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Changes in forest biomass carbon stock in the Pearl River Delta between 1989 and 2003

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Abstract

Forest ecosystems play a significant role in maintaining climate stability at the regional and global scales as an important carbon sink. Regional forest carbon storage and its dynamic changes in the Pearl River Delta have been estimated using the continuous biomass expansion factor (BEF) method based on field measurements of forests plots in different age classes and forest inventory data of three periods (1989–1993, 1994–1998, 1999–2003). The results show that regional carbon storage increased by 16.76%, from 48.57×10^6 to 56.71×10^6 tons, 80% of which was stored in forest stands. Carbon storage of other types of vegetation, with the exception of shrubland and woodland, increased. Carbon density of the regional forest increased by 14.31%, from 19.08 to 21.81 ton/hm^2. Potential carbon storage of the regional forest may reach 39.96×10^7 tons when the forest biomass peaks with succession.

Key words: forest; biomass; carbon storage; changes; the Pearl River Delta

Introduction

Global warming caused by the greenhouse effect of CO_2 has become a key global environmental issue (Detwiler and Hall, 1988; Dixon *et al*., 1994). Forest vegetation is considered as an important carbon sink, in which 76%–78% of the organic carbon of terrestrial ecosystems is stored. The amount of fixed carbon in forest vegetation accounts for 2/3 of the total carbon fixed annually in terrestrial ecosystems. Thus, forest vegetation has a significant contribution in reducing the impact of the global CO_2 emissions and maintaining regional or even global climate stability (Woodwell *et al.*, 1978; Haripriya *et al*., 2002; Hashimotio *et al*., 2000). Therefore, the study of carbon storage of forest ecosystems can play an improtant role in searching for sources and sinks of CO_2 in terrestrial ecosystems.

At present, dynamic changes in regional forest carbon storage in China have generally been studied based on the biomass of forest vegetation. In previous studies, using the continuous biomass expansion factor (BEF) method, Fang *et al*. (1996, 1998, 2001), Fang (2000), and Liu *et al*. (2000) have established a linear regression model between forest biomass and volume, and successfully estimated the biomass, carbon storage and their changes for Chinese national forests utilizing forest inventory data (FID). Subsequently, based on the regression equations provided by Fang *et al*. (1996), some scholars have estimated forest biomass and carbon storage as well as their dynamic changes in some regions of China (Cao *et al*., 2002; Jiao and Hu, 2005; Li *et al*., 2004; Guan and Chen, 2003). However, due to the large forested area and the various forest types in China, it was rather difficult to collect sufficient field measurements to establish those estimation equations, which consequently resulted in a relatively small number of sample plots for regression equations and hence restricted their applicability. Moreover, the sample plots in the existing literature utilized to develop these equations were mostly in mature forests, consequently, the consideration of undergrowth biomass was limited. As a result, those estimation equations that have been developed are unsuited to estimating forest biomass and carbon storage at the regional scale in the Pearl River Delta (PRD).

In this study, the regression equations for estimating regional forest biomass were developed using data from direct field measurements of total forest biomass and its stand volume in sample plots, as well as the BEF method. Regional forest biomass and its dynamic changes in the PRD have been estimated using the regression equations and forest inventory data of three periods (1989–1993, 1994–1998, 1999–2003). The carbon storage and carbon density of regional forest are evaluated based on regional forest biomass. This study can provide a demonstration of the approach to estimate forest carbon storage of other typical regions.

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1 Area description

The PRD (21°31′–23°10′N, 112°45′–113°50′E) is situated in the middle and southern areas of Guangdong Province in South China and it is the largest alluvial plain in lower subtropical China. Most of the PRD region lies to the south of the Tropic of Cancer and being in the subtropical oceanic monsoon climatic region, which is warm, damp and rainy. The forest cover rate in this region attains 50%. The zonal vegetation is subtropical evergreen broadleaf forest. Almost all the regional primary forest vegetation has been destroyed due to the changes in land use and human activities. The present regional vegetation is mainly *Pinus massoniana* forest, subtropical secondary evergreen broadleaf forest, and coniferous and broadleaf mixed forest. The regional forests in the PRD mainly fall into the categories of young and middle-aged forests which account for about 80% of the total regional forested area.

2 Study methods

2.1 Field measurement of forest community biomass

2.1.1 Biomass of the arbor layer

Total 69 sample plots of typical forest communities in different age classes were selected in study area. In each plot, a large quadrat (1,000 m^2) was arranged for measuring the biomass of the arbor layer. The height (H) and breast diameter (D) of all the arbor trees in the quadrats were measured to estimate aboveground biomass in the arbor layer using the regression equations of Guan (1989a). The ratio of biomass for aboveground to belowground was used to estimate belowground biomass from the above ground biomass (Fang *et al*., 1996; Guan, 1989a).

2.1.2 Biomass of the shrub and herbage layers

In each large quadrat (1,000 m^2), 10 small quadrats (2 m × 1 m) were arranged according to undergrowth characteristics in the study area. Then destructive sampling was performed in each small quadrat. After all the vegetation in the shrub and herbage layers had been harvested, they were separated into their component parts and weighed to determine their fresh weights. The appropriate amount of leaves, stems, branches, and roots of shrubs and aboveground and belowground parts in the herbage layer were collected (collected sample groups) and brought to laboratory immediately to calculate their moisture content.

2.1.3 Laboratory methods

Each collected sample group harvested in quadrats was first weighed in the laboratory and then dry weight for all components was obtained by fixing at 105°C for 30 min and subsequently drying at 80°C to a constant weight. This permitted calculation of the moisture content of each biomass component.

2.2 Establishment of equations for estimating the regional forest biomass and the estimation methods

The biomass and stem volume of 69 sample plots of forests were measured for different age classes. Regression equations between stand biomass and stem volume of the main forest types were established in the PRD using the continuous BEF method and direct field measurements. The types of forests sampled included *P. massoniana* forest, evergreen broadleaf forest, and coniferous and broadleaf mixed forest, which accounted for 85% of the total stand volume in the PRD. Meanwhile, the regression equations from Fang *et al*. (1996) were used to estimate biomass of fir plantations and other forests. Finally, regional forest biomass was estimated based on the forest inventory data and the regression equations of stand biomass and stem volume.

2.3 Estimation of regional forest net primary production

The net primary production (NPP) of forest is related to biomass, condition and age of forest. The NPP and age of forest are usually reflected by forest biomass (Fang *et al*., 1996). The formulas relating NPP and biomass in many forests established by Fang *et al*. (1996) and Guan and Chen (2003), have been used in this study.

2.4 Estimation of biomass and NPP of shrub land, woodland and orchard

The biomass of shrubland and woodland varies from 9 to 39 ton/hm^2 in the subtropics of China (Fang *et al*., 1996; Guan, 1989b). The mean biomass of shrubland and woodland was 19.76 ton/hm^2 in this area, the NPP was calculated by Eq.(1):

$$1/Y = 1.27/X^{1.196} + 0.056 \quad (1)$$

where, Y is the NPP (ton/(hm^2·year)) and X is the biomass (ton/hm^2). The mean biomass and NPP of orchard were 23.7 ton/hm^2 and 9.2 ton/(hm^2·year), respectively.

2.5 Estimation of biomass and NPP of bamboo forests

The biomass of bamboo was calculated from the value of 22.5 kg/plant (Fang *et al*., 1996). According to previous studies of bamboo forests in the Liuxi River (Guan, 1989a), the biomass of the undergrowth herbage layer of bamboo forest was 5 ton/hm^2, which was added to mean biomass of bamboo forest. In this region, cutting age is generally 5 years and thus the NPP of bamboo forests was calculated by the biomass value divided by 5.

2.6 Vegetation carbon storage

In this study, biomass was converted into carbon content using a conversion coefficient of 0.5 (Lieth and Whittaker, 1975; Myneni *et al*., 2001; Tan *et al*., 2007).

3 Results

3.1 Biomass and NPP of different forest types within different periods in the PRD

According to regression equations between biomass and stem volume of the main forest types which have been developed, the dynamic changes in forest biomass and NPP of different forest types in the PRD were analyzed based on the FID of three periods (Table 1), in which the first period (1989–1993) forms a baseline or start point. In terms of the regional forest stands, *P. massoniana* forest accounted for most of the total forest stand area for the three periods with 40.93%, 39.00%, and 36.14%, respectively (Table 1). Evergreen broadleaf forest accounted for 25.07%, 26.45% and 30.28% of the total forest stand area for the three periods respectively was the second most common major forest type. Stem volume and biomass of three main forest types increased annually. Stem volume and biomass of the evergreen broadleaf forest attained the highest growth rate, 50.78% and 32.92%, respectively. The most forest stand biomass in the PRD was provided by *P. massoniana* forest, evergreen broadleaf forest, and coniferous and broadleaf forest. Biomass of these three forest types accounted for about 80% of total regional forest stand biomass. Over the period of observation, biomass of these three forest types increased by 10.30×10^6 tons, accounting for 70.40% of the regional forest stand biomass increment. The NPP of these three forest types increased by 3.85%, from 15.86×10^6 to 16.47×10^6 tons/year, which accounted for 80% of the NPP of regional forest stands.

Within the observation period, the total forested area of the PRD slightly increased by 2.16%, from 254.5×10^4 to 260.0×10^4 hm^2. The area of forest stands, orchard, and bamboo forests were increased by 0.81%, 24.95%, and 4.65%, respectively. The area of shrubland and woodland decreased by 10.45%. Regional forest biomass increased by 16.75%, from 97.13×10^6 to 113.4×10^6 tons (Table 1). The biomass of forest stands made up most of the regional forest biomass (more than 80%) and the proportion of stand biomass to total regional biomass increased from 81.74% to 84.32%. Shrubland and woodland made the least contribution to regional forest biomass (2.658×10^6–2.968×10^6 tons, Table 1), which accounted for just 2.34%–3.06% of the regional forest biomass. The NPP of regional forest increased by 5.19%, from 25.44×10^6 to 26.76×10^6 ton/year (Table 1). The NPP of forest stands made up most of the NPP of the regional forest (81.65%–83.22%). The regional forest biomass and NPP will increase with succession because regional forests are still at the young and middle-aged stages.

3.2 Biomass and carbon storage of forest stands in different age classes in the PRD

In terms of forest stands in different age classes (Table 2), the area of young and middle-aged forests accounted for 81.58% of total area of regional forest stands. Both biomass and carbon storage of regional forest stands were mainly stored in young and middle-aged forests (76.32%). Of which, the young evergreen broadleaf forest accounted for 54.72% of the area, and accounted for 68.00% of biomass and carbon storage of those of regional young forest. The area and the biomass and carbon storage of middle-aged *P. massoniana* forest accounted for 43.06%, 39.95% of those of regional middle-aged forests, respectively.

From the overall view of regional forests in different age classes, young and middle-aged forests were the main components of forest stands in the PRD. They played a significant role in carbon sequestration of regional forest vegetation in the region.

3.3 Carbon storage and carbon density within different periods

Within the period 1989–2003, regional carbon storage increased by 16.76%, from 48.57×10^6 to 56.71×10^6 tons in the PRD (Table 3). Carbon storage of other types of

Table 1 Biomass and NPP of different forest types within different periods in the PRD

Period	Forest type	Area ($\times10^4$ hm^2)	Volume ($\times10^6$ m^3)	Unit area biomass (ton/hm^2)	Regional biomass ($\times10^6$ ton)	Unit area NPP (ton/(hm^2·year))	Regional NPP ($\times10^6$ ton/year)
1989–1993	*Pinus massoniana*	85.39	29.52	39.25	33.47	9.900	8.454
	Evergreen broadleaf	52.30	13.41	49.59	25.94	10.12	5.293
	Mixed conifer and deciduous	21.11	8.043	43.41	9.162	10.01	2.113
	Forest stands	208.6	64.46	41.41	85.25	9.633	20.09
	Orchard	19.08	–	23.70	4.522	9.200	1.755
	Shrubland and woodland	15.02	–	19.76	2.968	6.590	0.990
	Bamboo forest	11.84	–	37.06	4.388	7.412	0.878
	Total regional forest	254.5	–	30.48	97.13	8.209	23.71
1994–1998	*Pinus massoniana*	82.99	31.63	41.64	34.55	9.990	8.291
	Evergreen broadleaf	56.28	15.88	51.51	28.99	10.22	5.752
	Mixed conifer and deciduous	20.84	8.498	45.39	9.459	10.06	2.097
	Forest stands	212.8	72.45	43.86	92.43	9.680	20.60
	Orchard	21.23	–	23.70	5.032	9.200	1.953
	Shrubland and woodland	14.67	–	19.76	2.899	6.590	0.967
	Bamboo forest	12.21	–	40.94	4.999	8.188	1.000
	Total regional forest	260.9	–	32.07	105.4	8.415	24.52
1999–2003	*Pinus massoniana*	76.01	33.12	45.40	34.50	10.13	7.700
	Evergreen broadleaf	63.68	20.22	54.14	34.47	10.48	6.674
	Mixed conifer and deciduous	20.78	9.110	47.66	9.905	10.10	2.099
	Forest stands	210.3	81.87	47.35	99.92	9.754	20.51
	Orchard	23.84	–	23.70	5.650	9.200	2.193
	Shrubland and woodland	13.45	–	19.76	2.658	6.590	0.886
	Bamboo forest	12.39	–	41.87	5.188	8.374	1.038
	Total regional forest	260.0	–	33.17	113.4	8.480	24.63

"–": not available.

Table 2 Biomass and carbon storage of forest stands for different age in the PRD

Age class	Area ($\times10^4$ hm^2)	Total biomass ($\times10^6$ ton)	Carbon storage ($\times10^6$ ton)
Young forest			
Pinus massoniana	12.40	3.065	1.533
Evergreen broadleaf	31.94	14.24	7.120
Mixed conifer and deciduous	6.234	1.867	0.934
Regional young forest stands	58.37	20.94	10.47
Middle-aged forest			
Pinus massoniana	48.74	22.09	11.05
Evergreen broadleaf	21.47	13.82	6.910
Mixed conifer and deciduous	11.45	5.973	2.987
Regional middle-aged forest stands	113.2	55.32	27.66
Mature forest			
Pinus massoniana	14.86	9.347	4.674
Evergreen broadleaf	10.26	6.409	3.205
Mixed conifer and deciduous	3.089	2.064	1.032
Regional mature forest stands	38.70	23.66	11.83
Total regional forest stands	210.3	99.92	49.96

forest vegetation increased, with the exception of shrubland and woodland. The forest stand was the main carbon sink of the regional forest, and the growth rate of carbon storage of each forest vegetation type accorded with its biomass growth rate. Carbon storage of three forest types (*P. massoniana* forest, evergreen broadleaf forest and coniferous and broadleaf mixed forest) accounted for about 80% of regional stand carbon storage, which increased by 5.16×10^6 tons within three periods, accounting for 70.40% of total amount of regional stand carbon storage increment. The amount of carbon fixed by the regional forest in NPP increased by 3.88%, from 11.86×10^6 to 12.32×10^6 ton/year. The amount of carbon fixed by shrubland and woodland in NPP decreased by 10.51%, and that of forest stands, orchard, and bamboo forest increased by 2.09%, 24.94%, and 18.22%, respectively. The amount of carbon fixed by forest stands accounted for 83.28%–84.74% of the amount of carbon fixed by the regional forest in NPP, which played a significant role in carbon sequestration by the regional vegetation. Regional forest carbon density increased by 14.31%, from 19.08 to 21.81 ton/hm^2. Carbon density of forest stands and bamboo forests increased by 16.24% and 13.01%, respectively, but carbon density of orchards and shrubland and woodland remained stable.

4 Discussion

Volume-biomass method is commonly used to estimate forest biomass and carbon storage at regional or large scales, of which the continuous BEF method is a better estimation method (Brown *et al*., 1989; Fang *et al*., 1998). In the PRD, the young and middle-aged forests account for more than 80% of the total forested area, however, the mean biomass of them is relatively low. In the PRD undergrowth vegetation grows vigorously, the biomass and carbon storage of which greatly affect the estimation of total forest biomass and carbon storage in young or middle-aged forest stages of development. Therefore, the volume-biomass equation should be determined in the PRD. If the forest biomass equations are used from other areas which have a different forest status (Fang *et al*., 1996, 2001; Liu *et al*., 2000; Cao *et al*., 2002; Jiao and Hu, 2005; Li *et al*., 2004), this would bring great errors in regional forest biomass and carbon storage estimation in the PRD. This study has determined that, within the study period in the PRD, if existing estimation equations are used then the estimation results of biomass ranged from 117.81×10^6 to 128.48×10^6 tons, but the estimation results in this study using equations developed in the PRD range 85.25×10^6–99.92×10^6 tons. On average, the result obtained using existing equations developed outside the PRD was 34% larger than the estimation result of this study. These errors are mainly because existing estimation equations were established by data from published literature gained in mature forests, which would bring big errors in estimating the biomass of young or middle-aged forests.

Within 1989–2003, regional carbon storage increased by 16.76%, from 48.57×10^6 to 56.71×10^6 tons (Table 3), at an annual growth rate of 1.20% in the PRD. It is noteworthy that the carbon storage of forest stands increased by 17.19%, from 42.63×10^6 to 49.96×10^6 tons

Table 3 Carbon storage and density of different types of forest

Period	Forest type	Area ($\times10^4$ hm^2)	Carbon storage ($\times10^6$ ton)	Carbon mass in NPP ($\times10^6$ ton/year)	Carbon density (ton/hm^2)
1989–1993	Forest stand	208.6	42.63	10.05	20.44
	Orchard	19.08	2.261	0.878	11.85
	Shrubland and Woodland	15.02	1.484	0.495	9.880
	Bamboo forest	11.84	2.194	0.439	18.53
	Total regional forest	254.5	48.57	11.86	19.08
1994–1998	Forest stand	212.8	46.22	10.30	21.72
	Orchard	21.23	2.516	0.977	11.85
	Shrubland and Woodland	14.67	1.450	0.484	9.884
	Bamboo forest	12.21	2.500	0.500	20.48
	Total regional forest	260.9	52.69	12.26	20.20
1999–2003	Forest stand	210.3	49.96	10.26	23.76
	Orchard	23.84	2.825	1.097	11.85
	Shrubland and Woodland	13.45	1.329	0.443	9.881
	Bamboo forest	12.39	2.594	0.519	20.94
	Total regional forest	260.0	56.71	12.32	21.81

(Table 3), which accounted for 87.72% and 88.10% of total regional forest carbon storage. Therefore, changes in stand carbon storage greatly affected changes in regional carbon storage. In the PRD, carbon storage of young and middle-aged forests accounted for 76.32% of that of regional forest stands, consistent with distribution of forest stand carbon storage in different age classes in Hainan Province, China (neighboring area) which accounted for 71.6% of total regional forest stand carbon storage. However, the distribution of regional forest carbon storage in different age classes differed from that of national forest carbon storage within the same period. National forest stand carbon storage was mainly stored in middle-aged and mature forests, accounting for 85.3% of total forest stand carbon storage (Cao *et al*., 2002; Fang and Chen, 2001; Liu *et al*., 2000). Carbon density of regional forests increased by 14.31%, and attained 21.81 ton/hm^2 at the end of the study (Table 3). Carbon density of regional *P. massoniana* forest increased most rapidly (15.77%). Compared to mean carbon density of national forests (38.70 ton/hm^2) and of forests in neighboring Hainan Province (32.59 ton/hm^2) within the same period, mean carbon density in the PRD was relatively much lower than that of forests in Japan (Iwaki, 1983; 34.7 ton/hm^2), Europe (Dixon *et al.*, 1994; 32 ton/hm^2) and America (Turner *et al*., 1995; 61 ton/hm^2), and even lower than that of world forests (Dixon *et al*., 1994; 86 ton/hm^2). For most of the various forest ecosystems, the carbon density of the forest increases with forest age (Wang and Feng, 2000). At present, 80% of regional forests in the PRD are at the young or middle-aged stages. If young or middle-aged forests are better protected, with their gradual maturity and succession developed from *P. massoniana* to lower subtropical evergreen broadleaf forest with high carbon density (its mean biomass in mature stage can attain 380 ton/hm^2) (Peng and Zhang, 1994), potential carbon storage of regional forest can reach 39.96×10^7 tons. The forest may play an important role in mitigating the increase of CO_2 concentration in the atmosphere in this region.

5 Conclusions

Within 1989–2003, regional carbon storage increased by 16.76%, from 48.57×10^6 to 56.71×10^6 tons, around 80% of which was stored in forest stands and carbon storage of the forest stands was mainly accounted by *P. massoniana* forest, evergreen broadleaf forest and coniferous and broadleaf mixed forest. Their carbon storage increased by 5.16×10^6 tons, accounting for 70.40% of the total amount of the regional forest stand carbon storage increment. Carbon storage of other types of vegetation increased except for shrubland and woodland. Carbon density of regional forests increased by 14.31%, from 19.08 to 21.81 ton/hm^2. As 80% of regional forests are at the young or middle-aged stages, the potential carbon storage of regional forest when it becomes mature may reach 39.96×10^7 tons. The forest will play an important role in mitigating the increase of CO_2 concentration in the atmosphere if the young or middle-aged forests can be better protected.

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