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# Belowground carbon balance and carbon accumulation rate in the successional series of monsoon evergreen broad-leaved forest

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**Abstract** The balance, accumulation rate and temporal dynamics of belowground carbon in the successional series of monsoon evergreen broadleaved forest are obtained in this paper, based on long-term observations to the soil organic matter, input and standing biomass of litter and coarse woody debris, and dissolved organic carbon carried in the hydrological process of subtropical climax forest ecosystem—monsoon evergreen broad-leaved forest, and its two successional forests of natural restoration—coniferous and broad-leaved mixed forest and *Pinus massoniana* forest, as well as data of root biomass obtained once every five years and respiration measurement of soil, litter and coarse woody debris respiration for 1 year. The major results include: the belowground carbon pools of monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest, and *Pinus massoniana* forest are $23191 \pm 2538$ $g \cdot m^{-2}$, $16889 \pm 1936$ $g \cdot m^{-2}$ and $12680 \pm 1854$ $g \cdot m^{-2}$, respectively, in 2002. Mean annual carbon accumulation rates of the three forest types during the 24a from 1978 to 2002 are $383 \pm 97$ $g \cdot m^{-2} \cdot a^{-1}$, $193 \pm 85$ $g \cdot m^{-2} \cdot a^{-1}$ and $213 \pm 86$ $g \cdot m^{-2} \cdot a^{-1}$, respectively. The belowground carbon pools in the three forest types keep increasing during the observation period, suggesting that belowground carbon pools are carbon sinks to the atmosphere. There are seasonal variations, namely, they are strong carbon sources from April to June, weak carbon sources from July to September; while they are strong carbon sinks from October to November, weak carbon sinks from December to March.

**Keywords: monsoon evergreen broad-leaved forest, successional series of restoration, belowground, carbon pool, accumulation rate.**

The belowground part of terrestrial ecosystem is a huge carbon pool. It is believed that of the total 2500Gt carbon stored in global terrestrial ecosystem, soil carbon storage within the 1 m surface layer accounts for 2000Gt, which is 4-fold of vegetation carbon storage[1,2]. Compared with the carbon in the vegetation, carbon in the deep soil layers is much more stable, and it will stay in soil profile permanently unless geological vicissitude occurs.

Essentially, forest restoration is the process of land cover change, during which the gradual succession of aboveground vegetation results in the change of belowground carbon balance and accumulation rate. It is of great significance to study their relationship in order to evaluate accurately the contribution of regional forest cover change to global carbon balance. The monsoon evergreen broad-leaved forest, an important zonal climax vegetation type on the earth surface, mainly appears in lower subtropical China, its successional forests are abundant, almost including all the main non-zonal vegetation types in lower subtropical zone. A great amount of plantations that have been constructed in this area are mostly the successional types of monsoon evergreen broad-leaved forest. Therefore, it is of great representation to study the belowground carbon balance and accumulation rate of its successional series.

Taking Dinghushan monsoon evergreen broad-leaved forest and two of its successional forests (*i.e.*, coniferous and broad-leaved mixed forest and pine forest) as the research objects, we studied the dynamics of belowground carbon storage and its formation in each successional stage of the lower subtropical forest. The relationship between these vegetation types and their soil carbon densities and fluxes including carbon carried by water were investigated thoroughly. Results can provide experimental evidence for the effects of land use and land cover change on soil carbon density in the same or similar climatic areas.

## 1 Study objects

The objects of this study are lower subtropical climax vegetation—monsoon evergreen broad-leaved forest, and its successional series of restoration—coniferous and broad-leaved mixed forest and *Pinus massoniana* forest. The natural successional sequence of the three forest types is *Pinus massoniana* forests→coniferous and broad-leaved mixed forests→monsoon evergreen broad-leaved forest. They represent the main forest types in Dinghushan biosphere reserve at the altitude from 250 m to 300 m.

Dinghushan Biosphere Reserve (112°30′39″ − 112°33′41″E, 23°09′21″−23°11′30″N) is located in the central part of Guangdong Province, it is the first natural reserve of China with a long history of protection. It has an area of 1145 $\mathrm{hm}^2$ with lower subtropical monsoon climate. Mean annual air temperature is 20.9℃, mean annual relative humidity 80%, and mean annual precipitation and evaporation are 1929 mm and 1115 mm, respectively. The wet season and dry season appear from April to September and from October to March, respectively. Mean annual runoff coefficient varies between 0.455 to 0.492. The soils, with serious natural acidification and pH 4.1−4.9, are classified as hydration lateritic soil. The forest coverage is above 85% of the total area in Dinghushan Biosphere Reserve[3].

Monsoon evergreen broad-leaved forest has a complicated community structure. Its aboveground part could be divided into five layers, including three arbor layers, one shrub layer, one grass layer. In addition, it has many kinds of interlayer plant (liana and epiphyte). Among its floristic composition, evergreen plants are absolutely dominant and most of them are of tropics and subtropics. The biomass of this community is about 38000 $\mathrm{g \cdot m^{-2}}$ [4]. The soil of this community is hydration lateritic soil about 80 cm deep, developed from sandy shale.

The coniferous and broad-leaved mixed forest, which originated from artificial or natural *Pinus massoniana* forest after invasion by broad-leaved trees, is the representative forest type at the mid-successional stage, stepping in monsoon evergreen broad-leaved forest rapidly. Its aboveground vertical structure can be divided into four layers: two arbor layers, one shrub layer and one grass layer. In addition, it has many kinds of interlayer plant (liana and epiphyte). The biomass of this community is about 26000 $\mathrm{g \cdot m^{-2}}$ [5]. The soil of this community is lateritic soil about 30−60 cm deep, developed from sandy shale.

*Pinus massoniana* forest, above 40 years old, which consists of *Pinus massoniana* mainly and lower subtropical sun plants occasionally, is the representative forest type at the early-successional stage, advancing to coniferous and broad-leaved mixed forest rapidly. Its aboveground part can be divided into an arbor layer with open canopy and a well-developed shrub and grass layer. The biomass of this community is 12200 $\mathrm{g \cdot m^{-2}}$ approximately[4]. The soil under this community is lateritic soil about 30 cm deep, developed from sandy shale.

## 2 Carbon balance and study methods

### *2.1 Study methods*

In this paper, belowground is defined as the litter layer and the mineral soil layer up to 80 cm deep. In each of the three forest types, a permanent plot of 1 $hm^2$ was set, around which there were several relatively stable sites for sampling soils and roots.

(i) Litter. Litter input biomass and litter standing biomass were measured by using fifteen 1 m × 1 m litter collecting baskets in each of the three types of forest. Litter collecting and sorting were conducted once every month, the carbon content of each part of litter in different forest types was around 50% according to our long-term annual observation.

(ii) Coarse woody debris (CWD, hereafter). Standing biomass and annually input of CWD were calculated based on inventories. Any snag or log was considered as CWD if the length (logs)/height (snags) was longer than 1.0 m and the diameter was greater than 2.5 cm. For logs, length and diameter at the midpoint were measured; for snags height and diameter at breast height (DBH, diameter at height = 1.3 m) were measured. Those without sound form, *i.e.* partly decayed, broken logs, were divided into several segments, then length and diameter of each segment were measured. Characteristics of CWD including species and decomposition status were also recorded. Volume of CWD was calculated as a cylinder because all trees in Dinghushan Nature Reserve, both living and dead, were approximate to a cylinder. Biomass was calculated as the product of volume and average density. Average densities of woody debris were measured by water volume displaced by CWD[6]. Average CWD carbon content was around 50%.

(iii) Roots. Root system was divided into coarse and fine roots. Net production and mortality of coarse root were obtained from plot-based measurements. Four to five soil columns, with an area of 1 $m^2$ each, were dug to the substratum in destructive sampling sites of each forest type. Then coarse roots were collected from each layer, rinsed, dried until constant weight, and weighed, thus the biomass and mortality of coarse root were obtained. Coarse root net primary production was calculated according to eq. (1)[7,8].

$$\mathrm{NPP_{cr}} = (\mathrm{ANPP/AGB})\times \mathrm{B_{cr}}, \tag{1}$$

where $\mathrm{NPP_{cr}}$ is coarse root net primary production, ANPP is aboveground net primary production, AGB is aboveground biomass, and $\mathrm{B_{cr}}$ is coarse root biomass. ANPP and AGB were obtained according to the method described by Peng[4,5]; while $\mathrm{B_{cr}}$ was obtained according to the method mentioned above.

Measurement of fine roots was conducted during 2001—2002. Soil cores were obtained by using soil drill with inner diameter of 5.68 cm at different sites in every plot. Then soils were soaked, rinsed and sieved. Fine roots with diameter less than 5 mm were selected. Dead or live roots were distinguished according to their shape, color and flexibility, then weighed after air-dry. A subsample of fine roots was dried until weight constancy, and weighed to estimate the dry weight rate of root[9]. Fine root biomass was calculated according to eq. (2):

$$\text{Standing biomass or mortality of fine root } (\mathrm{g\cdot cm^{-2}}) = \frac{\text{Mean weight of root per core (g)}}{(5.68/2)^2\pi}. \tag{2}$$

Annual net production of fine root was calculated according to eq. (3)[9,10]:

$$P = P_{\max} - P_{\min} + M, \tag{3}$$

where $P$ is annual net production of fine root, $M$ is annual mortality of fine root, $P_{\max}$ and $P_{\min}$ are maximum and minimum of standing biomass of live fine root.

According to our long term observation, the mean carbon contents of root in monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest were 42%, 54% and 55%, respectively.

(iv) Soil organic matter. From 1978 on (absent for some years), the whole soil profiles were sampled[11] at 20 points in every forest types annually for the measurement of soil organic matter and its carbon content by standard analysis. The carbon content of soil organic matter in the three forest types were similar, averaged 58%. Additionally, soil bulk densities of three soil layers (0—20 cm, 20—40 cm, 40—60 cm) in each site were measured once every five years.

(v) $CO_2$ efflux from belowground. $CO_2$ fluxes from belowground in the three forest types were measured once a week by using static chamber-gas chromatograph technique. Two treatments were applied in each experimental plot: (1) bare soil surface (litter was removed previously); (2) litter or CWD + soil, so that $CO_2$ fluxes from mineral soil, litter and CWD can be determined, separately, which can be converted to C fluxes from them. CWD with different diameters and decay intensities were collocated in treatment (2) according to survey results in the three forest types. Soil $CO_2$ fluxes originate from autotrophic respiration of root and heterotrophic respiration of soil microbes and soil animals.

(vi) Dissolved organic carbon (DOC) and solid organic carbon (SOC). Precipitation, canopy throughfall, stem flow and runoff were monitored continuously using methods described by Zhou[3]. In the meantime, water samples from those hydrological processes were obtained periodically, then the DOC and SOC in them were measured by using TOC-V analyzer (Shimadzu Japan). DOC and SOC in water sample can be measured indiscriminately at one time by TOC-V analyzer, so the result from it was the total organic carbon.

From 2001 to 2002, soil and water loss did not occur in Dinghushan, therefore, it was considered that there was no carbon output by soil and water loss during this period.

### 2.2 *Calculation of belowground carbon balance*

(i) Carbon input ($I$). Carbon input to the belowground mainly consists of carbon inputs by litter ($I_l$) and CWD ($I_c$), followed by root-related carbon input ($I_r$) and carbon input by precipitation ($I_p$).

$$I = I_l + I_c + I_r + I_p . \tag{4}$$

Root-related carbon input includes carbon inputs by root net production ($I_{rg}$) and root mortality ($I_{rd}$).

$$I_r = I_{rg} + I_{rd} . \tag{5}$$

Carbon input by precipitation, which drew less attention in the past, includes carbon inputs by throughfall ($I_{pt}$) and stemflow ($I_{ps}$).

$$I_p = I_{pt} + I_{ps} . \tag{6}$$

(ii) Carbon output ($O$). Respiration ($O_g$) is the main part of carbon output from belowground, followed by organic carbon carried out by runoff ($O_n$).

$$O = O_g + O_n . \tag{7}$$

The measurement system in this study could divide belowground respiration into litter+CWD respiration ($O_{gl}$) and soil respiration ($O_{gs}$), as expressed by eq. (8):

$$O_g = O_{gl} + O_{gs} . \tag{8}$$

The organic carbon carried by runoff includes DOC ($O_{nl}$) and SOC ($O_{ns}$). No efforts were made to separate them in this study.

(iii) Carbon storage ($B$). The standing carbon storages in litter ($B_l$), CWD ($B_c$), soil organic matter ($B_o$) and root ($B_r$) constitute belowground carbon storage.

$$B = B_l + B_c + B_o + B_r . \tag{9}$$

Methods used to measure standing biomass of coarse root and fine root were different. Thus the carbon storage in root includes carbon storages in coarse root ($B_{rc}$) and fine root ($B_{rf}$).

$$B_r = B_{rf} + B_{rc} . \tag{10}$$

## 3 Results and analysis

### 3.1 *Belowground carbon pool and its dynamics in 2002*

The standing belowground carbon densities of the three forest types are given in Table 1.

The standing carbon densities of soil organic matter in monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest accounted for 70.8%, 65.9% and 83.0% of the total belowground carbon densities, respectively. The root carbon densities accounted for 22.1%, 28.1% and 13.5%, respectively, and the litter and CWD carbon densities accounted for 7.1%, 6.0% and 3.5%, respectively. Soil organic matter is the main part of the belowground carbon storage for the three forest types, which is beneficial to the stability of ecosystem as soil organic matter is the relatively stable carrier of carbon.

Comparing the standing carbon densities of several parts in the belowground among the three forest types, we found that carbon densities of CWD in different forest types varied most greatly, followed by those of coarse root and soil organic matter. Results of ANOVA test indicated that all of them differed significantly among the three forest types ($p<0.001$). Carbon den-

Table 1 Standing belowground carbon densities of three forest types in 2002 (Unit: $g \cdot m^{-2}$)

| Forest type | | Monsoon evergreen broad-leaved forest | Coniferous and broad-leaved mixed forest | *Pinus massoniana* forest |
|---|---|---|---|---|
| Soil organic matter | | 16410(2117)[a)] | 11129(1754) | 10518(1806) |
| Litter | | 328(71) | 497(103) | 436(146) |
| CWD | | 1320(1283) | 524(399) | 10(9) |
| Root | Fine root (<5 mm) | 479(114) | 518(152) | 516(97) |
| | Coarse root (≥5 mm) | 4654(545) | 4222(693) | 1200(382) |
| Total | | 23191(2538) | 16889(1936) | 12680(1854) |

a) Standard deviation in parenthesis, standard deviation of total is the square root of square sum of every component, the same hereafter.

sity of CWD in *Pinus massoniana* forest was only 2.0% of that in mixed forest and 0.8% of that in monsoon forest, while carbon densities of fine root in different forest types were very close. The fact that carbon density of litter in monsoon evergreen broad-leaved forest was significantly lower than ($p<0.001$) those in the other two forest types could be explained by the fact that the litterfall of this forest has been decreasing in recent years and the main type of litter (*i.e.*, pine needles) in the pine forest is hard to decompose.

### 3.2 *Carbon balance in 2002*

(i) Carbon input. Carbon inputs to belowground of the three forest types in 2002 are given in Table 2.

In 2002, the carbon inputs by growth and mortality of root in the monsoon evergreen broad-leaved forests, coniferous and broad-leaved mixed forests and *Pinus massoniana* forests accounted for 54.3%, 53.7% and 52.8% of the total carbon inputs to the belowground respectively, and those by litter and CWD were 44.2%, 43.9% and 44.0%, respectively. Carbon inputs by throughfall and stemflow were only 1.5%, 2.4% and 3.2%, respectively. However, this part of carbon input is of great importance because it enters the soil with water flow and easily becomes part of the soil organic matter pool.

In all the carbon inputs to the belowground, carbon input by CWD varied most greatly among different forest types, followed by carbon inputs by mortality and net increment of coarse root, litter and net increment of fine root. There were significant differences in carbon inputs by these types among different forest types ($p<0.001$). Carbon input by throughfall differed ($p<0.05$) among the three forest types, while that by stemflow did not ($p>0.1$).

(ii) Carbon output. Carbon output consists of soil respiration, litter and CWD respiration, DOC and SOC exported with runoff. The magnitudes of these processes are listed in Table 3.

Soil respiration was the main part of total carbon output in all the three forest types. Soil respiration in the monsoon evergreen broad-leaved forests, coniferous and broad-leaved mixed forests, and *Pinus massoniana* forest accounted for 73.1%, 55.2% and 67.7% of the total belowground carbon outputs, respectively. Carbon output by litter and CWD respiration accounted for 26.7%, 44.6% and 31.5%, respectively, while those by runoff were extremely small.

(iii) Analysis of carbon balance. From Tables 2 and 3, it can be calculated that the net belowground

Table 2 Carbon inputs to the belowground in 2002 (Unit: $g \cdot m^{-2} \cdot a^{-1}$)

| Forest type | | Monsoon evergreen broad-leaved forest | Coniferous and broad-leaved mixed forest | *Pinus massoniana* forest |
|---|---|---|---|---|
| Throughfall | | 16(11) | 29(34) | 23(15) |
| Stem flow | | 3(4) | 3(3) | 2(1) |
| Litter | | 357(50) | 465(51) | 337(64) |
| CWD | | 210(149) | 123(83) | 8(9) |
| Root | Fine root (<5 mm) net increment | 160(73) | 196(117) | 215(159) |
| | Dead fine root (<5 mm) | 93(18) | 110(45) | 104(66) |
| | Coarse root (≥5 mm) net increment | 306(82) | 349(178) | 84(74) |
| | Dead coarse root (≥5 mm) | 136(54) | 65(21) | 11(7) |
| Total | | 1281(200) | 1340(242) | 784(199) |

Table 3 Carbon output from belowground in 2002 (Unit: $g \cdot m^{-2} \cdot a^{-1}$)

| Forest type | Monsoon evergreen broad-leaved forest | Coniferous and broad-leaved mixed forest | *Pinus massoniana* forest |
|---|---|---|---|
| Runoff | 2(0.6) | 2(0.4) | 5(5) |
| Litter+CWD respiration | 303(79) | 447(100) | 198(53) |
| Soil respiration | 831(194) | 553(161) | 426(86) |
| Total | 1136(209) | 1002(190) | 629(101) |

carbon increases in monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest were 145 ± 289 $g \cdot m^{-2} \cdot a^{-1}$, 338 ± 308 $g \cdot m^{-2} \cdot a^{-1}$ and 155 ± 223 $g \cdot m^{-2} \cdot a^{-1}$ respectively, in 2002, suggesting that the belowgrounds of the three forest types were all sinks of atmospheric carbon. Except for increased carbon in DOC and SOC carried by throughfall and stemflow that could directly become part of soil organic matter, most of the increased carbon existed in the forms of litter, CWD, and root. These can be considered as "a temporary carbon pool" of the belowground, and the proportion that will be transformed into soil organic matter depends on biological and climatic environment.

### *3.3 Analysis of temporal dynamics of belowground carbon pool*

(i) Annual dynamics. Fig. 1 shows the annual dynamics of carbon stored in soil organic matter from 1978 to 2002 in the three forest types.

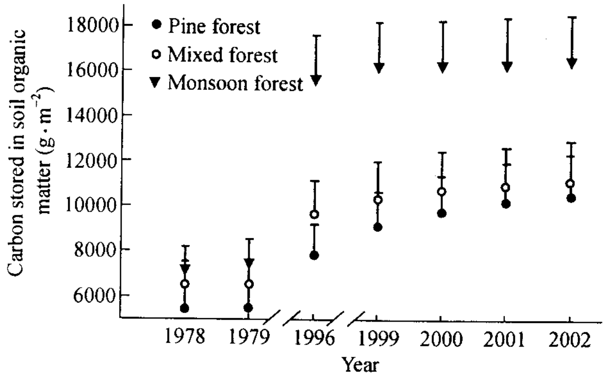

Fig. 1. The long-term dynamics of carbon stored in soil organic matter.

From 1978 to 2002, the net increases of carbon stored in soil organic matter in monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest were 9199 ± 2333 $g \cdot m^{-2}$, 4629 ± 2044 $g \cdot m^{-2}$ and 5117 ± 2065 $g \cdot m^{-2}$, respectively. The corresponding mean annual increasing rates of carbon were 383 ± 97 $g \cdot m^{-2} \cdot a^{-1}$, 193 ± 85 $g \cdot m^{-2} \cdot a^{-1}$ and 213 ± 86 $g \cdot m^{-2} \cdot a^{-1}$, respectively. According to Fig. 1, this period can be divided into four stages: 1978—1979, 1979—1996, 1996—1999 and 1999—2002, the mean annual increasing rates of carbon in each stage are shown in Fig. 2.

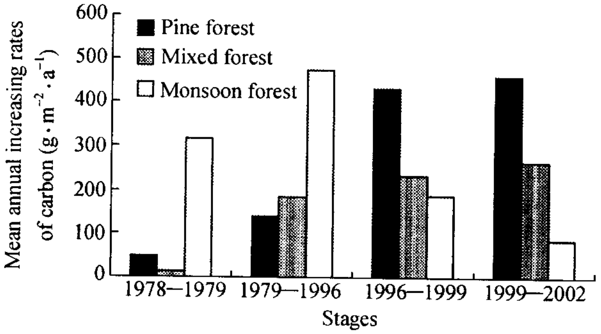

Fig. 2. Mean annual increasing rates of soil organic carbon in four stages during 1978—2002.

From 1978 on, the increasing rates of the carbon stored in soil organic matter of the mixed forest and the pine forest, especially the latter, has been accelerating. As for the monsoon evergreen broad-leaved forest, soil organic carbon increased with higher rate before 1996, but the increasing rate became smaller gradually since 1996, suggesting that the soil organic carbon in this forest was approaching its maximum.

Carbon inputs by litter to the belowground for many years in the three forest types are given in Fig. 3. It can be seen that carbon input by litter in pine forest has been increasing ($p<0.05$), while those in monsoon evergreen broad-leaved forest and mixed forest were stable, and the trend of decline was not significant as shown by statistical test ($p>0.05$). As far as the carbon input by litter in monsoon evergreen broad-leaved is concerned, a phenomenon of "small" and "big" year with an one-year cycle was observed ($p<0.001$). The

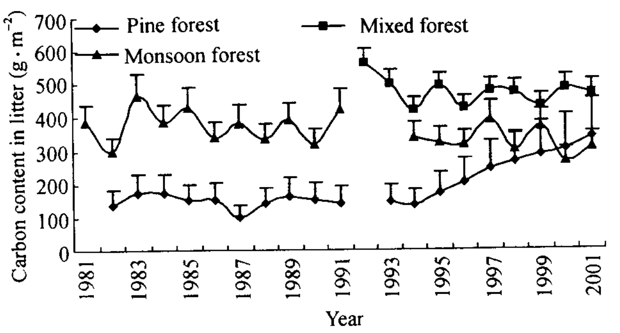

Fig. 3. Annual carbon input to the belowground by litter.

mean variation of carbon input by litter between "small" and "big" years reached 65 g · m$^{-2}$ · a$^{-1}$. Similar phenomenon was found in mixed forest, but the cycle of "small and big year" was not stable and the difference of carbon input by litter between "small year" and "big year" was not significant ($p > 0.05$). For pine forest, there was not such a phenomenon, which might be one of the differences between zonal vegetation and non-zonal vegetation.

From the results mentioned above, it can be seen that the soil organic carbon was the main part of belowground carbon storage. The soil organic carbon in monsoon evergreen broad-leaved forest was approaching its maximum with decreasing net accumulaztion rate, while those in the coniferous and broad-leaved mixed forest and *Pinus massoniana* forest have been increasing more rapidly. At present, the carbon inputs by litter in monsoon evergreen broad-leaved forest and coniferous and broad-leaved mixed forests have been stabilized, only that in the *Pinus massoniana* forest is still increasing. As the restoration of hydrological function is faster than that of other functions and ecosystem structure[12], the hydrological process of the three forest types has been stabilized (*e.g.* the amount of throughfall and stemflow in the three forest types have not changed for years). Consequently, water-borne carbon input to the belowground is stable from year to year unless the precipitation regime changes. Although data of carbon input by root for multiple years was unavailable in this paper, it is estimated that carbon input by root in the monsoon evergreen broad-leaved forest will change little from year to year, while those in the coniferous and broad-leaved mixed forest and *Pinus massoniana* forest will increase continuously.

(ii) Monthly and seasonal dynamics. As shown in Table 4, net carbon accumulation rates of litter in the monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest were 40.8 ± 6.7 g · m$^{-2}$ · a$^{-1}$, 10.8 ± 4.0 g · m$^{-2}$ · a$^{-1}$ and 43.9 ± 4.7 g · m$^{-2}$ · a$^{-1}$, respectively. The net carbon accumulation of litter mainly occurred from July to November every year with 80.4 ± 3.1 g · m$^{-2}$, 56.4 ± 3.1 g · m$^{-2}$ and 57.5 ± 3.7 g · m$^{-2}$, respectively in the three forest types, suggesting that the litter pool played the role of carbon sink to the atmosphere during this period. In the rest months (from December to June), the carbon output from the litter pool was bigger than carbon input to it. As a result, the net carbon outputs from the litter pool in the three forest types during this period were −39.6 ± 3.6 g · m$^{-2}$, −45.6 ± 2.6 g · m$^{-2}$ and −13.6 ± 5.6 g · m$^{-2}$, respectively, which means that the litter pool played the role of carbon source to the atmosphere during this period. The reason of this result is that the litter input mainly occurred from July to December every year in the three forest types[13].

The monthly patterns of soil respiration in the three forest types as shown in Fig. 4 followed the change of temperature. The carbon outputs from soil respiration in the monsoon evergreen broad-leaved forest, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest during the rainy season (April—September with higher temperature and humidity) accounted for 69.7%, 73.3% and 74.8% of the total carbon output from soil respiration in the whole year,

Table 4 The litter carbon balance (carbon input minus carbon output) in each month (Unit: g · m$^{-2}$)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M[a)] | −6.1 | 3.7 | 2.7 | 12.1 | 5.9 | −54.2 | 16.7 | 13.2 | 20.4 | 22.2 | 8.0 | −3.7 | 40.8 |
| C | −3.1 | 1.1 | −13.6 | 0.8 | −14.6 | −13.4 | 21.3 | 2.6 | 7.2 | 20.3 | 4.9 | −2.7 | 10.8 |
| P | 8.4 | −1.0 | −10.5 | −19.8 | −12.6 | −1.6 | 22.0 | 10.3 | −1.6 | 13.0 | 13.7 | 23.4 | 43.9 |

a) M, Monsoon evergreen broad-leaved forest; C, coniferous and broad-leaved mixed forest; P, pine forest.

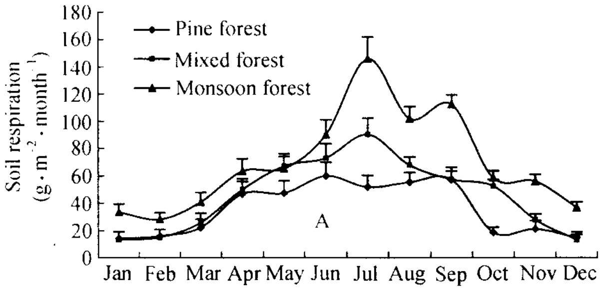

Fig. 4. Monthly pattern of carbon output from soil respiration.

respectively.

According to the seasonal dynamics of every component of belowground carbon storage described above, the carbon output from soil respiration, which was controlled by temperature, concentrated in April—September, thus soil carbon pool was a carbon source to the atmosphere during this period; the litter pool, which was controlled by the seasonal change of litter input, was a carbon sink to the atmosphere in July—November and became a carbon source to the atmosphere in December—June. Taking all these factors into consideration, the belowground carbon pools of the three forest types in Dinghushan may be considered to have similar monthly dynamics. That is, strong carbon sources appeared from April to June; weak carbon sources from July to September; strong carbon sinks from October to November; and weak carbon sinks from December to March.

## 4 Discussions

### *4.1 Analysis of errors and assumptions*

It is difficult to precisely estimate the belowground carbon allocation and balance of forest ecosystem. As shown in eq. (1), the net production of root is dependent on aboveground biomass and net primary production. Therefore, the long-term and accurate data of aboveground biomass and productivity are fundamental to study belowground carbon allocation and balance. Dinghushan Biosphere Reserve, as a permanent national research station, provided such data for this paper.

Soil organic matter is the most important carbon pool in the three forest types. Chemical measurement of soil organic matter is standard and reliable. Although the methods used to measure soil organic matter were somewhat different, the bias caused by different methods can be ignored. Because the sampling points were not the same each time in order not to destroy the soil structure, errors of soil organic matter measurement from year to year might be introduced. Nevertheless, errors were minimized by selecting at least 20 sampling points each time to cover the spatial variation. Therefore, the data of soil organic carbon storage in this paper were very reliable.

It is not difficult to measure the standing pool and input of litter, and the standing pool of CWD. The inputs of CWD were obtained by two plot-based measurements of standing pools of CWD. Although the accuracy of CWD measurements was high, errors in two measurements may result in large bias in CWD fluxes. More discussions will be given later.

The measurement of DOC and SOC in water could not cause much error. There might exist an error of 10%—20% in monitoring stream flow of lower subtropical forest ecosystem[12]. Luckily, the carbon in water accounted for only a very small portion of total carbon pool of belowground, so such error had little influence on belowground carbon allocation and balance.

The $CO_2$ flux from soil and litter+CWD measured by enclosed static chamber-gas chromatograph technique may be overestimated due to underpressurization when sample air was pumped from the chamber. Our experiment indicated that the error was about 5%. As respiration accounted for 99.2% of the total carbon output from belowground, the error in respiration estimates might result in 4%—5% error in total carbon output.

It is more difficult to measure the biomass, net production, and mortality of roots. Some studies[14,15] derived them from the corresponding aboveground counterparts and certain coefficients based on allometric theory. In this study, we directly measured the biomass, net production, and mortality of coarse roots and fine roots. The results in Tables 1 and 2 showed that there were some differences among independent measurements caused by unevenness of root spatial distribution. However, the difference between the measured and actual values of roots in the stand was less than 10%[9]. This would lead to the following errors of standing carbon densities in Table 1: 2.2% for monsoon evergreen broad-leaved forest, 2.8% for coniferous and broad-leaved mixed forest, and 1.4% for *Pinus massoniana* forest respectively; and 5.4%, 5.4%, and 5.3%, respectively, for the three forest types in Table 2.

The total standard deviation was calculated from the standard deviation of every component using eq. (11):

$$\sigma_C = \sqrt{\sigma_A^2 + \sigma_B^2 + \rho\sigma_A\sigma_B}\,, \qquad (11)$$

where $\sigma_C$, $\sigma_A$ and $\sigma_B$ stand for the standard deviations of C, A and B, respectively, $\rho$ the correlation coefficient between A and B, and C = A + B.

The total standard deviation computed from (11) would be overestimated if the ratio of A : C is different from that of B : C and the component with smaller ratio contributes a larger standard deviation. In Table 1, the percentage of root carbon density to the total carbon density was small and the root carbon density had a larger standard deviation, which could lead to larger calculated standard deviation for the total carbon density.

Giardina[14] calculated the total standard deviation based on standard deviation and weight of every component. This method is considered to be reasonable to some extent. However, it could result in an underestimated total standard deviation.

### 4.2 Comparison with other studies

Li[16] have reported that the litter standing pool in a tropical mountain rain forest ecosystem (18°'23′—18°52′N, 108°36′—109°02′E) at Jianfengling, Hainan Island was 590 g·m$^{-2}$, equivalent to 295 g·m$^{-2}$ of C. This value was smaller than that of monsoon broad-leaved forest as shown in Table 1. Considering the difference in latitude, the two results were consistent. The research of Zhang[17] has demonstrated that the litter standing pools in the succession series of evergreen broad-leaved forest in subtropics of China (29°48′N, 121°47′E) were 1152, 1044, 1027, 1037, 1045 g·m$^{-2}$, respectively, in *Pinus massoniana* forest, *Pinus massoniana* and *Schima superba* mixed forest, *Schima superba* forest, *Castanopsis fagasii* and *Schima superba* mixed forest, *Castanopsis fagasii* forest. The corresponding C pools were about 576, 522, 514, 519, 523 g·m$^{-2}$, respectively. These data were higher than those of succession series of monsoon evergreen broad-leaved forest as shown in Table 1, which might be attributed to latitudinal difference.

As affected by forest types and geographical environments, the C pools stored in CWD varied greatly[6,18,19], ranging from 368[18] to 4923 g·m$^{-2}$ [19]. The C pools stored in CWD of the Dinghushan monsoon evergreen broad-leaved forest and the coniferous broad-leaved mixed forest were within the range and consistent with the result of Tang[6].

The total root biomass values of different forest ecosystems in Changbai Mountain were in the range of 2578—5155 g·m$^{-2}$ [20], corresponding to 1289—2578 g·m$^{-2}$ of carbon. These values were smaller than those of Dinghushan monsoon evergreen broad-leaved forest and the coniferous and broad-leaved mixed forest but bigger than that of the *Pinus massoniana* forest. This difference mainly resulted from the vast difference of biomass between Changbai and Dinghushan ecosystems.

Table 5 lists the estimated soil organic carbon densities in this study and Li's research[2], together with those obtained from soil survey by Fang[21] and Wang[22]. It can be seen that all our results fell within the ranges of soil organic carbon densities of similar forest types.

Yang[20] investigated the belowground carbon stor-

Table 5 Comparison of soil organic carbon density in three forest types (Unit: g·m$^{-2}$)

| Forest type | This study | Li *et al.*[2] | Obtained from soil survey |
|---|---|---|---|
| Monsoon evergreen broad-leaved forest | 16410 | | |
| Evergreen broad-leaved forest | | 12920 | 9670—19600 |
| *Pinus massoniana* and broad-leaved mixed forest | 11129 | | |
| Mixed forest | | 22570 | 10130—23730 |
| *Pinus massoniana* forest | 10518 | | |
| Evergreen coniferous forest | | 17980 | 9000—11110 |

age in different forest ecosystems of Changbai Mountain, with 15494, 21006, 19819, 14233 and 7344 $g \cdot m^{-2}$ from high to low altitude. These values were similar to the results in Table 1.

The belowground carbon accumulation rate in natural forest ecosystems was hardly reported due to shortage of long term data. It is greatly affected by land cover type and climatic regime, resulting in poor comparability among different studies. According to Chen[8], the annual accumulation rates of belowground carbon in four Eucalypt savanna ecosystems located in northern Australia (12°14′ − 12°42′S, 131°0′ − 131°10′E) ranged from 170 $g \cdot m^{-2}$ to 190 $g \cdot m^{-2}$, similar to the results of this paper. Nevertheless, this comparison is referential because of the apparent differences in vegetation type and climate conditions.

## 5 Conclusions

Based on long-term field observations, belowground carbon pools and their dynamics of the lower subtropical monsoon evergreen broad-leaved forest and its successional series of restoration (*i.e.*, coniferous and broad-leaved mixed forest and *Pinus massoniana* forest) were systematically studied in this paper. The main results are as follows:

(1) Belowground carbon pools of monsoon evergreen broad-leaved forest, the coniferous and broad-leaved mixed forest and the *Pinus massoniana* forest in the year 2002 were 23191 ± 2538, 16889 ± 1936, and 12680 ± 1854 $g \cdot m^{-2}$, respectively. Carbon stored in soil organic matter accounted for 70.8%, 65.9%, and 83.0% of the belowground carbon pools, respectively in these forests.

(2) The net accumulation of belowground carbon in the monsoon evergreen broad-leaved forest, the coniferous and broad-leaved mixed forest and the *Pinus massoniana* forest in the year 2002 were 145 ± 289, 338 ± 308, and 155 ± 223 $g \cdot m^{-2} \cdot a^{-1}$, respectively, indicating that the belowground was a sink of atmospheric carbon.

(3) From 1978 to 2002, the mean annual increasing rates of belowground carbon in the monsoon evergreen broad-leaved forest, the coniferous and broad-leaved mixed forest and the *Pinus massoniana* forest were 383 ± 97, 193 ± 85, and 213 ± 86 $g \cdot m^{-2} \cdot a^{-1}$, respectively.

(4) The monthly dynamics of the belowground carbon pool in the three forest types were consistent. Strong carbon sources appeared from April to June; weak carbon sources from July to September; strong carbon sinks from October to November; and weak carbon sinks from December to March.

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## References

1. IPCC, Land Use, Land-Use Change, and Forestry, Cambridge: Cambridge University Press, 2000, 1−51.
2. Li, K. R., Wang, S. Q., Cao, M. K., Carbon storage in China's vegetation and soils, Science in China, Series D, 2003, 33(1): 72−80.
3. Zhou, G. Y., Luo, Y., Ouyang, X. J. *et al.*, Analysis on the concentration of some sediment elements in their transport process through monsoon evergreen broad-leaved forest ecosystem in Dinghushan, Guangdong Province, China, Acta Ecologica Sinica (in Chinese), 2003, 23(7): 1408−1414.
4. Peng, S. L, Zhang, Z. P., Studies on the biomass, productivity and energy use efficiency of the zonal vegetation in Dinghushan, Science in China, Series B, 1994, 24(5): 497−502.
5. Peng, S. L, Zhang, Z. P., Studies on the biomass, primary productivity and energy use efficiency of the mixed forest in Dinghushan, Acta Ecologica Sinica (in Chinese), 1994, 14(3): 300−305.
6. Tang, X. L., Zhou, G. Y., Zhou, X. *et al.*, Coarse woody debris in monsoon evergreen broad-leaved forests of Dinghushan nature reserve, Acta Phytoecologica Sinica (in Chinese), 2003, 27(4): 484−489.
7. Johnson, F. L., Risser, P. G., Biomass, annual net primary production, and dynamics of six mineral elements in a post oak-blackjack oak forest, Ecology, 1974, 55: 1246−1258.
8. Chen, X. Y., Hutley, L. B., Eamus, D., Carbon balance of a tropical savanna of northern Australia, Oecologia, 2003, 137: 405−416.
9. Wen, D. Z., Wei, P., Kong, G. H. *et al.*, Production and turnover rate of fine roots in two lower subtropical forest sites at Dinghushan, Acta Phytoecologica Sinica (in Chinese), 1999, 23(4): 361−369.
10. McClaugherty, C. A., Aber, J. D., The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems, Ecology, 1982, 63(5): 1481−1490.
11. Liao, C. H., Lin, S. M., Li, Y. Q. *et al.*, Study on the Decomposition of Forest litter, Tropic and Subtropical Forest Ecosystem (8) (in Chinese), Beijing: China Meteorology Press, 1998, 180−185.

12. Zhou, G. Y., Principles and Applications of Water and Heat in Ecosystem (in Chinese) Beijing: China Meteorology Press, 1997.
13. Tu, M.Z., Yao, W. H., Weng, H. *et al.*, Characteristics of litter in evergreen broadleaved forest of the Dinghu mountain, Acta Pedologica Sinica (in Chinese), 1993, 30(1): 34—42.
14. Giardina. C. P., Ryan, M. G., Total belowground carbon allocation in a fast-growing *Eucalyptus* plantation estimated using a carbon balance approach, Ecosystems, 2002, 5: 487—499.
15. Misra, R. K., Turnbull, C. R. A., Cromer, R. N. *et al.*, Below- and aboveground growth of *Eucalyptus nitens* in a young plantation I. Biomass, Forest Ecology and Management, 1998, 106: 283—293.
16. Li, Y. D., Wu, Z. M., Zeng, Q. B., Carbon pool and carbon dioxide dynamics of tropical mountain in rain forest ecosystem at Jiangfengling, Hainan Lsland, Acta Ecologica Sinica (in Chinese), 1998, 18(4): 371—378.
17. Zhang, Q. F., Xu, R. D., Standing crops of the litterfall in the succession series of evergreen broad-leaved forest in Tiantong, Zhejiang Province, Chinese Journal of Ecology (in Chinese), 1999, 18(2): 17—21.
18. Li, L. H., Xing, X. R., Huang, D. M. *et al.*, Storage and dynamics of coarse woody debris in *Castanopsis eyrei* forest of Wuyi mountain, with some considerations for its ecological effects, Acta Phytoecologica Sinica (in Chinese), 1996, 20(2): 132—143.
19. Liu, W. Y., Xie, S. C., Xie, K. J. *et al.*, Preliminary studies on the litterfall and coarse woody debris in mid-mountain humid evergreen broad-leaved forest in Ailao Mountains, Acta Botanic Sinica (in Chinese), 1995, 37(10): 807—814.
20. Yang, L. Y., Li, W. H., The underground root biomass and C storage in different forest ecosystems of Changbai Mountains in China, Journal of Natural Resources (in Chinese), 2003, 18(2): 204—209.
21. Fang, J. Y., Liu, G. H., Xu, S. L., Carbon reservoir of terrestrial ecosystem in China, in Monitoring and Relevant Process of Greenhouse Gas Concentration and Emission (in Chinese),. Beijing: China Environmental Science Publishing House, 1996, 109—128.
22. Wang, S. Q., Zhou, C. H., Li, K. R. *et al.*, Study on spatial distribution character analysis of the soil organic carbon reservoir in China, Journal of Geographical Sciences, 2001, 11(1): 3—13.