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Characteristics of carbon and nitrogen of soil microbial biomass and their relationships with soil nutrients in *Cunninghamia lanceolata* plantations

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Abstract The soil microbial biomass and nutrient status under the native broadleaved forest and *Cunninghamia lanceolata* plantations at the Huitong National Research Station of Forest Ecosystem (in Hunan Province, midland of China) were examined in this study. The results showed that after the native broadleaved forest was replaced by mono-cultured *C. lanceolata* or *C. lanceolata*, soil microbial biomass and nutrient pool decreased significantly. In the 0–10 cm soil layer, the concentrations of soil microbial carbon and nitrogen in the broadleaved forest were 800.5 and 84.5 mg/kg, respectively. These were 1.90 and 1.03 times as much as those in the first rotation of the *C. lanceolata* plantation, and 2.16 and 1.27 times as much as those in the second rotation of the plantation, respectively. While in the 10–20 cm soil layer, the microbial carbon and nitrogen in the broadleaved forest were 475.4 and 63.3 mg/kg, respectively. These were 1.86 and 1.60 times as much as those in the first rotation, and 2.11 and 1.76 times as much as those in the second rotation, respectively. Soil nutrient pools, such as total nitrogen, total potassium, $\text{NH}_4^+\text{-N}$, and available potassium, also declined after the *C. lanceolata* plantation replaced the native broadleaved forest, or Chinese fir was planted continuously. Less litter and slower decay rate in pure Chinese fir plantation were the crucial factors leading to the decrease of soil microbial biomass and nutrient pool in this area. Human disturbance, especially slash-burning and site preparation, was another factor leading to the decrease. There

were significant positive correlations between soil microbial carbon and nitrogen and soil nutrients. To improve soil quality and maintain sustainable productivity, some measures, including planting mixed conifer with hardwood, preserving residues after harvest, and adopting scientific site preparation, should be taken.

Keywords *Cunninghamia lanceolata* plantation, evergreen broadleaved forest, soil microbial biomass, soil fertility

1 Introduction

Soil microbial biomass is a driving force for the conversion and circulation of soil organic substance and nutrient, accounting for 1%–3% of soil nutrient (Jenkinson and Ladd, 1981). It can serve as the reservoir of available nutrients to the plants in soil. Many researches have been reported on the reliability of soil microbial biomass as a biological indicator of soil fertility nationally and internationally (Sun et al., 1999; van Bruggen and Semenov, 2000; Jiang et al., 2002; Li et al., 2003; Huang et al., 2004). It has been proved that soil microbial biomass carbon is positively correlated with soil nutrient, and is closely related to the ecological system's primary productivity and soil health. Soil microbial biomass is highly sensitive to the changes of maintenance practices. It can be an indicator showing the changes of total soil organic substances at an early stage (Dalal et al., 1991; Gregorich et al., 1994.).

Cunninghamia lanceolata (Lamp) Hook is a fast-growing coniferous species specifically grown in subtropical China. At present, the *C. lanceolata* plantation covers 1.21×10^7 hm² approximately, or 24% of the total plantation forest area in China (Chen and Wang, 2004). Following the practice of *C. lanceolata* replacement of evergreen broadleaved forests and continuous replanting of mono-cultured *C. lanceolata*, soil fertility declined. This seriously affected and hindered the productivity of *C. lanceolata* plantations and its sustainable management (Chen et al., 1990). So far, there are very few studies on soil microbial biomass in *C. lanceolata* plantations

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(Jiang et al., 2002; Xu and Xu, 2003; Wang et al., 2005). In this connection, this study was conducted in Huitong County, Hunan Province, the central Chinese fir production region. Our target was to observe the changes of soil microbial carbon, nitrogen and soil nutrient in the first and second rotation of *C. lanceolata* plantation and evergreen broadleaved forests. The purpose of the study is to find out the effects of microbial biomass on soil nutrient circulation and conversion, and to check the possibility of microbial biomass as an indicator of forestland soil quality, and eventually to provide scientific evidence for sustainable utilization of *C. lanceolata* plantations.

2 Materials and methods

2.1 Site descriptions

The research site is located in the Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, in Hunan Province (110°08'E, 27°09'N), with altitude ranging from 200 to 500 m. The region is characterized by low altitude, hilly topography and oxisols. It has a humid mid-subtropical monsoon climate with an annual average temperature of 16.5°C, an annual precipitation of 1,200 mm, and an annual relative humidity of around 80%. The native subtropical evergreen broadleaved forest is typical of this area, mainly composed of *Castanopsis fargesii*, *Machilus pauhoi*, *Cyclobalanopsis glauca*, *Lithocarpus glaber*.

The first rotation of *C. lanceolata* plantation was established in 1983 after clear-cutting of the former second evergreen broadleaved forests in 1982, and such site preparation practices as slash-burning and full excavation were conducted. The planting density was at 2,000 trees per hectare. The second rotation of *C. lanceolata* plantation was done in 1982 at the site where the first generation of pure *C. lanceolata* plantation was removed in 1982. Likewise, the slash burning and full excavation were conducted as site preparation measures and the planting density was at 2,000 trees per hectare as well.

2.2 Methods

The soil samples were taken from the sites of the first rotation of pure *C. lanceolata* plantation, the second rotation of pure *C. lanceolata* plantation, and the evergreen broadleaved forests. General information of these three types of forest

stands is listed in Table 1. Soil samples were taken from three plots of 10 m × 10 m in each site. From each plot, 10 points were selected randomly and a special driller (with diameter of 4.5 cm) was used to take soils at 0–10 cm and 10–20 cm depth, respectively. The sample for each plot was collected from mixed soil of the same layer from all 10 points after visible plant roots and residuals in the soil were removed. The soil sample was divided into two halves. One half was put in a refrigerator (3°C approximately for no more than four days) after being sieved (by 2 mm sieve) to measure the microbial biomass. The other half was sieved after being wind-dried to measure soil nutrients.

Chloroform-fumigation extraction was used to measure microbial biomass (Vance et al., 1987). The organic carbon and nitrogen in the extracts and the organic carbon in the soil were both measured by Elementar High TOCII+N, while the soil nutrient indicators were measured by normal analytical method.

2.3 Data analysis

Data collected from the field survey and laboratory analysis were processed and analyzed by Microsoft Excel (XP) and SPSS 11.5.

3 Results and discussion

3.1 Soil microbial carbon and nitrogen

Soil microbial carbon and nitrogen were significantly less in pure *C. lanceolata* plantation sites than the evergreen broadleaved forest site, lower in the second generation of *C. lanceolata* plantation site than the first generation (Table 2). At the 0–10 cm layer in the first generation and the second generation of *C. lanceolata* plantation sites, the microbial carbon is 52.7% and 46.3% of the evergreen broadleaved forests, while the microbial nitrogen is 96.9% and 78.6% of the evergreen broadleaved forests, respectively. Similarly, at the 10–20 cm layer in the first generation and the second generation of *C. lanceolata* plantation sites, microbial carbon is 53.9% and 47.5%, while microbial nitrogen is 62.5% and 57.0%, respectively. At both 0–10 cm layer and 10–20 cm layer, there were significant differences in soil microbial carbon between the three types of forest sites ($p < 0.05$) (as shown in Table 2). The soil microbial biomass decreased as the soil depth increased. In evergreen

Table 1 General information of different forest stands and general physical and chemical characteristics of soil

| Forest stand | Age /year | Elevation /m | Aspect | Slope /° | SOC /(g·kg ⁻¹) | C:N | pH /(H ₂ O) | Bulk density /(g·cm ⁻³) |
|--------------|-----------|--------------|--------|----------|----------------------------|-------|------------------------|-------------------------------------|
| CK | 41 | 391 | NE | 30 | 39.20 | 14.73 | 4.66 | 1.14 |
| FCF | 21 | 521 | NE | 20 | 37.80 | 19.20 | 4.43 | 1.16 |
| SCF | 21 | 521 | N | 25 | 24.69 | 15.61 | 4.73 | 1.20 |

CK: evergreen broadleaved forest; FCF: first generation plantation of Chinese fir; SCF: second generation plantation of Chinese fir. It is the same in the context below.

Table 2 Content of soil microbial biomass and nutrients in different forests (\pm SD)

| Soil layer /cm | Forest stand | MBC / $(\text{mg} \cdot \text{kg}^{-1})$ | MBC/SOC /% | MBN / $(\text{mg} \cdot \text{kg}^{-1})$ | MBN/TN /% | TN / $(\text{g} \cdot \text{kg}^{-1})$ | TK / $(\text{g} \cdot \text{kg}^{-1})$ | NH_4^+ -N / $(\text{mg} \cdot \text{kg}^{-1})$ | AK / $(\text{mg} \cdot \text{kg}^{-1})$ |
|----------------|--------------|--|------------------------------|--|------------------------------|--|--|---|---|
| 0–10 | CK | 800.5 \pm 43.7 ^a | 2.05 \pm 0.08 ^a | 84.5 \pm 8.5 ^a | 3.34 \pm 0.88 ^a | 2.66 \pm 0.80 ^a | 35.8 \pm 1.2 ^a | 17.0 \pm 1.8 ^a | 215.8 \pm 7.8 ^a |
| | FCF | 421.7 \pm 19.7 ^b | 1.13 \pm 0.17 ^b | 81.9 \pm 2.6 ^a | 4.29 \pm 1.00 ^a | 1.97 \pm 0.40 ^a | 33.7 \pm 0.7 ^a | 12.1 \pm 4.3 ^a | 218.0 \pm 27.9 ^a |
| | SCF | 370.9 \pm 4.9 ^{bc} | 1.50 \pm 0.03 ^c | 66.4 \pm 7.0 ^{ab} | 4.21 \pm 0.16 ^a | 1.58 \pm 0.22 ^a | 22.9 \pm 0.1 ^b | 9.4 \pm 5.0 ^a | 175.6 \pm 43.4 ^a |
| 10–20 | CK | 475.1 \pm 17.7 ^a | 2.04 \pm 0.40 ^a | 63.2 \pm 2.0 ^a | 3.07 \pm 0.42 ^a | 2.08 \pm 0.23 ^a | 35.2 \pm 3.6 ^a | 13.2 \pm 3.2 ^a | 172.3 \pm 34.3 ^a |
| | FCF | 256.0 \pm 12.6 ^b | 1.13 \pm 0.12 ^b | 39.5 \pm 2.9 ^b | 2.52 \pm 0.49 ^a | 1.62 \pm 0.45 ^a | 25.9 \pm 5.0 ^{ab} | 9.7 \pm 1.7 ^a | 143.3 \pm 38.9 ^a |
| | SCF | 225.8 \pm 8.9 ^{bc} | 1.03 \pm 0.19 ^b | 36.0 \pm 1.1 ^b | 2.27 \pm 0.43 ^a | 1.63 \pm 0.39 ^a | 23.4 \pm 4.3 ^{ab} | 8.2 \pm 2.4 ^a | 109.9 \pm 25.1 ^a |

Different letters in the same column and soil layer present significant at 5% level.

broadleaved forest, microbial carbon and nitrogen at 10–20 cm layer is 40% and 25.3% lower than in the 0–10 cm layer. In pure *C. lanceolata* plantation, microbial carbon and nitrogen at the 10–20 cm layer is 40% and 25.3% of the 0–10 cm layer.

According to Xu and Xu (2003), microbial carbon ranges from 117 to 948 mg/kg in broadleaved forests and from 65 to 402 mg/kg in *C. lanceolata* plantations. Our result was basically in agreement with this previous study. Another research by Jiang et al. (2002) found that microbial biomass is higher in evergreen broadleaved forests than that in *C. lanceolata* plantations. They believed the difference in soil microbial carbon between different sites is related to the litter decomposing process and the soil microflora around roots induced by forests.

Behera and Sahani (2003) reported that microbial biomass content and its availability in *Eucalyptus* plantation is lower than that in natural forests. This study found that soil microbial C/N ratio ranged from 4.76 to 7.00 with an average of 5.87 in the *C. lanceolata* plantation site, from 7.03 to 10.59 with an average of 8.49 in the broadleaved forest site. This result illustrated that microbial C/N ratio in *C. lanceolata* plantation soil is lower than that in broadleaved forest soil. It has been proven that C/N ratio of fungus (7–12) is higher than for bacteria (3–6) (Marumoto et al., 1982). In this connection, the lower soil microbial C/N ratio in *C. lanceolata* plantation compared with broadleaved forest soil, could be the result of different microflora constitutions around the root system. For instance, bacteria increases while fungus decreases.

The ratio of soil microbial carbon to organic carbon (MBC/SOC), named as soil microbial quotient, could be used as an indicator to predict changes of soil organic matter, and to monitor soil degradation and restoration (Hart et al., 1989). Therefore, plenty of scholars believed this microbial indicator is extremely useful in soil management. From Table 2, it can be found that soil microbial quotient ranged from 1.03 to 2.05, and that the value was significantly lower in the *C. lanceolata* plantation site than that in broadleaved forest soil. Xu and Xu (2003) also reported that the ratio of soil microbial carbon to organic carbon in broadleaved forests (2.27%) is higher than that in the *C. lanceolata* plantation (1.52%). At the 0–10 cm layer, soil microbial nitrogen's share of the total nitrogen in the *C. lanceolata* plantation was

higher than that in the broadleaved forest. At the layer of 10–20 cm, the case was just opposite. However, the same trend was found that soil microbial nitrogen was higher in the first generation of *C. lanceolata* plantation than that in the second generation. Sparling (1992) believed that in case of soil overexploitation, soil microbial carbon pool would decrease rapidly, and eventually it would lead to the decrease in soil microbial moisture. In the *C. lanceolata* plantation, the quality and quantity of litter were poorer than that in broadleaved forests, which in turn, reduced the carbon source and nutrient available to microorganism. Thus, it resulted in decreased microbial biomass, and subsequently microbial moisture decreased.

3.2 Soil nutrients

During the process of pure *C. lanceolata* plantation establishment and development, a large quantity of soil nutrients was consumed. The available nutrients in soil decreased as the number of successive pure plantation rotation increased. Ying (1997) reported that the soil hydrolytic nitrogen, available phosphorous and potassium in the second generation of *C. lanceolata* plantation decreased significantly by 34.8%, 60.4% and 39.8%, respectively, compared with the first generation of *C. lanceolata* plantation. Moreover, with the generations of plantation increasing, the total nitrogen in the second and the third generation of *C. lanceolata* plantation decreased by 13.40% and 20.86% compared with the first generation; total phosphorous by 22.81% and 36.84%; and the total potassium by 4.5% and 15.10% (Ma et al., 2000). According to Xu and Xu (2003), it was also proven that repeated plantations of *C. lanceolata* caused soil nutrient depletion. This study also found that soil nutrient content in *C. lanceolata* plantation was lower than that in the broadleaved forests (Table 2). In addition, it was lower in the second generation of *C. lanceolata* plantation than that in the first generation. However, the difference is not significant ($p > 0.05$). At layers of 0–10 and 10–20 cm, there was significant difference in total potassium ($p < 0.05$) but not in total nitrogen, NH_4^+ -N and available potassium. These results indicated that soil fertility decreased with successive plantations of *C. lanceolata*. Total soil nitrogen also tended to drop with the *C. lanceolata* plantation replacement of

broadleaved forests. In comparison with the first generation of *C. lanceolata* plantation, total soil nitrogen in the second and third generations of *C. lanceolata* plantation dropped by 7.84% and 18.63%; total potassium dropped by 15.57% and 18.10%; hydrolytic nitrogen decreased by 1.79% and 15.44%; available phosphorous decreased by 6.67% and 20.00%; available potassium both dropped by 2.00% (Yang et al., 2000). Because of the poor quality of litter in *C. lanceolata* plantation (e.g. high ratio of C/N), short rotation and bad litter disposal practice, inappropriate management measures, less nutrients returned to the soil, which led to the lack of soil nutrients. Wang et al. (1997) had studied soil nutrient return in pure *C. lanceolata* plantation and its mixture with *Michelia macclurei*. They found that soil nutrient returned was much higher in mixture forest than that in *C. lanceolata* plantation. Total nitrogen, $\text{NH}_4^+\text{-N}$ and available potassium are 1.64, 1.82 and 1.63 times of *C. lanceolata* plantation litter. Nutrient return to soil under the first generation of *C. lanceolata* plantation is 1.56 and 1.13 times of the second and third generations, respectively (Yang et al., 1998). As the number

of generations of successive *C. lanceolata* plantation increased, forest closure rate decreased and the undergrowth increased, which resulted in an increase in annual litterfall from the undergrowth. Therefore, the quality and quantity of the undergrowth, and its decomposition played a very important role in maintaining soil fertility. Lack of soil nutrient in *C. lanceolata* plantation was also related to soil loss. Following *C. lanceolata* plantation replacement of broadleaved forest and continuous pure *C. lanceolata* plantation, the soil erosion control capacity reduced, and water and soil loss intensified (Yang et al., 1999).

3.3 Relevance of soil microbial and soil nutrition

On the one hand, soil microbes can decompose and transform soil organic matter into available nutrients. On the other hand, they can also maintain inorganic nutrient elements in soil. The larger the microbial biomass is, the stronger the capacity of fertility maintenance. In this case, soil nutrients tend to accumulate. Thus, soil microbial biomass is the source of

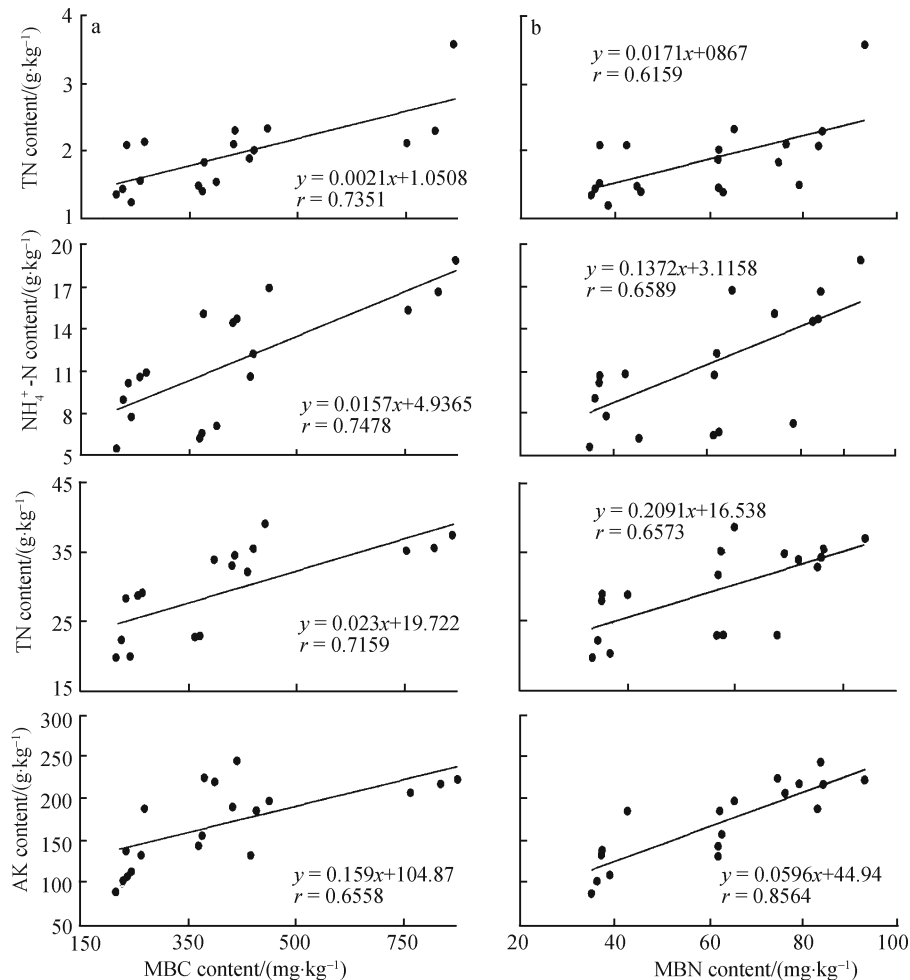


Fig. 1 Relationship of soil microbial biomass carbon (a), nitrogen (b) and nutrients
 TN: total nitrogen; TK: total potassium; AK: available potassium; MBC: microbial biomass carbon; MBN: microbial biomass nitrogen.

mineral nutrients of plants. They catalyze the process of fixed nutrients into available nutrients (Coleman et al., 1983; Carter and Rennie, 1984). It is already proven by previous researches that even minor changes of microbial biomass reservoir can affect the cycling and availability of nutrients (Boy and Sigh, 1994). This study discovered that soil microbial carbon content was extremely positively correlated with total nitrogen, $\text{NH}_4^+\text{-N}$, total potassium and available potassium ($P < 0.01$) (Fig. 1). Moreover, microbial nitrogen was also extremely correlated to total nitrogen, $\text{NH}_4^+\text{-N}$, total potassium and available potassium (Fig. 1). Smith and Paul (1991) reported that microbial N, P and S maintained a certain kind of dynamic balance with soil available N, P and S. The research of Liu et al. (2003) showed that soil microbial carbon is weakly correlated ($R^2 = 0.188$, $n = 16$) with soil hydrolytic nitrogen. However, it was positively correlated to available phosphorous, although not significantly correlated ($R^2 = 0.312$, $n = 16$). It was not significantly correlated to available potassium ($R^2 = 0.428$, $n = 16$). These findings showed that soil microbial carbon content was more accurate than soil organic carbon to indicate the dynamic changes of soil fertility, which can be used to reflect soil fertility changes dynamically (Jenkinson and Ladd, 1981; Chen and He, 1998). Therefore, soil microbial carbon can be used as an indicator of forest soil fertility.

4 Conclusion

Compared with the evergreen broadleaved forests, microbial carbon and nitrogen, soil microbial quotient, and soil nutrients were significantly lower in pure *C. lanceolata* plantation, and additionally, they were lower in the second generation of *C. lanceolata* plantation than in the first generation.

Soil microbial carbon showed a significantly positive correlation with soil total nitrogen, total potassium, $\text{NH}_4^+\text{-N}$ and available potassium. Moreover, soil microbial nitrogen was extremely positively correlated to the soil nutrients. Therefore, soil microbial carbon and nitrogen could be used as an important biological indicator to judge soil quality in *C. lanceolata* plantation soil.

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References

Behera N, Sahani U (2003). Soil microbial biomass and activity in response to *Eucalyptus* plantation and natural regeneration on tropical soil. *For Ecol Manage*, 174: 1–11

Boy S, Sigh J S (1994). Consequences of habitat heterogeneity for availability of nutrients in a dry tropical forest. *J Ecol*, 82: 503–509

Carter M R, Rennie D A (1984). Dynamics of soil microbial biomass N under zero and shallow tillage for spring wheat, using ^{15}N urea. *Plant Soil*, 76: 157–164

Chen G C, He Z L (1998). Study on microbial biomass of red soil under different land use. *Chin J Soil Sci*, 29(6): 276–278 (in Chinese)

Chen C Y, Wang S L (2004). *Ecology of Mixed Plantation Forest*. Beijing: Science Press

Chen C Y, Zhang J W, Zhou C L, Zheng H Y (1990). Researches on improving the quality of forest land and the productivity of artificial *Cunninghamia lanceolata* stands. *Chin J Appl Ecol*, 1(2): 97–106 (in Chinese)

Coleman D C, Reid C P P, Cole C V (1983). Biological strategies of nutrient cycling in soil systems. *Adv Ecol Res*, 13: 1–55

Dalal R C, Henderson P A, Guasby J M (1991). Organic matter and microbial biomass in a Vertisol after 20 years of zero-tillage. *Soil Biol Biochem*, 23: 435–441

Gregorich E G, Carter M R, Angers D A, Monreal C M, Ellert B H (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Can J Soil Sci*, 74: 376–385

Hart P B S, August J A, West A W (1989). Long-term consequences of topsoil mining on select biological and physical characteristics of two Zealand loessial soils under grazed pasture. *Land Degrad Rahab*, 1: 77–88

Huang Y, Wang S L, Feng Z W, Gao H, Wang Q K, Hu Y L, Yan S K (2004). Soil quality assessment of forest stand in different plantation ecosystems. *Chin J Appl Ecol*, 15(12): 2,199–2,205 (in Chinese)

Jenkinson D S, Ladd J N (1981). Microbial biomass in soil: Measurement and turnover. In: Paul E A, Ladd J N, eds. *Soil Biochemistry*. Marcel New York: Dekker Inc. 415–458

Jiang P K, Xu Q F, Yu Y W (2002). Microbial biomass carbon as an indicator for evaluation of soil fertility. *J Zhejiang For Coll*, 19(1): 17–19 (in Chinese)

Li S F, Yu Y C, He S (2003). Correlation between dissolved organic carbon and soil factors of the forest soil in southern of China. *J Zhejiang For Coll*, 20(2): 119–123 (in Chinese)

Liu S X, Liu J S, Zhao M D, Wang J D, Yu J B, Cong X M (2003). Relationship between active soil organic carbon, nutrient bioavailability and crop yield. *J Jilin Agric Univ*, 25(5): 539–543 (in Chinese)

Ma X Q, Fan S H, Liu A Q, Chen S X, Lin S J (2000). A comparison on soil fertilities of Chinese fir plantations of different generations. *For Res*, 13(6): 577–582 (in Chinese)

Marumoto T, Anderson J P E, Domsch K H (1982). Decomposition of ^{14}C and ^{15}N -labelled microbial cells in soil. *Soil Biol Biochem*, 14: 469–475

Smith J L, Paul E A (1991). The significance of soil microbial biomass estimations. In: Jean-Marc B, Stotzky G, eds. *Oil Biochemistry*. New York: Marcel Dekker Inc, 359–396

Sparling G (1992). Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. *Aust J Soil Res*, 135: 79–87

Sun Q W, Yang C D, Jiao R Z (2003). The changes of soil properties of the successive Chinese fir plantation in Dagang mountain of Jiangxi Province. *Sci Silv Sin*, 39(3): 1–5 (in Chinese)

Sun B, Zhang T L, Zhao Q G (1999). Fertility evolution of soil derived from quaternary red clay in low-hilly region in middle subtropics II. Evolution of soil chemical and biological fertilities. *Acta Pedol Sin*, 36(2): 203–217 (in Chinese)

van Bruggen A H C, Semenov A M (2000). In search of biological indicators for soil health and disease suppression. *Appl Soil Ecol*, 15: 13–24

Vance E D, Brooks P C, Jenkinson D S (1987). An extraction method for measuring soil microbial biomass. *Soil Biol Biochem*, 19: 703–707

Wang S L, Liao L L, Ma Y Q (1997). Nutrient return and productivity of mixed *Cunninghamia lanceolata* and *Michelia macclurei* plantations. *Chin J Appl Ecol*, 8(4): 347–352 (in Chinese)

- Wang Q K, Wang S L, Gao H, Yu X J (2005). Dynamics of soil active organic matter in Chinese fir plantations. *Chin J Appl Ecol*, 16(7): 1,270–1,274 (in Chinese)
- Xu Q F, Xu J M (2003). Changes in soil carbon pools induced by substitution of plantation for native forest. *Pedosphere*, 13: 271–278
- Yang Y S, Cheng G S, Huang B L (2000). Variation in soil water and nutrients between different rotation stands of Chinese fir. *J Nanjing For Univ*, 24(2): 25–28 (in Chinese)
- Yang Y S, Chen G S, Peng J C, Qiu R H (1999). The changes in soil antierodibility in different Chinese fir rotations. *J Mount Sci*, 17(2): 163–167 (in Chinese)
- Yang Y S, Qiu R H, He Z M, Yu X T, Huang B L (1998). Studies on the stand net productivity and biological cycle of nutrient elements in the 29-year-old plantations of Chinese fir on different rotations. *Sci Silv Sin*, 34(6): 3–11 (in Chinese)
- Ying J H (1997). Comparative study on the growth and soil properties under different successive rotation of Chinese fir. *J Jiangsu For Sci Technol*, 24(1): 31–43 (in Chinese)