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RESEARCH ARTICLE

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C and N stocks under three plantation forest ecosystems of Chinese fir, *Michelia macclurei* and their mixture

Abstract Chinese fir (*Cunninghamia lanceolata*), a type of subtropical fast-growing conifer tree, is widely distributed in South China. Its plantation area covers more than 7×10^6 hm^2, accounting for 24% of the total area of plantation forests in the country. In recent decades, the system of successive plantation of Chinese fir has been widely used in southern China due to anticipated high economic return. However, recent studies have documented that the practice of this system has led to dramatic decreases in soil fertility and forest environment as well as in productivity.

Some forest ecologists and managers recognize the ecological role performed by broadleaf trees growing in mixtures with conifers, and a great deal of studies on mixture effects have been conducted, particularly on mixture species of temperate and boreal forests, but these research results were not completely consistent. Possibilities include dependence of the mixture effects in large part to specific site conditions, the interactions among species in mixtures and biological characteristics of species. Although some researchers also studied the effects of mixtures of Chinese fir and broadleaf tree species on soil fertility, forest environment and tree growth status, little information is available about the effects of Chinese fir and its mixtures with broadleaves on carbon and nitrogen stocks.

The experimental site is situated at the Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, Hunan Province (26°40′–27°09′ N, 109°26′–110°08′ E). It is located at the transition zone from the Yunnan-Guizhou Plateau to the low mountains and hills of the southern bank of the Yangtze River at an altitude of 300–1,100 m above mean sea level. At the same time, the site is also a member of the Chinese Ecosystem Research Network (CERN), sponsored by the Chinese Academy of Sciences (CAS). This region has a humid mid-subtropical monsoon climate with a mean annual precipitation of 1,200–1,400 mm, most of the rain falling between April and August, and a mean temperature of 16.5°C with a mean minimum of 4.9°C in January and a mean maximum of 26.6°C in July. The experimental field has red-yellow soil.

After a clear-cutting of the first generation Chinese fir (*Cunninghamia lanceolata*) plantation forest in 1982, three different plantation forest ecosystems, viz. mixture of *Michelia macclurei* and Chinese fir (MCM), pure *Michelia macclurei* stand (PMS) and pure Chinese fir stand (PCS), were established in the spring of 1983. A comparative study on C and N stocks under these three plantation forest ecosystems was conducted in 2004. Results showed that carbon stocks were greater under the mixtures than under the pure Chinese fir forest and the pure broad-leaved forest, and the broadleaves and the mixtures showed higher values in nitrogen stocks compared with the pure Chinese fir forest. The spatial distribution of carbon and nitrogen stocks was basically consistent, the value being greater in soil layer, followed by tree layer, roots, understory and litter layer. The carbon and nitrogen stocks in soil layer were both highly correlated with the biomass in understory and litter layer, indicating that understory and forest litterfall exerted a profound effect on soil carbon and nitrogen stocks under plantation ecosystems. However, correlations among soil carbon, nitrogen stocks and below ground biomass of stand have not been observed in this study.

Keywords Chinese fir plantation, mixtures of Chinese fir and broad-leaved forest, carbon stock, nitrogen stock

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1 Introduction

Carbon cycle is the primary process for the cycle of mass and energy in forest ecosystems. Forest plants absorb and transform CO_2 in the air into organic matter and fix them in plants; on the other hand, CO_2 is released to the air through the respiration of plants, animals and microbes as well as the decomposition of litter. It is referred to as carbon sink in the former case and carbon source in the latter. In other words, the carbon balance of a forest ecosystem is determined by the processes of carbon input and output, and their difference is called the net ecosystem production (NEP). A positive NEP value indicates that the ecosystem features a CO_2 sink, and conversely, a negative NEP value suggests a CO_2 source.

A great number of studies worldwide have been reported on carbon storage and stock potential in forest ecosystems, yet most focused on natural forests (Chen et al., 2000, Fang et al., 2004), and few researches on plantations are documented. So far, such studies on Chinese fir (*Cunninghamia lanceolata*) plantations are especially rarely reported except for those by Chen et al. (2000), Fang et al. (2002, 2004) and He et al. (2003), and literature on the comparison of continuously planted pure Chinese fir plantation, Chinese fir-broadleaf mixture and pure broad-leaved plantation were never found. This study investigated carbon storage in the three forest ecosystems mentioned above to provide a scientific basis for sustainable productivity of Chinese fir plantations. At the same time, this study also attempts to offer fundamental information for the estimation of C balance in China's forest ecosystems, and further giving some theoretical basis for the government in planning forestry development and environmental protection.

Nitrogen is one of the most abundant elements in ecosystems, and is also an element inhibited during the primary production of most terrestrial ecosystems (Vitousek et al., 1979; Mooney et al., 1987; Vitousek and Howarth, 1991; Han et al., 1999; He et al., 2003). Meanwhile, the cycling of nitrogen is always coupled with other elements such as carbon, sulphur and phosphor. In addition, nitrogen can form into various greenhouse gases (Ludwig et al., 1989; Peterjohn and Schlesinger, 1990). Researches on nitrogen are hence attracting global attention. As a macroelement, nitrogen plays a key role in the substance cycling of forest ecosystems. Until now, few studies have reported on nitrogen stocks in forest ecosystems, and those on Chinese fir plantations were rarely documented. The investigation on nitrogen storage in Chinese fir plantations in this study was tailored to understand and estimate the mass production potential through a comparison between pure and mixed Chinese fir plantations.

2 Materials and methods

2.1 Study area

The study was finished in the Huitong Experimental Station of Forest Ecology, Chinese Academy of Sciences, which is located in Huitong County, west Hunan Province. The site belongs to a subtropical humid climate with a mean annual temperature of 16.5°C. The mean monthly temperature is 4.5°C in January and 27.5°C in July. The site has an annual precipitation of 1,200–1,400 mm and annual evaporation of 1,100–1,300 mm. The relative humidity is over 80% and the soil is mountain reddish yellow earth.

After clear cutting of the first-generation Chinese fir in 1982, three kinds of plantations were set up in the cutting site in 1983: pure *Cunninghamia lanceolata* stand (PCS), pure *Michelia macclurei* stand (PMS) and their mixture (MCM), with a planting density of 2,000 trees/hm^2 for each kind. The ratio of conifers to broadleaves in MCM is 8:2. Throughout the experiment, the study area did not suffer any disturbance including human activities except, for investigation and sampling.

2.2 Soil sampling, biomass survey and nutritional element test

Six layers of soil (0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm deep) were sampled using a multipoint method in the three types of plantations in March, 2005. The arbor biomass was measured using average tree method, root biomass was determined by digging, understory vegetation and herb biomass were measured after harvest, and litter amount was weighed after collecting (Feng et al., 1999). Bulk density of the soil was measured using a ring sampler; total N content determined by Kjeldahl method; and organic matter content was measured by potassium dichromate method (Liu, 1996).

2.3 Measurement of C and N storage

C content in the collected trunks, branches, barks, leaves and roots was measured, and C content in a given biomass for each part was calculated. Fresh samples of 10–20 g every 2 m along the trunk were collected and weighed; branches and leaves were classified into upper, middle and lower layers, and roots were divided into thick, middle and fine roots. Fresh samples of 10–20 g in each layer or class were then collected; four mixed litter samples (100–200 g each) were weighed to measure the C and N contents. The C and N stocks of vegetation (including arbor layer, root systems and litter) were calculated using the product from multiplying the biomass of each part with its C or N content (Finer et al., 2003).

The soil N content was measured in the six layers, that is, the soil in each layer mentioned above was sampled respectively to determine N content. The stocks of C and N within 100 cm can be calculated according to the following formula (Luo et al., 2000)

$$S = BD \times C \times T$$

where S is the stock of C or N (g/cm^2), BD is the soil bulk density (g/cm^3), C is the content of C or N (%) and T is the soil thickness (cm).

2.4 Data processing

Data obtained from field investigation and the laboratory were analyzed by statistical software EXCEL (2000) and SPSS (10.0).

3 Results and discussion

3.1 Vegetation C stock in plantation ecosystems and its spatial distribution pattern

The C stocks in every part of the vegetation were measured based on their C content (Table 1). It shows that the vegetation C stock in Chinese fir-broadleaf plantation was higher than in pure Chinese fir or pure broadleaf plantation. C stock of MCM (86.29 t/hm^2) is 8.79% higher than that of PCS, and increases much more (31.70%) than PMS. Findings on C stock of PCS in this study are roughly the same with those of Chen et al. (2000). Regression analysis shows that vegetation C stocks in different plantations are linearly correlated with vegetation biomass (Fig. 1), but not significantly with the mean vegetation C content, which suggests that C stock is determined largely by biomass.

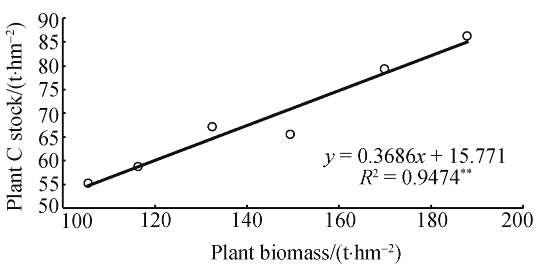

Fig. 1 Relationship between plant C stock and plant biomass

In terms of spatial distribution of vegetation C stocks in different stands, vegetation C is mainly concentrated in the arbor layer, accounting for over 95% of the total C stock; trunks account for a major part of the C stock, usually amounting to more than 60% of total vegetation C stock and exceeding 70% of that in the arbor layer; understory layer and litter layer accommodated little C stock, usually not more than 2% (Table 1). The spatial distribution pattern of vegetation C stock varies with tree species. The C stock of arbor layer in PCS accounts for 97.31% of the total vegetation, while understory layer and litter layer share 1.58% and 1.11% respectively; trunks take the highest percentage at 61.54%, followed by root system (14.31%), barks (9.04%), leaves (7.02%), and branches (5.04%). For the broad-leaved PMS, arbor layer holds 96.05% of the whole vegetation C stock, and understory layer and litter layer cover 2.30% and 1.65% respectively; trunks also have the biggest percentage at 63.08%, followed by root system (11.68%), and different from PCS leaves (8.17%) and branches (7.55%) of PMS share more C stock than barks (5.57%). This difference might be caused by the biological characteristics of different species. The spatial distribution pattern of vegetation C stock in MCM follows the order of trunks > root systems > barks > leaves > branches.

3.2 Vegetation N stock in plantation ecosystems and its spatial distribution pattern

With N content in every part of the vegetation, N stocks in each part can be calculated (Table 2). Table 2 indicates that MCM possesses a higher vegetation N stock than PCS and PMS. The vegetation N stock of MCM (0.94 t/hm^2) is 8.05% higher than that of PCS and 28.77% higher than that of PMS. The vegetation N stocks of the three plantation ecosystems are all higher than that of Norway spruce mixed forest (0.584 t/hm^2) with an age over 140 years (including root system and litter) (Finer et al., 2003). Additionally, a regression analysis also shows a linear relationship between vegetation N stocks of different plantation ecosystems and vegetation biomass (Fig. 2), indicating the dominant impact of vegetation biomass on N stocks.

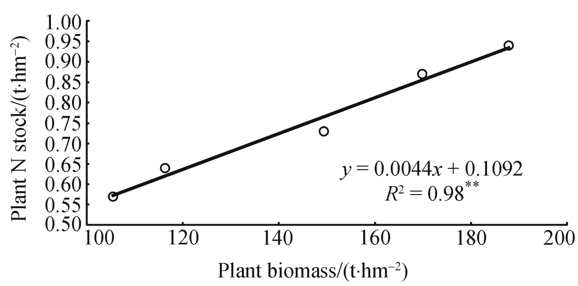

Fig. 2 Relationship between plant N stock and plant biomass

Table 1 C stocks (t/hm^2) of vegetation and its spatial distribution under different plantation ecosystems

Item	PCS		MCM		PMS	
	C stock/(t·hm^{-2})	Percentage /%	C stock/(t·hm^{-2})	Percentage /%	C stock/(t·hm^{-2})	Percentage /%
Trunks	48.81	61.54	53.31	61.78	41.33	63.08
Stem barks	7.17	9.04	7.58	8.78	3.65	5.57
Branches	4.28	5.40	5.10	5.91	4.95	7.55
Leaves	5.57	7.02	5.56	6.44	5.35	8.17
Root systems	11.35	14.31	12.03	13.94	7.65	11.68
Sum	77.18	97.31	83.58	96.85	62.93	96.05
Understory and herbs	1.28	1.58	1.70	1.97	1.51	2.30
Litter	0.89	1.11	1.01	1.18	1.08	1.65
Total	79.32	100	86.29	100	65.52	100

Table 2 N stocks of vegetation and its spatial distribution under different plantation ecosystems

Item	PCS		MCM		PMS	
	N stock/(t·hm^{-2})	Percentage /%	N stock/(t·hm^{-2})	Percentage /%	N stock/(t·hm^{-2})	Percentage /%
Trunks	0.39	44.83	0.39	41.49	0.20	27.40
Stem barks	0.079	9.08	0.10	10.64	0.087	11.92
Branches	0.031	3.56	0.049	5.21	0.095	13.01
Leaves	0.16	18.39	0.16	17.02	0.17	23.29
Root systems	0.15	17.24	0.16	17.02	0.10	13.70
Sum	0.81	93.10	0.86	91.38	0.65	89.32
Understory and herbs	0.038	4.37	0.055	5.85	0.046	6.30
Litter	0.019	2.53	0.026	2.77	0.033	4.38
Total	0.87	100	0.94	100	0.73	100

As for the spatial distribution of vegetation N stocks of the three ecosystems, vegetation N mainly centers on the arbor layer, accounting for over 90% of the total vegetation N stocks (except for MCM which is 89.32%); trunks are the main carrier of vegetation N stock, holding 27.40%–44.83% of vegetation N stock and 30.59%–48.15% of arbor layer N stock in the three plantations; the N stock in litter layer is minimal, usually not higher than 5%, and also in the understory layer. The spatial distribution pattern of vegetation N stock also fluctuates with tree species. In PCS, the arbor layer shares 93.10% of the total vegetation N stock, while the understory layer and litter layer carry 4.37% and 2.53% respectively. Trunks possess 89.32% of the arbor layer N stocks, followed by leaves (18.39%), root systems (17.24%), barks (9.08%) and finally branches (3.56%). The N stock of arbor layer of PMS accounts for 89.32% of the total vegetation N stock, and understory layer and litter layer account for 6.30% and 4.38% respectively: trunks share the highest percentage at 27.40%, followed by leaves (23.29%), root systems (13.70%), branches (13.01%) and barks (11.92%). The vegetation N stock of PCS is concentrated mostly in trunks, leaves and root systems, and the three parts together carry 80.46% of the total vegetation N stock; but in PMS the three parts share only 64.39%; the understory layer, herb layer and litter layer together hold the total vegetation N stock 3.21-fold that of PCS. This difference might also be caused by the biological characteristics of different tree species.

3.3 Soil C stock in plantation ecosystems and its spatial distribution pattern

From soil C content and soil bulk density, we can calculate the soil C stocks in plantations (Fig. 3). Figure 3 shows that C stocks in MCM and PMS are higher than in PCS. The soil C stock in MCM is 100.59 t/hm^2, 11.51% higher than that in PCS; compared with the soil C stock of PCS, which in PMS is 16.23% higher. In terms of spatial scale, soil C stocks of MCM and PMS are usually higher than that of PCS for the same soil layers. The soil C stocks at depths below 40 cm tend to decrease. The results observed in this study are fundamentally in accordance with Fang et al. (2002); the investigated soil C stocks in the three plantations are nevertheless lower than the average values in similar forest types reported by Zhou et al. (2000) which were 205.23, 335.58 and 101.30 t/hm^2. Especially the soil C stocks of PCS and PMS are only half or one third of the reported average values investigated by Zhou et al. (2000). The reasons might be the follows.

3.3.1 The difference in soil thickness

Considering that the impacts of human disturbance and global environmental change on soil thickness are not more than 1 m, the measurements on carbon pool in some studies are traditionally calculated in a soil thickness within 1 m. However, forests in China are mostly distributed in mountains with a greatly fluctuant topography, which leads to a

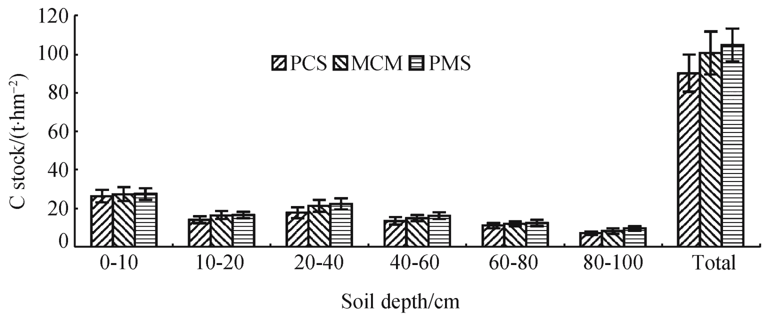

Fig. 3 C stocks of soil at different depths

marked difference in soil thickness that directly influences the estimation of soil carbon pool. The soil carbon density was reported to be positively correlated with soil thickness (Fang et al., 2004).

3.3.2 The difference in research methods

The estimation of soil carbon stocks in most studies is based on general soil survey or empirical data collected from some literature, but few through field investigation on forest, vegetation type, and soil texture, which will inevitably reduce the estimation accuracy; even in the same soil texture and vegetation type, different stand ages might result in diverse soil C stocks. For instance, in the research on soil C stocks in Chinese fir plantations of different ages, Fang et al. (2002) found that soil C stock is 107.73 t/hm^2 in a ten-year-old Chinese fir plantation and 88.06 t/hm^2 in a seven-year-old one, the former 22.34% higher than the latter. In addition, the selection of forest ecosystem type is also an important factor causing the difference.

3.3.3 The impact of different climatic zones on the accumulation of soil organic carbon

The rich heat and precipitation, and the rapid biocycle and metabolism of organic matter in the tropics, are disadvantageous to accumulation of organic matter in soil. Fang et al. (2004) found that moisture and heat are two key factors restricting soil density.

In addition, the soil C stock in the 20-year-old PCS in this study is higher than that in the same aged PCS reported by Chen et al. (2000), which might be due to the difference in soil thickness sampled in the study. The estimation of soil C stock by Chen et al. (2000) is based on soil layer 0–60 cm thick, while the result of this study depends on 0–100 thick soil layer.

Therefore, the estimation of C stocks in the same climatic zone could be accurate only comprehensively considering soil texture, forest or vegetation type, and based on different soil C content. Thus, the accurate prediction of soil C stocks in Chinese fir plantation ecosystem in the whole country should take three elements into consideration: climatic zone, soil texture and forest age.

Forest plant and animal remnants are the major sources of soil organic C and form substrate structures in forest soils due to climatic and biological factors. The organic C contents and C stocks vary with soil thickness. Based on spatial distribution of forest soil C stocks, the organic C content in topsoil (0–10 cm) is much higher than that in other layers, and its stock accounts for 24.49%–29.32% of the total C stocks, followed by that in 20–40 cm thick layers, sharing 19.27%–21.35% of the total C stocks. Therefore, 0–40 cm thick soil layers are the major carriers of soil C stocks, which holds 60.45%–64.79%. Fang et al. (2004) once reported that 0–30 cm thick soil layer possesses 53.52% of the total soil C stocks. Because soil C is mainly distributed in topsoil, and human management activities mainly center on the soil surface, human management will surely profoundly affect soil C stocks and determine whether the carbon pool is a “source” or “sink”. Baties (1996) reported in his study on global soil C stocks that in 0–100 cm deep soils, 0–30 cm and 0–50 cm deep soils account for 37%–59% and 62%–81% of soil C stocks, 49% and 67% on average (Fang et al., 2004). Detwiler found in the study of the impact of land-use changes on soil C storage in tropics and subtropics that 0–40 cm thick soils hold 35%–80% of C stocks in 0–100 cm thick soils, 57% on average (Fang et al., 2004). Comparatively, the C stocks in 0–40 cm thick soils in the areas of this study are a little higher than in other regions, which reflects to some extent a fragile forest soil system and likely soil carbon loss. Therefore, it is of great significance to reduce human disturbance to forests and strengthen the protection of forest vegetation to increase soil carbon storage and maintain global climatic changes, especially to relieve climbing CO_2 concentration.

3.4 Soil N stock in plantation ecosystems and its spatial distribution pattern

The total soil N stock can be calculated according to total N content and soil bulk density (Fig. 4). We can find from Fig. 4 that the total soil N stocks of MCM and PMS are higher than that of PCS. The total soil N stock of MCM is 15.42 t/hm^2, 14.99% higher than that of PCS; compared with PCS, PMS has a much higher increase of up to 18.34%. From different soil layers, total soil N stocks of MCM and PMS are generally higher than that of PCS at the same layer. Similar to soil C stock, soil N stock at depths below 40 cm shows a declining tendency. The soil N stocks in the three plantations are much higher than that of primary tropical mountain forests (9.58 t/hm^2) (Finer et al., 2003), and far higher than

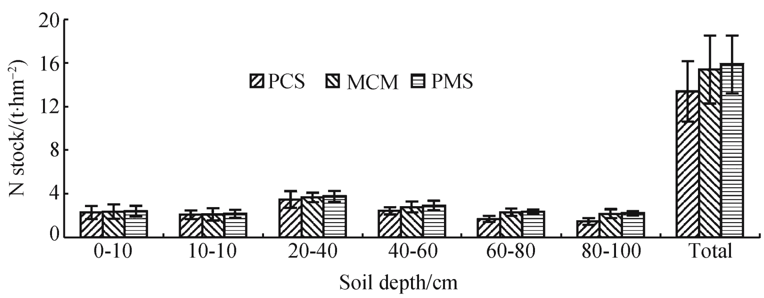

Fig. 4 N stocks of soil at different depths

that of Norway spruce mixed forest with an average age of over 140 years (2.258 t/hm^2) (Finer et al., 2003). Thus, similar to the estimation of soil C storage in forest ecosystem, the accurate prediction of soil N stock also requires a comprehensive consideration of soil texture, vegetation type, climatic zone and forest age.

The remains of plants and animals in forest, litter and precipitation are main sources of soil nitrogen, and a hierarchical structure forms in the soil due to climatic and biological factors. The total N content and total N stock vary accordingly with soil depth. The spatial distribution of total soil N stock differs with that of C stock: although the total N stock in topsoil (0–10 cm) is higher than those of other layers; 20–40 cm thick soil harbored the highest percentage of total N stock in all soil layers, generally accounting for 20.03%–25.95%. This suggests that soil bulk density and soil thickness have a significant impact on soil N stocks. The N stock in topsoil (0–10 cm thick) ranked next to that of 20–40 cm thick soil, accounting for 15.19%–20.03% in general; the N stock below 40 cm thick soil commonly shared 40% of the total soil N stocks. In general, C stocks were distributed mainly in upper soil layers, especially in layers 0–40 cm thick; N stocks, on the other hand, were more dispersed: the percentage of N stocks in 0–40 thick soil was not more than 60%, fluctuating from 52.62%–58.93%. Therefore, human activity will surely affect soil N stocks, and some natural ecological processes such as precipitation, eluviation and mineralization, also have a significant impact on the content and distribution of nutrients.

3.5 C stock in plantation ecosystems and its spatial distribution pattern

Figure 5 indicates that the total C stock in MCM was higher than those of PCS and PMS, and followed the order of MCM (186.88 t/hm^2) > PMS (170.37 t/hm^2) > PCS (169.53 t/hm^2). Although the soil C stock of PMS was higher than that of PCS, its vegetation C stock was lower, as its biomass was lower than that of PCS. Thus, there was minimal difference in the C stocks of the two plantations. The C stocks of the three plantations in this study are all higher than the average of warm temperate coniferous plantations (163.8 t/hm^2) (Luo et al., 2000). The C stock of 20-year-old PCS was higher than that of an 11-year-old (142.22 t/hm^2) (Tian et al., 2003). In general, the C stock of PCS increased with forest age: it is 106.01, 19.80 and 144.22 t/hm^2 for seven-, ten- and 11-year-old PCS respectively (Tian et al., 2003). Additionally, the C stock of 20-year-old PCS in this study is higher than that investigated by Chen et al. (2000), which might be due to the difference in soil thickness in the estimation.

The C stocks in the three plantations had the same spatial distribution pattern with the soil layers as main holder, which accounted for 52.23%–61.54%, followed by arbor layer (32.45%–41.71%), and root systems, understory vegetation layer and litter layer (all lower than 1%) (Table 3). This disagrees with the results of Chen et al. (2000) who found that vegetation layer (including litter layer) was the main carbon pool of the Chinese fir plantation ecosystem, sharing 59.7% of the total, and soil layers only held 40.3%. The percentage

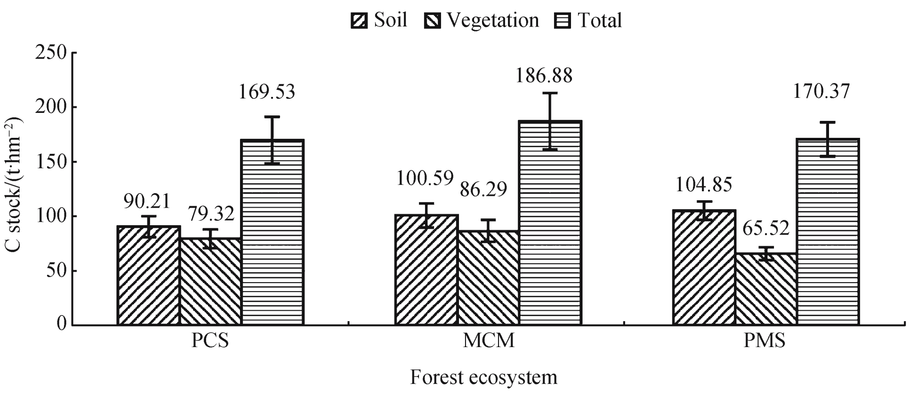

Fig. 5 C stocks under different plantation ecosystems

Table 3 Spatial distribution (%) of C stocks under different plantation ecosystems

Item	Soil layer	Arbor layer	Root systems	Understory and herbs	Litter layer	Total
PCS	53.21	38.83	6.69	0.74	0.52	100
	(8.96)	(5.03)	(1.14)	(0.17)	(0.18)	
MCM	53.83	38.29	6.44	0.91	0.54	100
	(9.12)	(6.41)	(1.47)	(0.16)	(0.17)	
PMS	61.54	32.45	4.49	0.89	0.63	100
	(7.87)	(4.79)	(0.47)	(0.21)	(0.14)	

Values in the brackets are standard deviation.

of C stock of vegetation layer (including litter layer) to the total C stocks (38.46%–47.77%) was higher than that of vegetation of warm coniferous forests (32.66%) (not considering understory and litter layers) (Zhou et al., 2000), which suggests that the study area has a relatively lower soil C stock. In the study of the ratio of aboveground C stock to underground C stock for different forest types in subtropical southern Jiangsu Province, Ruan et al. (1997) found that the ratio was 1:1.1 for a 40-year-old oak forest, 1:1.2 for a 27-year-old Chinese fir forest and 1:1 for a foreign pine forest. This study found that the ratio was 1:1.53 for PCS, 1:1.55 for MCM and 1:2.0 for PMS. Comparatively, the ratios in this study are low for the three plantation systems, which suggest that the three plantation systems have potential to fix carbon to some extent, especially for the vegetation layer, and the theoretical potential of carbon fixation of PMS is the highest. Despite having less than 1% of total C stock, litter layer harbors are still the main source of soil organic carbon and the linking pool for carbon cycle in soil-vegetation system; this effectively reduces soil loss for its coverage on the surface. Some researches suggested that the change of standing stock of forest litter has a great impact on soil C stocks (Ruan et al., 1997; Tian et al., 2003). The standing stock of litter in Chinese fir plantation ranges from 0.72–5.94 t/hm^2, and its soil C stock (0–60 cm thick) varies from 88.06–107.33 t/hm^2 (Tian et al., 2003). The results of Ruan et al. (1997) showed that the standing stock of *Larix gmelinii* in the Great Xing'an Mountains was 42.8 t/hm^2, and its soil C stock (10–78 cm thick) was 347.4 t/hm^2; the standing stock of secondary oak forest in Xiashu, Jiangsu Province, east China was 9.2 t/hm^2 and its soil C stock was 69.7 t/hm^2.

Scatter diagrams were worked out to show the relationships between the standing stock of litter, understory vegetation and root systems and soil C stock (Figs. 6–8). Figure 8 shows that root system biomass and soil C stock have no significant linear correlation. Nevertheless, Figs. 6 and 7 indicate a notable linear relationship between soil C stock and the standing stock of litter ($y = 7.258{,}3x + 45.638$, $R^2 = 0.820{,}6$, $p < 0.05$) and between soil C stock and understory vegetation biomass ($y = 14.286x + 41.406$, $R^2 = 0.934{,}8$, $p < 0.01$), which suggests that understory vegetation and litter have a marked impact on soil C stocks.

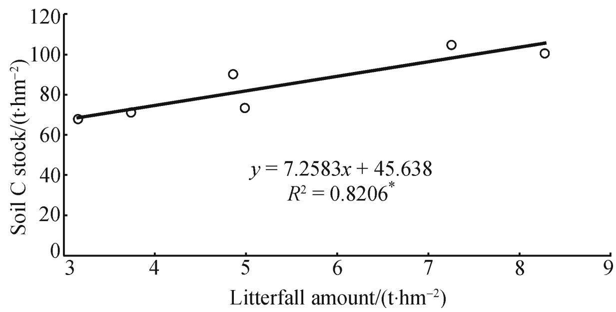

Fig. 6 Relationship between living litter stock and C stock

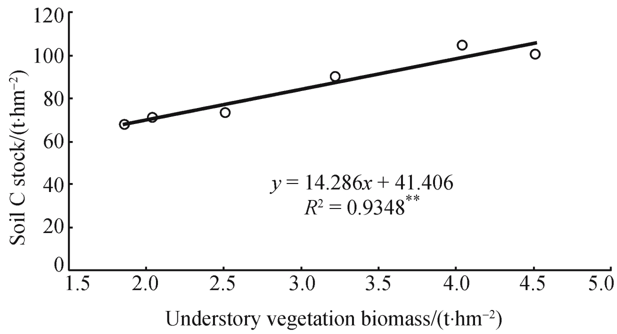

Fig. 7 Relationship between understory vegetation biomass and C stock

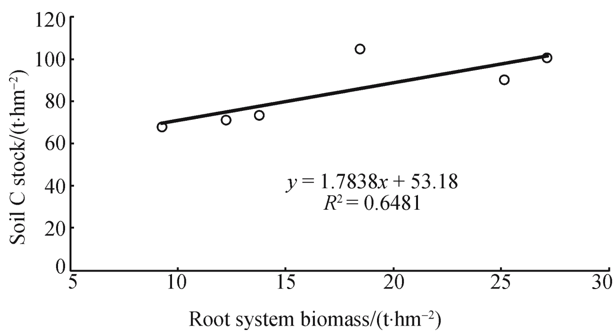

Fig. 8 Relationship between root system biomass and C stock

3.6 N stock in plantation ecosystems and its spatial distribution pattern

Figure 9 illustrates that for the 20-year-old plantations, PMS had the highest N stock (16.60 t/hm^2), followed by MCM (16.36 t/hm^2) and PCS (14.28 t/hm^2). The N stock of PMS and MCM is higher than the average N stock of mature PCS (14.03 t/hm^2) reported by some researchers, and the N stock of 20-year-old PCS is similar to the average value (Tian et al., 2003). The N stocks of the three plantations in this study are far richer than that of mixture plantations with an average age of 140 years (2.842 t/hm^2) (Luo et al., 2000).

The spatial distribution of N stocks in the three plantation systems has a roughly identical pattern: soil N stock is predominant, accounting for 91.54%–95.60%, followed by arbor layer (3.31%–7.01%), root systems, and understory vegetation and litter (both less than 1%) (Table 4). This pattern is generally in accordance with the results of Finer et al. (2003). Yang (1998) also suggested that in the Chinese fir plantation system, nutritional elements are stocked mostly in soils and very few in vegetation layer; for the part of vegetation (not including root systems), arbor layer contains a predominant portion of nutritional elements, and the arbor layers of first, second and third generation fir plantations share 92.90%, 88.37% and 80.57% of the whole vegetation part (excluding root systems). Tian et al. (2003) once investigated the ratio of N stocks of aboveground parts to underground parts for differently aged Chinese fir plantations in mid-subtropical

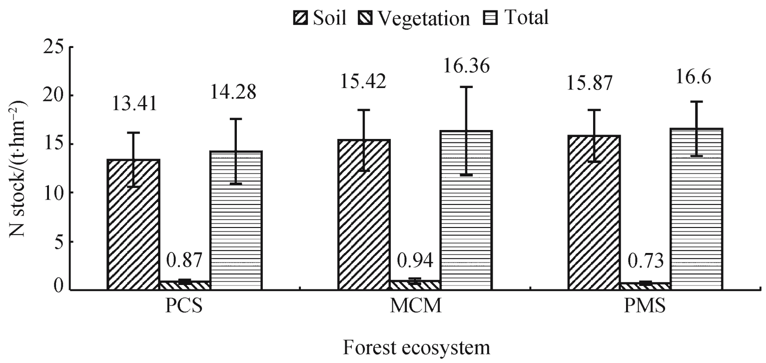

Fig. 9 N stocks under different plantation systems

Table 4 Spatial distribution (%) of N stocks under different plantation ecosystems

Item	Soil layer	Arbor layer	Root systems	Understory and herbs	Litter layer	Total
PCS	93.91	4.62	1.05	0.27	0.13	100
	(10.19)	(1.13)	(0.27)	(0.065)	(0.033)	
MCM	94.25	4.28	0.98	0.34	0.16	100
	(12.14)	(1.51)	(0.30)	(0.079)	(0.047)	
PMS	95.60	3.31	0.60	0.28	0.20	100
	(8.79)	(0.94)	(0.14)	(0.045)	(0.029)	

The number in parentheses is standard deviation.

regions, and found that the ratio is 1:79.19 in rapid growth period, 1:59.49 in trunk forming period, 1:31.18 in mature period and 1:31.87 in over-aged period. For the present study, the ratio is 1:18.21 for PCS, 1:19.45 for MCM and 1:25.54 for PMS. It can be found that the ratios of the six plantation ecosystems in the present study are relatively higher, which suggests that these six systems still have great potential to fix nitrogen, especially soil nitrogen part, and broad-leaved pure plantation theoretically has the most promising potential. Although litter layer shares less than 1% of the total N stocks, it remains one of the main soil N sources and acts as the linking pool for soil-plant nitrogen cycling. In addition, the litter layer effectively curbs soil N loss for its coverage on soil surface.

Scatter diagrams showing the relationships among the living stock of litter, understory vegetation biomass, root biomass and soil N stock (Figs. 10–12) were obtained. Similar to soil C stock, soil N stock is linearly correlated both with the living stock of litter ($R^2 = 0.838{,}8$, $p < 0.01$) and with understory vegetation biomass ($R^2 = 0.948{,}5$, $p = 0.01$). It was suggested that forest litter and understory vegetation have significant impacts on the soil N stock; it is unlikely that root biomass has a less significant correlation with soil N stock (Fig. 12). The understory vegetation attracts much attention in the study of nutrient elements cycle due to the high content of nutrient elements but rather short lifespan of understory vegetation (Feng et al., 1985, 1988; Robert, 1993; Yang, 1998). According to the study of Chinese fir plantation ecosystems by Yang (1998), although the amount of understory vegetation is limited, the annual accumulation of nutrient elements is 3.28 times as high as that in the arbor layer, which suggests that understory vegetation has a substantial impact on the accumulation of soil nutrients, including nitrogen, and its quantity and quality play a crucial role in the restoration of site conditions.

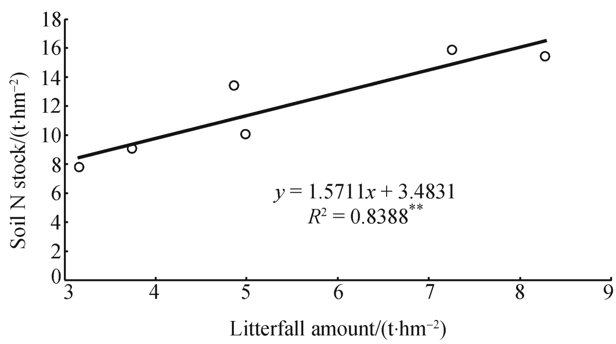

Fig. 10 Relationship between living litter stock and N stock

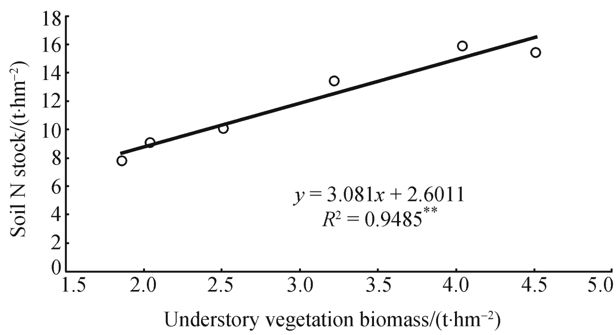

Fig. 11 Relationship between understory vegetation biomass and N stock

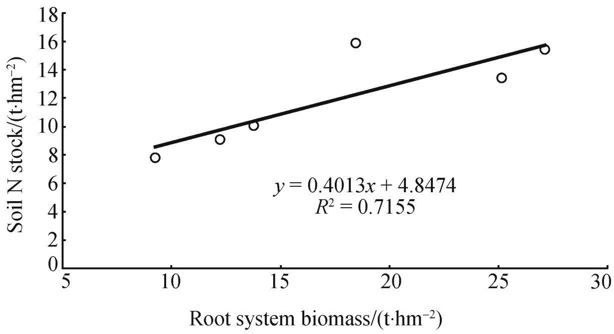

Fig. 12 Relationship between root system biomass and N stock

4 Conclusions

The C and N stocks in the mixed plantation of Chinese fir and broadleaves were both higher than those of pure ones. The spatial distribution patterns of organic C and N in the three plantations in this study were roughly the same—the soil layer accounts for the most part, followed by the arbor layer and root systems, and understory vegetation layer and litter layer (both less than 1%). The soil C and N stocks were well linearly correlated with understory vegetation biomass and the living stocks of litter respectively, indicating that understory vegetation and litter both have a crucial impact on the soil C and N stocks. Only by comprehensively considering factors such as soil texture, forest and vegetation type, climatic zone and forest age and employing different soil C and N content can we accurately estimate the C and N stocks of forest ecosystems. This principle also works for the estimation of soil C and N stocks of Chinese fir plantation ecosystems in China, i.e. we should take into account three factors: climatic zone, soil texture and forest age.

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