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REGULAR ARTICLE

Spatial and temporal patterns of carbon storage from 1992 to 2002 in forest ecosystems in Guangdong, Southern China

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Abstract
Aims The overall goal of this study was to examine the spatial and temporal patterns of C storage from 1992 to 2002 in forest ecosystems in Guangdong, China.
Methods We used 2237, 2103, and 1978 plot data from three continuous forest inventory in 1992, 1997, and 2002, respectively, four TM images and one soil survey data in Guangdong to examine the spatial and temporal patterns of C storage in forest ecosystems during 1992–2002. The uncertainty analysis of forest C storage in Guangdong in 1992 and 2002 was also conducted to provide the range of estimations.
Results The forest coverage percent in Guangdong increased from 37.1 % in 1992 to 57.2 % in 2002 while the total forest C storage in Guangdong increased from 144.73±6.20 Tg in 1992 to 215.03±8.48 Tg in 2002. The order of average forest biomass C storage increase during 1992–2002 among the four regions is Western Guangdong (GW)>Eastern Guangdong (GE)>the Pearl River Delta (PRE)>Northern Guangdong (GN). The factors including tree species and altitude and slope aspect can explain 58–67 % variation of Veg C storage multiple regression model in Guangdong. However, the multiple regression model for SOC storage can only explain about 18–39 % variation of SOC storage in Guangdong. Total ecosystem C is mainly determined by SOC storage.
Conclusions The total forest C storage in Guangdong increased about 49 % from 1992 to 2002 partially due to the increasing forest coverage percent over the period. The spatial distribution of forest C storage in Guangdong was uneven and this pattern reflects differences in forest management and economic and social development. Future forest management should focus on the selection of tree species, management of forest stand structures and implementation of sustainable practices so that Veg C sequestration potentials can be maximized.

Keywords Forest resource inventory · Carbon storage · Forest ecosystems · Guangdong Province

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Abbreviations

C	Carbon
DBH	Diameter at breast height
DEM	Digital Elevation Model
GE	Eastern Guangdong
GN	Guangdong
GW	Western Guangdong
PRE	The Pearl River Delta
SOC	Soil organic C
Veg C	Forest vegetation C

Introduction

Forest ecosystems store about two–thirds of the organic carbon (C) in terrestrial ecosystems (Schlesinger 1991). They play an important role in regulating the global C cycle, mitigating the increase of atmospheric CO_2 concentrations, and maintaining global climate (Dixon et al. 1994). Information concerning the distribution of C sources and sinks and their changes over time is critical for understanding the mechanisms controlling the global terrestrial C cycle and the sustainability of current C sinks. Such information is also essential for formulating climate change policies (Houghton 2005). Therefore, C budgets at national or regional scales have received increasing attention. For example, the C storage of forest ecosystems has been estimated in the United States (Turner et al. 1995), Russia (Alexeyev et al. 1995), China (Fang et al. 2001), and Europe (Ciais et al. 2008; Nabuurs et al. 2010) based on forest inventory data.

The forest inventory method has been used to evaluate C storage and its dynamics in forest vegetation in China (Fang et al. 1996, 2001; Liu et al. 2000; Wang et al. 2001; Ren et al. 2011b); Yu and Ren (2007) summarized C storage estimates for Chinese terrestrial ecosystems in these studies. Overall, the C storage estimates for forests in China differ substantially. The differences among estimates were partially caused by the differences in geography, vegetation, soil type boundaries, and data measurement and use. One common limitation in these studies is that the spatial pattern of C storage was not examined at the provincial scale. Another limitation of these studies is the lack of uncertainty analysis on C storage estimate because only one C storage estimate was provided for a specific time.

Among provinces in China, Guangdong has the largest area of plantations but is also one of the most economically developed (Peng et al. 2009). The 7th forest resource inventory of the province was completed in 2007. The new forest resource inventory data provide an opportunity to study C storage of forests and its dynamics (Guangdong Forestry Bureau 2007). A few studies on forest resources and C storage in Guangdong were reported in the past several years. Lin et al. (2008) studied the changes in forest resources and the policy affecting the changes in Guangdong during 1983–2005. Zhou et al. (2008) quantified the C accumulation of forest vegetation during the forest restoration that occurred from 1994 to 2003 in Guangdong. They reported that the reforestation program had increased the total C storage by 41.67 Tg and forest C storage by 1.58 Mg/C ha in that period. Peng et al. (2009) found that the percentage of forest cover increased steadily from 26.23 % in 1979 to 50.11 % in 1998 because of the forest restoration project in Guangdong. Moreover, they estimated that the total annual CO_2 sequestration by forests and soils was 118.05 Tg, which was about half of the annual CO_2 emission in Guangdong. Ye and She (2010) examined C storage, C density, and their dynamics in forests of Guangdong by using the forest inventory data from 1988 to 2007. Zhang et al. (2010) also quantified the C storage of forest vegetation by using a volume-derived method in 2007. These studies, however, reported means of C storage of forests for the entire province and did not consider the spatial distribution and temporal change within the province. Thus, it is not clear how spatial and temporal patterns of C storage in forests changed during 1992–2002 in Guangdong province, southern China.

The overall goal of this study was to examine the spatial and temporal patterns of C storage from 1992 to 2002 in forest ecosystems in Guangdong, China. The three research questions were: (1) How did the total C storage of forest ecosystems change in Guangdong over the period? (2) What were the temporal and spatial patterns of C storage of forest ecosystems in Guangdong? And (3) Which factors were associated with the C storage of forest ecosystems in Guangdong?

Materials and methods

Description of Guangdong Province

Guangdong Province is located in southern China (20 °09′–25 °31′N, 109 °45′–117 °20′E). The total land area is 179,766 km^2. This area represents 1.87 % of China's land and consists of mountains (33.7 %), hilly lands (24.9 %), platform (14.2 %), plains (21.7 %), and rivers and lakes (5.5 %). The province includes central subtropical, lower subtropical, and tropical regions. Guangdong has a subtropical and tropical monsoon and ocean climate, with an average annual temperature of 21 °C and an average annual rainfall of 1,777 mm. From north to south, the zonal soil in Guangdong is laterite soil, laterite red soil, and red soil. The zonal vegetations from north to south are subtropical evergreen broad-leaved forest, subtropical monsoon evergreen broad-leaved forest, tropical seasonal forest, and tropical rain forest. Existing forest vegetation mainly includes coniferous forest, broad-leaved mixed forest, coniferous and broad-leaved mixed forest, bamboo, mangroves, as well as shrub and herb community with dominant species such as *Baeckea frutescens, Rhodomyrtus tomentosa,* and ferns (Peng et al. 2009).

Remote sensing image processing

We collected four-phase Landsat TM satellite images (December 1985; November 1992; December 1997; November 2002), 1: 250,000 Digital Elevation Model (DEM), and Guangdong forest maps (1: 50,000) and administrative maps. We processed the images by ERDAS IMAGINE 8.31. This included geometric correction processing, vegetation information extraction, image classification, and determination of area statistics (Jobin et al. 2003).

During the process of geometric correction of the image, we matched TM images with digitized 1:250,000 DEM, then used the Albers projection to select 20 uniformly distributed control points, and finally used the binary quadratic polynomial for geometric correction (Elvidge et al. 1995). The root-mean-square error of geometric registration was less than 0.5 pixels. This precision is sufficient for accurate multi-temporal analysis of dynamic changes. Finally, we selected the field control points to correct the actual situation, and then overlaid the digital map of the administrative boundary onto a map with area statistics (Jobin et al. 2003; Lee and Yeh 2009; Ren et al. 2011a).

Forest inventory data

We used three continuous forest inventory databases and archival material of Guangdong Province. The data were collected in 1992, 1997, and 2002. The inventory data included statistical report data, plots database, and sample trees database. The plot database contained more than 60 factors including plot number, name of dominant species, average tree diameter at breast height (DBH), average tree height, stand volume, number of standing trees (or bamboo), and litter thickness. The sample trees database contained 11 factors including the number of sampled trees, stand type, plot number, DBH, and volume.

For the plot database, plots were established using a systematic sampling method in May to August 1992. A 1:50,000 topographic map was used to select the location of plots. The southwest crossing point of each grid was used as a reference point to establish a 25.82 m×25.82 m plot within a 6 km×8 km grid. The area of each sample was 667 m^2. A total of 3,685 plots were established in 1992. Among them, 2,237 were forest plots. In total, 2,237, 2,103, and 1,978 forest plots were measured in 1992, 1997 and 2002, respectively. Some plots that were measured in 1992 were unavailable in 1997 and 2002 because of land-use change.

C storage in forest ecosystems includes the C pool in tree biomass, understory, ground layer, and soil. This paper focuses on the C storage in tree biomass and soil. The biomass of trees was calculated by using the Biomass Expansion Factor (f_{BEF}) method and regression equations for different forest types. f_{BEF} is defined as the ratio of all stand biomass to growing stock volume. So we can use this method to convert timber volume to mass and account for noncommercial components, such as branches, leaves, and roots. The following formula was used:

$$f_{BEF} = a + b/V \quad (1)$$

where V is forest stand volume (V, m^{3}ha^{-1}), a and b are parameters of the conversion factor of a specific tree species from volume to biomass. Different type has different constants of a and b (Table 1). The conversion factor values for different dominant tree species were obtained from previous studies in Guangdong Province (Table 1). Therefore, the biomass of a forest stand (B, Mg ha^{-1}) can be calculated by the following formula:

$$B = \sum_{i=1}^{k} A_i \times f_{BEF_i} \times V_i \tag{2}$$

where i is the dominant species of a forest type, A_i is the forest stand area, V_i is the average storage volume, and $f_{\mathrm{BEF}i}$ is the corresponding conversion factor of the i dominant species in the forest type.

Calculation of C storage of forest vegetation at the scale of city and province

According to the Chinese forestry administration system, the data in the plot database were collected by the forestry bureau of each city. Therefore, we first calculated C storage for forest vegetation at the city scale.

The biomass of the j-th plot in the i-th city (Bij) can be calculated by the following formula:

$$B_{ij} = aV_{ij} + b \tag{3}$$

where the units of B_{ij} and V_{ij} are Mg ha^{-1} and m^3 ha^{-1}, respectively, and a and b are conversion factors of the dominant species (Table 1). The formula for determining the average biomass of the i-th city (B_i, Mg ha^{-1}) is:

$$B_i = \frac{1}{n} \sum_{j=1}^{n} B_{ij} \tag{4}$$

where n is the total number of plots in the i-th city. The formula for determining the total biomass of the i-th city (Ti) is:

$$T_i = 100{*}A_i{*}C_i{*}B_i \tag{5}$$

where A_i is the land area (unit: km^2) in the i-th city, C_i is the forest coverage percent in the i-th city, B_{i} is the average biomass of the i-th city (Mg ha^{-1}), and 100 is the unit conversion factor.

The total forest biomass in Guangdong Province (T) can be summed for all 21 county-level cities as:

$$T = 100 \sum_{i=1}^{21} A_i{*}C_i{*}B_i \tag{6}$$

Forest vegetation C (Veg C) storage is calculated by multiplying forest biomass (T) by the C concentration. The commonly used conversion factor of 0.5 is used in this paper. We used Matlab for all the calculation.

Soil survey and C storage data

The 2nd soil survey in Guangdong was completed in 1992. In this survey, soil genera were the basic classification unit. A total of 522 typical soil profiles were selected across the province. Soil organic matter content, soil depth, bulk density, and other data were collected in accordance with the soil layers of soil profiles (Office of Soil Survey 1993; Gan et al. 2003). The data of soil organic C (SOC) storage were added to a 1:10,000,000 soil map of Guangdong Province to form a 1992 SOC storage map for Guangdong (Wan et al. 2005; Tian et al. 2006; Wen et al. 2010).

SOC storage in the j-th plot of the i-th city ($\mathrm{SOCD_{ij}}$) was calculated as:

$$SOCD_{ij} = 0.58{*}100{*}W_{ij}{*}D_{ij}{*}R_{ij} \tag{7}$$

where the units for $\mathrm{SOCD_{ij}}$ are Mg ha^{-1}; $\mathrm{W_{ij}}$ is soil bulk density (g cm^{-3}), $\mathrm{D_{ij}}$ is soil depth (cm, soil depth ranged from 60 to 100 cm for different soil types), and $\mathrm{R_{ij}}$ is average soil organic matter content (%) of the j-th plot in the i-th city; 0.58 is the conversion coefficient from organic matter to organic C; and 100 is the unit conversion factor. The SOCDi of the i-th city was calculated as:

$$SOCD_i = 0.58{*}100{*}\frac{1}{n}\sum_{j=1}^{n} W_{ij}{*}D_{ij}{*}R_{ij} \tag{8}$$

The total ecosystem C storage of i-th city (Total $\mathrm{C_i}$, Mg ha^{-1}) is summed up by Veg $\mathrm{C_i}$ and SOCD. Therefore, we used the same calculation approach to obtain C storage data for different cities in Guangdong. All the calculations were conducted with Matlab.

We overlaid the spatial distribution map of tree biomass C storage in 1992 and the spatial distribution map of SOC storage in 1992 to form the spatial distribution map of the ecosystem C storage in Guangdong in 1992.

Statistical analysis

Factors that could potentially affect Veg C storage can be divided into qualitative variables (e.g., soil type, slope aspect, dominant species, and forest type) and quantitative variables (e.g., altitude, gradient, soil depth, forest age, DBH, height, and canopy coverage). We used analysis of variance (ANOVA) to determine whether the qualitative variables have significant effects on the dependent

Table 1 The conversion factors used in previous studies for estimating biomass of dominant tree species in Guangdong Province

Dominant species	*a*	*b*	*N**	R^{2**}	References
Cunninghamia lanceolata	0.3999	22.541	39	0.67	Fang et al. 1996, 2001 Zhao and Zhou 2004
Pinus elliottii	0.5168	33.2378	16	0.91	Fang et al. 1996, 2001 Zhao and Zhou 2004
Pinus massoniana	0.52	0	29	0.71	Zhou et al. 2008
Coniferous mixed plantation	0.5168	33.2378	15	0.75	Zhou et al. 2008
Acacia plantation	0.6255	91.0013	21	0.77	Fang et al. 2001 Zhao and Zhou,2004
Camellia oleifera	0.7564	8.3103	3	0.66	Fang et al. 2001 Zhao and Zhou 2004
Eucalyptus	0.7893	6.9306	21	0.75	Zhou et al. 2008
Coniferous and broad-leaved mixed plantation	0.8019	12.2799	11	0.95	Zhou et al. 2008
Casuarinn equiestifolia	0.9505	8.5648	14	0.96	Zhou et al. 2008
Native broad-leaved species forest	1.0357	8.0591	10	0.87	Fang et al. 2001 Zhao and Zhou,2004
Other broad-leaved species	0.8873	4.5539	21	0.92	Zhou et al. 2008
Bamboo	0.237	0	14	0.88	Ye and She 2010 Zhou et al. 2008

*n is the number of trees used in developing the regression model

**R^2 is the coefficient of determination. All the regression models are significant ($P<0.05$)

variables Veg C storage, SOC storage, and Total C storage. We used Pearson correlation analysis to determine whether the quantitative variables were correlated with Veg C storage, SOC storage, and Total C storage.

To identify the primary factors that may influence Veg C, SOC, and Total C, we used stepwise multiple regression analysis (Cohen et al. 2003; Graham 2003). Ahead of this, each qualitative variable was assigned the relative values according to the importance of its categories on the dependent variables, referring to the 1–9 scale of relative importance in Analytic Hierarchy Process (Saaty 1990, 2008). To this end, all the categories of a qualitative variable are sorted by the corresponding dependent variable. The smallest type was assigned by 1, the next one was assigned by 2, and so on. For example, we sorted dominant species (12 categories) according to Veg C. The dominant species with the smallest Veg C storage was assigned by 1 (Pinus massoniana plantation), and the dominant species with the largest Veg C storage was assigned by 12 (broad-leaved tree). Similarly, we assigned values to these dominant species according to SOC or Total C storage, when they are dependent variables of regression equations.

The uncertainty of estimations was conducted by analysis of the different error sources. The main sources of errors include errors with the model itself, input data and model parameters (Raupach et al. 2005; Ren et al. 2011a). Input data and model parameters were considered the most important error sources (Böttcher et al. 2008; Larocque et al. 2008; Ren et al. 2011b). In this study, uncertainty analysis of forest C storage estimate in Guangdong was conducted by considering the error sources associated with input data such as inventory of forest area and volume and regression coefficients used for estimation of dominant tree biomass. The Monte-Carlo method (Li and Wu 2006) was used to calculate the uncertainty of total forest C storage in Guangdong. We determined that the distribution of errors in input data and regression coefficients was normal distribution (that is, standard errors of the mean have a normal distribution). Average biomass and standard deviations were calculated by inputting random biomass data of simulated dominant species 1,000 times into the forest volume-biomass conversion model (Ren et al. 2011b). The standard deviations from the regression coefficients were used to derive uncertainties in a and b coefficients. The errors associated with inventory of forest area included different conversional units of forest area used, various decimal number in data record, and potential data recording error. Similarly, the standard deviation of inventory of forest area was used to derive uncertainties in forest area. Uncertainty of each estimate was expressed as ±2 SD of 200–400 calculations, depending on the number required for the variance to stabilize.

All statistical tests including ANOVA, Pearson correlation analysis and multiple regression analysis were performed using SPSS 13.0 for Windows (SPSS Software Inc., USA). Statistical tests were significant if $0.05>P>0.01$ and highly significant if $P\leq0.01$.

Results

The forest coverage percent during 1985–2002

The forest coverage percent (defined as the percentage of total land area in a region that is covered by forests) in Guangdong province increased from 27.2 % in 1985 to 37.1 % in 1992. Moreover, the forest coverage reached 57.2 % in 2002 (Fig. 1 and Table 2).

The spatial distribution of tree biomass C storage in forest ecosystems from 1992 to 2002

According to the plot distribution map, plantations account for most forests in Guangdong and the dominant tree species are conifers (e.g., *Pinus massoniana, Pinus elliottii, Cunninghamia lanceolata)*, broadleaved species (e.g., *Eucalyptus, Acacia* and some native species), bamboo, and fruit trees (Fig. 2). In 1992, tree biomass C storage was less than 10 Mg ha^{-1} in many plots and was greater than 40 Mg ha^{-1} in only a few plots (Table 3).

The tree biomass C storage gradually increased from 1992 to 2002 in Guangdong Province (Fig. 3). The spatial distribution and the increase of tree biomass C storage, however, were not homogenous across the province. The average C storage was larger in the Northern Guangdong (GN) than in other three regions from 1992 to 2002. For example, the average C storage in 1992 was 30.9 Mg ha^{-1} in GN, 19.7 Mg ha^{-1} in the Pearl River Delta region (PRE), 15.3 Mg ha^{-1} in the Eastern Guangdong region (GE), and 14.7 Mg ha^{-1} in the Western Guangdong region (GW) (Table 3 and Fig. 3). A similar regional rank was observed in 1997 and 2002. During 1992–2002, the smallest increase in average C storage (16.8 %) occurred in GN. The largest increase in average C storage (51.8 %) appeared in GW while the increase was 29.4 % in PRE and 37.9 % in GE (Table 3 and Fig. 3).

The total forest C storage (tree biomass only) in Guangdong was 144.73±6.20, 204.28±7.23, and 215.03±8.48 Tg C in 1992, 1997, and 2002, respectively (Tables 4 and 5). Over the decade, the total forest C storage in Guangdong increased by 48.6 %. In particular, forest C storage increased rapidly in plantations of *Pinus elliottii*, *Cunninghamia lanceolata*, and *Eucalyptus* (Table 4). From 1992 to 2002, the total forest C storage in these three plantations increased by 95, 55, and 100 %, respectively.

Uncertainty analysis of total forest C storage

The results of uncertainty analysis of total forest C storage indicated that forest C storage errors were mainly caused by the model parameters (regression coefficients a, b), accounting for 97.26 % (±6.03 Tg C), 96.96 % (±7.01 Tg C), and 95.75 % (±8.12 Tg C) of the total error in 1992, 1997, and 2002, respectively (Table 5). The forest area and volume only contributed a small error to forest C storage estimate, accounting for 2.74 % (±0.17 Tg C), 3.04 % (±0.22 Tg C), 4.25 % (±0.36 Tg C) in 1992, 1997, and 2002, respectively (Table 5).

The spatial distribution of SOC storage and ecosystem C storage in Guangdong in 1992

The total SOC storage in Guangdong was about 1.75 Pg. The SOC storage ranged from 50 to 150 Mg ha^{-1} with an average of 104.4 Mg ha^{-1}. The SOC storage was higher in the south than in the north (Fig. 4). The spatial distribution of ecosystem C storage (combination of tree biomass C storage and SOC storage) in 1992 was not homogenous across the province (Fig. 5). The ecosystem C storage was highest in GN, intermediate in GE and GW, and lowest in PRE.

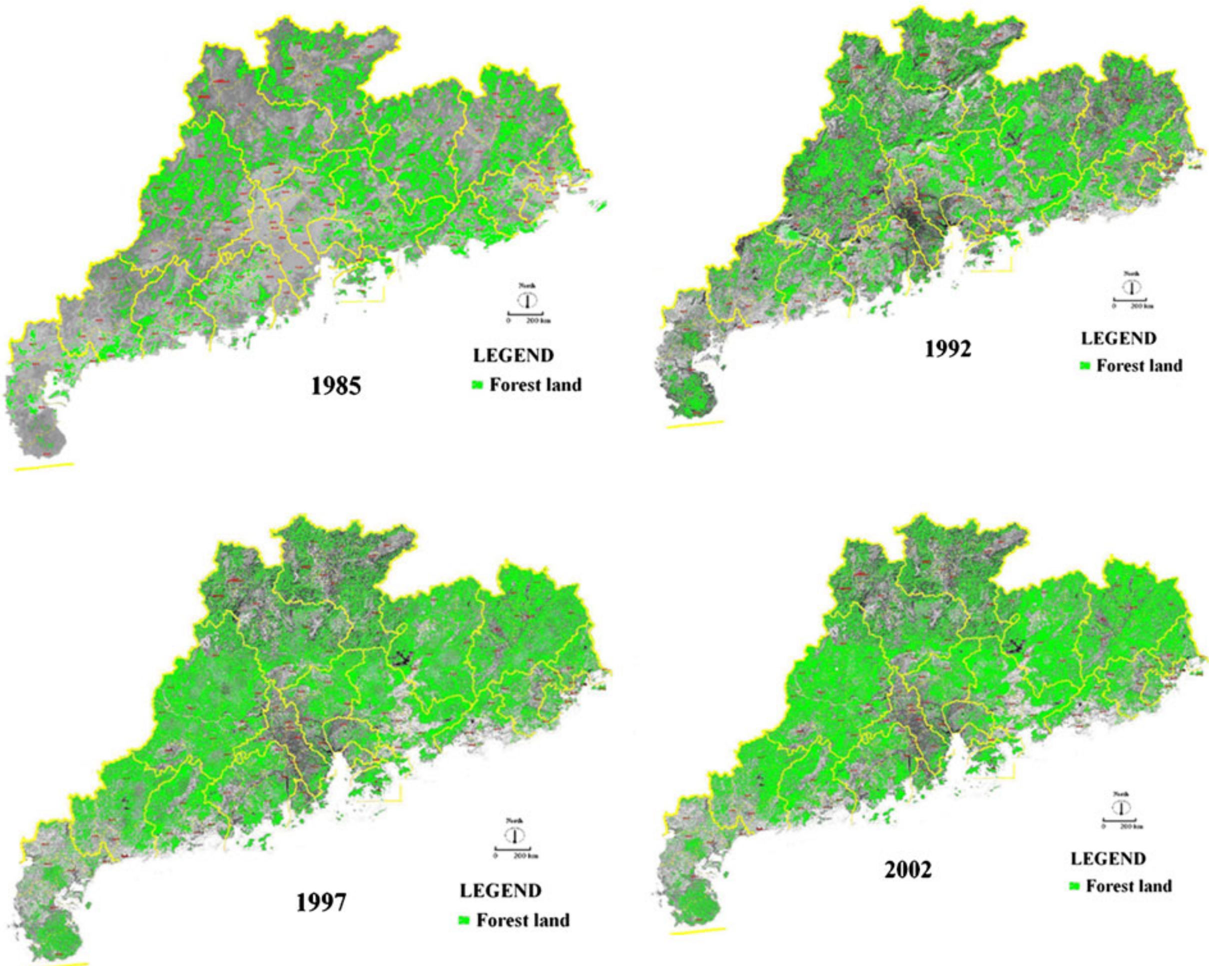


Fig. 1 Multi-temporal TM imagery of Guangdong Province

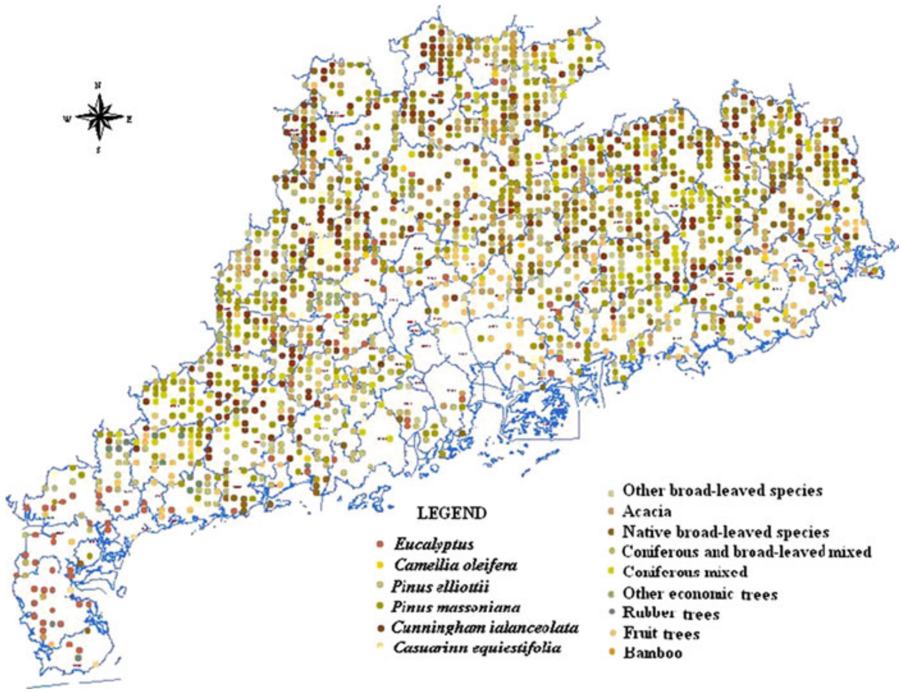
Factors associated with C storage of forest ecosystems

ANOVA indicated that dominant species and forest type had significant effects on Veg C storage in Guangdong overall (across all four regions) (Table 6). The only exception to this is that forest type in PRE showed no significant difference on Veg C storage. Veg C storage was significantly affected by soil type in most regions except for GE and GW but not slope aspect (Table 6). Overall, SOC storage and Total C storage was significantly influenced by soil type, slope aspect, dominant species,

Table 2 Forest coverage percent in Guangdong during 1985 to 2002

Year	Forest land (10^3 ha)							Forest coverage percentage
	Total	Woodland	Open woodland	Shrubland	Immature forest plantation	Nursery land	Bare land	
1985	10204.0	4638.0	1030.0	259.0	177.0	–	4100.3	27.7
1992	10347.0	6543.1	508.5	906.3	1405.6	–	983.5	37.1
1997	10414.5	8107.5	178.1	841.9	237.5	9.6	930.7	46.4
2002	10808.1	9211.9	52.0	706.0	526.0	5.4	521.1	57.2

Fig. 2 The plot distribution map



and forest type in Guangdong, but this did not always hold true in every region. For example, SOC storage in GN was not significantly influenced by soil type, slope aspect, dominant species, and forest type at all (Table 6).

Pearson correlation analysis (Table 6) indicated that Veg C storage in Guangdong and its four regions was positively and significantly correlated with all quantitative variables including altitude, gradient, forest age, DBH, height, canopy coverage except soil depth. The

Table 3 The number of plots within five ranges of forest C storage (Mg/ha) among four regions in Guangdong Province

Region	Year	Ranges of C density (Mg/ha) and number of plots within each range					Total number of plots	Average C density (±SD)
		0–10	10–20	20–30	30–40	>40		
Guangdong East (GE)	1992	105	100	40	8	17	270	15.31±0.89
	1997	64	97	48	13	21	243	19.10±1.03
	2002	119	137	85	26	61	428	21.11±0.89
Pearl River Delta (PRE)	1992	87	67	36	13	34	237	19.71±1.20
	1997	46	65	61	12	47	231	25.52±1.29
	2002	70	84	80	33	65	332	26.64±1.15
Guangdong West (GW)	1992	69	72	25	9	9	184	14.68±0.85
	1997	46	57	75	8	12	198	19.39±0.82
	2002	49	60	65	23	23	220	22.17±0.99
Guangdong North (GN)	1992	58	80	46	31	84	299	30.88±1.51
	1997	41	87	56	30	98	313	32.64±1.60
	2002	40	66	82	36	126	350	36.09±1.44

Eastern Guangdong (GE) includes Shantou, Chaozhou, Jieyang, Shanwei, Heyuan, and Meizhou city; Western Guangdong (GW) includes Zhanjiang, Maoming, Yangjiang, and Yunfu city; Pearl River Delta (PRE) includes Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Zhongshan, Dongguan, Huizhou, and Zhaoqing city; Northern Guangdong (GN) includes Shaoguan and Qingyuan city

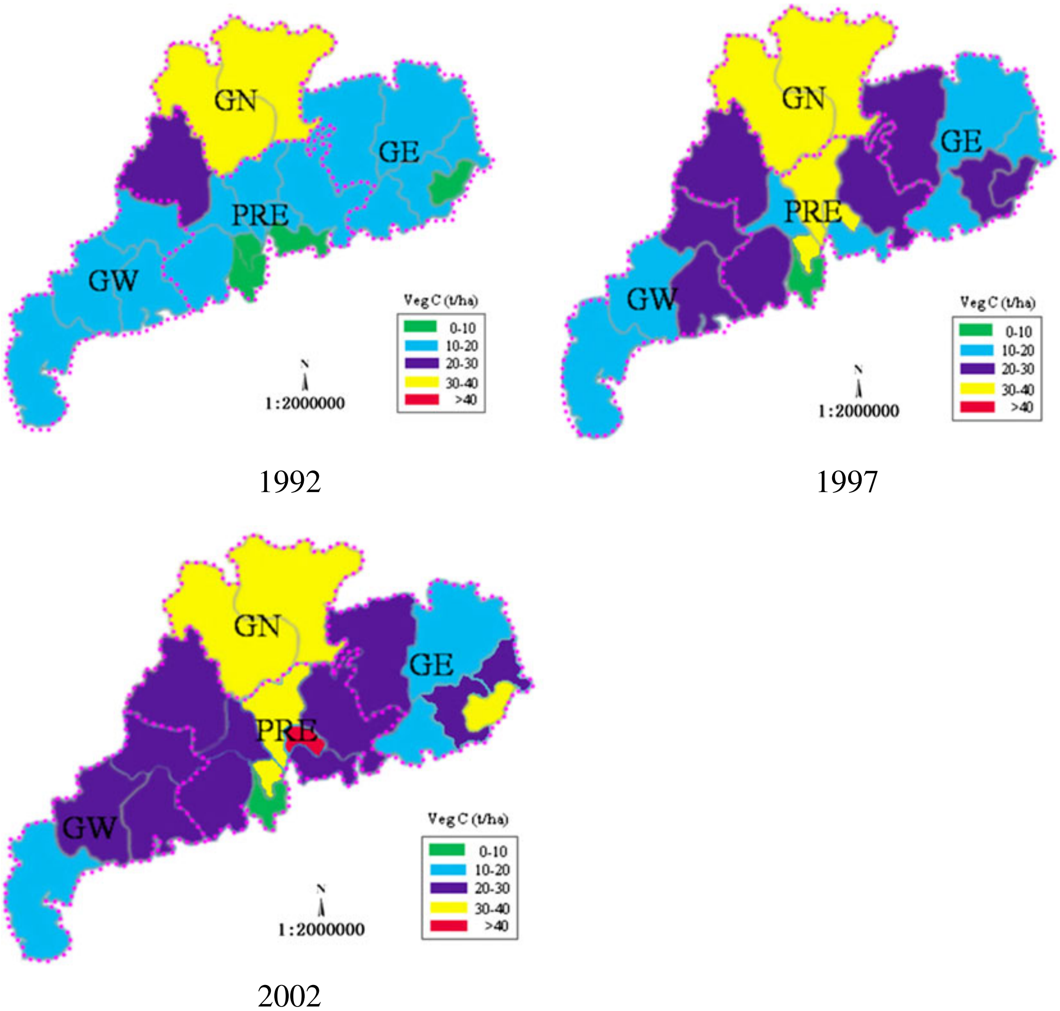


Fig. 3 The spatial distribution of forest C storage in four regions in Guangdong Province in 1992, 1997, and 2002. *GN* Northern Guangdong, *GE* Eastern Guangdong, *GW* Western Guangdong, *PRE* Pearl River Delta

correlation coefficient (r) between Veg C storage and each variable varied from 0.12 to 0.53. SOC storage in Guangdong was positively and significantly correlated with most quantitative variables except for DBH, although this was not always true in GW and GN. The correlation coefficient (r) between SOC storage in Guangdong and each quantitative variable ranged from 0.11 to 0.39. Total C storage in Guangdong was positively and significantly correlated with all the seven quantitative variables, although this was not always true in the four regions. The correlation coefficient (r) between Total C storage in Guangdong and each quantitative variable ranged from 0.11 to 0.33.

Table 7 shows the results of the multiple regression models for Veg C, SOC, and Total C storage at the provincial and regional scale. All the models were significant but the coefficient of determination (R^2) values differed. For example, 63 % of variation in Veg C storage at the provincial scale was explained by altitude, slope aspect, dominant tree species, forest age, DBH, height, and canopy coverage. Only 27 % of variation in SOC storage at the provincial scale was explained by altitude, slope aspect, soil depth, forest type, height, and canopy coverage. The multiple regression model of Total C storage at the provincial scale indicated that 34 % of variation of Total C storage was explained by altitude, slope aspect, soil

Table 4 Total forest C storage (Tg C) in Guangdong in 1992, 1997, and 2002

Forest type	1992	1997	2002
Eucalyptus plantation	2.99	5.08	5.98
Pinus elliottii plantation	10.99	20.42	21.44
Acacia plantation	8.75	8.59	8.33
Bamboo	0.55	0.58	0.78
Casuarinn equiestifolia plantation	0.56	0.33	0.19
Other broad-leaved species plantation	36.78	63.24	65.08
Cunninghamia lanceolata plantation	29.38	42.46	45.52
Pinus massoniana plantation	2.67	2.61	2.94
Native broad-leaved species forest	15.8	19.71	21.83
Camellia oleifera plantation	0.02	0.09	0.19
Coniferous and broad-leaved mixed plantation	19.17	20.63	21.32
Coniferous mixed plantation	17.07	20.54	21.43
Total	144.73	204.28	215.03

depth, forest type, dominant tree species, height, and canopy coverage.

Regional-scale models had similarities and differences (Table 7). For example, variation in Total C storage was associated with altitude, soil depth, and canopy coverage at PRE but altitude, soil depth, forest type, dominant species, and forest age at GN (Table 7). The models accounted for 58 to 67 % of the variation in Veg C storage, 18 to 39 % of the variation in SOC storage, and 22 to 43 % of the variation in Total C storage.

Discussion

The total forest C storage (tree biomass only) in Guangdong increased from 144.73±6.20 Tg in 1992 to 215.03±8.48 Tg in 2002. During 1992–2002, the total forest C storage in this province increased by 70.30 Tg. At the same time, the forest C storage increased from 15.24 Mg ha^{-1} in 1992 to 20.09 Mg ha^{-1} in 2002. The increase of total forest C storage in Guangdong during 1992–2002 is partially the result of net increase of forest coverage rate by 20 % over the decade (Table 2). The increase of forest C storage in Guangdong over the period is similar to the average increase observed in forest ecosystems in China (Fang et al. 2001). However, the average forest C storage of 20.09 Mg ha^{-1} in Guangdong was lower than the average forest C storage of 44.91 Mg ha^{-1} in China in 1998. This is partially attributed to the fact that forest C storage in Guangdong was underestimated. In this study, only C storage of tree biomass and SOC was considered while C storage in the understory and litter layer was not included. Even comparing with other neighbor provinces with similar climatic and hydrothermal conditions, the estimate of average forest C storage in this study is low. This is due in part to the dominance of young forests in Guangdong at the time of the survey. As the young trees develop, the

Table 5 The results of uncertainty analysis on two major source errors of forest C storage estimates in Guangdong Province

Year	Total forest C storage (Tg C)	SA (Two major source errors) (Tg C)		
		SA1	SA2	Total forest C storage
1992	144.73	0.17	6.03	6.20
1997	204.28	0.22	7.01	7.23
2002	215.03	0.36	8.12	8.48

Uncertainty analysis are from two major source errors, input data SA1 (area and volume) and parameter calibration SA2 (a and b are constants for a forest type, see Table 1)

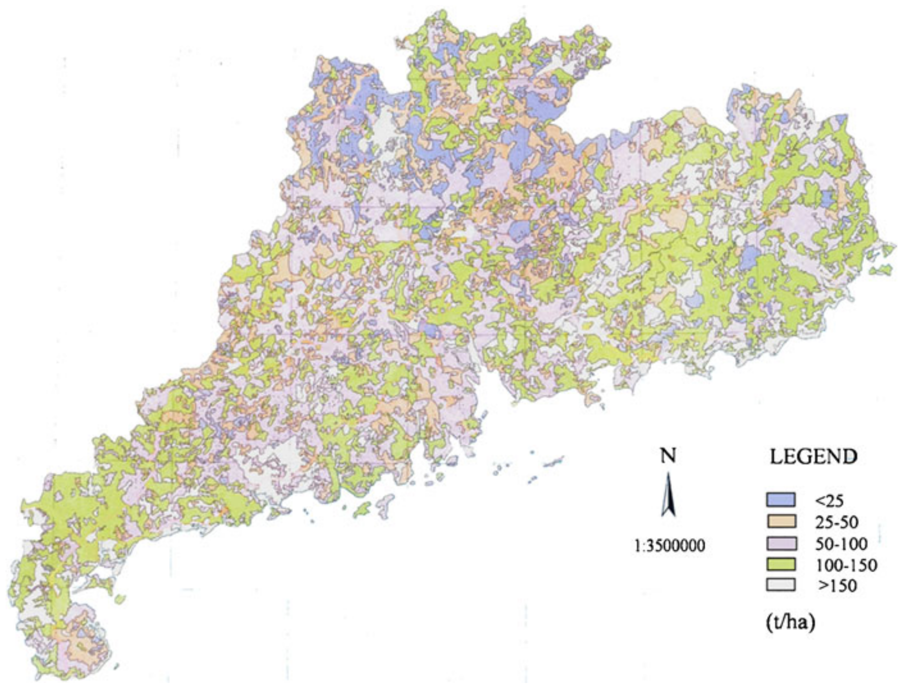


Fig. 4 The map of soil organic C storage in Guangdong in 1992

C sequestration capacity of the forests in Guangdong will increase. The current forests in Guangdong are mainly composed of plantations of coniferous and broad-leaved pioneer species whose C storage accounts for about 80 % of the total C storage in forests in Guangdong. In general, the C storage is higher in native broad-leaved forest ecosystems than in the coniferous plantations. Given that plantations in Guangdong are being gradually converted to include more native broad-leaved species (Ren et al. 2007), the capacity for C storage in Guangdong forests should further increase.

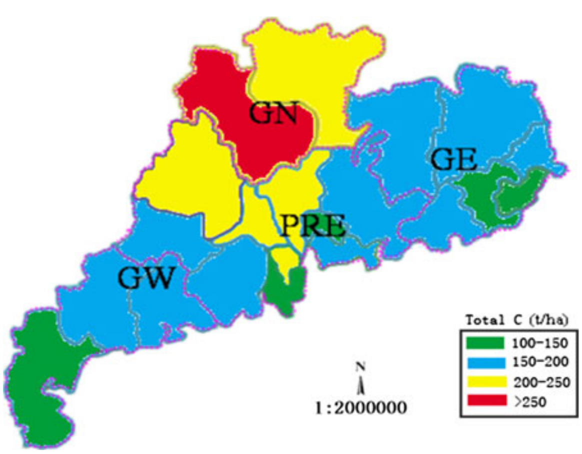


Fig. 5 The spatial distribution map of forest ecosystem C storage in Guangdong in 1992. *GN* Northern Guangdong, *GE* Eastern Guangdong, *GW* Western Guangdong, *PRE* Pearl River Delta

Our estimates of province-wide total forest C storage were different from those in previous studies but are more reliable. Fang et al. (1996, 2001) reported that the total forest C storage in Guangdong was 114.54 Tg, while Wang et al. (2001) reported only 34.81 Tg during 1984–1988, although they used the same data set (the 3rd forest inventory survey). Zhou et al. (2008) found that forest C storage in Guangdong was 169.61 Tg in 1994 and 211.28 Tg in 2003 while Ye and She (2010) reported that the forest C storage in this province was 285.40 Tg in 2008. Many factors may contribute to these differences. The use of different vegetation classification systems and different data sources were the major reasons. We used the satellite-based remote sensing data and 1:50,000 forest maps as the basis to estimate the total area of different vegetation types, and Fang et al. (1996, 2001) and other authors (Wang et al. 2001; Ye and She 2010) used 1:1,000,000 land or vegetation maps to estimate the area of forests. The utilization of a higher resolution forest map in this study leads to a better estimation of forest areas of different forest types. Moreover, the vegetation classification system used in this study

Table 6 Factors associated with C storage at the provincial and regional scale as indicated by P values from ANOVA and values of P and r (correlation coefficient) from Pearson correlation analysis in Guangdong

Factors	Method	Guangdong			Pearl River Delta (PRE)			Guangdong East (GE)			Guangdong West (GW)			Guangdong North (GN)		
Qualitative variables		Veg C	SOC	Total C	Veg C	SOC	Total C	Veg C	SOC	Total C	Veg C	SOC	Total C	Veg C	SOC	Total C
Soil type	ANOVA	**	**	**	*	*	**	NS	**	**	NS	**	**	*	NS	NS
Slope aspect		NS	**	**	NS	NS	NS	NS	NS	NS	NS	*	**	NS	NS	NS
Dominant species		**	**	**	**	*	**	**	NS	**	**	*	**	**	NS	**
Forest type		**	**	**	NS	NS	NS	**	**	**	**	*	**	**	NS	*
Quantitative variables																
Altitude	Pearson correlation analysis (r value)	0.36**	0.27**	0.33**	0.41**	0.22**	0.30**	0.30**	0.22**	0.28**	0.18**	0.35**	0.36**	0.29**	0.20**	0.26**
Gradient		0.23**	0.12**	0.16**	0.22**	0.13*	0.17**	0.12**	0.01	0.04	0.24**	0.25**	0.28**	0.31**	0.08	0.15**
Soil depth		−0.03	0.39**	0.36**	0.11	0.55**	0.54**	−0.10	0.33**	0.30**	0.03	0.41**	0.40**	−0.03	0.43**	0.40**
Forest age		0.34**	0.12**	0.19**	0.26**	0.10	0.15**	0.25**	−0.03	0.02	0.28**	0.19**	0.23**	0.51**	0.18**	0.29**
DBH		0.26**	0.05	0.11**	0.19**	0.04	0.08	0.16**	−0.02	0.01	0.20**	0.25**	0.27**	0.34**	−0.05	0.04
Height		0.45**	0.11**	0.20**	0.44**	0.17**	0.26**	0.52**	0.02	0.13**	0.30**	0.14*	0.19**	0.43**	0.03	0.13*
Canopy coverage		0.49**	0.21**	0.30**	0.49**	0.24**	0.33**	0.53**	0.13**	0.24**	0.44**	0.18**	0.25**	0.44**	0.17**	0.26**

NS statistical test was judged not significant if $P>0.05$

*statistical test was judged significant if $0.05>P>0.01$

**statistical test was judged highly significant if $P\leq0.01$

Table 7 Multiple regression models of Veg C, SOC, and Total C at the provincial and regional scale in Guangdong*

Dependent variable	Region	Regression equation	R^2
Veg C	Guangdong	$y_1 = -35.931 + 0.006x_1 + 0.339x_2 + 3.135x_7 + 0.415x_8 + 0.584x_9 + 1.780x_{10} + 0.215x_{11}$	0.63
	Pearl River Delta (PRE)	$y_1 = -37.469 + 3.270x_7 + 0.289x_8 + 0.973x_9 + 1.571x_{10} + 0.263x_{11}$	0.64
	Guangdong east (GE)	$y_1 = -23.368 + 2.506x_7 + 0.313x_8 + 1.998x_{10} + 0.190x_{11}$	0.58
	Guangdong west (GW)	$y_1 = -38.425 + 4.022x_6 + 2.740x_7 + 0.952x_9 + 1.191x_{10} + 0.253x_{11}$	0.62
	Guangdong north (GN)	$y_1 = -41.017 + 0.977x_2 + 4.071x_7 + 1.030x_8 + 1.985x_{10} + 0.142x_{11}$	0.67
SOC	Guangdong	$y_2 = -105.915 + 0.109x_1 + 3.173x_2 + 1.792x_5 + 7.610x_6 + 2.147x_{10} + 0.303x_{11}$	0.27
	Pearl River Delta (PRE)	$y_2 = -82.206 + 0.064x_1 + 2.277x_5 + 4.457x_{10}$	0.34
	Guangdong east (GE)	$y_2 = -17.886 + 0.117x_1 + 1.418x_5$	0.18
	Guangdong west (GW)	$y_2 = -136.523 + 0.128x_1 + 4.395x_2 + 1.615x_5 + 3.698x_9 + 0.740x_{11}$	0.39
	Guangdong north (GN)	$y_2 = -119.062 + 0.076x_1 + 4.409x_2 + 2.318x_5 + 15.282x_6 + 2.162x_8 - 3.255x_9$	0.30
Total C	Guangdong	$y_3 = -143.222 + 0.114x_1 + 2.791x_2 + 1.782x_5 + 12.067x_6 + 3.626x_7 + 5.078x_{10} + 0.492x_{11}$	0.34
	Pearl River Delta (PRE)	$y_3 = -113.803 + 0.067x_1 + 2.289x_5 + 4.446x_7 + 7.747x_{10}$	0.40
	Guangdong east (GE)	$y_3 = -33.513 + 0.123x_1 + 1.369x_5 + 0.746x_{11}$	0.22
	Guangdong west (GW)	$y_3 = -145.794 + 0.134x_1 + 4.392x_2 + 1.629x_5 + 4.553x_9 + 1.098x_{11}$	0.43
	Guangdong north (GN)	$y_3 = -148.320 + 0.085x_1 + 2.430x_5 + 20.122x_6 + 4.769x_7 + 2.302x_8$	0.34

*Dependent variables: y_1: Veg C y_2: SOC y_3: Total C.

Independent variables: x_1 : Altitude x_2: Slope aspect x_3: Gradient x_4: Soil type x_5 : Soil depth

x_6 : Forest type x_7 : Dominant species x_8 : Forest age x_9 : DBH x_{10} : Height x_{11} : Canopy coverage

All models are significant ($P<0.05$)

was different from the one in previous studies. We used 12 forest types but Fang et al. (2001) and others (Wang et al. 2001; Zhou et al. 2008; Ye and She 2010) only involved 8 forest types. Moreover, we conducted uncertainty analysis of forest C storage in Guangdong (Table 5). In the previous studies (Fang et al. 2001; Wang et al. 2001; Zhou et al. 2008; Ye and She 2010), only a forest C storage value in Guangdong for a specific year was estimated, no uncertainty analysis about the estimation was conducted. In this study, we conducted uncertainty analysis of forest C storage contributed by forest area and volume estimate and model parameters (regression coefficients a, b) associated with different forest types (Table 5). Therefore, our estimates of forest C storages in Guangdong are more reliable than the ones estimated in previous studies (Fang et al. 2001; Zhou et al. 2008). Furthermore, we also considered the spatial heterogeneity of forest C storage in this province (Fig. 3, 4 and 5).

The spatial distribution of forest C storage in Guangdong was uneven (Table 3, Figs. 3 and 5) and the heterogeneity of spatial distribution is related with land use policy, forest resources utilization model, regional economic development, and many biotic factors (Tables 6 and 7) (see Discussion in last paragraph). The order of average forest biomass C storage in 1992 among the four regions is Northern Guangdong (GN)>the Pearl River Delta (PRE)>Eastern Guangdong (GE) and Western Guangdong (GW). A similar order was observed in 1997 and 2002. The pattern of forest C storage in Guangdong reflects the integrated results of land use policy implementation and forest resource utilization model application, which have been influenced by two major factors. First, the Guangdong provincial government attaches great importance to forestry. The provincial government proposed an initiative of "Planting Trees Within 5 Years and Green Guangdong Within 10 Years" in 1985. The green targets were achieved in 1993. In 1994, the government encouraged the practice of sustainable and efficient modern forestry, with a shift in emphasis from obtaining timber only from plantations to obtaining ecosystem services from more complex forests. In 2005, a government initiative also focused on ecological conservation and sustainable development of forestry (Lin et al. 2008; Li et al. 2011). Second, forest distribution is related to the economic structure of Guangdong. For historical reasons, most mountainous area in northern Guangdong has not experienced economic development and has retained primary forests that contain more native species and greater diversity than plantations. The forests in this region are well protected to provide important ecological services in this province (Deng and Lin 2009). That is why the forest C storage was highest in northern Guangdong during 1992 to 2002 (Table 3, Figs. 3 and 5). Because of rapid population and economic development in the Pearl River Delta since early 1980s, however, the primary forests were quickly cut down and then replaced with plantations. These plantations serve to protect and adjust the urban environment (Deng and Lin 2009). The distribution of old plantations leads to a higher forest C storage in this region, right after northern Guangdong. Similarly, western Guangdong has many eucalyptus forests because of massive reclamation and establishment of commercial plantations. In the eastern Guangdong, coastal shelter belt was developed to serve the water conservation forest in this province (Deng and Lin 2009). Forest C storage in the western and eastern regions was low, likely because of the large area occupied by young plantations. At the provincial scale, forest C storage in Guangdong has increased mainly because of the positive impact of forest policy. At the regional scale within the province, the spatial distribution of forest C storage reflects differences in economic and social development and differences in forest management.

Many biotic factors were associated with C storage of forest ecosystems in this study. The selection of dominant tree species and forest types played important role in influencing Veg C storage in Guangdong. Our previous studies indicated that some native tree species could contribute more than 5–10 %C storage in forest ecosystems than that of current species given the same area and age (Yu and Peng 1997; Ren et al. 2002). These species include *Castanopsis carlesii, C eyrei, C. hystrix, Cinnamomum porrectum, Manglietia fordiana* in GN region, *C. fissa, Machilus chinensis, Altingia chinensis* in GE region, *Michelia macolurei, Schima wallichii, Mytilaria laosensis* in GW region, and *C. burmanii, C. chinensis, Cryptocarya chinensis* in PRE region. This result is consistent with previous studies (Kirby and Potvin 2007; Woodall et al. 2011). For example, Kirby and Potvin (2007) studied C storage contributed by different tree species in eastern Panama and found that the selection of tree species for plantations is important in increasing C sequestration. In Guangdong, more and more plantations using native broad-leaved tree species in addition to Eucalyptus and pine plantations were established due to their high contribution to forest C storage during 1992 to 2002 (Table 4). All quantitative factors of tree species such as DBH, height, canopy coverage, and forest age were positively correlated with Veg C storage (Table 6) but soil depth showed no correlation. This may be due to the fact the soil depth of most forest plots in this province is not deep with little variation. Moreover, these quantitative factors of tree species and altitude and slope aspect can explain 58–67 % variation of Veg C storage in Guangdong based on the multiple regression model (Table 7). However, the model for SOC storage can only explain about 18–39 % variation of SOC storage in Guangdong. Factors associated with Total C storage of forest ecosystems are very similar to factors associated with SOC storage. Total ecosystem C is mainly determined by SOC storage. Thus, it is very important to do more soil survey in addition to forest survey in order to understand C dynamics in forest ecosystems. The SOC storage of broad-leaved forest is higher than that of coniferous forest. Since the C storage is higher in the forests composed by the native species, more native tree species should be selected for plantations to increase C sequestration. Future forest management should focus on the selection of tree species, management of forest stand structures and implementation of sustainable practices so that C sequestration potentials of forests can be maximized.

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