. (2003, 2008b).

Soil SOC and SON in hot water were measured for the 0–10 and 10–20-cm soil samples using the method described by Chen et al. (2005a, b). In brief, 6.0 g (dry weight equivalent) of air-dried soil was incubated with 30 ml of deionized water in a capped test tube at 70°C for 18 h, and test tubes were then shaken for 5 min on an end-to-end shaker and filtered through a Whatman 42 paper (Whatman Ltd., Maidstone, UK), followed by a 0.45-μm filter membrane. SOC and total soluble N (TSN) concentrations in the filtrate were determined using an SHIMADZU $TOC_{-VCPH/CPN}$ analyzer (fitted with a total N (TN) unit).

SOC and SON in 2 M KCl were measured for soil samples at both depths by extracting 5.0 g (dry weight equivalent) of air-dried soil with 50 ml of 2 M KCl, shaking on an end-to-end shaker for 1 h and filtering through a Whatman 42 paper. SOC and TSN concentrations in the filtrate were determined using SHIMADZU $TOC_{-VCPH/CPN}$ analyzer (fitted with a TN unit). In order to avoid salt precipitation on the surface of the Pt/Al_2O_3 catalyst, KCl extracts were diluted fivefold before analysis.

Concentrations of NH_4^+–N and NO_3^-–N in the hot water and 2 M KCl extracts were determined using the LACHAT Quickchem Automated Ion Analyzer (QuikChem Method 10-107-06-04-D for NH_4^+–N and QuikChem Method 12-107-04-1-B for NO_3^-–N). Soil soluble inorganic N (SIN) was calculated as the sum of NH_4^+–N and NO_3^-–N. The SON in the different extracts was calculated as the difference between TSN and the sum of NH_4^+–N and NO_3^-–N (SIN).

Soil microbial biomass C (MBC) and N (MBN) were measured using the fumigation-extraction method described by Vance et al. (1987). In brief, fumigated and non-fumigated soils (10 g dry weight equivalent) were extracted with 40 ml of 0.5 M K_2SO_4 (soil/extractant ratio 1:4). Samples were shaken for 30 min and filtered through a Whatman 42 filter paper. Soil SOC and TSN in the fumigated and nonfumigated samples were determined as above. MBC and MBN were calculated using a conversion factor for C (E*c*) of 2.64 (Vance et al. 1987) and for N (E*n*) of 2.22 (Brookes et al. 1985; Jenkinson 1988).

2.3 Statistical analysis

Analysis of variance (ANOVA) and principal component analysis (PCA) were carried out for all data on soil chemical and biological properties using the Statistical Package for the Social Sciences for Windows version 15.0. The normality of all data was checked and met before ANOVA and PCA, while we acknowledged that the limitation of this experimental study was pseudoreplication, although BP1 and BP2 and CBMP1 were sampled six times meanwhile the other five plantations only three times in

each forest ecosystem. Tukey's Honestly Significant Difference ($P<0.05$) was used to separate the means when differences were significant. The multiple scatter regression analysis between soil C and N pools was conducted using the software of SigmaPlot 10.0.

3 Results

In this study, most of the plots were located on the hillside with shallow slopes (<10°) to reduce the slope variability ($P > 0.05$; data not shown). A significant interaction between forest ecosystems and soil depths was found for the majority of soil parameters measured (results not shown), suggesting that the effects of forest ecosystems on most soil parameters measured varied with soil depths.

3.1 Soil basic properties

There were no significant differences in soil bulk density, pH, and C:N ratio in the 0–10 and 10–20-cm soils among all eight plantations, except for lower bulk density in the 0–10-cm soil under CBMP2 (Table 1). In general, soil total C (TC) and TN were greater under broadleaf plantations (BP1 and BP2) and conifer–broadleaf mixed species plantations (CBMP1 and CBMP2; except for CBMP3) than those under coniferous plantations (CP1 and CP2; see Table 1). There were no significant differences in soil moisture, TC and TN, in the 0–10 and 10–20-cm soils within coniferous plantations (CP1 and CP2) and within broadleaf plantations (BP1 and BP2), while soil TC and TN were greater at both depths under CBMP1 and CBMP2 than under CBMP3.

3.2 Hot water-extractable organic C and N

The average concentration of SON_{HW} was 47.8 mg kg^{-1} in the 0–10-cm layer and 21.0 mg kg^{-1} in the 10–20-cm layer, respectively. In the 0–10-cm soil depth, SON_{HW} accounted for 65–77% of the total soluble N (TSN_{HW}) and 3.7–5.1% of soil total N. Concentrations of SON_{HW} decreased with depth (Table 2). Concentrations of hot water-extractable N (SON_{HW}) were generally greater at both 0–10 and 10–20-cm depths under broadleaf plantations (BMP, BP1, and BP2) and mixed conifer–broadleaf plantations (CBMP1 and CBMP2) than under coniferous plantations (CP1 and CP2) except for CBMP3 (Table 2). There were no significant

Table 1 Selected soil properties under eight different forest ecosystems in subtropical China

Forest ecosystems	BD (g cm^{-3})	Soil moisture (%)	pH	TC (%)	TN (%)	C:N ratio
0–10 cm						
CP1	1.62 a	15.4 bcd	4.3 a	0.85 c	0.055 c	16 a
CP2	1.62 a	11.6 d	4.4 a	1.23 bc	0.079 bc	16 a
CBMP1	1.56 ab	17.1 abc	4.3 a	1.29 abc	0.091 abc	14 a
CBMP2	1.26 b	21.2 a	4.3 a	1.82 ab	0.133 ab	14 a
CBMP3	1.63 a	15.5 bcd	4.1 a	0.87 c	0.061 c	14 a
BMP	1.47 ab	19.9 ab	4.5 a	1.95 ab	0.132 ab	15 a
BP1	1.50 ab	14.8 cd	4.4 a	1.38 abc	0.099 abc	14 a
BP2	1.45 ab	17.2 abc	4.5 a	2.04 a	0.143 a	14 a
10–20 cm						
CP1	1.58 a	17.5 ab	4.3 a	0.51 b	0.040 b	13 a
CP2	1.55 a	13.4 b	4.4 a	0.83 ab	0.063 ab	13 a
CBMP1	1.60 a	17.0 ab	4.3 a	0.82 ab	0.061 ab	13 a
CBMP2	1.54 a	18.9 a	4.5 a	1.01 a	0.081 a	12 a
CBMP3	1.64 a	15.2 ab	4.1 a	0.51 b	0.039 b	14 a
BMP	1.48 a	18.6 a	4.2 a	1.21 a	0.086 a	14 a
BP1	1.63 a	15.3 ab	4.3 a	0.86 ab	0.067 ab	13 a
BP2	1.45 a	17.9 a	4.3 a	1.24 a	0.097 a	13 a

Data in the column are mean values (n=3 for CBMP1, BP1, and BP2; n=6 for CP1, CP2, CBMP2, CBMP3, and BMP), which are compared among forest ecosystems within each depth and are not different at the 5% level of significance if followed by the same letter

BD soil bulk density, *TC* soil total carbon, *TN* soil total nitrogen, *C:N ratio* the ratio of soil total C to soil total N *CP1* Masson pine, *CP2* Pitch pine, *CBMP1* mixed Slash pine and Sweetgum, *CBMP2* mixed Slash pine and Camphortree, *CBMP3* mixed Masson pine, Sweetgum, and Chinese Gugertree, *BMP* mixed Sweetgum and Chinese Gugertree, *BP1* Chinese Gugertree, *BP2* Sweetgum

Table 2 Soil soluble inorganic N (SIN) and organic N (SON) in hot water (HW) and KCl extracts under eight different forest ecosystems in subtropical China

Forest ecosystems	SIN_{HW} (mg kg^{-1})		SOC_{HW}	SON_{HW} (mg kg^{-1})	$C:No_{HW}$ (%)	SIN_{KCl} (mg kg^{-1})		SOC_{KCl} (mg kg^{-1})	SON_{KCl}	$C:No_{KCl}$ (%)
	NH_4^+–N	NO_3^-–N				NH_4^+–N	NO_3^-–N			
0–10 cm										
CP1	8.9 c	1.4 a	262 c	20.7 c	13 b	9.2 b	0.4 a	222 c	35.1 c	7.1 a
CP2	12.4 bc	0.0 a	424 c	34.3 bc	12 b	11.7 ab	0.0 a	312 bc	50.8 bc	6.3 a
CBMP1	13.0 bc	0.5 a	634 bc	42.3 bc	15 ab	11.8 ab	0.2 a	563 ab	73.7 abc	7.7 a
CBMP2	16.0 abc	2.3 a	957 ab	60.9 ab	16 a	14.1 ab	0.1 a	814 a	110.0 a	7.4 a
CBMP3	8.7 c	0.2 a	354 c	23.9 c	15 b	8.5 b	0.0 a	315 bc	37.8 bc	8.4 a
BMP	19.7 ab	0.0 a	889 ab	58.1 ab	15 a	17.0 a	0.0 a	689 a	87.6 ab	7.9 a
BP1	14.4 abc	0.5 a	639 abc	48.9 abc	13 ab	14.3 ab	0.1 a	576 ab	83.8 abc	7.1 a
BP2	22.8 a	0.0 a	1,007 a	72.8 a	14 a	20.1 a	0.0 a	805 a	116.9 a	6.9 a
10–20 cm										
CP1	5.6 c	0.4 ab	157 c	9.4 bc	18 bcd	7.0 c	0.1 a	175 d	17.8 cd	10.7 ab
CP2	8.5 bc	1.1 ab	305 bc	19.2 abc	16 d	10.5 abc	0.0 a	345 bcd	40.0 bcd	8.8 b
CBMP1	12.5 b	2.4 a	373 abc	16.8 abc	23 ab	12.7 abc	0.0 a	468 abc	52.2 abc	9.0 b
CBMP2	14.7 ab	0.9 ab	480 ab	22.7 abc	21 abc	15.0 ab	0.0 a	592 ab	59.4 ab	10.1 ab
CBMP3	8.0 bc	0.0 b	214 c	8.4 c	25 a	8.7 bc	0.0 a	242 cd	11.2 d	25.9 a
BMP	14.2 ab	0.3 ab	570 a	27.0 a	21 abc	13.6 ab	0.0 a	646 a	59.4 ab	11.0 ab
BP1	9.2 bc	0.0 b	413 abc	24.9 ab	17 cd	10.9 abc	0.0 a	519 abc	61.3 ab	8.8 b
BP2	18.4 a	0.4 ab	601 a	30.6 a	20 abcd	16.4 a	0.0 a	700 a	78.2 a	9.0 b

For abbreviations of different forest ecosystems, see Table 1

SIN_{HW} soil soluble inorganic nitrogen extracted in hot water, *SOC_{HW}* total soluble organic carbon extracted in hot water, *SON_{HW}* soil soluble organic nitrogen extracted in hot water, *$C:No_{HW}$* soil soluble organic carbon and nitrogen extracted in hot water, *SIN_{KCl}* soluble inorganic nitrogen extracted in KCl solution, *SOC_{KCl}* total soluble organic carbon extracted in KCl solution, *SON_{KCl}* soluble organic nitrogen extracted in KCl solution, *$C:No_{KCl}$* soil soluble organic carbon and nitrogen extracted in KCl solution

Data in the column are mean values (n=3 for CBMP1, BP1, and BP2; n=6 for CP1, CP2, CBMP2, CBMP3, and BMP), which are compared among forest ecosystems within each depth and are not different at the 5% level of significance if followed by the same letter

differences in SON_{HW} between the same types of forest ecosystems (e.g., coniferous species or broadleaf species) except for CBMP3. Trends in the hot water-extractable C (SOC_{HW}) pools among the different plantation were similar to those in SON_{HW} (Table 2). Across different forest ecosystems at both depths, NH_4^+–N was the dominant form in inorganic N pool (>8.7 mg kg^{-1}), while concentrations of NO_3^-–N were generally <2.5 mg kg^{-1}. In general, the trend in concentration of NH_4^+–N across different forest ecosystems was similar to that in SON_{HW} and SOC_{HW}. In the 0–10-cm layer, the hot water-extractable C:N ratio ($C:No_{HW}$) was similar among all forest ecosystems while the ratio of the C: No_{HW} increased with soil depth (Table 2).

3.3 KCl-extractable organic C and N

Concentrations of KCl-extractable N (SON_{KCl}) were larger than those of SON_{HW} among the forest ecosystems, with an average concentration of 79.1 mg kg^{-1} at the 0–10-cm and of 51.9 mg kg^{-1} at the 10–20-cm soil depth (Table 2). The concentration of SON_{KCl} accounted for 75–89% of the KCl-extractable soluble N (TSN_{KCl}) and 5.9–8.3% of soil total N in the 0–10-cm soil layer (data not shown). Impacts of different forest ecosystems on the concentrations of SON_{KCl} and SOC_{KCl} were similar to those on SON_{HW} and SOC_{HW} (Table 2) with concentrations of SON_{KCl} and SOC_{KCl} being higher under broadleaf forest ecosystems than the conifer–broadleaf forest ecosystem (CBMP1, CBMP2), and the pure coniferous forest ecosystems (CP1 and CP2) in the 0–10-cm soil, except for CBMP3. The NH_4^+–N in KCl extracts was also dominant form in inorganic N pool at both depths among the different forest ecosystems, which was similar to that in hot water extracts, while concentrations of NO_3^-–N were very low (<1 mg kg^{-1}) regardless of types of forest ecosystems (Table 2). In the 0–10-cm soil depth, the KCl-extractable C:N ratio ($C:No_{KCl}$) was similar among all forest ecosystems while the ratio of the $C:No_{KCl}$ increased with soil depth (Table 2).

3.4 Soil microbial biomass C and N

The average concentration of MBC was 316 mg kg^{-1} in the 0–10-cm soil layer and 143 mg kg^{-1} in the 10–20-cm soils, respectively (Fig. 1). Concentrations of MBC were greater in soils at both depths under broadleaf (BMP, BP1, and BP2) and mixed conifer–broadleaf (CBMP1 and CBMP2) than those under coniferous (CP1 and CP2) plantations, except for CBMP3. There were significant differences in MBC between CBMP2 (or BMP) and CP1 in the 0–10-cm soils and between BMP and CP1 (or CBMP3) in the 10–20-cm soils. The average concentration of MBN was 39.0 mg kg^{-1} in the 0–10-cm soils and 21.1 mg kg^{-1} in the 10–20-cm soil layer, respectively. A similar trend (to MBC) was observed in soil MBN across different forest ecosystems (Fig. 1). Microbial C:N ratio was not significantly different among all forest ecosystems at both depths and the ratio of MBC to MBN was similar in the 0–10 and 10–20-cm soils (data not shown).

3.5 Relationships between soil properties

Soil SOC and SON were highly correlated with soil MBC and MBN and soil total C and N across the treatments. The relationships were stronger between SON_{HW} and MBC (R^2 = 0.90, P < 0.001) and between SON_{HW} and TC (R^2 = 0.93, P < 0.001) than those between SON_{KCl} and MBC (R^2 = 0.76, P < 0.001) and between SON_{KCl} and TC (R^2 = 0.84, P < 0.001; Fig. 2a, c). SON_{HW} was significantly related to MBN (R^2 = 0.85, P < 0.001) and to TN (R^2 = 0.90, P < 0.001), which was stronger than SON_{KCl} related to MBN (R^2 = 0.78, P < 0.001) and to TN (R^2 = 0.88, P < 0.001; see Fig. 2b, d). In addition, SOC_{HW} has a good correlation with TC (R^2 = 0.94, P < 0.001), TN (R^2 = 0.95, P < 0.001), and MBC (R^2 = 0.82, P < 0.001), which was stronger than SOC_{KCl} with TC (R^2 = 0.71, P < 0.001), TN (R^2 = 0.79, P < 0.001), and MBC (R^2 = 0.55, P < 0.001), and the relationship between SOC_{HW} and MBN (R^2 = 0.78, P < 0.001) is similar as that between SOC_{KCl} and MBN (R^2 = 0.79, P < 0.001; data not shown).

3.6 Principle components analysis (PCA) of soil parameters

The 20 soil parameters were used for the PCA (data not shown). Only principle components with eigenvalues >1 and that explain >5% of the total variance were retained. In general, there were three significant PCs that together explained more than 83.3% in the 0–10-cm soils and more than 88.0% in the 10–20-cm soils of the total variance. In the 0–10-cm soils, PC1 accounting for 63.5% of the total variance, was mainly attributed to soil C and N pools that showed relatively high loadings (thirteen positively weighted (the value of TSN, SON, SIN, SOC extracted in hot water and KCl solution, TC, TN, MBC, MBN and soil moisture) and one negatively weighted (bulk density) parameters). PC2, which explained 10.6% of the total variance, included three positively weighted (soil moisture, C: No ratio of SOC and SON extracted in hot water and KCl solution) parameters. PC3 loadings accounting for 9.2% of the total variance reflected the levels of C: N ratio (negatively) (data not shown). In the 10–20-cm soils, PC1 accounting for 60.0% of the total variance, was mainly

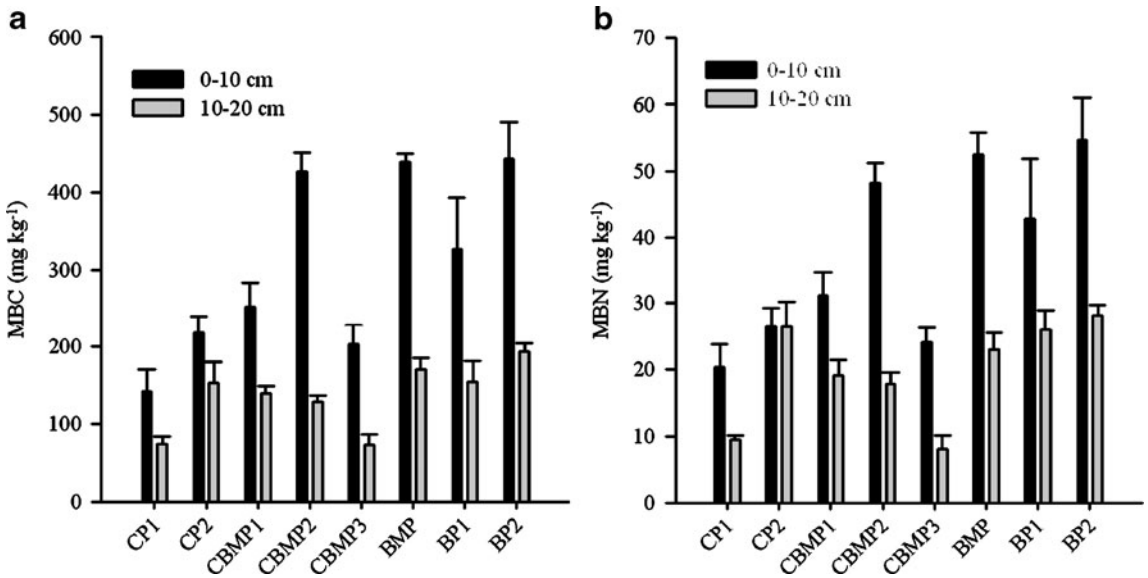

Fig. 1 Impact of different forest ecosystems on microbial biomass C (MBC) (**a**) and N (MBN) (**b**) in the 0–10 and 10–20-cm soils. *CP1*, Masson pine; *CP2*, Pitch pine; *CBMP1*, Slash pine and Sweetgum; *CBMP2*, Slash pine and Camphortree; *CBMP3*, Masson pine and Sweetgum and Chinese Gugertree; *BMP*, Sweetgum and Chinese Gugertree; *BP1*, Chinese Gugertree; and *BP2*, Sweetgum. *Error bars* represent standard errors of the mean (n=3 for CBMP1, BP1, and BP2; n=6 for CP1, CP2, CBMP2, CBMP3, and BMP)

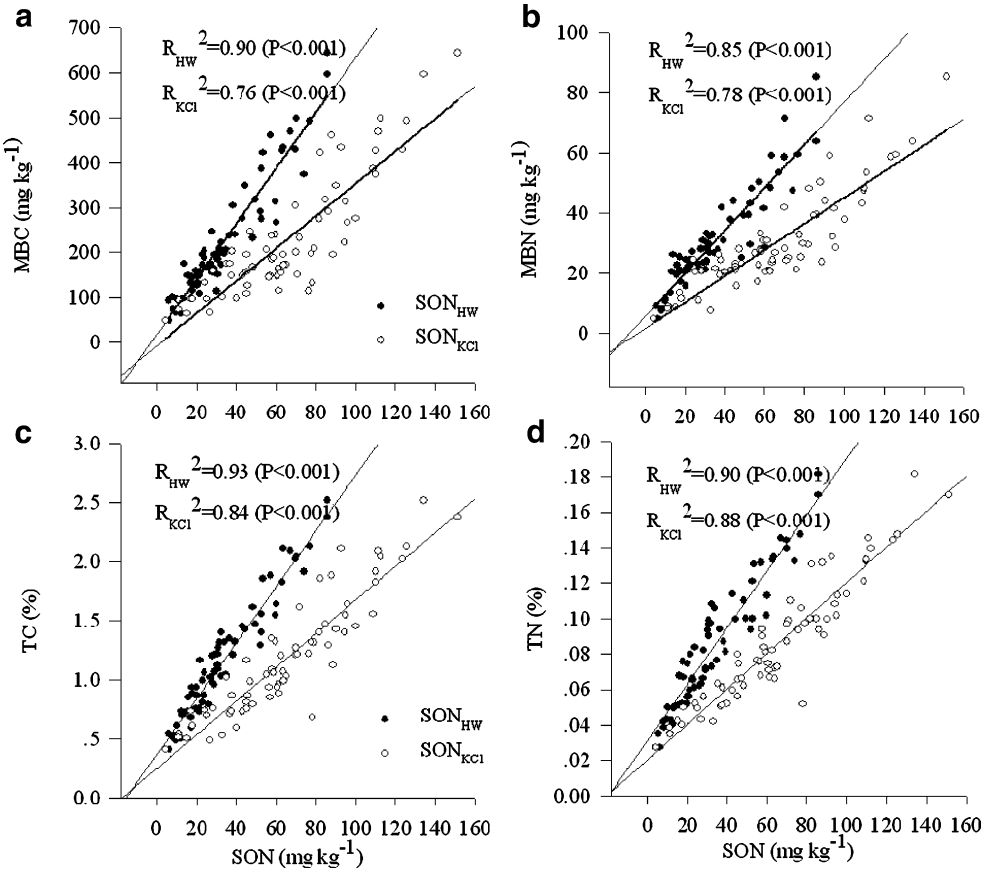

Fig. 2 Correlations between the chemical and biological properties across different forest ecosystems and soil depths n=66). SOC_{HW} and SON_{HW}, hot water-extractable soil soluble organic C and N; SOC_{KCl} and SON_{KCl}, KCl-extractable soil soluble organic C and N; *MBC*, soil microbial biomass C; *MBN*, soil microbial biomass N; *TC*, soil total C; and *TN*, soil total N

attributed to soil C and N pools (the similar relationship between PC1 score and the 15 soil parameters as showed in 0–10-cm soils) that showed relatively high loadings. PC2, which explained 12.9% of the total variance, included two negatively weighted (C: N ratio and C: No ratio in KCl solution) parameters. PC3 loadings consisted of 7.1% of the total variance, reflecting the level of MBN (negatively weighted parameter), ratio of C: No in hot water and ratio of MBC: MBN (positively weighted parameter) (data not shown). The ordination of forest ecosystems was further plotted in two dimensions based on the scores of PC1 and PC2 in the 0–10 (Fig. 3a) and 10–20-cm soils (Fig. 3b). Distinct separations of different forest ecosystems were showed for the two soil depths (Fig. 3a, b). Results also showed that the PC1 score had significant correlations with soil total C and N, MBC and MBN, and SOC and SON extracted by hot water and 2 M KCl solutions in the two soil depths (Fig. 4).

4 Discussion

4.1 The size of soil SOC and SON pools

The pool sizes of soil SOC and SON varied with hot water and salt extraction methods used (e.g. Jones and Willett 2006) in the 0–10 and 10–20-cm layers. The different pools of the SON extracted by the two methods (Table 2) could be related to the SON form present (adsorbed, exchangeable or readily decomposable fraction) in soil (Curtin et al. 2006). In this study, the soil SON_{HW} pool is lower than the soil SON_{KCl} pool (Table 2) among all of the eight forest ecosystems, which is consistent with the research of Xing et al. (2009), whilst both of them are inconsistent with the previous research (Burton et al. 2007). This may be related to the different soil types involved in the different studies (Xing et al. 2009). The stronger relationships found between water-extractable C and N and MBC and MBN than those between KCl-extractable C and N and MBC and MBN clearly demonstrated the greater proportions of SON_{HW} and SOC_{HW} might have been derived from dissolution and decomposition of microbes in soil than SON_{KCl} and SOC_{KCl} (Fig. 2).

4.2 The effect of forest ecosystems on SOC and SON pools

The eight forest ecosystems have shared similar forest management practices during forest restoration and the soils were developed from the same basaltic parent material. Hence, it is reasonable to assure that the differences in SOC and SON pools were the result of effects of the different types of forest ecosystems.

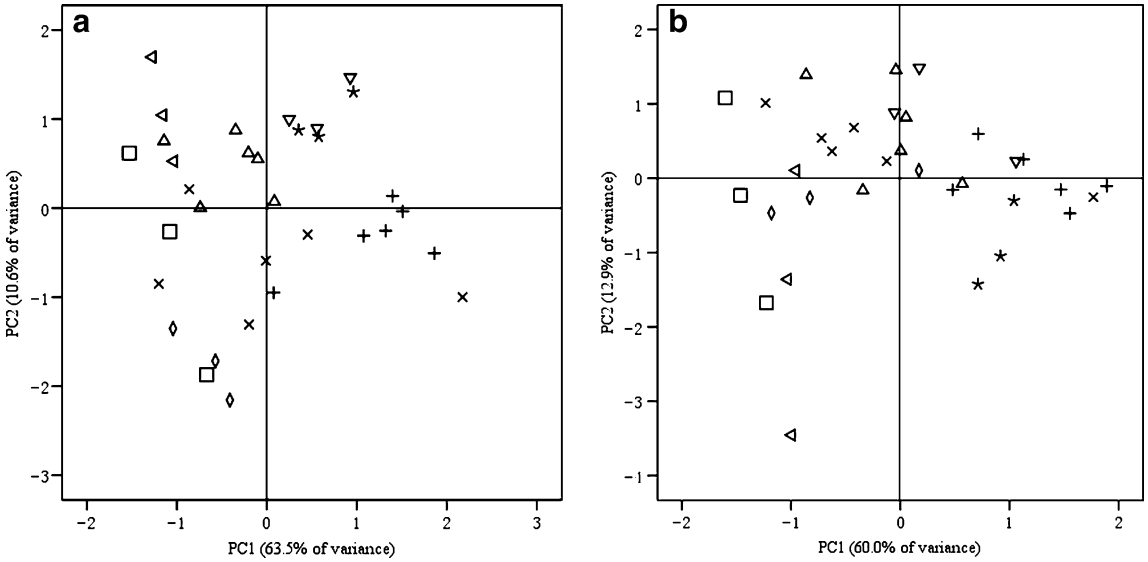

Fig. 3 The effect of forest ecosystems on the first and second principle components in the 0–10-cm soil (**a**) and in the 10–20-cm soil (**b**) of the soil parameters. *Individual symbols* represent the principle component scores of individual forest ecosystem. *CP1*, Masson pine; *CP2*, Pitch pine; *CBMP1*, Slash pine and Sweetgum; *CBMP2*, Slash pine and Camphortree; *CBMP3*, Masson pine and Sweetgum and Chinese Gugertree; *BMP*, Sweetgum and Chinese Gugertree; *BP1*, Chinese Gugertree; and *BP2*, Sweetgum

It has been suggested that most of SON and SOC in soils were derived from root exudation, litter decomposition, transformation of organic matter and immobilization of inorganic N and C (Kalbitz et al. 2003; Neff et al. 2003; Chen and Xu 2006; Chen and Xu 2008). Therefore, quantity and quality of organic inputs and associated microbially mediated processes determine the size and dynamics of soil SON and SOC pools. Increasing research suggests that tree species can influence SON pools through affecting the organic matter input, the composition of leachates, and the size, activity and diversity of the mesofaunal and microbial communities (Priha et al. 1999; Smolander and Kitunen 2002; Landi et al. 2006). Wang and Wang (2007) found that higher concentrations of hot water-extractable soil SON in native broadleaf plantations than in coniferous plantations were related to the greater amount and higher quality of soil organic matter in native broadleaf forest compared with the coniferous plantation. In the present study, the size of all SOC, SON and SIN pools in both depths generally decreased according to the following order: broadleaf forest ecosystems (BP1, BP2, and BMP), mixed forest ecosystem of conifer–broadleaf species (CBMP1), and conifer forest ecosystems (CP1, CP2) (except for CBMP3) (Table 2), which was consistent with the results reported by Smolander and Kitunen (2002), Burton et al. (2007) and Xing et al. (2009). However, in this study, leaf litter biomass was the highest under the CP2 forest ecosystem (16 t ha^{-1}), and lowest under the BP2 forest ecosystem (7 t ha^{-1}), and the other six forest ecosystem were intermediate (11–13 t ha^{-1}) (data not shown), which could not explain the trend in the pool sizes of SOC and SON. It is postulated that the shift of SOC and SON in the eight different forest ecosystems could be related to litter decomposition rates and soil microbial organisms involved, which were also reflected by the positively relationships between MBC (MBN) and SOC (SON) pools (Fig. 2a, b).

The C: N ratio is an important indicator of soil organic matter quality and fertility in forest ecosystems. In the present study, the broadleaf plantations (BP1, BP2, BMP) and mixed broadleaf and coniferous species plantations (CBMP1, CBMP2) had the lower leaf litter C: N ratio than the coniferous plantations (CP1, CP2) (data not shown). This indicated that broadleaf plantations and mixed broadleaf and coniferous species plantations may be better in improving soil N status than the pure coniferous plantations. The significantly negative relationship between C: N ratio of leaf litter layer and SOC and SON in the 0–10-cm soil depth (i.e. the R^2 is 0.46, 0.42, 0.45, or 0.41 ($P<0.001$) between C: N ratio of leaf litter layer and SOC_{HW}, SON_{HW}, SOC_{KCl}, or SON_{KCl}) (data not shown), indicated that the different SOC and SON patterns among the forest ecosystems would be closely related to the litter C and N, particularly in terms of quality of organic inputs.

The relative low concentrations of SON, SOC, SIN, MBC and MBN in the CBMP3 compared with the other mixed broadleaf and coniferous species plantations may be associated with spatial variation or the specific interactions of three broadleaf and coniferous species, which warrants further study.

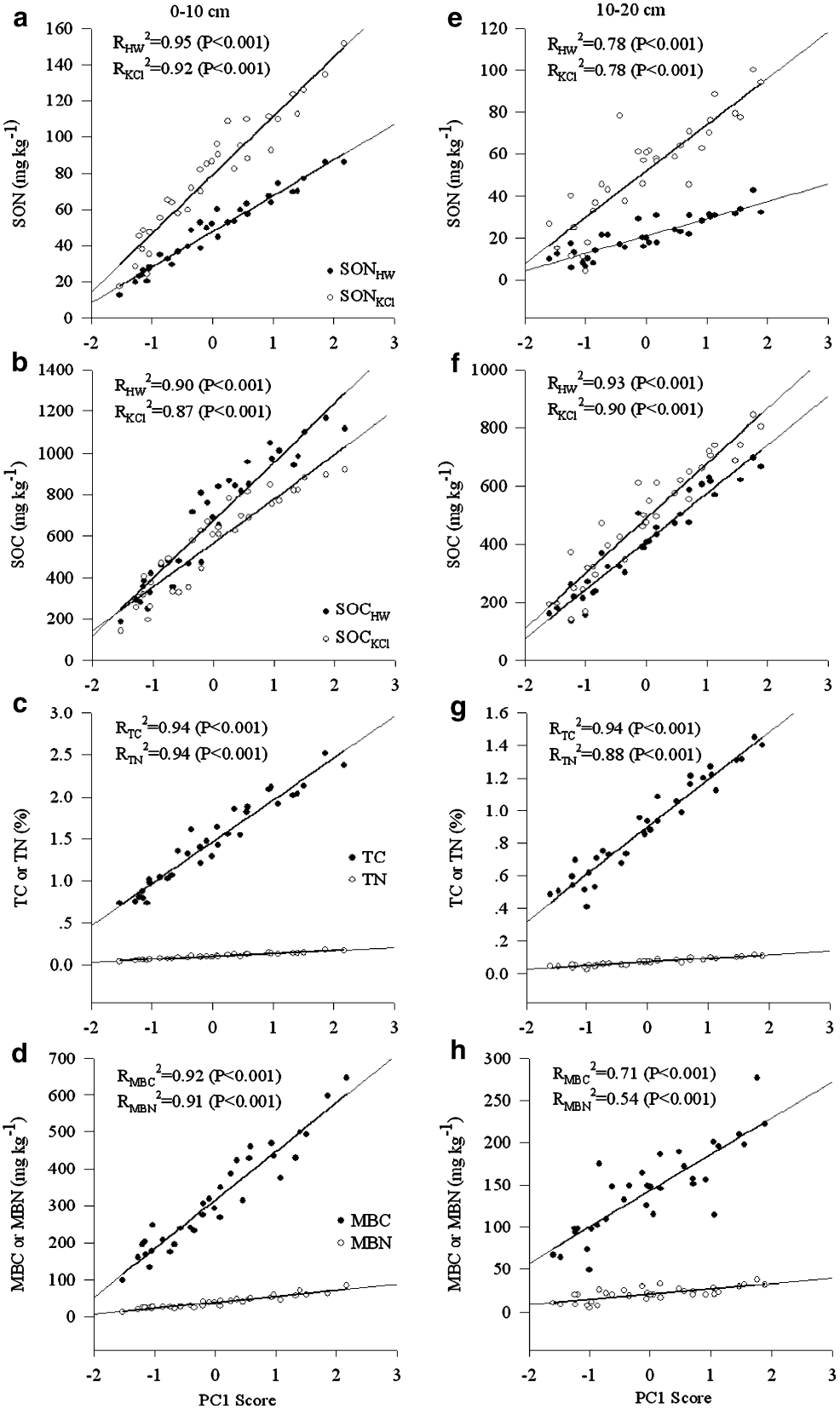

Fig. 4 Correlations between the first principle component scores and the soil properties in the 0–10-cm (**a, b, c, d**) and 10–20-cm soil (**e, f, g, h**) (n=33). SOC_{HW} and SON_{HW}, hot water-extractable soil soluble organic C and N; SOC_{KCl} and SON_{KCl}, KCl-extractable soil soluble organic C and N; *MBC*, soil microbial biomass C; *MBN*, soil microbial biomass N; *TC*, soil total C; and *TN*, soil total N

4.3 Relationships among types of forest ecosystems, SON, and other soil parameters

PCA using all soil parameters measured in this study has shown that monoconifer forest ecosystems (CP1, CP2), mixed conifer–broadleaf forest ecosystems (CBMP1, CBMP2, and CBMP3), and mono- and mixed broadleaf forest ecosystems (BMP, BP1, and BP2) could be well separated in the 0–10-cm soils (Fig. 3a). In the 10–20-cm soils, the CBMP3 was clustered into a group of monoconifer forest ecosystems (CP1, CP2), the CBMP1 and CBMP2 were clustered in the other group, and most broadleaf forest ecosystems were grouped together (Fig. 3b). The comparison of the PC scores showed that PC1was capable of accounting for most of the complex differences among the tested forest ecosystems, except for the CBMP3 in the 10–20-cm soils. The optimum competence of candidate PC1 to be the best indicator of the changes in soil C and N pools resulting from the different forest ecosystems were further confirmed by its close relationships with the relevant soil chemical and biological properties (Fig. 4). Therefore, all the quantitative and qualitative soil parameters with significant loadings on PC1 were the most informative measures that would be responsible for the complex impacts of different forest ecosystems on soil quality and fertility.

5 Conclusions

Results from this study have demonstrated that the different restored forest ecosystems had significant impacts on soil chemical and biological properties. From the conifer and conifer–broadleaf forest ecosystems to the broadleaf forest ecosystems, the amounts of soil SOC and SON as well as the MBC and MBN generally increased, which indicated that the broadleaf forest ecosystems and mixed broadleaf and coniferous species plantations could be used for the restoration of degraded red soil. However, the role of the individual species in restoring soil quality is unclear and requires further study. In addition, a further study is also necessary to sample over seasons in order to understand whether the significant impacts on soil properties are related to the sample time.

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