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Soil carbon, nitrogen and microbial biomass dynamics of subalpine *Abies fabri* forest in Gongga Mountain, Southwest China

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Soil organic carbon (SOC), soil microbial biomass C, soil total nitrogen (N), NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N dynamics were measured in subalpine *Abies fabri* forest at different growth phases which include the mature forest (MF, 3100 m a.s.l.), the middle age forest (MAF, 2998 m a.s.l.) and the succession forest of mixed *Abies fabri* and *Populus purdomii* Rehd (SF, 2947 m a.s.l.) of Gongga Mountain, Southwest China. SOC concentrations decreased significantly with increasing depth and at a given depth (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm and 60-100 cm), SOC was greater in MF than that in MAF and SF. The average SOC concentration in MF (50.99 g kg\textsuperscript{-1}) was almost six times than that in MAF (7.97 g kg\textsuperscript{-1}) and SF (6.25 g kg\textsuperscript{-1}). Soil microbial biomass C fluctuated in time and was higher in August than that in June and October under all *A. fabri* forests. Soil NH\textsubscript{4}\textsuperscript{+}-N, NO\textsubscript{3}\textsuperscript{-}-N and soil available N (NH\textsubscript{4}\textsuperscript{+}-N + NO\textsubscript{3}\textsuperscript{-}-N) were higher in MF than those in MAF and in SF. The average soil available N concentrations were 21.61, 12.57 and 10.91 mg kg\textsuperscript{-1} under MF, MAF and SF, respectively.

**Key words:** Soil organic carbon, soil nitrogen, *Abies fabri* forest, Gongga Mountain.

INTRODUCTION

Soil carbon (C) pool containing about 1500-2000 Pg C, has been considered as the largest pool of C in terrestrial ecosystems and plays an important role in the global carbon cycle (Li et al., 2005; Rasmussen et al., 2006). Forests are the most extensively distributed vegetation-type ecosystems in the world and cover approximately one-third of the earth land surface (Li et al., 2000). Approximately 40% of the global soil C inventory resides in forest ecosystems and a relatively small change in forest soil C inventories could have important implications for the global C budget (Carten et al., 1999; Diochon et al., 2009). Therefore, the study of soil carbon dynamics is critically important to our ability to understand the carbon balance in forest ecosystems and their responses to future global climate change (Davidson et al., 2000).

Soil organic carbon (SOC) is well known to maintain several functions. Being the major component of soil organic matter (SOM), it is a determinant of soil physical and chemical properties, an important proxy for soil biological activity and a measure of soil productivity (Batjes and Sombroek, 1997; Rossi et al., 2009). SOC plays an important role in climate change processes by acting either as source or sink of atmospheric CO\textsubscript{2} (Jiménez et al., 2008). Microorganisms have a fundamental role in the biogeochemical cycles of the elements and in the formation of soil structure, it is widely accepted that a high level of microbial size and activity is necessary for the maintenance of an adequate quality of soil (Bastida et al., 2007; Anderson et al., 2008; Feng et al., 2009). Microbial C, especially the microbial C-to-SOC ratio, can reveal the status of microorganisms in the C availability of forest soils and is considered to be a quantitative indicator for carbon dynamics in soils (Xu et al., 2006, 2007). Nitrogen (N) is generally considered the...
single element most likely to be limiting to forest production (Knoepp and Swank, 2002; Schimel and Bennett, 2004), and affects biogeochemical cycles of other elements mainly through the process of litter decomposition (Wang et al., 2007). Therefore N is important in regulating ecosystem process (Vitousek et al., 1997). Soil is the primary and most immediate N pool for plants and microbes in forested ecosystems (Wang et al., 2007). Although there are typically large quantities of N in soil ecosystems, most is bond in organic forms unavailable to plants. Only small quantities of N are in accessible mineral forms, such as ammonium (NH$_4^+$) and nitrate (NO$_3^-$) (Bonito et al., 2003). NH$_4^+$-N and NO$_3^-$-N are the main forms which microorganisms and plants take N from soil. The mechanism and rate of soil organic N mineralization which the amount of N released through the decomposition of organic matter during a certain period of time has important influence on the availability of NH$_4^+$ and NO$_3^-$ to microorganisms and plants in forests (Diekmann and Falkengren-Gerup, 1998; Vestgarden and Kjennaas, 2003). NH$_4^+$ derived from organic matter mineralization is being transformed into NO$_3^-$ through the nitrification process (Gallardo et al., 2006). NH$_4^+$-N and NO$_3^-$ N content variations with different season because of temperature, moisture and other ecological factors have been found in many forests (Pinay et al., 1995; Smith et al., 1998; Laverman et al., 2000; Pérez et al., 2004; García-Oliva et al., 2006).

As one of the most important species of subalpine dark coniferous forest, Abies fabri grows in the southwestern mountains of China, especially in the Gongga Mountains at elevations between 2800~3400 m. There are a few studies of soil C, N cycles in subalpine dark coniferous forest of Gongga Mountain (Cheng and Luo, 2003; Dong et al., 2003; Wang et al., 2004, 2005; Lu and Cheng, 2009) that provides an understanding of how natural and human-related disturbances may affect the size and rate of change in soil C, N pools, and consequences for the structure, composition and functioning of the forest soil. But there are no reports of soil C, N dynamics related to different A. fabri forest types. The aim of this study was to determine the SOC, soil microbial biomass C, soil total N, NH$_4^+$-N and NO$_3^-$N dynamics of the subalpine A. fabri forest located in the Gongga Mountain, which will improve our understanding about the dynamics of forest soil C, N so as to provide a scientific basis for the research of the response mechanism of the soils to the climate change.

**MATERIALS AND METHODS**

**Study area**

Gongga Mountain is situated on the Quaternary sections of the eastern Tibetan Plateau with the longitude 29° 20′~30° 20′ and the latitude 101° 30′~102° 15′, and is the highest mountain in Sichuan province with the summit of 7556 m above sea level. The great height difference (1100~7556 m) derived from the Quaternary Neotectonic movement leads to the prominent vertical zonation of vegetation with forest types ranging from valley subtropical vegetation to alpine cold vegetation gradient (Wang et al., 2004; Pan et al., 2008). Rich species resources with strong primary ecological environment and well preserved original conditions provides ideal sites for scientific research of background regimes of forest ecosystem C, N pools and cycles and their comparative studies under different anthropogenic disturbances. The Gongga Mountain Region is located in the transitional region from the subtropical monsoon climate zone to frigid climate zone of the Qinghai-Tibet Plateau. This region to be characterized by high precipitation, cloudy days, cold winters and cool summers due to the impacts of east-southern monsoon from the Pacific (Dong et al., 2003; Shan et al., 2004).

The subalpine A. fabri forest in this study was at 2900~3100 m altitude in the Hailuogou valley which located on the east slope of Gongga Mountain. Alpine ecosystem observation and experiment station of Gongga Mountain (3000 m observation plot) which belongs of the Chinese Ecosystem Research Network (CERN) is located in this area. Based on meteorological data collected by the station, the annual mean air temperature is 3.8°C, the lowest mean air temperature occurred in January (~4.5°C), and the highest mean air temperature occurred in July (~12.7°C). The average annual precipitation is 1949 mm, 70% of which occurs from June to October, and annual potential evaporation averages 264 mm (Cheng and Luo, 2003; Shan et al., 2004; Lu et al., 2008; He and Tang, 2008). The virgin forest succession gradient is very good here, having the A. fabri forest, the main body of the frigid-temperate-zone subalpine dark coniferous forest of the east slope of Gongga Mountain, including the mature forest of the climax succession phase (MF), the middle age forest of the middle succession phase (MAF) and the succession forest of mixed A. fabri and Populus pseudomii Rehd (SF). The soil is the typical mountain dark brown soil in A. fabri forest, which has a high sand content (> 65%) and strong permeability.

**Soil samples**

Soil samples were collected from three types A. fabri, including the mature forest (MF, 3100 m a.s.l.), the middle age forest (MAF, 2938 m a.s.l) and the succession forest of mixed A. fabri and Populus pseudomii Rehd (SF, 2947 m a.s.l.). Six plots were established in each forest stand, provides six replications. Soil sampling was conducted by depth with separation into five soil horizons (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm and 60-100 cm) to analyzed soil physical and chemical property differences in September 2005. Soil samples for microbial biomass C in each forest stands were collected three times in June, August and October 2005 with the depth of 0-20 cm. And soil samples for soil NH$_4^+$-N and NO$_3^-$-N were collected four times in April, June, August and October 2005 with the same depth (0-20 cm). Samples were randomly taken at 6~8 m apart each plot and later pooled to one sample per plot. Soil samples were kept in cool boxes to the laboratory and analyzed immediately.

**Laboratory analyses**

Soil physical and chemical properties were determined as per the regular analysis methods (Liu, 1996). Soil bulk densities (g cm$^{-3}$) calculations were based on volume of bulked soil cores and oven dried mass determinations. Soil particle-size fractions were determined by the pipette method following H$_2$O$_2$ treatment to destroy organic matter and subsequent dispersion of soil suspensions by Na-hexametaphosphate. SOC was determined using wet oxidation with K$_2$Cr$_2$O$_7$. Total nitrogen analysis followed the micro-Kjeldahl digestion method. The determination of total P
There were clear effects of A. fabri forest type on soil bulk density, soil texture, total N, total P and total K concentrations (Table 1). At a given depth soil bulk density was greater in MF than that in MAF and SF, and soil bulk density increased significantly with increasing depth. The soils under MF had lower sand contents (75.32%) than soils under MAF (79.40%) and SF (78.79%), but higher clay contents (43.33%) than under MAF (27.33%) and SF (26.69%). There were significant differences for sand, silt and clay contents among the different depths in MF and MAF (Table 1). The sand content of soils under MF and MAF increased significantly with increasing depth and the silt and clay content of soils decreased significantly with increasing depth, but the soil texture of soils under SF did not significantly differ among different depths (Table 1). Soil total N concentrations ranged from 4.71 to 1.32 g kg⁻¹ in MF, from 0.89 to 0.17 g kg⁻¹ in MAF and from 0.91 to 0.15 g kg⁻¹ in SF with the depth of soils from 0-10 cm to 60-100 cm and total N concentrations significantly decreased with depth under all the forests. Soil total P concentrations were not significant difference among different forests and different depths. At a given depth soil total K concentrations were lower in MF than that in MAF and SF (Table 1).

### RESULTS

#### Soil physical and chemical properties

There were clear effects of A. fabri forest type on soil bulk density, soil texture, total N, total P and total K concentrations (Table 1).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>BD (g·cm⁻³)</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>N total (g·kg⁻¹)</th>
<th>P total (g·kg⁻¹)</th>
<th>K total (g·kg⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>The mature Abies fabri forest (MF)</td>
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<td>0-10</td>
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<td>27.50ᵃ</td>
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<td>25.41ᵇ</td>
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<td>18.96ᵃ</td>
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<td>1.30ᵇ</td>
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<td>40-60</td>
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<td>15.50ᵇ</td>
<td>3.28ᵇ</td>
<td>1.81ᶜᵈ</td>
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<td>60-100</td>
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<td>0.15ᵇ</td>
<td>1.04ᵃ</td>
<td>30.83ᵃ</td>
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</table>

1 BD: Bulk Density; 2 BD of soil layer 0-20 cm, mean values followed by different letters are different from each other at P < 0.05.

As carried out using the NaOH digestion method and the determination of total K as carried out using the HF-HClO₄ digestion method.

Microbial biomass C was determined according to the CHCl₃ fumigation–extraction method in field-moist samples (Vance et al., 1987). Fumigated and nonfumigated samples were incubated during 24 h at 25°C at constant moisture content. Microbial C was extracted from both fumigated and nonfumigated samples with 0.5 M K₂SO₄. C was measured using the automated CO₂ analyzer. Microbial biomass C was calculated by subtracting the extracted C in unfumigated samples from that measured in fumigated samples and dividing it by a Kᵣ value of 0.45 (Joergensen, 1996). Inorganic N as NH₄⁺ and NO₃⁻ was extracted from a 5 g fresh soil sample by shaking for 30 min with 50 ml of 2 M KCl. The extracts were filtered and nitrate and ammonium were determined calorimetrically by the phenol-hypochlorite method.

### Statistical analysis

Statistical analyses were carried out using the statistical package SPSS 11.5. Analysis of Variance (ANOVA) was used to test the statistical significance of trends in SOC data. Significantly different averages were separated with standard error of means to evaluate least significant difference (LSD). All tests were evaluated at p<0.05. Additionally, soil microbial biomass C, soil NH₄⁺-N and NO₃⁻-N were analyzed using generalized linear mixed models (GLMM).

### SOC and microbial biomass C

SOC of Surface soil (0-10 cm) concentrations were 80.92 g kg⁻¹ under MF, 15.56 g kg⁻¹ under MAF and 15.67 g kg⁻¹ under SF.
under SF and SOC concentrations decreased significantly with increasing depth (Figure 1). SOC concentrations declined to 27.49, 5.25 and 5.34 g kg⁻¹ in the 60-100 cm layer under MF, MAF and SF respectively. At a given depth SOC was greater in MF than that in MAF and SF and the average SOC concentration in MF (50.99 g kg⁻¹) was almost six times than that in MAF (7.97 g kg⁻¹) and SF (6.25 g kg⁻¹). Soil microbial biomass C was much higher under MF than that under MAF and SF. For example, soil microbial biomass C in MF was about 3 times in comparison with that in MAF and about 2 times in comparison with that in SF (Figure 2). Microbial biomass C fluctuated in time, with a considerable variation in concentrations among different months (Table 2). Soil microbial biomass C was higher in August than that in June and October under all A. fabri forests.

DISCUSSION

Soil C, N dynamics

Soil NH₄⁺-N and NO₃⁻-N concentrations in the different A. fabri forest types in time are presented in Figure 3. In general, soil NH₄⁺-N, NO₃⁻-N and soil available N (NH₄⁺ -N + NO₃⁻ -N) were higher in MF than those in MAF and in SF. Soil NH₄⁺-N concentrations in three forest types were higher in April and June and lower in August and in October. Soil NO₃⁻-N concentrations kept the same variation trends as the soil NH₄⁺-N concentrations. Soil available N concentration was defined as the sum of soil NH₄⁺-N concentration and soil NO₃⁻-N concentration. The average soil available N concentrations were 21.61, 12.57 and 10.91 mg kg⁻¹ under MF, MAF and SF respectively. Soil available N also showed higher concentrations in April and in June and lower in August and October. The highest ratio (2.83) of soil NH₄⁺-N to NO₃⁻-N appeared in October under MAF and the lowest value (0.69) of soil NH₄⁺-N / NO₃⁻-N ratio appeared in June under MF. Soil NH₄⁺-N / NO₃⁻-N ratio was higher in August and October under MAF and SF than those in April and June. Under MF soil NH₄⁺-N / NO₃⁻-N ratio appeared in April (Table 2).

Figure 1. SOC at 0-100 cm depth of Abies fabri forest in Gongga Mountain: (1) MF, (2) MAF, (3) SF.
which microorganisms and plants uptake N from soil. The availability of NH$_4^+$-N and NO$_3^-$-N is believed to limit forest production because many forests show growth response to improve mineral N fertilizers (Pastor et al., 1984; Bonito et al., 2003). Soil NH$_4^+$-N and NO$_3^-$-N showed clearly seasonal variations in many forests. For example, in two typical riparian forests along the River Garonne, southwest France soil NH$_4^+$-N concentration increased similarly after the flood events and in late summer in both sites and soil NO$_3^-$-N increased sharply in summer (Pinay et al., 1995). In southern Chilean forest ecosystems soil available N (NH$_4^+$-N + NO$_3^-$-N) showed marked seasonality in these lowland rainforests, with a higher internal N flux during the winter months, and found that soil available N in upper and deep soil horizons positively correlated with monthly precipitation (Pérez et al., 2004).

In subalpine A. fabri forests of Gongga Mountain soil NH$_4^+$-N and NO$_3^-$-N concentrations in three forest types were higher in April and June and were lower in August and October. Soil NH$_4^+$-N / NO$_3^-$-N ratio was higher in August and October under MAF and SF than those in April and June and under MF soil higher NH$_4^+$-N / NO$_3^-$-N ratio appeared in April. During the growing season plant growth is stimulated by rising soil temperature and increasing fluxes of photosynthetically active radiation; this increases the demand for inorganic N. The period of maximum plant uptake was preceded by peaks in the rates of soil microbial production of inorganic N, and variations in seasonal patterns of N transformation matched the variation in plant growth.

**Comparisons among different type A. fabri forests**

The A. fabri forest in the eastern slope of Gongga Mountain is one type of subalpine dark coniferous forests of southwestern China. According to field investigation
the oldest age of mature natural A. fabri forest is about 160 years, the average age of middle aged A. fabri forest and mixed A. fabri and Populus purdomii Rehd forests are 80 and 40 years respectively (Gao and Gao, 2007). The MF community is dominated by A. fabri, its composition is very complex and its stratification obvious. The species composition of SF is much more complicated than that of the MF and the species composition of MAF lies between that of the MF and the SF. The proportions of A. fabri found in the MF, MAF and SF are 80, 79 and 51%, which shows an decreasing trend and this phenomenon agrees with the characteristics of A. fabri at different evolving phase (Gao and Gao, 2007). Dong et al (2003) reported that the flux in relations to soil N\textsubscript{2}O emission of all the three sites appear as MF> SF>MAF, and the CH\textsubscript{4} consumption flux as MF>MAF>SF. The existence of the above relations is related to soil physiochemical properties and differences of community compositions of various sites. Cheng and Luo (2003) found that for MF site the soil had complete structure and higher organic content and soil C pool for the whole layer is 143.1 t ha\textsuperscript{-1}, contributing 82.5% in the upper layer and 27.5% in the lower layer; and for MAF site the soil C pool was only 30.7 t ha\textsuperscript{-1}. In the present study the result shows that SOC and soil microbial biomass C were greater in MF than those in MAF and SF. For example, soil microbial biomass C in MF was about 3 times in comparison with that in MAF and about 2 times in comparison with that in SF. Soil N concentrations kept the same trends. Soil NH\textsubscript{4}\textsuperscript{+}-N, NO\textsubscript{3}\textsuperscript{-}-N and soil

Figure 3. Soil NH\textsubscript{4}\textsuperscript{+}-N and NO\textsubscript{3}\textsuperscript{-}-N dynamics of Abies fabri forest in Gongga Mountain: (a) NH\textsubscript{4}\textsuperscript{+}-N, (b) NO\textsubscript{3}\textsuperscript{-}-N, c . NH\textsubscript{4}\textsuperscript{+}-N + NO\textsubscript{3}\textsuperscript{-}-N, d. NH\textsubscript{4}\textsuperscript{+}-N / NO\textsubscript{3}\textsuperscript{-}-N.
available N (NH$_4^+$ -N + NO$_3^-$ -N) were also higher in MF than those in MAF and in SF.

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