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Aboveground biomass and corresponding carbon sequestration ability of four major forest types in south China

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We estimated aboveground biomass carbon (T_{ABC}) and net carbon accumulation rates (T_{NEP}) for trees in four major forest types based on national forest inventory data collected in 1994–1998 and 1999–2003. The four types were *Pinus massoniana* forest, *Cunninghamia lanceolata* forest, hard broad-leaved evergreen forest and soft broad-leaved evergreen forest. We analyzed variations in T_{ABC} and T_{NEP} for five stand ages (initiation, young, medium, mature and old). In both time periods, estimated T_{ABC} in all four forest types increased consistently with forest stand age and the oldest stage had the largest T_{ABC} compared with other stages. Broad-leaved forests (hard and soft) had higher T_{ABC} than needle-leaved forests (*Pinus massoniana* and *Cunninghamia lanceolata*) for each of the five age stages. The difference of T_{ABC} between broad-leaved and needle-leaved forests increased with forest stand age. Comparison of estimated T_{NEP} by age category indicated T_{NEP} increased from the initiation stage to the young stage, and then decreased from the mature stage to old stage in all four forest types. T_{NEP} for any particular stage depended on the forest type; for instance, broad-leaved forests at both the mature and old stages had greater T_{NEP} than in needle-leaved forests. A logistic curve was applied to fit the relationship between T_{ABC} and forest stand age. In each period, correlations in all four forest types were all statistically significant ($P < 0.01$) with $R^2 > 0.95$. T_{ABC} was therefore predicted by these regression functions from 2000 to 2050 and the mean T_{NEP} during the predicted period was estimated to be about 41.14, 31.53, 75.50 and 75.68 g C m^{-2} a^{-1} in *Pinus massoniana* forest, *Cunninghamia lanceolata* forest, hard broad-leaved forest and soft broad-leaved forest, respectively. Results from both forest inventory and regression prediction suggest broad-leaved forests are greater carbon sinks, and hence have greater carbon sequestration ability especially in the mature and old stages when compared to needle-leaved forests. Broad-leaved forests should have high levels of carbon sequestration when compared with needle-leaved forests in south China.

broad-leaved forest, needle-leaved forest, aboveground biomass, carbon accumulation rate, logistic regression

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Globally, forest ecosystems are significant carbon pools because forests absorb carbon dioxide (CO_2) from the atmosphere through photosynthesis [1]. Tropical and subtropical forests have accounted for more than 40% of global gross primary production [2] and net carbon uptake over the past two decades [3–5]. Carbon sequestration in tropical and subtropical regions has been receiving increased attention because these forests grow year round and have intense photosynthetic activity and a wide diversity of species [6,7].

Biomass directly reflects forest carbon pools, while the net carbon accumulation rate (T_{NEP}) determines the potential of carbon sequestration in forest ecosystems [8]. Many previous studies have reported the changes of biomass and T_{NEP} with forest stand age [9–11]. Few studies have examined the differences of biomass carbon and net carbon sequestration ability related to forest stand age among different forest types, especially in tropical and subtropical forests.

In the present study, aboveground biomass carbon (T_{ABC}) and T_{NEP} for trees in four major forest types were estimated using the national forest inventory data from two periods,

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1994–1998 and 1999–2003. In each period, T_{ABC} and T_{NEP} were compared for five age categories: initiation, young, medium, mature and old (Table 1). Also, T_{ABC} and mean T_{NEP} were estimated based on the logistic regression function between T_{ABC} and forest stand age, with T_{ABC} estimated for each decade from 2000 to 2050. The objectives of this study were (1) to explore the ability of four forest types in five age categories to sequester carbon, and (2) to provide a scientific basis for future policy decisions related to the sustainable management of forests in an environment-friendly manner in southern China.

1 Methods

1.1 Study site and forest type

The study site covers most of the tropical and subtropical regions in south China (3°30′–30°72′N, 103°36′–122°45′E), including eight provinces (region): Fujian, Guangdong, Guangxi, Guizhou, Hainan, Hunan, Jiangxi and Zhejiang (Figure 1). The total area of land surface is about 1.2×10^{12} m^2. Highly diverse evergreen forests dominate the area of broad-leaved and needle-leaved species. The forested area within the study site covers about 4.1×10^{11} m^2 with a timber volume of 2.1×10^{9} m^3, including 23.4% and 15.0% of the total forest area and timber volume in China, respectively [12]. The region has a typical tropical and subtropical monsoon climate with distinct wet and dry seasons. The mean annual precipitation in the eight provinces ranges from 1200 to 1800 mm and the mean annual temperature varies from 16 to 20°C. Table 2 summarizes additional details of site characteristics.

Based on the "National Forest Resources Inventory of Continuous Technical Regulations" [13], four forest types,

Table 2 Ecological characteristics of eight provinces in the tropical and subtropical regions of south China

Forest type	Forest stand age (a)				
	Initiation (A)	Young (B)	Medium (C)	Mature (D)	Old (E)
Masson pine forest	<11	11–20	21–30	31–50	>50
Cunninghamia forest	<11	11–20	21–25	26–35	>35
Hard broad-leaved forest	<41	41–60	61–80	81–120	>120
Soft broad-leaved forest	<21	21–40	41–50	51–70	>70

Table 1 Division of the five age stages for the four forest types

Province/region	Latitude(N)	Longitude(E)	Mean temperature in winter (°C)	Mean temperature in summer (°C)	Average annual precipitation (mm)
Hainan	3°30′–20°18′	108°37′–111°05′	17–22	26–29	900–2600
Guangdong	20°13′–25°31′	109°39′–117°19′	9–23	27–29	1500–2000
Guangxi	20°54′–26°24′	104°26′–112°04′	6–15	23–28	1300–2400
Fujian	23°33′–28°20′	115°50′–120°40′	7–13	28–30	1200–2200
Guizhou	24°30′–29°13′	103°31′–109°30′	4–9	20–28	900–1500
Hu'nan	24°38′–30°08′	108°47′–114°15′	4–7	26–30	1300–1700
Jiangxi	24°07′–29°09′	114°02′–118°28′	4–9	28–30	1300–1800
Zhejiang	27°08′–30°27′	118°05′–122°45′	3–7	28–30	1200–1800

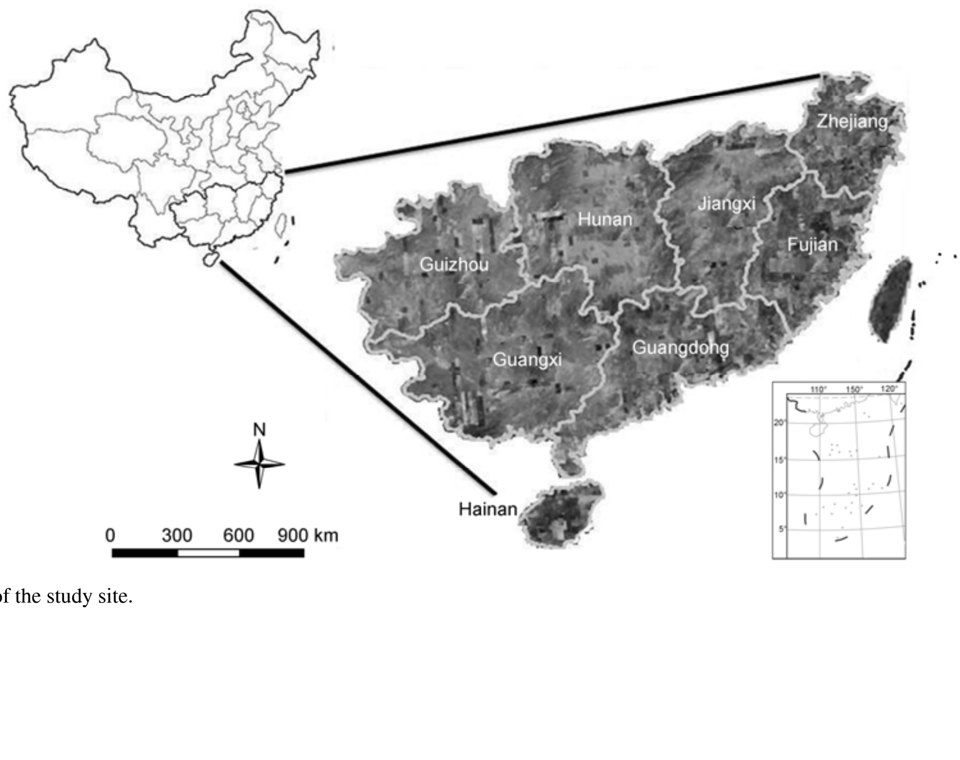

Figure 1 Location of the study site.

containing 10 tree species, were chosen for the present study. They could be divided into the two groups, needle-leaved and broad-leaved forests. Needle-leaved forests include both Masson pine (*Pinus massoniana*) and Cunninghamia (*Cunninghamia lanceolata*). Broad-leaved forests include two types, hard broad-leaved forest (oak, *Cinnamomum camphora*, *Phoebe zhennan* and hard broad-leaved mixed species) and soft broad-leaved forest (Betulaceae, Tiliaceae, Scrophulariaceae and soft broad-leaved mixed species). These four forest types occupied 87.7% of the area and contained 89.0% of the timber volume of the entire study site. Basically, they were representatives of all forest types in the tropical and subtropical regions of south China [12]. Using the forest stand age division standards of the Chinese forest inventory [13], all four forest types were classified into these five age categories: initiation (A), young (B), medium (C), mature (D) and old (E). Table 1 provides a breakdown of the stand age classifications.

1.2 Calculation of aboveground biomass carbon (T_{ABC})

The national forest resources inventory has been conducted every five years to review changes in forest area and timber volume including stand age and forest type (species) in each province. This study used inventory data from two periods, 1994–1998 and 1999–2003, to calculate T_{ABC} (g C m^{-2}) of the tree layer as follows:

$$T_{ABC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} B_{i,j} \times S_{i,j}}{\sum_{i=1}^{n} S_i}, \qquad (1)$$

where n and m represent forest type and tree species, respectively. S_i is the area (m^2) of the ith forest type, S_{ij} is the area of the jth tree species in the ith forest type, B_{ij} is the aboveground carbon biomass (g C m^{-2}) of the jth tree species in the ith forest type. B_j can be estimated as follows:

$$B_j = 0.5 \times \frac{\delta_j \times V_j}{S_j}, \qquad (2)$$

where 0.5 is the convention coefficient of carbon to biomass, V_j is the timber volume (m^3) of the jth tree species, S_j is the area (m^2) of the jth tree species. δ_j is the specific biomass expansion factor (g m^{-3}) of the jth tree species, which can be estimated as follows:

$$\delta_j = C_1 + \frac{C_2}{V_j}, \qquad (3)$$

where C_1 (g m^{-3}) and C_2 (g) are estimated parameters for specific tree species, more extensive description of the methods to estimate C_1 and C_2 were shown in a previous study [14]. If there were no estimated C_1 and C_2 for some species in the present study, parameters derived from a similar species in the same region were used. We used eqs. (1) – (3) to calculate T_{ABC} for all five forest stand age stages. A logistic regression curve was applied to fit the relationship between T_{ABC} and forest stand age. In each period, correlations in all four forest types were all statistically significant ($P < 0.01$) with $R^2 > 0.95$ (Figure 2).

1.3 Calculation and prediction of the carbon accumulation rate (T_{NEP})

T_{NEP} was estimated as follows

$$T_{NEP} = \frac{T'_{ABC} - T^0_{ABC}}{t' - t^0}, \qquad (4)$$

where t is the time (year), and T^0_{ABC} and T'_{ABC} are the values of aboveground biomass carbon (g C m^{-2}) at t^0 and t' time, respectively. Using the logistic curve derived from forest inventory data, T_{ABC} was predicted until 2050 and T_{NEP} was estimated at intervals of 5 years for the initiation, young and medium stages and at intervals of 10 years for the mature and old stages.

1.4 Data analysis

The effects of stand age on the variations of T_{ABC} and T_{NEP} were examined by performing one-way analysis of variance, and multiple comparisons using the ANOVA procedure of SAS (Version 8.0; SAS Institute Inc., 1999). The logistic regression curves (variation of T_{ABC} with forest stand age) were plotted using the built-in statistical program Origin (Version 8.0; Origin Lab, 2007).

2 Results

2.1 Changes in T_{ABC}

Figure 3 shows the estimated T_{ABC} increased continuously with forest stand age across all four forest types in the two time periods, 1994–1998 and 1999–2003, respectively. Previous studies had reported T_{ABC} maintained a balance or slight decline in mature and old forest stages [15–17], but this study found a significant increase of T_{ABC} between mature and old stages (Figure 3). The differences of T_{ABC} among all age stages were significant ($P < 0.01$) for the four forest types (Figure 3).

From the initiation stage to the old stage, T_{ABC} increased from 484.6 g C m^{-2} to 3030.4 g C m^{-2} and from 431.5 to 2224.7 g C m^{-2} for Masson pine forest and Cunninghamia forest, respectively in the period of 1994–1998. For the two broad-leaved forest types, T_{ABC} increased from 1343.9 to 10626.5 g C m^{-2} and from 1816.1 to 6910.3 g C m^{-2} for hard broad-leaved forest and soft broad-leaved forest, respectively. Similar results were found for the period of 1999–2003. Accordingly, there was no significant difference in T_{ABC} between the two periods for the same forest type ($P_{\text{Masson pine}} = 0.96$, $P_{\text{Cunninghamia}} = 0.75$, $P_{\text{hard boardleaf}} = 0.92$, $P_{\text{soft boardleaf}} = 0.86$) (Figure 3).

T_{ABC} in broad-leaved forests was much greater than T_{ABC}

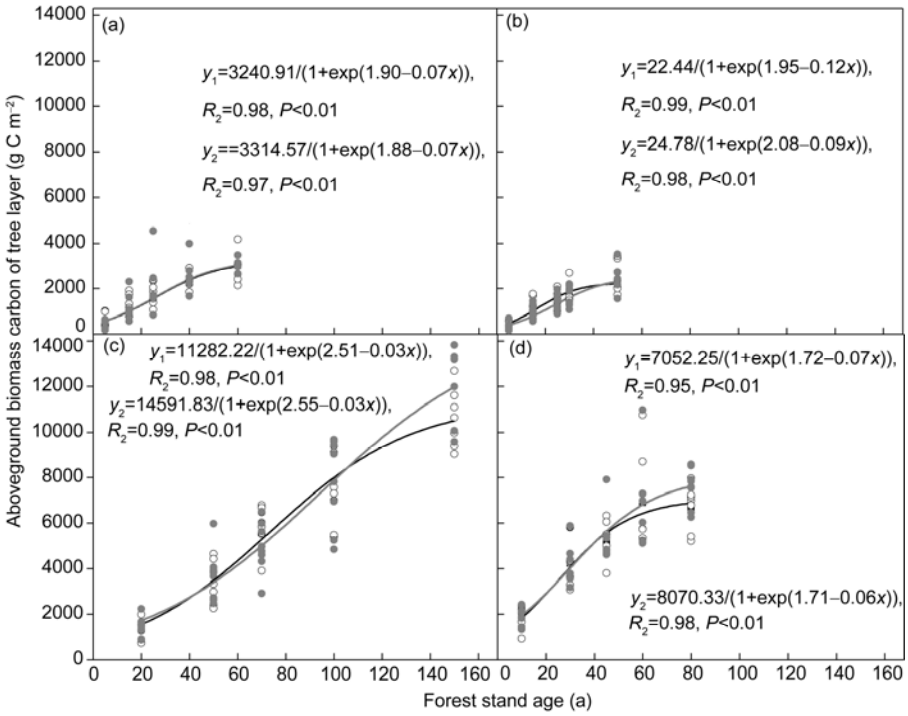

Figure 2 Logistic regression curves for the variations of aboveground biomass carbon (T_{ABC}, g C m^{-2}) of the tree layer with forest stand age in the four forest types: Masson pine forest (a), Cunninghamia forest (b), hard broad-leaved forest (c) and soft broad-leaved forest (d). Empty dots (○) and filled dots (●) represent T_{ABC} of the eight provinces in the two periods of 1994–1998 and 1999–2003, respectively. y_1 and y_2 are logistic regression equations for the two periods of 1994–1998 and 1999–2003, respectively.

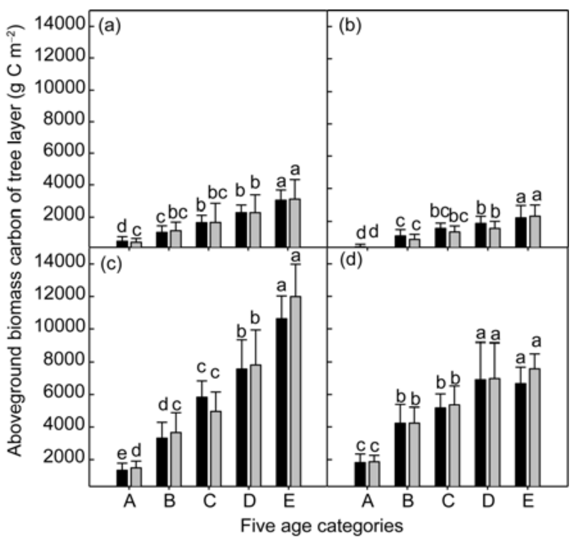

Figure 3 Aboveground carbon biomass in the tree layer (T_{ABC}, g C m^{-2}) for the five age categories (initiation (A), young (B), medium (C), mature (D) and old (E)) in the four forest types: Masson pine forest (a), Cunninghamia forest (b), hard broad-leaved forest (c) and soft broad-leaved forest (d). Mean and standard deviation of the estimated T_{ABC} were calculated for the years 1994–1998 (grey bars) and 1999–2003 (dark bars) based on data from the eight provinces (region). For clarity, only the upper error bars for the four plots are shown.

in needle-leaved forests. Figure 3 also shows these differences increased with forest stand age. For the four forest types, the mean T_{ABC} was the largest in hard broad-leaved forest and the least in Cunninghamia forest. The differences of T_{ABC} among the four forest types were significant in both time periods, 1994–1998 ($P_{1994–1998}$ = 0.03) and 1999–2003 ($P_{1999–2003}$ = 0.01).

2.2 Changes in T_{NEP}

Figure 4 shows the estimated T_{NEP} for each age stage and forest type. T_{NEP} in both periods (1994–1998 and 1999–2003) increased from the initiation stage to the young stage, and then decreased from the mature stage to the old stage in the four forest types. Figure 4 shows T_{NEP} was the largest in the young stage in all forest types except for hard broad-leaved forest. The differences of T_{NEP} among all age stages were significant ($P < 0.01$) for all four forest types (Table 3).

In the period of 1994–1998, T_{NEP} were 3.6–63.4, 10.7–61.8, 31.3–109.6, 36.0–125.1 g C m^{-2} a^{-1} for all five age stages for Masson pine forest, Cunninghamia forest, hard broad-leaved forest, and soft broad-leaved forest, respectively. For 1999–2003, a slightly greater T_{NEP} in all four forest types was found compared with data from 1994–1998. This probably reflected global changes such as rising atmospheric CO_2, warming, nitrogen deposition and so on [18,19].

The mean T_{NEP} in broad-leaved forests was much greater (81.4 g C m^{-2} a^{-1}) than mean T_{NEP} in needle-leaved forests (41.8 g C m^{-2} a^{-1}). For the four forest types, the mean T_{NEP} was the largest in soft broad-leaved forest (90.4 g C m^{-2} a^{-1})

Table 3 Statistical multiple comparison of T_{NEP} across the five age categories (initiation (A), young (B), medium (C), mature (D) and old (E)) for the four forest types

Age category	Masson pine forest		Cunninghamia forest		Hard broad-leaved forest		Soft broad-leaved forest	
	1994–1998	1999–2003	1994–1998	1999–2003	1994–1998	1999–2003	1994–1998	1999–2003
A	a	ab	ab	ab	b	b	a	a
B	a	a	a	a	a	a	a	a
C	a	ab	ab	a	a	a	ab	ab
D	b	b	b	b	b	a	bc	bc
E	c	c	c	c	c	b	c	c

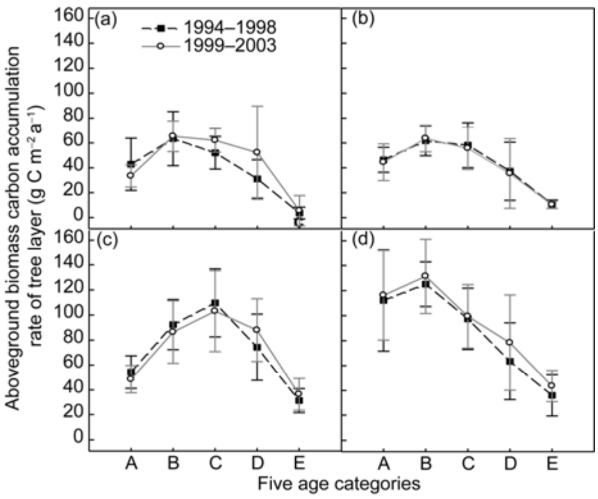

Figure 4 Aboveground biomass carbon accumulation rates in the tree layer (T_{NEP}, g C m^{-2} a^{-1}) for the five age categories (initiation (A), young (B), medium (C), mature (D) and old (E)) in the four forest types: Masson pine forest (a), Cunninghamia forest (b), hard broad-leaved forest (c) and soft broad-leaved forest (d). Mean and standard deviation of the estimated T_{NEP} were calculated in the two periods of 1994–1998 and 1999–2003 from the eight provinces (region).

and the least in Masson pine forest (41.2 g C m^{-2} a^{-1}). The differences of T_{NEP} among the four forest types were significant in both periods of 1994–1998 ($P_{1994-1998}$ = 0.04) and 1994–1998 ($P_{1999-2003}$ = 0.03). Although T_{NEP} decreased clearly in the mature or old stage for all the four forest types, T_{NEP} in broad-leaved forests at the mature or old stage was still larger than the mean T_{NEP} during the five age stages in needle-leaved forests.

2.3 Increment of carbon storage and rate of carbon sequestration in the future

We assumed the area of each forest type in the period of 1999–2003 was the average level in 2000, which would not be disturbed and would be maintained in the study sites. Using the estimated parameters in the logistic regression functions in the period of 1999–2003, carbon storage in the four forest types was estimated from 2000 to 2050 (Table 4). The total carbon storage in aboveground biomass of trees in the four forest types started at 0.57 Pg C in 2000 and would reach 1.42 Pg C in 2050. The net carbon sequestration was 0.85 Pg C during this period, and the mean annual rate of increment was 4.27×10^{-3} Pg C a^{-1}.

Of the four forest types, hard broad-leaved forest and Masson pine forest showed the largest mean annual rate of carbon sequestration from 2000 to 2050 (Table 4). In comparing the mean annual rate increment per unit area, both broad-leaved forests (hard and soft) showed greater carbon sequestration ability than the needle-leaved forest types (Table 4). We concluded the larger mean annual rate increment in Masson pine forest was driven by the larger forest area. However, the larger mean annual rate increment in hard broad-leaved forest was driven by the larger T_{NEP}.

The above results indicate the four forest types will be important carbon sinks in the future in south China. However, their carbon sequestration rates will differ, with the largest potential in hard broad-leaved forest as it has both the large forest area and T_{NEP}.

3 Discussion

3.1 Reliability of logistic regression as a proxy for carbon sequestration prediction

A number of studies on tree growth indicate plant biomass increases with forest stand age, and reaches an equilibrium or declines slightly in mature and old stages [15–17]. However, increasing amounts of soil organic carbon were found in many old-growth forests [3]. Old-growth forests have been considered to be carbon sinks worldwide [20,21]. Generally, biomass carbon accumulation rates increase continuously until the forest canopy closes; after that, it tends to decrease. Many studies reported these age-related patterns with logistic regression curves [15,17,22]. Using the data from the national forest inventory from 1994–1998 and 1999–2003, Figure 2 shows the relationship between T_{ABC} and forest stand age over time. A good trend of the logistic regression curve was also found in the present study.

The two logistic regression curves in each plot in Figure 2 were very similar, except for broad-leaved forests. At the mature or old stage, T_{ABC} for broad-leaved forests was larger in 1999–2003 than in 1994–1998, which was probably the result of positive impacts of human activates or

Table 4 Predictions of aboveground biomass carbon storage and increment of carbon sequestration ability of tree layer for the four forest types from 2000 to 2050[a)]

Forest type	Forest area in 2000 ($\times 10^9$ m^2)	Aboveground biomass carbon storage (Pg C)						Increment of carbon sequestration ability	
		2000	2010	2020	2030	2040	2050	Mean annual rate of increment (10^{-3} Pg C a^{-1})	Mean annual rate of increment per unit area (g C m^{-2} a^{-1})
Masson pine forest	133.48	0.14	0.20	0.28	0.34	0.38	0.41	5.49	41.14
Cunninghamia forest	118.46	0.10	0.16	0.22	0.26	0.28	0.29	3.73	31.53
Hard broad-leaved forest	74.98	0.23	0.28	0.33	0.39	0.45	0.52	5.66	75.50
Soft broad-leaved forest	28.79	0.10	0.13	0.15	0.18	0.20	0.21	2.18	75.68
Total carbon storage		0.57	0.77	0.98	1.16	1.31	1.42		

a) 1 Pg = 10^{15} g.

environmental factors on forest carbon sequestration in the second period. However, comparing the parameters in the logistic regression curves derived from the same forest type in the two periods, no statistically significant ($P > 0.05$) difference was found between the two periods, and correlations in all four forest types were statistically significant ($P < 0.01$) with $R^2 > 0.95$, which suggests the logistic regression curves could be used to predict T_{ABC} in our study.

3.2 Carbon sequestration ability in the future in south China

The two broad-leaved forest types studied are two major mixed forest types, while *Pinus massoniana* and *Cunninghamia lanceolata* forests are representative of pure coniferous forests in the tropical and subtropical regions of south China. T_{ABC} in these forests reflects the total forest carbon pools and their T_{NEP} determines the potential of forest carbon sinks in this study site.

T_{ABC} in broad-leaved forests is higher than in needle-leaved forests across five age categories, which indicates broad-leaved forests have larger aboveground biomass carbon pools per area. Also, the differences of T_{ABC} between broad-leaved and needle-leaved forests become larger as forest stand age increases. In south China, the areas of needle-leaved forests are much larger, influencing the magnitude of forest carbon sequestration in the future. This increase is also supported by the future carbon storage predicted by logistic regression. We concluded that all four forest types will be important carbon pools. T_{NEP} in all four forest types is above zero at each stage of the five age categories, which implies that trees in all forest types accumulate carbon in their biomass throughout their lifespan. T_{NEP} in broad-leaved forests is larger than T_{NEP} in needle-leaved forests, especially in the mature and old stages. The multi-layer canopy in broad-leaved forests may be one of the reasons causing these differences in T_{NEP}. As tree biomass increases in a given forest stand, the competition for nutrients and water among trees intensifies leading to an increased mortality rate for dominant trees during forest succession [23,24]. Gaps left by dead individuals allow a secondary canopy of trees to grow; this maintains the strong productivity of aboveground biomass [21,25,26]. There are usually two or three layers of tree canopy in mature or old broad-leaved forests. Although T_{NEP} in broad-leaved forests decreased significantly in mature and old stages as the canopy closed, it is still greater than T_{NEP} in needle-leaved forests. Therefore, we believe broad-leaved forests are better solutions for afforestation and reforestation in south China in light of their greater potential carbon accumulation ability compared with needle-leaved forests.

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