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RESEARCH ARTICLE

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Carbon sink in *Phoebe bournei* artificial forest ecosystem

Abstract Biomass, carbon content, carbon storage and spatial distribution in the 32-year-old *Phoebe bournei* artificial forest were measured. The mean biomass of the forest stand was 174.33 t/hm^2, among which the arbor layer was 166.73 t/hm^2, which accounted for 95.6%. Carbon contents of stems, barks, branches, leaves, root, shrub layer, herb layer, lichen layer and litter layer were 0.5769 g C/g, 0.4654 g C/g, 0.5232 g C/g, 0.4958 g C/g, 0.4931 g C/g, 0.4989 g C/g, 0.4733 g C/g, 0.4143 g C/g, 0.3882 g C/g, respectively. The mean carbon content of soil was 0.0139 g C/g, which reduced gradually along with soil depth. Total carbon storage of the *P. bournei* stand ecosystem was 227.59 t/hm^2, among which the arbor layer accounted for 40.13% (91.33 t/hm^2), the shrub layer accounted for 0.17% (0.38 t/hm^2), the herb layer accounted for 0.76% (1.71 t/hm^2), the lichen layer accounted for 0.28% (0.63 t/hm^2), and the litter layer accounted for 0.29% (0.66 t/hm^2). Carbon content (0–80 cm) of the forest soil was 58.40% (132.88 t/hm^2). Spatial distribution ranking of carbon storage was: soil layer (0–80 cm) > arbor layer > herb layer > litter layer > lichen layer > shrub layer. Net production of the forest stand was 8.5706 t/(hm$^2\cdot$a), in which the arbor layer was 6.6691 t/(hm$^2\cdot$a), and it accounted for 77.82%. Net annual carbon sequestration of the *P. bournei* stand was 4.2536 t/(hm$^2\cdot$a), and the arbor layer was 3.5736 t/(hm$^2\cdot$a), which accounted for 84.01%.

Keywords *Phoebebournei* plantation, carbon sink, biomass, carbon content, net productivity, carbon storage

1 Introduction

Forests are a principal part of terrestrial ecosystems and account for 86% of the vegetation carbon pool (Woodwell et al., 1978) and 73% of the soil carbon pool (Post et al., 1982). In comparison with other ecosystems, forest ecosystems have high productivity. Forest ecosystems fix two-thirds of the carbon in all terrestrial ecosystems annually. Moreover, forest ecosystems play an irreplaceable role in regulating the carbon balance, mitigating greenhouse gas concentrations, such as carbon dioxide, and maintaining global climates.

In recent years, the vegetation carbon balance has been investigated in China, especially the carbon sink of forests. Wang and Feng (2000) and Fang and Chen (2001) calculated the forest carbon pool as well as its variation over the last 50 years based on forest biomass and productivity together with the national forest resource inventory. Kang et al. (1996) and Shi and Ding (1996) concluded that the net carbon fixation of Chinese forests was 8630 g C/a and 13990 g C/a, respectively. Further, Fang et al. (2002, 2003), Lei et al. (2004), Zhou and Jiang (2004), Ma et al. (2007) studied carbon content, carbon storage as well as the spatial distribution of Chinese fir (*Cunninghamia lanceolata*), Masson pine (*Pinus massoniana*), Camphor tree (*Cinnamomum camphora*), Mao bamboo (*Phyllostachys pubescens*) plantations and natural spruce (*Picea asperata*) forests. There are four sources and five forest types. These investigations can contribute to the research on forest carbon sinks in China.

Phoebe bournei is a valuable tree species because of its fine wood properties. It is a typical species of evergreen broad-leaved forests in subtropical regions of China and is mainly found in the Sichuan, Guizhou, Hunan and Fujian provinces. Until now, there have been few documented cases of organic matter accumulation, variation, distribution and the carbon cycle of *P. bournei* plantations. Our

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study analyzes biomass, carbon content, carbon storage and spatial distribution of *P. bournei* plantations. Simultaneously, we provide basic data for further studies on the function of carbon cycles and carbon sinks of *P. bournei* forest ecosystems.

2 Methods

2.1 Study area

Our sample plots were located in the Lingyan Mountain (31°1′–31°4′N, 103°34′–103°43′E) in Dujiangyan, which is a landform type of low hills. Our study was conducted at an elevation of about 800 m, with a slope of 20°. Soil is yellow and developed on sandstone, the soil thickness is between 60 to 100 cm and pH ranges from 4.5 to 5.5. Because of heavy rainfall, a gley phenomenon occurred between the illuvial horizon and the parentaterial. The soil is fairly fertile and has a good ability to retain water and nutrients. The survey area was located in a zone with a subtropical climate and an average annual temperature of 15.2°C. The maximum and minimum temperatures are 38°C and -10°C and the average annual relative humidity is 81%. The average annual rainfall is 1243 mm and the number of frost-free days is 269.

P. bournei forests have been growing here for 32 years and were reforested after Locust trees (*Robinia pseudoacacia*) were harvested. Initial planting density was 3333 plants/hm^2. There has been no regular tending, but occasionally, selection cutting has taken place. At present the average number is still 833 live trees/hm^2. The canopy density of the forest stands is 0.7, the average diameter at breast height (DBH) is 18.0 cm and the average height is 15.6 m. The shrub layer consists of raspberry (*Rubus* L.), shrub lespedeza (*Lespedeza bicolor*), Chinese mahonia (*Mahonia fortunei*), zanthoxylum (*Zanthoscylum simulans*), pittosporum (*Pittosporum glabratum*) and others, accounting for about 10% of the forest floor cover. The herb layer consists mainly of ferns (*Pteridophyte*), cyprus (*Carex pallideviridis*), iris (*Iris japonica*), dwarf lilyturf (*Ophiopogon japonicus*), false staghorn fern (*Diranopteris dichotoma*) etc., with cover about 60%. The lichen layer is mainly hill thuidiaceae (*Abietinella abietina*) with a coverage of 70%.

2.2 Indices of determination

2.2.1 Determination of net biomass and production

Biomass of the tree layer was estimated by an allometric method. In order to measure the biomass of every organ accurately, each tree was surveyed by setting two sample plots of size 20 m×30 m. According to the DBH distribution, starting from a 5 cm DBH class and increasing by intervals of 2 cm, one tree in each class was selected as the standard which consisted, in total, of nine trees. By dividing the woody parts in layers and by using mixed sampling methods, the fresh weight of trunks, bark, branches and leaves were measured. Root biomass was determined by selecting dominant, average and suppressed trees. Roots were dug out from the different soil layers (0–20, 20–40, 40–60 and 60–80 cm) and samples were taken from stumps, coarse roots (>2 cm), medium roots (1.1–2 cm), small roots (0.5–1.0 cm) and fine root (<0.5 cm) according to their natural conditions, and their fresh weights were recorded. All samples were dried in an oven at 80°C to a constant weight and dry weights were recorded. Based on an empirical formula established for estimating each organ biomass of an individual tree, dry biomass of each organ and per hectare were determined.

Average net production values of stem timber, bark, branches and roots were a function of biomass divided by the age of trees. Average net leaf production was calculated using four-year old samples. Due to serious human disturbance, there were few shrubs. Therefore, the average net shrub production was calculated using four-year old samples. The average net herbal production was determined in the same manner.

2.2.2 Measurement of biomass of undergrowth vegetation and litter fall

In each of the plots, given their plum-shaped distribution, five quadrates of size 2 m×2 m were established. Undergrowth vegetation and herbal biomass were determined by using a harvesting method by quadrates, while litter fall was measured by means of collection (Feng et al., 1999).

2.2.3 Chemical analysis of samples

Before our chemical analyses, 500 g of each sample was collected from different components including trunk, bark, branches, leaves and roots. In order to measure soil density and soil quality, 500 g soil samples were collected from different layers (0–20, 20–40, 40–60 and 60–80 cm). We used a potassium dichromate-hydration heating method to determine the carbon content (Liu, 1996).

3 Results and analysis

3.1 Stand biomass

3.1.1 Biomass accumulation of tree layer

Empirical formulas for estimating the biomass of each organ of individual trees were established (Table 1). From these calculations, the total biomass of the tree layer was estimated to be 166.73 t/hm^2. Biomass and the proportion allocated to each organ of the tree are listed in Table 2. In

Table 1 Regression equations of *P. bournei* organ dry weight as a function of DHB and tree height

organ	regression equation	r	SD
stem timbers	$\lg W = 0.9419\lg(D^2H) - 1.4299$	0.9680^{**}	0.0632
bark	$\lg W = 1.0106\lg(D^2H) - 2.8452$	0.9744^{**}	0.0613
branches	$\lg W = 0.9952\lg(D^2H) - 2.3262$	0.9488^{**}	0.0701
leaves	$\lg W = 1.0108\lg(D^2H) - 2.8632$	0.9194^{**}	0.0754
above-ground	$\lg W = 0.9599\lg(D^2H) - 1.3695$	0.9352^{**}	0.0716
stump roots	$\lg W = 1.5745\lg(D^2H) - 4.4154$	0.9355^{**}	0.0715
coarse roots	$\lg W = 2.2478\lg(D^2H) - 7.2974$	0.9637^{**}	0.0636
medium roots	$\lg W = 1.2446\lg(D^2H) - 4.2709$	0.9012^{**}	0.0789
small roots	$\lg W = 2.0241\lg(D^2H) - 7.4546$	0.9015^{**}	0.0787
fine roots	$\lg W = 1.7216\lg(D^2H) - 6.7177$	0.9048^{**}	0.0781
under-ground	$\lg W = 1.7222\lg(D^2H) - 4.7629$	0.9879^{**}	0.0526

Note: W is dry weight, diameter at breast height (D) and tree height (H) were 13 – 24 cm and 9 – 17 cm, respectively. **differences significant at $\alpha = 0.01$.

Table 2 Biomass and proportion allocated to each organ in tree layer (unit: $\mathrm{t \cdot hm^{-2}}$)

stems	bark	branches	leaves	roots	total
102.02 (61.17)	6.98 (4.19)	20.51 (12.31)	6.67 (4.00)	30.55 (18.32)	166.73 (100)

Note: numbers in brackets mean percentage.

addition, root biomass and proportions allocated to dominant, average and suppressed trees are listed in Table 3.

Table 3 Root biomass and proportion allocated to dominant, average and suppressed trees (unit: kg)

item	stump roots	coarse roots	medium roots	small roots	fine roots	total
dominant tree	27.61 (48.68)	19.35 (34.11)	4.75 (8.37)	3.65 (6.44)	1.36 (2.40)	56.72 (100)
average tree	18.10 (49.37)	13.99 (38.16)	2.68 (7.31)	1.17 (3.19)	0.72 (1.96)	36.66 (100)
suppressed tree	11.44 (56.63)	6.52 (32.28)	1.40 (6.93)	0.59 (2.92)	0.24 (1.22)	20.20 (100)

Note: numbers in brackets mean percentage.

3.1.2 Biomass accumulation of shrub layer

Because of poor development and an uneven distribution, the shrub layer under the trees consisted of raspberry, shrub lespedeza, Chinese mahonia, zanthoxylum, and pittosporum etc., which accounted for a 10% cover. Biomass of this shrub layer was 0.76 t/hm^2, in which the above-ground biomass was 0.5 t/hm^2 and the under-ground biomass was 0.26 t/hm^2.

3.1.3 Biomass of herb, lichen and litter layers

Herbal plants and lichen grew well and had large numbers of species because of high humidity. Their average cover was 70%. Their biomass allocation is presented in Table 4.

Table 4 Biomass of herb, lichen and litter layers (unit: $\mathrm{t \cdot hm^{-2}}$)

herb layer			lichen layer	litter layer	total
above-ground	under-ground	total			
2.149	1.470	3.620	1.513	1.713	6.846

3.2 Carbon content of various components in the ecosystem of a *P. bournei* plantation

3.2.1 Carbon content of tree layer

Ranking of the carbon content of each organ of the tree layer was as follows: trunks > branches > leaves > roots > barks (Table 5), and its range was 0.4654 – 0.5769 g C/g.

3.2.2 Carbon content of undergrowth vegetation and soil

The carbon content of the shrub, herbal and lichen layers were 0.4989, 0.4733, 0.4143 g C/g, respectively (Table 6). The carbon content of shrubs was higher than that of the other two layers; the carbon content decreased with a decrease in height and degree of lignification of individual plants.

Due to the decomposition of organic matter, the carbon content of the litter layer was lower than that of other above-ground layers. Part of decomposition products entered the soil in the form of organic carbon, but most of the remaining carbon was released into the atmosphere in the form of CO_2. The average carbon content of litter was 0.3882 g C/g and the average carbon content of the soil was 0.0143 g C/g. The soil carbon content declined with an increase in soil depth (Table 7).

3.3 Carbon storage of each organ in the ecosystem of a *P. bournei* plantation

3.3.1 Carbon storage of each organ of tree layer

Carbon storage of each organ is the product of biomass and carbon content. Therefore, carbon storages of each organ

Table 5 Carbon content of different organs of *P. bournei* (unit: $\mathrm{g\,C \cdot g^{-1}}$)

item	trunks	branches	leaves	barks	stump roots	coarse roots	medium roots	small roots	fine roots	average
average value	0.5769	0.5232	0.4958	0.4654	0.5167	0.5205	0.5079	0.4621	0.4583	0.4931
coefficient of variation	8.25	9.34	10.75	5.03	5.70	6.03	6.22	7.48	7.90	

Table 6 Carbon content of undergrowth vegetation (unit: g C·g^{-1})

vegetation	layer	carbon content
shrubs	above-ground	0.5078
	under-ground	0.4900
	average	0.4989
herbs	above-ground	0.4856
	under-ground	0.4610
	average	0.4733
lichens		0.4143

Table 7 Soil carbon content under *P. bournei* stands (unit: g C·g^{-1})

layer	component	carbon content
litter	undecomposed litter	0.4827
	semi-decomposed litter	0.4424
	decomposed litter	0.2396
	average	0.3882
soil layer	0–20 cm soil layer	0.0217
	0–20 cm soil layer	0.0132
	0–20 cm soil layer	0.0119
	0–20 cm soil layer	0.0102
	average	0.0143

and component are closely related to biomass. The trunk had the largest amount of biomass at 102.02 t/hm^2 and accounted for 61.19% of the tree layer. Carbon storage in the trunk was also high at 58.88 t/hm^2 and accounted for 64.47% of the tree layer (Table 8).

3.3.2 Distribution of biomass and carbon storage in each organ at various diameter classes of tree layer

From Table 8, the number of standing trees in the 18 cm diameter class reached a maximum with 317 trees/hm^2; the number of trees in the 20, 16, 22 and 14 cm diameter class were 200, 102, 83 and 81 per hectare, respectively. The lowest number of standing trees, only 50 per hectare, was found in the 24 cm diameter class. The distribution of the number of trees in each diameter-class was a negatively skewed exponential function (similar to the Weibull function). The distribution of biomass and carbon storage of the various diameter classes also complied with this distribution. The above-ground biomass and carbon storage of individual trees increased with the increase in diameter class. Biomass and carbon storage of the 18 cm diameter class reached a maximum, with 57.96 and 31.75 t/hm^2 respectively, which accounted for 34.77% of the tree layer. Biomass and carbon storage of the 20, 22, 16, 24 and 14 cm diameter classes accounted, respectively, for 26.60%, 26.60%, 14.29%, 10.02%, 9.52% and 5.00%.

3.4 Spatial distribution of carbon storage of ecosystem of a *P. bournei* plantation

Spatial distribution of carbon storage is the distribution of various layers involving tree, shrub, herbal, lichen and litter layers as well as soil layers. According to the biomass of their various components or soil quality, and given their corresponding conversion coefficients of carbon content, carbon storage and spatial distribution of various components in the *P. bournei* forest ecosystems were calculated (Table 9).

3.5 Net production and net annual carbon sequestration of a *P. bournei* stand

3.5.1 Average net productivity of *P. bournei* stand

CO_2 assimilation capacity is one of the important issues of productivity research of forest ecosystems. Among some of the other issues are production of the stand (Y_n), litter and drying matter productivity (ΔL_n) and the amount of loss from consumption by animals (ΔG_n). However, it is very difficult to determine ΔG_n, so the level of productivity is usually measured as the average net production W_Q. The average net productivity of our *P. bournei* stand is shown in Table 10.

3.5.2 Net annual carbon sequestration of *P. bournei* stand

Net annual carbon sequestration of the various components were calculated from their average net productivity and

Table 8 Distribution of number of trees, biomass and carbon storage of tree layer by diameter class (unit: t·hm^{-2})

diameter class/cm	number of trees	stems		barks		branches		leaves		roots		total	
		biomass	carbon storage	biomass	carbon storage	biomass	carbon storage	biomass	carbon storage	biomass	carbon storage	biomass	carbon storage
14	81	5.00	2.89	0.37	0.18	0.76	0.40	0.33	0.17	1.53	0.76	7.99	4.40
16	102	10.15	5.86	0.60	0.28	2.25	1.18	0.63	0.32	3.06	1.51	16.69	9.15
18	317	35.61	20.55	2.37	1.11	7.39	3.87	2.19	1.09	10.40	5.12	57.96	31.75
20	200	27.61	15.93	1.97	0.92	4.69	2.45	1.87	0.93	8.22	4.06	44.36	24.29
22	83	14.61	8.43	1.04	0.49	2.77	1.45	0.81	0.40	4.59	2.27	23.82	13.05
24	50	9.04	5.22	0.63	0.30	2.65	1.39	0.84	0.42	2.75	1.36	15.91	8.69
total	833	102.02	58.88	6.98	3.28	20.51	10.74	6.67	3.33	30.55	15.08	166.73	91.33

Table 9 Spatial distribution of carbon storage of *P. bournei* forest ecosystems

component	carbon content /(g C·g^{-1})	carbon storage /(t·hm^{-2})
tree layer	0.5467	91.33
shrub layer	0.4989	0.38
herb layer	0.4733	1.71
lichen layer	0.4143	0.63
litter layer	0.3882	0.66
0–20 cm soil layer	0.0217	48.09
20–40 cm soil layer	0.0132	30.23
40–60 cm soil layer	0.0119	29.31
60–80 cm soil layer	0.0102	25.25
total		227.59

Table 10 Average net production and net annual carbon sequestration of each component of *P. bournei* stand

component	mean annual net production/(t·hm^{-2})	annual net sequestration /(t C·hm^{-2})
trunks	3.1881	1.8393
bark	0.2181	0.1015
branches	0.6406	0.3352
leaves	1.6675	0.8268
roots	0.9547	0.4708
tree layers	6.6691	3.5736
shrub layers	0.1900	0.0948
herb layers	0.9050	0.4284
ground cover layers	0.3783	0.1568
total	8.1423	4.2536

corresponding carbon content (Table 10). The net annual carbon sequestration of the *P. bournei* stand was 4.2536 t/(hm^2·a), and that of the tree layer was 3.5736 t/(hm^2·a), accounting for 84.01%. The net annual carbon sequestration of shrub, herbal and ground cover layers was 0.0948, 0.4284 and 0.1568 t/(hm^2·a) and accounted for 2.23%, 10.07% and 3.69%, respectively.

4 Discussion

Based on considerable studies of global forest ecosystems, American scientists discovered that carbon content increased with an increase in height and degree of lignification of individual plants. The distribution of the average carbon content of our 32-year-old *P. bournei* plantation was as follows: tree layer 51.09%, shrub layer 49.89%, herbal layer 47.33%, lichen layer 41.43% and litter layer 38.82%. Ranking of the carbon content of each organ of the tree layer was as follows: trunks > branches > leaves > roots > bark, and ranged from 0.4654–0.5769 g C/g. The average carbon content of the soil was 0.0143 g C/g, which declined with an increase in soil depth.

In the spatial distribution of biomass in forest ecosystems, there are differences between young and mature forests. In general, biomass of the tree layer of young forests is lower, while that of mature forests is higher. The spatial distribution of biomass is affected by different stages of succession. Carbon biomass of the tree layer in early succession stages is lower than that in late succession stages (Kimmins, 2004). The results indicate that the tree layer played the most important role in the biomass of the *P. bournei* plantation. The total biomass of forest stands was 174.33 t/hm^2, where the tree layer, with 166.73 t/hm^2, accounted for 95.6%. The biomass of the trunk was the highest at 102.02 t/hm^2 and accounted for 61.19% of the biomass of the tree layer. Carbon storage in the trunk, up to 58.88 t/hm^2, accounted for 64.47% of the tree layer. Ranking of the spatial distribution of carbon storage was as follows: soil layer (0–80 cm) > tree layer > herbal layer > litter layer > lichen layer > shrub layer. Therefore, this 32-year-old *P. bournei* plantation had the characteristics of spatial biomass distribution of a mature forest.

There are some differences in carbon storage of different diameter classes (Jiang et al., 2002). The results showed that the distribution of the numbers of trees of each diameter class, biomass and carbon storage followed partially a negatively skewed exponential function, similar to a Weibull function. The aboveground biomass and carbon storage of individual trees increased with an increase in diameter. Biomass and carbon storage of the 18 cm diameter class reached a maximum, with 57.96 and 31.75 t/hm^2 respectively, which accounted for 34.77% of the tree layer. In second place came the 20 cm diameter class with 44.36 and 24.29 t/hm^2, respectively, and a cover of 26.60%. All the same, those of the 24 and 14 cm diameter classes represented minimum values, accounting only for 9.52% and 5.00%, respectively.

In general, evergreen broad-leafed forest ecosystems have a high capacity for carbon sequestration (Waring and Running, 1998). Our research results basically agree with the rules. From the viewpoint of productivity, the average net production of the forest stand is 8.1423 t/(hm^2·a), in which the tree layer contributes 6.6691 t/(hm^2·a), accounting for 81.91%. Net annual carbon sequestration of the *P. bournei* stand was 4.2536 t/(hm^2·a), that of the tree layer 3.5736 t/(hm^2·a), accounting for 84.01%. According to results elsewhere, the average net production of Masson pine natural forests in subtropical regions is 5.473 t/(hm^2·a), where the tree layer contributed 5.163 t/(hm^2·a) (Feng, 1982). Average net production of the tree layer of Chinese fir plantations was 8.300 t/(hm^2·a) (Pan, 1981) and that of Homana (*Michelia macclurei*) plantations 27.590 t/(hm^2·a) (Feng et al., 1983). The average net production of Camphor tree plantations was 12.100 t/(hm^2·a), in which the tree layer accounted for 9.550 t/(hm^2·a) (Yao et al., 2003), for natural spruce forests in southwestern subalpine regions 6.8385 t/(hm^2·a) (Ma et al., 2007), for Japanese larch (*Larix leptolepis*) plantations 3.810 t/(hm^2·a) (Li, 1984), for Locust trees in warm temperate zones 1.550 t/(hm^2·a) (Chen, 1986) and the average net production of oriental oak (*Quercus variabilis*) plantations was 2.060 t/(hm^2·a) (Bao, 1984). It can be seen that the average net production of our *P. bournei* plantation is much higher than that of Masson pine, Japanese larch, Locust trees and oriental oak, and likely, other species. On the other hand, it is slightly lower than that of natural spruce forests, such as Chinese fir and Camphor tree plantations, and is considerably lower than that of Homana plantations in southern subtropical regions. The net annual carbon sequestration of *P. bournei* stands was 4.254 t/(hm^2·a). The is lower than that of the tree layer of tropical mountain rain forests (13.648 t/(hm^2·a)) (Li et al., 1998), however, it is higher than that of Chinese fir plantations in tropical regions (3.4890 t/(hm^2·a)) and natural spruce forests in subalpine regions (3.5850 t/(hm^2·a)) (Fang et al., 2002; Ma et al., 2007). We can conclude that *P. bournei* has a high capacity for carbon sequestration.

As a tree planted in cities, *P. bournei* plays an important role in improving the urban environment and regulating atmospheric CO_2. Moreover, *P. bournei* produces valuable timber and is usually used in expensive furniture and as building material. Therefore, its carbon storage will be preserved permanently and can be a carbon sink of forest production. It is important that *P. bournei* regulate its atmospheric carbon turnover rate and the amount of carbon turnover.

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