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Tree species composition rather than biodiversity impacts forest soil organic carbon of Three Gorges, southwestern China

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Abstract

Forest soil represents an important resource for mitigating the climate change. Besides, plant composition and diversity and their roles in ecosystem functioning are becoming a central issue in forest soil organic carbon (SOC) research. The primary objective of this research is to investigate the effects of tree species diversity and composition on potential of C sequestration of forest soil in Three Gorges area and provide basic information to future research on climate change. Two dominant forest ecosystems were selected: mixed conifer-broadleaf forest (F_m) and evergreen broadleaf forest (F_b). Then study transects were established and investigated. Soil samples were collected and determined for bulk density, SOC concentration and stock, nitrogen (N) concentration and C:N ratio. The results showed that the statistical differences of SOC concentrations and stocks between F_m and F_b were caused by tree species composition rather than the tree species diversity. And the most significant differences were found in the first two soil horizons (0–15 cm and 15–30 cm). The average C:N values of four different horizons in F_m were decreased with increasing soil depth as well as F_b. Not only SOC concentrations but also stocks of the two studied forests were decreased with increasing soil depth. However, F_m showed a larger capacity to store SOC with an average stock of 183.50 t/ha than that of F_b (100.44 t/ha) in study area. Thus, forest which is composed of conifer and evergreen broadleaf tree species may be the best choice for local afforestation and reforestation aimed at alleviating climate change in Three Gorges region.

Keywords

Soil organic carbon, tree species composition, biodiversity, C:N ratio, Three Gorges

Introduction

Scientists have long been concerned with soil carbon (C), because it is often the master variable determining soil fertility (Malhi et al. 1999; Johnson and Curtis 2001; Johnson et al. 2002). C enters the soil through both litterfall and rhizodeposition and leaves the soil mainly as CO_2 via root and microbial respiration (Sulzman et al. 2005; Cleveland et al. 2010; Díaz-Pinés et al. 2011; Sayer et al. 2011). However, as one of the most important green house gases, the tightly relationship between CO_2 and soil C is generally accepted in the context of global climate change. Thus, known soil C stock has become very important for assessing changes in atmospheric CO_2 concentrations and of global climate (Dixon et al. 1994; Schimel 1995; Søe et al. 2004). As the largest pool of terrestrial organic carbon in the biosphere, more C is stored in soil than is contained in plants and the atmosphere combined (Jobbágy and Jackson 2000). Global surveys of mineral soil organic carbon (SOC) indicate that the soil holds about 1500 Pg C in the upper meter of soil (Post et al. 1982; Eswaran et al. 1993; Jobbágy and Jackson 2000), and most of this SOC (roughly 70% of all SOC) is contained in forest soils (Dixon et al. 1994; Batjes 1996; Jandl et al. 2007).

The potential C sequestration of forest ecosystems is widely accepted (Batjes 1996; Jandl et al. 2007). In fact, by sequestering large amounts of atmospheric C, forest plays an essential role in the global C cycle and is thought to offer a mitigation strategy to reduce global warming (Dixon et al. 1994; Chiti et al. 2012). However, the extent to which the vegetation layer influences SOC stocks in natural mountain forest land of Three Gorges area is still poorly understood. Moreover, many articles about SOC have been focusing on its stock of a large area, for example, global scale, hemispheric scale or national scale (Eswaran et al. 1993; Dixon et al. 1994; Batjes 1996; Fang et al. 2001; Goodale et al. 2002; Li et al. 2004; Chiti et al. 2012). The SOC of smaller scale, such as forest communities and ecosystems, is not considered enough, especially in the aspect of relation between SOC and forest composition and diversity. Composition of tree species has a pivotal effect on soil processes, including the cycling and accumulation of C (García-Oliva et al. 2006; Díaz-Pinés et al. 2011). For example, trees drive litterfall inputs, rhizodeposition, animal manure and rainfall distribution, soil temperature, and consequently they shift soil microbial quantity and activity (Simón et al. 2013). Based on composition, the forest area can be classified into various types. Proportion of different species in the same plant community can be quantified through species composition investigation. Therefore, it is important to consider the influence of tree species composition on SOC stock at given sites, as it may provide a basis for quantifying C pool in forest, which plays a relevant role in the global C cycle (Mathers and Xu 2003; Chen et al. 2004). Our study will be added to the growing body of information on soil C storage in subtropical mountain forest of China. But beyond that, the relationship between plant diversity (i.e.: totality of genes, species, and ecosystems of a region) and biogeochemical process that regulates the ecosystem has been a central issue in both ecological and environmental sciences recently (Bunker et al. 2005; Chen 2006). Many studies have suggested that plant communities with high species diversity may promote more efficient use of resources compared with those of less species diversity and thus lead to greater net primary production, and consequently higher C sequestration (Saha 2008; Saha et al. 2009; Meier and Bowman 2010; Wang et al. 2011). However, Huston and Marland (2003) indicated that ecosystems with multiple species are not necessarily more productive than ecosystems with few species. Many natural ecosystems with low plant diversity, even near monocultures, are highly productive. Nevertheless, ecosystems with multiple species indeed provide some insurance that they may be steadier and continue to perform a particular function even if one of the species is lost. However, quantitative estimates of effects of tree species composition on SOC stocks under natural forest ecosystems remain scarce (Chapin III et al. 2000; Berger et al. 2002; Díaz-Pinés et al. 2011). Therefore, forest composition or biodiversity, which can be confirmed as the dominant effect on ecosystem C sequestration? The issue needs further researches.

In natural ecosystem, nitrogen (N) is a primary nutrient that limits vital activities of plant and microbe (Vitousek and Howarth 1991; Hu et al. 2001; LeBauer and Treseder 2008; Wei and Sun 2009). C cycling is consequently influenced by soil N and C:N ratio (Cleveland and Liptzin 2007; Cleveland et al. 2011), and both factors partly indicate activity of microbe and level of soil C decomposition by respirations of roots and microbes. Thus, both C stock and effects of C:N ratio have been hot spots of scientific interest in global change (Hungate et al. 2003; Chen 2006; Davidson and Janssens 2006).

Because of the alleviation effect on global warming, C sequestration ability of forest is expected for more and more focus (Wu et al. 2003; Lal 2004; Bonan 2008; Tarnocai et al. 2009). Especially in China, the large developing country all through the world, the conflict between environment and develop is becoming sharper and sharper. In order to reduce the green house gas, Chinese government has been struggling since a long time ago. Many measures have been conducted particularly in forestry. In last decades, although millions of hectares were planted (afforestation and reforestation) per year, making a huge C pool, the SOC stocks of forests in China have not restored from the continuously forestry C sequestration reducing since late 1940s (Fang et al. 2001). However, little attention was paid on the composition of tree species during silviculture and afforestation. It may cause inefficient C sequestration and cause unintended disastrous environmental consequences, especially in arid and semiarid regions (Gao et al. 2011). Nevertheless, C sequestration of natural forest should be studied in detail for "close-to-nature" afforestation and reforestation and finding the best forest management plan. Moreover, about 28 to 35% of forest C storage occurs in the southwestern region (including the provinces of Sichuan, Chongqing, Tibet, Yunnan, Guangxi, and Guizhou) which is the largest in China (Fang et al. 2001). Thus, forest C sequestration study in this region is important for afforestation and reforestation aiming at reducing green house gas in China. Since the end of 20^{th} century, the Natural Forest Protection Project has been conducted in Three Gorges of southwestern China (http://english.forestry.gov.cn/index.php/information-services). Vegetation coverage in this area was 35.62% by the end of 2007 and it was far greater than average of China (20.36%) (Zhao 2007). The natural forest ecosystems of the area are great potential for C stock. But study on this is still rarely showed. Therefore, the aims of this study are as follows: (1) Study the effects of forest composition on SOC concentration and stock. (2) Analyze the effects of tree species diversity on SOC concentration and stock. (3) Difference of SOC decomposition in different forests is showed by C:N ratio.

Materials and methods

Description of research area

Our study was carried out at Jinyun Mountain, Three Gorges area, southwestern China. The forest area is totally 1112.7 ha which accounts for 96.6% local land area, and typical subtropical forest species are abundant. The study area is bounded by the two major river systems of the region, i.e., the Yangtze River and the Jialingjiang River. Elevation ranges from 350 to 952 m. This region has a subtropical monsoon climate with long warm to hot humid summers and short cool to cold and cloudy winters with the lowest total number of sunshine days in China (about 1000 hours per year). The mean annual temperature is 13.6 °C and the average annual precipitation is 1611.8 mm. Soil type is Kandihumults of Ultisols (Staff 2010).

Methods for investigating, sampling and determining

In our study, we investigated two natural forest ecosystems in April, 2011: the mixed conifer-broadleaf forest (F_m) and the evergreen broadleaf forest (F_b). These two forests are close to each other (separated from each other by approximately 100 m) and have similar elevation and same aspect. The basic information, including vegetation, soil and topography characteristics, is showed in Table 1. The total area of F_m was 17.3 ha, and the area of F_b is 12 ha. Transect method was performed to survey trees, shrubs and herbs. Soil samples were collected by establishing plots in transects. Parallel transects (100 × 40 m) separated by about 50 m, were established in forest F_m (n = 7) and F_b (n = 5). Then two 20 m × 20 m plots were randomly selected in each single transect. Unfortunately, only thirteen plots were set in F_m because of topographical reason. After this, the total inventory of all tree species was conducted in every plot. Shrub species were surveyed in three randomly selected 2 m × 2 m subplots involved in each 20 m × 20 m plot. And within each 2 m × 2 m subplot, herb species were recorded by setting one 1 m × 1 m quadrate. Plant species were recorded and counted. Biodiversity indices

Table 1. Basic information of studied forest ecosystems.

Site	Dominant tree species	Shrub species	Herb species	Soil type	Range of slope (°)	Aspect	Mean elevation (m)	Range of canopy density	Total area (ha)
F_m	*Pinus massoniana* Lamb. *Cunninghamia lanceolata* (Lamb.) Hook. *Symplocos setchuensis* Brand *Lindera kwangtungensis* (Liou) Allen	*Maesa japonica* (Thunb.) Moritzi. *Eurya nitida* Korthals *Sarcandra glabra* (Thunb.) Nakai *Smilax china* *Rosa multiflora* Thunb. *Eurya fangii* Rehd. *Elaeagnus bockii* Diels *Rubus assamensis* Focke *Rubus malifolius* Focke *Rubus corchorifolius* L. f. *Camellia cuspidata* (Kochs) Wright ex Gard.	*Woodwardia japonica* (L. f.) Sm. *Lophatherum gracile* Brongn. *Oplismenus compositus* (Linn.) Beauv. *Hicriopteris glauca* (Thunb.) Ching *Commelina communis* Linn. *Stenoloma chusanum* Ching *Miscanthus sinensis* Anderss. *Hemerocallis fulva* (L.) L. *Conyza canadensis* (L.) Cronq. *Phyla nodiflora* (L.) Greene	Kandihumults of Ultisols	15–24	N	820	0.85–0.97	17.3
F_b	*Lindera kwangtungensis* (Liou) Allen *Symplocos setchuensis* Brand *Castanopsis fargesii* Franch. *Adinandra bockiana* *Gordonia acuminata* Chang	*Maesa japonica* (Thunb.) Moritzi. *Eurya nitida* Korthals *Sarcandra glabra* (Thunb.) Nakai *Smilax china* *Neolitsea aurata* (Hay.) Koidz *Eurya fangii* Rehd. *Symplocos lancifolia* Sieb. & Zucc. *Rubus malifolius* Focke *Camellia cuspidata* (Kochs) Wright ex Gard.	*Woodwardia japonica* (L. f.) Sm. *Oplismenus compositus* (Linn.) Beauv. *Hicriopteris glauca* (Thunb.) Ching *Commelina communis* Linn. *Stenoloma chusanum* Ching *Miscanthus sinensis* Anderss. *Hemerocallis fulva* (L.) L. *Conyza canadensis* (L.) Cronq. *Phyla nodiflora* (L.) Greene	Kandihumults of Ultisols	12–28	N	822	0.88–0.94	12

were calculated according to the inventory process mentioned above. Then mineral soil samples were collected by depth (0–15, 15–30, 30–50 and 50–100 cm or bedrock when the profile is not deep down to 100 cm.) in all quadrates. Soils from 1 m × 1 m quadrates in the same 20 m × 20 m plot were mixed and homogenized by depth. Consequently, one composite sample of mineral soil of each single horizon was collected in a plot. The total number of soil composite samples of F_m was 50 and that of F_b was 34. These samples were transported to the lab shortly after sampling (Díaz-Pinés et al. 2011) and air dried in shade. Soil bulk density and volume proportion of gravel at each soil sampling horizon were determined according to Landsberg et al. (2003). The Kjeldahl method was carried out to obtain N concentrations of soil (Gong et al. 2012). The SOC concentrations were tested according to the dichromate acid wet oxidation method (Yeomans and Bremner 1988).

Calculation

SOC concentrations and stocks and their vertical distributions were studied. The statistical differences of SOC in 0–100 cm between the two studied forests were analyzed by T-test. The statistical differences of SOC in each horizon (i.e.: 0–15cm, 15–30 cm, 30–50 cm and 50–100 cm) between the two studied forests, as well as those among horizons, were analyzed by one-way ANOVA respectively. And this method was performed to test the differences between tree species diversity of the two researched forests. The results were summarized to explain the effects of tree species composition and diversity on SOC accumulation. In order to study the effect of tree diversity on SOC sequestration, the correlations between SOC and tree species diversity indices of F_m, as well as F_b, were then estimated by regression analysis. As an important controller of SOC decomposition, soil C:N ratio was also analyzed. One-way ANOVA was performed to evaluate the differences between C:N ratios of the two studied forests so as to understand the condition of SOC decomposition. Data analysis was implemented by using Microsoft Office Excel 2003 (Microsoft Corporation, US) and SPSS-17 (IBM Corporation, US).

SOC stock was calculated according to following formula:

$$ST = \sum_{i=1}^{n} C_i \times \rho_i \times h_i \times (1 - \theta_i)/1 \qquad (1)$$

Where ST is SOC stock (t/ha), i is soil horizon code, n is the number of soil horizons, C_i is SOC concentration (g/kg), ϱ_i is soil bulk density (g/cm^3), h_i is soil horizon thickness (cm), θ_i is volume proportion (%) of gravel with diameter (φ) >2 mm.

Tree species diversity was presented by following indices (Li and Li 2006):

Simpson's index (biodiversity index):

$$D = 1 - \sum_{i=1}^{S} \left(\frac{n_i(n_i - 1)}{N(N-1)} \right) \qquad (2)$$

Shannon - Wiener index (biodiversity index):

$$H = -\sum_{i=1}^{S} \frac{n_i}{N} \log_2\left(\frac{n_i}{N}\right) \qquad (3)$$

Margalef index (richness index):

$$R = \frac{S-1}{\ln N} \qquad (4)$$

Where N is total number of trees in plot, i is tree species type, n_i is number of individuals of tree species i, S is number of tree species.

Results

SOC under the two studied forests

SOC concentrations of the studied forests remarkably decreased with increasing depth of mineral soil. These correlations could be simulated as follows:

$$SOC\ concentration(F_m) = 19.967 \ln(soil\ depth) - 99.282\ (R^2 = 0.4712, n = 50, p < 0.001)$$

$$SOC\ concentration(F_b) = 18.066 \ln(soil\ depth) - 79.115\ (R^2 = 0.5818, n = 34, p < 0.001)$$

SOC concentrations of F_m and F_b may be calculated by above empirical models. But it indeed needs more samples for accuracy.

Significant differences (p<0.001) were found among the four soil horizons in both F_m and F_b (see Fig. 1A). The statistical difference of total SOC concentrations of 0-100 cm mineral soil between the two studied forests was significant with p=0.0016 (see Fig. 1A and Table 2). It indicated that the average concentration of 0-100 cm SOC in F_m (85.62 g/kg) was remarkably larger than F_b (46.18 g/kg) (see Fig. 1A, Table 2). Compared with F_m, SOC of F_b (46.18 g/kg) only accounted for 53.94% of its SOC concentration. In the first two soil horizons, the SOC concentrations were even more remarkably different: 0–15 cm soil with p=0.0101 and p=0.0338 for 15–30 cm soil (see Fig. 1A, Table 2). In the other two horizons, that the p values were 0.2068 (30–50 cm) and 0.1539 (50–100 cm) respectively indicated insignificant differences between SOC concentrations of F_m and F_b. The most remarkable difference was found in the first mineral soil horizon. 0–15 cm SOC concentration of F_m (52.38 g/kg) was significantly larger than that of F_b (31.02 g/kg). The other horizons of F_m had greater SOC than F_b as well even though the statistical differences were not remarkable (see Fig. 1A, Table 2).

SOC stocks in 0–100 cm of F_m and F_b (Fig. 1B, Table 2) were statistically different (p=0.0052). However, 0–15 cm SOC stocks of the two forests were not significantly different with a p value of 0.0843 in contrast with 0–15 cm SOC concentrations (see Fig. 1A, B and Table 2). But the statistical difference of SOC stocks in 15–30 cm soil was remarkable (p=0.0294) (Fig. 1A). The SOC stocks, at the last two horizons, were

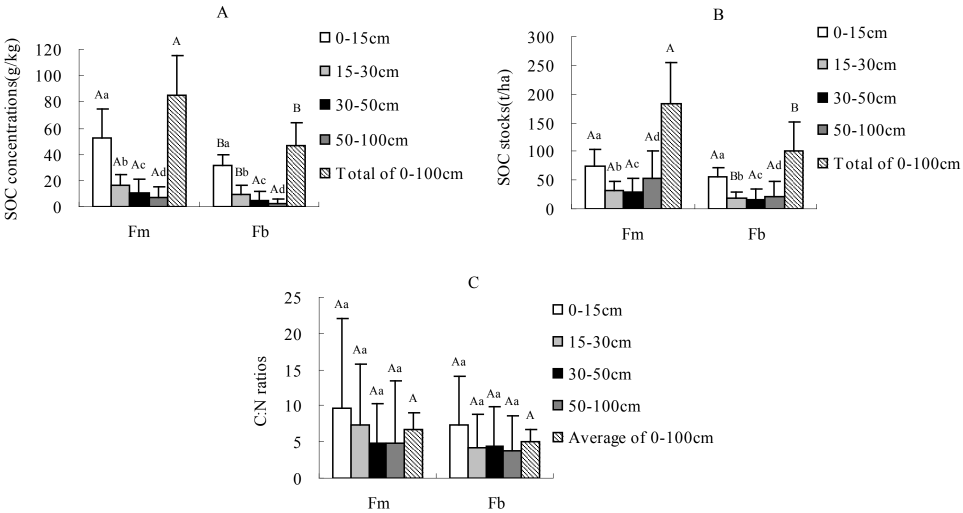

Figure 1. SOC concentrations (Fig. 1A), SOC stocks (Fig. 1B) and C:N ratios (Fig. 1C) of F_m and F_b. Where solid columns of different colors respectively show average values of each single horizon under the F_m and F_b. The columns with oblique lines are mean values of total SOC concentrations, total SOC stocks and average C:N ratios of 0-100 cm soil in F_m and F_b separately. Letters above each error bar indicate the statistical difference. The different capital letters show significant difference between value series of two forests (p<0.05), for example, capital letters on top of the two white columns (A and B) show difference between average 0–15 cm SOC concentrations of F_m and F_b. The different lowercase letters present remarkably differences of values among different soil horizons within a studied forest (p<0.001), for example, differences among SOC concentrations of 0–15 cm, 15–30 cm, 30–50 cm and 50–100 cm horizon of F_m were significant according to "a, b, c and d".

both not statistically different between F_m and F_b as the same as those of SOC concentrations (see Fig. 1A, B and Table 2). Both SOC stocks of F_m and F_b along soil horizons were found to be significantly different (p=0.0013 for F_m, p=0.00006 for F_b, Fig. 1B). The change of SOC stocks from topsoil to bottom was performed as follows:

$$SOC\ stock(F_m) = 7.1205\ln(soil\ depth) - 73.184\ (R^2 = 0.0325, n = 50, p < 0.5)$$

$$SOC\ stock(F_b) = 14.68\ln(soil\ depth) - 87.567\ (R^2 = 0.2184, n = 34, p < 0.005)$$

SOC stocks of F_m and F_b were decreased from 0-15 cm to 30-50 cm firstly, then they were increased (Fig. 1B and Table 2).

As shown in Fig. 1B and Table 2, the average total SOC stocks (0-100 cm) ranged from 183.50 t/ha of F_m to 100.44 t/ha of F_b. The quantitative relationship between SOC stocks of F_m and F_b was consistent with that of SOC concentrations (see Fig. 1A, B and Table 2). In F_m, 62.91% of the total SOC down to 1 m was in the top 30 cm (Fig. 1B and Table 2). The proportion was even more in F_b (83.08%). However, the main difference of SOC stock was found in 15-30 cm soil rather than the first horizon (Fig. 1B and Table 2).

Table 2. Mean value (`x) ± standard deviation (σ) of SOC concentration, SOC stock and C:N ratio. The p values which are less than 0.05 indicate significant difference between F_m and F_b.

	F_m	F_b					
	$\bar{x} \pm \sigma$	$\bar{x} \pm \sigma$	p	F	*Critical values of F*	t	*Statistical values of* t
SOC concentration							
0–15 cm	52.38±22.49	31.02±8.88	0.0101	7.9880	4.3248	——	——
15–30 cm	16.45±7.66	9.51±6.37	0.0338	5.1562	4.3248	——	——
30–50 cm	10.62±9.77	5.19±6.31	0.2068	1.7229	8.3997	——	——
50–100 cm	7.57±7.52	2.89±4.41	0.1539	2.2275	8.3997	——	——
0–100 cm	85.62±30.17	46.18±18.44	0.0016	——	——	2.0796	3.6342
SOC stock							
0–15 cm	75.23±29.09	56.96±14.58	0.0843	3.2841	4.3248	——	——
15–30 cm	32.03±14.88	18.70±11.55	0.0294	5.4666	4.3248	——	——
30–50 cm	29.00±24.38	15.09±18.60	0.2114	1.6865	4.4513	——	——
50–100 cm	53.59±47.01	20.30±28.37	0.1092	2.8583	4.4513	——	——
0–100 cm	183.50±71.59	100.44±50.38	0.0052	——	——	2.0796	3.1159
C:N ratio							
0–15 cm	9.63±12.47	7.44±6.71	0.5853	0.3071	4.3248	——	——
15–30 cm	7.30±8.41	4.27±4.45	0.3162	1.0544	4.3248	——	——
30–50 cm	4.82±5.54	4.51±5.36	0.8910	0.0194	4.4513	——	——
50–100 cm	4.89±8.53	3.83±4.72	0.7780	0.0821	4.4513	——	——
0–100 cm	6.66±2.29	5.01±1.64	0.4464	0.8175	3.9574	——	——

C:N ratios of F_m and F_b

Concentrations of SOC and soil N of F_m (r=0.6656, n=50, p<0.001) were linearly and remarkably correlated as well as those of F_b (r=0.5566, n=34, p<0.001). The results showed that soil N may have important effects on SOC. However, as a metric of SOC quality, the soil C:N ratios of the studied forests were not statistically different (Fig. 1C and Table 2). The above results indicated that C:N ratio may not lead to the differences of SOC between the two studied forests. However, the C:N ratio was decreased with increasing soil depth (Fig. 1C and Table 2). From the first to the forth horizon, the average C:N values of F_m were respectively 9.63, 7.30, 4.82 and 4.89 (Fig. 1C and Table 2). And those of F_b were 7.44, 4.27, 4.51 and 3.83 (Fig. 1C and Table 2). Although the average C:N ratio of 30–50 cm soil under F_b was larger than 15–30 cm soil, and the mean C:N ratio of 50–100 cm under F_m was larger than 30–50 cm soil, the C:N ratio was also generally decreased from 0–15 cm with maximum to 50–100 cm with minimum.

Relationship between tree species diversity and C

Average values of tree species diversity indices were shown in Table 3. That the average values of diversity indices of F_m were greater than those of F_b except for D indicated

Table 3. Average values of tree species diversity indices.

Forests	R (Margalef)	H (Shannon-Wiener)	D (Simpson's)
F_m	1.542	1.832	0.693
F_b	1.406	1.663	0.812

that the biodiversity (H) and richness (R) were the best in F_m, whereas another biodiversity index D of F_b was the greatest. And the one-way ANOVA analysis supplied the estimation: the statistical difference between biodiversity indices of F_m and F_b was not significant. According to the linear correlation analysis between SOC and tree species diversity of F_m and F_b, the SOC concentrations, including SOC in each individual horizon and total soil profile, were not significantly correlated with the three diversity indices as well as SOC stocks (p>0.05).

Discussions

The main differences of SOC concentrations of F_m and F_b were presented in 0–15 cm and 15–30 cm soil with p value of 0.0101 and 0.0338 respectively. The reason may be that roots are mainly distributed in 0–50 cm soil horizon (Waisel et al. 1991; Upson and Burgess 2013). However, the difference of SOC concentrations was insignificant in 30–50 cm horizon (p=0.2068). The SOC stocks of F_m and F_b were only significantly different in 15–30 cm horizon (p=0.0294). Totally, SOC concentrations of 0–100 cm in the two forests (p=0.0016) were significantly and statistically different as well as SOC stocks (p=0.0052) (Fig. 1A, B and Table 2). Thus, tree species compositions of forest ecosystems could be considered as a reasonable factor for distinguishing SOC from each other especially in surface soil (0–30 cm). Currently, Chinese government has been carried out many protection programs of forest in order to build a healthy natural ecosystem, for example, Land Conversion from Farmland back to Forestland Project, Wildlife Protection and Nature Reserve Development Program and Natural Forest Protection Project, etc (http://english.forestry.gov.cn/index.php/information-services). Simultaneously, afforestation and silviculture are implemented all through the country to decelerate global warming. Ecological conditions of China have a continual improvement and C sink potential keeps increasing. However, problems are also existed: monoculture afforestation, lack of forest management, and contradiction between food shortage and returning crop land to forest. Forest quality is influenced by those problems. These issues should be properly solved. In Three Gorge area, because of our SOC stock estimates, mixed conifer-broadleaf forest (F_m) with the largest soil C pool (183.50 t/ha) may be the best choice for local afforestation and reforestation aimed at alleviating climate change.

Liu (2005) suggested that broadleaf forest was climax communities in succession process of Mt. Jinyun with mixed conifer-broadleaf forest being inferior community. Several works (Malhi et al. 1999; Marín-Spiotta and Sharma 2013) suggested that both land use change and forest succession gradient were generally thought to have effect on SOC stocks, especially for surface soil. Nevertheless, the successional effects of forest communities in Three Gorges are still not understood well. Thus, the specific studies under local conditions are very necessary. Not only the 0–15 cm SOC concentrations were remarkably different (p=0.0101) between F_m and F_b, but also the 15–30 cm SOC concentrations were significantly different from each other (p=0.0338). Although insignificant, the difference of 0–15 cm SOC stocks between forests was indeed existent with p value of 0.0843. Nevertheless SOC stocks of 15–30 cm soil were remarkable different between F_m and F_b (p=0.0294). And the differences of SOC concentrations and stocks between F_m and F_b became weaker and weaker with increasing soil depth where roots of bottom soil were far less than surface soil. The above analysis showed that succession effects may be another reason which could control SOC stock of forest by influencing tree species composition.

Our total C stock estimates of 0-100 cm mineral soil under the two forest ecosystems (100.44–183.50 t/ha, Fig. 1B and Table 2) were beyond the range of values estimated for the mineral soil under forests of Mt. Dinghu with the similar climate (30.90-127.90 t/ha) (Fang et al. 2003), but included the estimate for the Ultisols soil (144.80 t/ha) in Chongqing city (Huang et al. 2005) (Table 4). In Mt. Dinghu (Fang et al. 2003), the SOC stocks in mixed conifer-broadleaf forests (30.90-107.10 t/ha) were less than those of evergreen broadleaf forests (95.00-127.90 t/ha). Chen (2007) suggested that mixed conifer-broadleaf forest (92.33-127.13 t/ha) sequestrated less C than evergreen broadleaf forest (151.63-290.82 t/ha) in Three Gorges region (Table 4). The results were contrary to our data. However, study in Spain showed that mixed conifer-broadleaf forest caught more SOC than evergreen broadleaf forest as well as in other regions of Mediterranean conditions which belongs to subtropics as the same as our research area (Díaz-Pinés et al. 2011) (Table 4). Li et al. (2004) also suggested that SOC stock of evergreen broadleaf forest (129.2 t/ha) in China was less than that of mixed conifer-broadleaf forest (225.70 t/ha) (Table 4). Ni (2001) estimated the SOC stocks of the two types of forests in China: 124.00-142.00 t/ha for evergreen broadleaf forest and 130.00-150.00 t/ha for mixed conifer-broadleaf forest (Table 4). Mixed forest caught more SOC than evergreen broadleaf forest. The differences of C stock among regions may be also due to climatic (Díaz-Pinés et al. 2011; Chiti et al. 2012) and geologic conditions etc (Schaefer et al. 2009). Besides, sampling time may also affect estimating value of C stock in forest soil. However, in southwestern China, the average forest biomass C stock was 60 t/ha which was the largest all through the country (Fang et al. 2001). And that the SOC is far more than biomass C is widely accepted. It indicated that natural forest in this region is a great container for C. Our results were greater than the average SOC stock of Ultisols soil on the Earth (Eswaran et al. 1993), which also showed the strong C sequestration of forests in the research area (Table 4). However, Woodwell (1984) indicated that Ultisols soil under virgin and secondary forests on Earth stored more SOC (180.00-240.00 t/ha) than the two forests in this study (Table 4).

Both the average soil C:N ratios of F_m and F_b were decreasing with increasing soil depth. And the average C:N ratios of F_b were less than those of F_m in each soil horizons.

Table 4. Published values of SOC in comparable mixed conifer-broadleaf forest and evergreen broadleaf forest in subtropical region.

Locatoin	Vegetation type	SOC stocks (t/ha)	Soil type	Source
Earth	Virgin and secondary forests	180.00–240.00	Ultisols	Woodwell (1984)
Earth	——	83.00	Ultisols	Eswaran et al. (1993)
China	Mixed conifer-broadleaf forest	130.00–150.00	——	Ni (2001)
China	Evergreen broadleaf forest	124.00–142.00	——	Ni (2001)
Fujian, China	Mixed conifer-broadleaf forest	30.90–107.10	Ultisols	Fang et al. (2003)
Fujian, China	Evergreen broadleaf forest	95.00–127.90	Ultisols	Fang et al. (2003)
China	Mixed conifer-broadleaf forest	225.70	——	Li et al. (2004)
China	Evergreen broadleaf forest	129.20	——	Li et al. (2004)
Chongqing, China	——	144.8	Ultisols	Huang et al. (2005)
Three Gorges region, China	Mixed conifer-broadleaf forest	92.33–127.13	Ultisols and Alfisols	Chen (2007)
Three Gorges region, China	Evergreen broadleaf forest	151.63–290.82	Ultisols and Alfisols	Chen (2007)
Central Spain	Mixed conifer-broadleaf forest	80.00–100.00	Inceptisols and Alfisols	Díaz-Pinés et al. (2011)
Central Spain	Evergreen broadleaf forest	40.00–70.00	Inceptisols and Alfisols	Díaz-Pinés et al. (2011)
Three Gorges region, China (Chongqing section)	Mixed conifer-broadleaf forest	183.50	Ultisols	This study
Three Gorges region, China (Chongqing section)	Evergreen broadleaf forest	100.44	Ultisols	This study

The C:N ratio provides some indication about the relative quality and biochemical stability of soil organic materials (Díaz-Pinés et al. 2011; Bui and Henderson 2013). The C:N ratio hinted a weak SOC decomposition in our studied forests. Therefore, SOC stock of study area was larger than the average value of Utisols soil on the earth (Eswaran et al. 1993) as well as forest soil in southwestern China (Fang et al. 2001). However, the C:N values of F_m and F_b were not statistically different (p=0.3879). On the other hand, SOC concentrations (p=0.0474) and stocks (p=0.0116) of F_m and F_b were remarkably different. The results showed that SOC differences between F_m and F_b were influenced by C:N ratio little, which indicated that SOC decompositions of F_m and F_b were similar. The composition of tree species may be a rational factor for distinguishing the differences between C sequestrations of forests in study area as above analysis.

The relationship between tree species diversity and SOC under studied forest ecosystems was not linear in our study. However, Chen (2006) suggested that SOC stocks were linearly increased with growing H indices of forests in Northeastern China. Nevertheless, in Sichuan Province of southwestern China (closely located in the west of our study area), the correlations between SOC and R and H of forests were as the same as our findings (Zhang et al. 2011). Kirby and Potvin (2007) did not find any linear relationship at soil profiles under forests in Eastern Panama either. The environmental factors of different region (Ewel et al. 1991; Berendse 1998; Forrester et al. 2006) and various forest productivities (Vandermeer 1989; Tilman et al. 1997) may cause the different relationships. And more studies are needed to explain the correlation between biodiversity and SOC in order to develop forest management and establish forest with great C sequestration. However, the statistical difference between biodiversity indices of F_m and F_b was not significant (Table 3). Thus, in contrast to plant species composition, biodiversity may not make difference in forest soil C sequestrations.

Conclusions

Tree species composition significantly and statistically influenced SOC concentrations and stocks of F_m and F_b. In first two soil horizons (0-15 cm and 15-30 cm), these differences were even more significant. However, SOC of F_m and F_b were not influenced by tree species diversity due to the very low linear coefficients. And the statistical difference between biodiversity indices of F_m and F_b was not significant. Thus, in contrast to plant species composition, biodiversity may not make difference in forest soil C sequestrations. The average C:N values of F_m in four different horizons were decreased with increasing soil depth as well as F_b. And the values were larger in F_m. But the difference between C:N ratios of F_m and F_b was not remarkable. C:N ratio contributed little to the difference between SOC of the two studied forests. Not only SOC concentrations of F_m and F_b were decreased with increasing soil depth but also SOC stocks reduced from surface soil to bottom. F_m showed a large capacity to store SOC rather than F_b in the area. Thus, mixed conifer-broadleaf forest may be the best choice for local afforestation and reforestation aimed at alleviating climate change in Three Gorges region. However, conflict issues can still be found in the relation between SOC and tree species diversity in studies all over the world. It needs more detail researches in different scale to explain.

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