CHANGES AND INFLUENCING FACTORS OF SOIL CARBON IN EVERGREEN BROADLEAVED FOREST INVADED BY *PHYLLOSTACHYS PUBESCENS* IN JIANGXI PROVINCE, SOUTH CHINA

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In southern China, moso bamboo (*Phyllostachys pubescens*) forests have been expanding into surrounding vegetation such as natural broadleaved forests and coniferous plantation forests. It has been speculated that the expansion of moso bamboo forest could alter soil carbon content and soil environmental condition. Soil samples were taken at 0–20 cm depth from three vegetation types, i.e. evergreen broadleaved forest, moso bamboo forest and mixed forest with broadleaved and moso bamboo. It was found that soil properties, especially soil microbes and nitrogen, contributed significantly to the variations in soil organic carbon. Soil carbon was higher under mixed forest with broadleaved and moso bamboo compared to evergreen broadleaved forest and moso bamboo forest. In soil environment, the direct contribution of bacteria and fungi to soil carbon content was highest. If the microbe indirect effect and nitrogen direct effect were considered, the expansion of moso bamboo could have substantial consequences on soil organic carbon. The finding indicated that the expansion of moso bamboo forest into evergreen broadleaved forest could increase soil carbon content. To better understand the effects of moso bamboo invasion on ecosystem functions, future studies on soil carbon dynamics and carbon cycling is required.

Keywords: Moso bamboo forest, evergreen broadleaved forest, soil carbon stock, soil properties

INTRODUCTION

The world's total forest area is just over 4000 Mha, i.e. 31% of the total land area (FAO 2010). According to the latest National Forest Inventory, China has 195.5 Mha of forests, which account for 4.9% of the global forest area (Jia 2009). Although around 13 Mha of global forests were converted to other uses or lost through natural causes during 2000 to 2010, Chinese forests had an average annual increase of 1.6 Mha over this period. This increase is mainly attributed due to large-scale afforestation and/or reforestation campaigns in China. During 2000 to 2010, bamboo plantations increased 25.5% percent, making them the second most rapidly expanding new forest plantations. The area of bamboo forests increased to 5.4 Mha, distributed among 19 provinces, of which 1.7 Mha are managed as plantations and 3.7 Mha are dense, natural bamboo forests (Anonymous 2010). China has the largest bamboo resource in the world having 300–500 species (Zhu et al. 1994). The most common species, moso bamboo (*Phyllostachys pubescens*) is growing in more than 3.9 Mha and its rapid growth results in invasion of adjacent areas.

The rapid invasion of bamboo into forests has ecological effects on forest productivity, soil biodiversity and nutrient cycling (Blundell et al. 2003, Umemura & Takenaka 2015, Fukushima et al. 2015). In addition, it has been inferred that bamboo invasion hydrologically affects disaster frequency and water resources (Hiura et al. 2004, Shinohara et al. 2010). However, little is known about the mechanism of the effects upon establishment and expansion to adjacent forest on soil carbon pool. This study selected a distinct belt in Jiangxi Province, South China, where the dominant tree species converted from broadleaf to moso bamboo forest and mixed forest with broadleaved and moso bamboo, to study the influence of moso bamboo forest expansion on soil carbon content. Evergreen broadleaved forest (*Castanopsis fargesii*) and moso bamboo forest are the dominant forests of South China. The mixed forest with broadleaved and moso bamboo is formed by moso bamboo expansion into its adjacent evergreen broadleaved forest. Main objectives of the present study includes (1) to investigate the changes of soil carbon content and soil characteristic in the selected forest types and (2) to examine the effects of moso bamboo forest establishment and expansion to adjacent forest on soil carbon content.

MATERIALS AND METHODS

Study site

The study site is located between 27° 30'–27° 50' N, 114° 30'–114° 45' E in Nianzhu Forestry Farm, Dagangshan, Jiangxi Province, South China, which has a typical humid subtropical climate with distinct rainy and dry seasons. The mean annual precipitation is 1590 mm, approximately 45% falling between April and June and 13% between October and December. The maximum daily precipitation is 195.7 mm and the mean annual potential evaporation is 1503 mm. The mean annual temperature is 16.8 °C and monthly mean temperature ranges from 5.2 °C in January to 28.8 °C in July. The frost-free period is 265 days. The soils are dominated by red or yellow soils and their derivatives.

In the present study three forest stands, viz. evergreen broadleaved forest, moso bamboo forest and mixed forest with broadleaved and moso bamboo, growing adjacent to each other on the same soil material (granite) and soil type (yellow soils), and having similar aspects (facing south-east), slope (27°) and elevation (~300 m) were selected. The evergreen broadleaved forest is dominated by *Casfanopsis fargesii*. The mean tree age in the selected stand was 45 years. The mean tree diameter at breast height (dbh) was 17.8 cm. The moso bamboo forest was converted from a young evergreen broadleaved forest stand in 1987. There were 3050 trees ha^{-1} with mean DBH of 12.4 cm. The mixed forest with broadleaved and moso bamboo was converted from a young evergreen broadleaved forest by moso bamboo forest expansion, 30 years ago. Except for occasional selective cutting bamboo, moso bamboo forest's extensive management is without fertiliser. All stand characteristics of evergreen broadleaved forest, moso bamboo forest and mixed forest with broadleaved and moso bamboo are shown in Table 1.

Soil sampling and analysis

Three 20 × 20 m plots for each forest stand were established in May 2011. In each plot within the 3 stands (9 plots), three soil samples were taken at the depth of 0–20 cm. After removing visible roots and organic residues, each soil sample was divided into two sub-samples. The first sub-sample was sieved through a 2 mm sieve and stored at 4 °C for analysis of microbial populations. The other sub-sample was sieved through a 2 mm sieve and subsequently air-dried for soil chemical properties (soil organic carbon, total nitrogen, pH, phosphorus and potassium. Soil organic carbon content was digested in $K_2Cr_2O_7$-H_2SO_4 solution using oil-bath heating and the carbon concentration was determined by titration. Total nitrogen in the soil was extracted with H_2SO_4 by Kjeldahl's azotometer (Ministry

Table 1 General characteristics of three selected study sites

Parameter	EBF	MF	MBF
Altitude (m)	285	290	295
Average dbh (cm)	17.8	14.5	12.4
Mean tree height (m)	14.3	15.9	18.7
Stand density (stem hm^{-2})	3050	1400	900
Canopy coverage (%)	80	85	75

EBF = evergreen broad-leaved forest, MBF = moso bamboo forest, MF = mixed forest with broad-leaved and moso bamboo of Forestry 2000). Available phosphorus was extracted with 0.03N NH_4F–0.025N HCl and estimated by a spectrophotometer (Bray & Kurtz 1954). Available potassium was extracted with 1.0 M NH_4OAc and determined by flame spectrophotometer (Thomas 1982).

Soil microbial properties (bacterial, fungal and actinomycete populations) were assessed by counting colony forming units on selective agar media as follows, Martin's medium for fungi, peptone-tryptone-yeast extract-glucose agar for bacteria and alkalinised water-agar medium (pH 10.5) for actinomycetes (Wollum 1982).

Soil physical properties (bulk density, field water capacity and available water capacity) were analysed. Bulk density was calculated through soil corer (5 cm diameter) methods. The wet sample mass was measured and then dried at temperature 105 °C till constant mass was achieved, for determination of bulk density and porosity. Field water capacity and available-water capacity of the soil samples were determined following the method of Gradwell (1968).

Data analysis

Statistical analyses were conducted using SPSS Version 11.5 for Windows. All comparisons were performed using analysis of variance (ANOVA) followed by least significant difference test between forests, significance levels were set at $p < 0.05$. Data was expressed as means with standard error. The relationship among the parameters was studied by Pearson linear correlation and path analysis. Direct influence of independent variable (soil properties) upon dependent variable (soil organic carbon) and indirect influence of one independent variable through another were measured with path coefficients. Based on multiple lineal regression analysis, path coefficients were calculated according to Li et al. (2011).

RESULTS

Soil organic carbon

Soil organic carbon concentrations were significantly different among three forest types. Mean soil organic carbon content was 20.47, 34.38 and 26.53 g kg^{-1} in the evergreen broadleaved forest, mixed forest with broad-leaved and moso bamboo and moso bamboo forest, respectively. Soil organic carbon followed the order, mixed forest > moso bamboo forest > broadleaved forest (Table 2).

Soil physical properties

At the depth of 0–20 cm, the bulk density ranged from 0.91 to 1.26 g cm^{-3}. The bulk density was low in the moso bamboo forest soil (Table 2) and the expansion of bamboo into evergreen broadleaved forest resulted in a significant increase of bulk density. The bulk density in evergreen broadleaved forest was higher than that in the mixed forest with broadleaved and moso bamboo and moso bamboo forest. Field

Table 2 Soil physicochemical characteristics of surface soils (0–20 cm) in the selected study stands

Physicochemical property	EBF	MF	MBF
Bulk density (g cm^{-3})	1.26 ± 0.12 a	0.96 ± 0.10 b	0.91 ± 0.06 b
Field water capacity (%)	40.50 ± 0.69 b	52.10 ± 0.24 a	39.30 ± 1.14 b
Available water capacity (%)	26.40 ± 1.59 ab	28.80 ± 0.52 a	21.90 ± 0.60 b
pH	4.57 ± 0.40 b	4.88 ± 0.07 a	4.45 ± 0.19 b
Soil organic carbon (g kg^{-1})	20.47 ± 0.76 c	34.38 ± 2.10 a	26.53 ± 0.38 b
Total nitrogen (g kg^{-1})	1.72 ± 0.13 b	2.26 ± 0.17 a	2.01 ± 0.12 ab
Soil C:N ratio	11.90 ± 0.16 c	15.21 ± 0.22 a	13.20 ± 0.09 b
Available phosphorus (mg kg^{-1})	2.25 ± 0.13 c	4.38 ± 0.15 a	2.93 ± 0.06 b
Available potassium (mg kg^{-1})	24.31 ± 0.99 c	55.64 ± 1.78 a	35.29 ± 0.31 b

Means ± SD; different letters denote significant differences between plantations at $p < 0.05$; EBF = evergreen broadleaved forest, MBF = moso bamboo forest, MF = mixed forest with broad leaved and moso bamboo.

water capacity and available water capacity were significantly different among the three forest types. Mean field capacity was 40.5%, 52.1% and 39.3% while mean available capacity was 26.4%, 28.8% and 21.9% in the evergreen broadleaved forest, mixed forest with broad-leaved and moso bamboo and moso bamboo forest, respectively.

The soil pH in evergreen broadleaved forest, mixed forest with broadleaved and moso bamboo and moso bamboo forest were 4.57, 4.88 and 4.45, respectively (Table 2). The conversion of evergreen broadleaved forest into moso bamboo forest resulted in a significant increase of total nitrogen, where total nitrogen was highest in the mixed forest with broadleaved and moso bamboo. For evergreen broadleaved forest, mixed forest with broadleaved and moso bamboo and moso bamboo forest, the mean soil C:N ratios were 12, 15 and 13 respectively. Both available potassium and available phosphorus, i.e total nitrogen, followed the order, mixed forest with broadleaved and moso bamboo > moso bamboo forest > evergreen broadleaved forest (Table 2).

Soil microbial properties

The soil microbial properties showed significant variations in the three types of forests (Table 3). Following the same trend as soil organic carbon, bacteria number was higher in soils under mixed forest with broadleaved and moso bamboo (1.34×10^6 g^{-1}) compared to moso bamboo forest (0.66×10^6 g^{-1}) and evergreen broadleaved forest (0.34×10^6 g^{-1}). Fungi number increased significantly between evergreen broadleaved forest (1.33×10^4 g^{-1}) and mixed forest with broadleaved and moso bamboo (2.00×10^4 g^{-1}). However, the moso bamboo forest had greater actinomycete number than the soil formed from it.

Relationship between soil organic carbon and soil environmental factors

There was a highly significant correlation between soil organic carbon and field water capacity, available water capacity, total nitrogen, phosphorus, potassium, bacteria, fungi and actinomycetes, in the three forests (Table 4).

Table 3 Microbial properties of the selected study stands

Microbial property	EBF	MF	MBF
Bacteria (10^6)	0.34 ± 0.10 c	1.34 ± 0.09 a	0.66 ± 0.06 b
Fungi (10^4)	1.33 ± 0.10 c	2.00 ± 0.11 a	1.77 ± 0.11 b
Actinomycete (10^4)	0.73 ± 0.11 b	1.25 ± 0.04 a	0.95 ± 0.16 b

EBF = evergreen broadleaved forest, MBF = moso bamboo forest, MF = mixed forest with broadleaved and moso bamboo

Table 4 Correlation coefficients between soil organic carbon content and soil property

*	SOC	BD	FWC	AWC	pH	N	P	K	Bacteria	Fungi	Actinomycetes
BD	-0.50	1									
FWC	0.89**	-0.35	1								
AWC	0.95**	-0.48	0.96**	1							
pH	0.44	0.24	0.66	0.45	1						
N	0.87**	-0.39	0.61	0.68*	0.40	1					
P	0.97**	-0.48	0.89**	0.92**	0.53	0.88**	1				
K	0.99**	-0.52	0.88**	0.92**	0.49	0.87**	0.99**	1			
Bacteria	0.98**	-0.45	0.89**	0.91**	0.57	0.89**	0.99**	0.99**	1		
Fungi	0.91**	-0.49	0.68*	0.74*	0.41	0.99**	0.92**	0.92**	0.93**	1	
Actinomycete	0.89**	-0.37	0.91**	0.85**	0.75*	0.77*	0.92**	0.91**	0.94**	0.83**	1

SOC = soil organic carbon, BD = bulk density, FWC = field water capacity, AWC = available water capacity, pH = pH, N = total nitrogen, P = phosphorus, K = potassium, Bacteria = bacteria number, Fungi = fungi number, Actinomycetes = actinomycetes number; *, ** significant at $p < 0.05$ and $p < 0.01$, respectively

Bulk density and pH showed a low correlation with soil organic carbon.

The path model had high explanatory power with adjusted R^2 values of 0.943. Bacteria and fungi were the strongest direct effects (1.87, -1.27) on soil organic carbon followed by total nitrogen (0.86) (Table 5). The relatively high positive indirect effects on organic carbon were also caused by bacteria. In contrast, phosphorus and field water capacity had zero direct effect on soil organic carbon whereas the indirect effects (especially from bacteria) were positive and higher than direct effects. Its high correlation coefficient with soil organic carbon was mainly caused by the direct effects.

The decomposition of the overall correlations between bulk density and soil organic carbon is

$$r_{BD} = P_{BD} + r_{BD\text{-}FWC} P_{FWC} + r_{BD\text{-}AWC} P_{AWC} \;..... + r_{BD\text{-}Actinomycetes} P_{Actinomycetes} \quad (1)$$

where r = correlation coefficients, P = path coefficients, BD = bulk density, FWC = field water capacity, AWC = available water acpacity, P_{BD}, P_{FWC} & $P_{Actinomycetes}$ = direct effect of bulk density on soil organic carbon, $r_{BD\text{-}FWC} P_{FWC}$ and $r_{BD\text{-}AWC} P_{AWC}$ = indirect effects via FWC and AWC.

DISCUSSION

Soil carbon and vegetation

This study set out to determine the relative effects of changes in soil and tree species on soil carbon. In the present study, the mixed stand between moso bamboo and evergreen broadleaved tree species showed a significant higher soil organic carbon concentration than pure moso bamboo forest and pure evergreen broadleaved forest. Tree species affected the soil organic carbon content and its vertical distribution in the mineral soil (Schulp et al. 2008). Kaye et al. (2000) also reported improvement of soil carbon sequestration in mixed-species forests. The soil carbon concentration in moso bamboo forest was higher than that in evergreen broadleaved forest, a similar trend observed by Wang et al. (2011). This partly explained the soil carbon rise.

Further, litter constitutes an important flux of soil organic carbon (Wang et al. 2009). Fine root turnover is another important flux of soil organic carbon where amount of carbon equals to litter (Rasse et al. 2005). Moso bamboo forests may allocate more biomass to their roots which can transfer more root detritus to the soil (Xiao et al. 2010). Thus moso bamboo significantly increased soil organic concentrations at 0–20 cm depth compared to evergreen broadleaved forest. The litter production in mixed forests with broadleaved and moso bamboo was higher than that in pure moso bamboo forest, which increased their surface soil organic carbon concentrations (Liao 2010). Zhang et al. (2008) also reported that litter production in mixed forests was higher than that in pure forest. Higher carbon stocks in mixed forest than pure moso bamboo forest and pure evergreen broadleaved forest could be due to, not only the expansion

Table 5 Path coefficients of the effects of soil property on soil organic carbon of the selected study stands

	BD→ SOC	FWC→ SOC	AWC→ SOC	pH→ SOC	N→ SOC	P→ SOC	K→ SOC	Bacteria→ SOC	Fungi→ SOC	Actinomycetes→ SOC
BD	-0.02	0.00	-0.05	-0.11	-0.33	0.00	0.39	-0.84	0.62	-0.17
FWC	0.01	0.00	0.11	-0.44	0.56	0.00	-0.65	1.66	-0.86	0.41
AWC	0.01	0.00	0.11	-0.20	0.58	0.00	-0.68	1.70	-0.94	0.39
pH	0.00	0.00	0.05	-0.46	0.34	0.00	-0.36	1.06	-0.52	0.34
N	0.01	0.00	0.08	-0.18	0.86	0.00	-0.65	1.66	-1.26	0.35
P	0.01	0.00	0.10	-0.24	0.75	0.00	-0.73	1.85	-1.17	0.42
K	0.01	0.00	0.10	-0.22	0.74	0.00	-0.74	1.85	-1.17	0.41
Bacteria	0.01	0.00	0.10	-0.26	0.76	0.00	-0.73	1.87	-1.18	0.43
Fungi	0.01	0.00	0.08	-0.19	0.85	0.00	-0.68	1.73	-1.27	0.38
Actinomycetes	0.01	0.00	0.10	-0.34	0.66	0.00	-0.68	1.75	-1.05	0.46

SOC = soil organic carbon, BD = bulk density, FWC = field water capacity, AWC = available water capacity, pH = pH, N = total nitrogen, P = phosphorus, K = potassium, Bacteria = bacteria number, Fungi = fungi number, Actinomycetes = actinomycetes number of moso bamboo species, but also the mixture per se. Thus, as compared with pure forest, mixed forests improved litter production and soil organic carbon sequestration.

Soil properties and their effect on soil carbon

Similar to other studies, the data suggested that vegetation plays a pivotal role in soil processes (Saetre 1999, Díaz-Pinés et al. 2011). For example, the nutrient turnover rate was higher in broadleaved forests than conifer forests, resulting in higher nutrient levels under broadleaved forests (Quideau et al. 1996). Soil properties can be transformed through biochemical and physico-chemical mechanisms. Moso bamboo had higher biomass and nitrogen content of litter than evergreen broadleaved forest (Gao & Fu 2007). Litter of mixed forests is more diverse than those of pure forests (Fontaine et al. 2003), thus requiring a larger variety of soil microbes for decomposition resulting in richer soil nutrients and higher soil microbial biomass (Table 3). These results were linked because the characteristics of litter (quantity or quality) affected its mineralisation rate, which in turn interacted to affect the changes of soil properties (Wang et al. 2013a). In this study, the soil properties under mixed forest with broadleaved and moso bamboo was better compared to moso bamboo forest and evergreen broadleaved forest in surface soil. The same trend was observed by Wang et al. (2013b), suggesting that the expansion of moso bamboo into evergreen broadleaved forest could change soil structure and enhance soil nutrients and microbial activity.

The soil organic carbon in this study was influenced by soil and vegetation. Correlation analysis showed that soil bacteria was the most influential of the ten factors on soil carbon content, followed by fungi. The bulk density and pH had weak effects on soil organic carbon (Table 4). Path analysis indicated that bacteria and fungi were the most important factors directly affecting soil carbon content (Table 5). Plant inputs to soil from leaf and root litter and rhizodeposition are important mechanisms through which the composition and activity of soil microbial community is influenced and consequently soil carbon affected. Møller et al. (1999) reported that soil microorganisms affected the decomposing of litter leaves and water-soluble organic carbon fraction quality. Soil microbial biomass was lower under pure forest (poplar or birch) compared to their mixed forests (Wang et al. 2013b). Moreover, nitrogen had high direct effect on soil organic carbon and indirect effects through bacteria and fungi. Nitrogen affects soil carbon through effects on plant growth, litter production and decomposition and stabilisation of soil organic matter. Overall, moso bamboo invasion into evergreen broadleaved forest clearly altered soil carbon due to changes in soil biological properties, (e.g. bacteria and fungi) and physicochemical parameters, (e.g. nitrogen). The details of these processes should be studied by examining changes in soil carbon dynamics and carbon cycling following moso bamboo invasion.

CONCLUSIONS

In this study of the effects of moso bamboo expansion on soil carbon content, it was found that soil properties, especially soil bacteria and fungi, contributed significantly to variations in soil organic carbon concentrations following moso bamboo invasion. Soil carbon increased as vegetation developed from broadleaved to mixed forest with broadleaved and moso bamboo. The direct contribution of bacteria and fungi to soil carbon content was highest. If the indirect effect of microbes and the direct effect of nitrogen were considered, the expansion of moso bamboo could have substantial consequences on soil organic carbon. The results indicated that over-arching ecological factors, such as soil microbial community, are the main drivers of changes in soil organic carbon in forest ecosystem. They have implications on the ecosystem rehabilitation and conservation in south China region. To better understand the effects of moso bamboo invasion on ecosystem functions, future studies on soil carbon dynamics and carbon cycling is required.

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