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Inventory-based estimates of forest biomass carbon stocks in China: A comparison of three methods

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ABSTRACT

Several studies have reported different estimates for forest biomass carbon (C) stocks in China. The discrepancy among these estimates may be largely attributed to the methods used. In this study, we used three methods [mean biomass density method (MBM), mean ratio method (MRM), and continuous biomass expansion factor (BEF) method (abbreviated as CBM)] applied to forest inventory data to estimate China's forest biomass C stocks and their changes from 1984 to 2003. The three methods generated various estimates of the biomass C stocks: the lowest (4.0–5.9 Pg C) from CBM and the highest (5.7–7.7 Pg C) from MBM, with an intermediate estimate (4.2–6.2 Pg C) from MRM. Forest age class is a major factor responsible for these method-induced differences. MBM overestimates biomass for young-aged forests, but underestimates biomass for old-aged forests; while the reverse is true for MRM. Further, the three methods resulted in different estimates of biomass C stocks for different forest types. For temperate/subtropical mixed forests, MBM generated a 92% higher estimate than CBM and MRM generated a 14% lower than CBM. The degree of the overestimates is closely related with the proportion of young-aged forest within total area of each forest type.

1. Introduction

Biomass of forests accounts for 85–90% of terrestrial vegetation biomass (Whittaker and Likens, 1973; Olson et al., 1983; Dixon et al., 1994), and its stock changes significantly from harvesting, land-use, climate variability, and disturbance (Canadell et al., 2007; Luyssaert et al., 2007). Therefore, forests play an important role in the global carbon cycle (Dixon et al., 1994; Goodale et al., 2002; Houghton, 2003, 2005; Canadell et al., 2007). Estimating broad-scale biomass C stocks has been a focus of global C cycle studies, and attracted the interest of researchers for several decades since the time of the International Biological Programme (IBP, 1965–1975). Appropriate methods for estimating regional forest biomass are critical for accuracy of the estimation, which in addition to enriching our understanding of the global carbon cycle, may also be used to estimate the forestry part of national greenhouse gas inventories reported to the United Nations (IPCC, 2006).

In the IBP period, the mean biomass density method (MBM), defined as multiplying mean biomass density calculated from direct field measurements by forest area, had been widely used to estimate regional-, national-, and global-scale forest biomass (e.g. Whittaker and Likens, 1973; Kira, 1976; Woodwell, 1978; Brown and Lugo, 1982). Some of the MBM estimates have been the basis of contemporary global change research (e.g. Prentice and Fung, 1990; Fang et al., 2003, 2006). However, the direct field measurements made for these studies tend to be carried out in forests with greater biomass than the average level in a region or a country, so MBM usually overestimates forest biomass (Brown and Lugo, 1984; Dixon et al., 1994; Fang et al., 2005).

Since the early 1980s, regional or national forest inventories, with a large number of statistically valid plots, have been widely recognized as powerful and appropriate data for calculating forest biomass on a large scale (e.g. Brown and Lugo, 1984; Birdsey, 1992; Birdsey and Heath, 2001; Kauppi et al., 1992, 2006; Turner et al., 1995; Schroeder et al., 1997; Fang et al., 1998, 2001, 2005; Brown and Schroeder, 1999; Smith et al., 2003, 2004). Most forest inventories collect detailed information on forest area and merchantable timber (stem) volume by age class and by forest type. To estimate forest biomass using inventory data, it is necessary to calculate a biomass expansion factor (BEF) that converts stem volume to biomass to account for traditionally noncommercial components such as branches, roots, and leaves. Here, we define the term BEF as the ratio of all stand biomass to stem volume, and call the method of estimating forest biomass with a mean BEF value as the mean ratio method (abbreviated as MRM).

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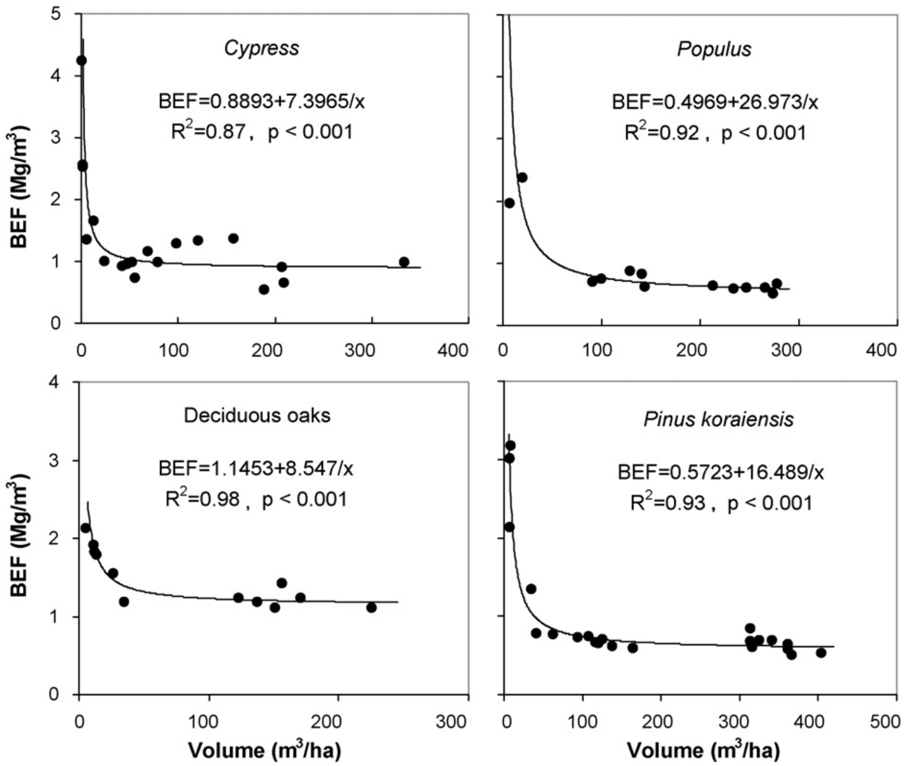

Fig. 1. Relationships between BEF and stem volume for four forest types in China.

Sharp et al. (1975) was probably the first to use MRM to estimate regional forest biomass. In their study, a constant BEF of 2.0 Mg/m^3 was used to calculate the forest biomass in North Carolina, USA, based on the forest inventory data. Later, MRM was used to estimate broad-scale forest biomass for other regions, such as tropical forests (Brown and Lugo, 1984), forests in USA (Birdsey, 1992; Turner et al., 1995; Birdsey and Heath, 2001), and European forests (Kauppi et al., 1992). However, further studies have indicated that the BEF is not a constant, but varies with forest age, site class, and stand density (Brown and Lugo, 1992; Turner et al., 1995; Fang et al., 1998, 2001; Brown and Schroeder, 1999; Nilsson et al., 2000; Fang and Wang, 2001). Applying a constant value of BEF across all age classes and all site classes within a forest type or a type group underestimated forest biomass of younger and less productive stands, but overestimated the biomass of older and more productive ones (e.g. Turner et al., 1995; Fang et al., 1996, 1998; Schroeder et al., 1997; Brown and Schroeder, 1999; Goodale et al., 2002).

Therefore, forest biomass should be calculated by using variable BEF values, which correspond to age, site, and stand density classes in forest inventory (Brown and Lugo, 1984, 1992; Schroeder et al., 1997; Fang et al., 1998, 2001, 2005, 2007; Brown and Schroeder, 1999; Nilsson et al., 2000). Because it is difficult or inefficient to obtain the BEF value for each age and site class at regional or national scale, Brown and her group (e.g. Brown and Lugo, 1992; Schroeder et al., 1997; Brown and Schroeder, 1999; Brown et al., 1999) and Fang and his group (Fang et al., 1996, 1998, 2001, 2005) found that the BEF could be expressed as a consistent function of timber (stem) volume, in spite of age, site and stand density classes. Fang and his colleagues (Fang et al., 1996, 1998, 2001, 2005, 2007; Fang and Wang, 2001) have derived a simple reciprocal equation from direct field measurements to express the BEF–stem volume relationship for a specific forest type (Eq. (1), Fig. 1).

$$\mathrm{BEF} = a + \frac{b}{x} \qquad (1)$$

where x is stem volume per unit area, a and b are constants for a specific forest type.

Since stem volume (x) in Eq. (1) reflects the influence of forest age, site class, stand density, and other biotic and abiotic factors on forest biomass, it can be used to calculate forest biomass, based on the corresponding area and volume in forest inventory data, even without information of forest age, site class, or any others (Fang et al., 2002a,b). Additionally, Fang et al. (2002a) proved that this method could scale up directly from field measurements to regional estimates of forest biomass. We name this BEF–volume relationship as the continuous BEF method (abbreviated as CBM) (Fang and Wang, 2001; Fang et al., 2005).

The three methods (MBM, MRM, and CBM) described above have been used to estimate broad-scale forest biomass worldwide, but different methods may generate various estimates. For example, in the last decades a number of studies estimating China's forest biomass (e.g. Fang et al., 1996, 2001; Liu et al., 2000; Zhou et al., 2000; Pan et al., 2004; Zhao and Zhou, 2006; Xu et al., 2007; Wu et al., 2008) produced estimates that are quite different due to the different methods used. Here we assess these methods, focusing on how forest age and forest type affect the method-derived estimates, by comparing the estimates of China's forest biomass C stocks using each of the methods and forest inventory data from 1984 to 2003.

2. Data and methods

2.1. Data

2.1.1. Forest inventory data

China's forest inventory periodically documents the information about forest area and timber volume by age class and forest type. The forest inventory data used in this study include four periods: 1984–1988, 1989–1993, 1994–1998, and 1999–2003 (Chinese Ministry of Forestry, 1989, 1994, 1999, 2004). In the inventories, forests are divided into five age groups: young-aged, middle-aged, premature, mature, and overmature forests. In addition, forests are defined to include three categories: stands (including natural and planted forests), economic forests (woods with the production of fruits, edible oils, drinks, flavorings, industrial raw materials, and medicinal materials as the main purposes), and bamboo forests, of which stands are documented with detailed information of age class, area, and volume in the forest inventories. Therefore, in this study, “forest” only refers to regular forest stands, excluding economic and bamboo forests.

2.1.2. Field measurement data

In order to obtain parameters for Eq. (1), as well as the mean biomass density and the mean BEF value corresponding to each forest type in the forest inventory data, Fang et al. (1996) established a corresponding database by collecting all biomass data published before 1992. We have updated the data set by adding new field measurements. The parameters for Eq. (1), mean biomass densities, and mean BEFs of major forest types are shown in Table 1. Here biomass includes all the living biomass in a sample plot, including aboveground and belowground living biomass of trees, shrub, and forest floor herb.

2.2. Methods

As mentioned above, we first derived statistically the parameters for Eq. (1), mean biomass densities, and mean BEFs of all major forest types in China (Table 1), based on sampled data of field measurements. These parameters are respectively used in the three methods (CBM, MBM, and MRM) for estimating national forest biomass, which can be simply expressed as follows:

$$\mathrm{CBM}: B = \sum_{i}^{n} A_i \cdot x_i \cdot \mathrm{BEF}_i$$

$$\mathrm{MBM}: B = \sum_{i}^{n} A_i \cdot \overline{\mathrm{BD}_i}$$

$$\mathrm{MRM}: B = \sum_{i}^{n} V_i \cdot \overline{\mathrm{BEF}_i}$$

where B stands for total forest biomass in China, n is the number of forest types according to forest inventory data. A_i, V_i, $\overline{\mathrm{BD}_i}$, $\overline{\mathrm{BEF}_i}$, x_i are the total area, total volume, mean biomass density, mean BEF, and volume per unit area of forest type i, respectively. The continuous BEF for forest type i is represented as BEF_i calculated by Eq. (1). In this study, a ratio of 0.5 is used to convert biomass to carbon stock.

3. Results

3.1. Biomass C stock

All the three methods indicate that biomass C stock of China's forests has increased over the period of 1984 to 2003. The magnitude of the C stock varies with the different methods (Table 2). CBM generates the lowest forest biomass storage, from 4.0 Pg C in 1984 to 5.9 Pg C in 2003, while MBM results in the highest value (5.7–7.7 Pg C), 32–42% greater than the estimates by CBM. MRM generates intermediate, but close to CBM-derived estimates (4.2–6.2 Pg C). Despite large differences in the estimates of total C stocks using the three methods, the biomass C sink (the difference in C stocks between 2003 and 1984) over the study period does not differ very much, with a range of just 1.8–2.0 Pg C. However, over 10-year periods, there is an accidental high degree of variability among estimates of the carbon sink by the three methods.

3.2. Biomass C stock by age class

We further estimate forest biomass C stocks for each age class using the three methods. As shown in Fig. 2 (also see supplementary Table S1), the three methods generate a large difference in C stocks for different age classes. For young-aged forests, MBM estimates much higher C stocks (278–298% of that obtained from CBM) than those from the other two methods, while MRM calculates much lower estimates (71–78% of that obtained from CBM). For middle-aged forest, CBM and MRM generate a very close estimate, but MBM calculates an estimate 40% higher than those from the other two methods (CBM and MRM). For premature forests, the three methods generate similar estimates (results from MBM and MRM account for 105–110% of that from CBM). For mature and overmature forests, MBM and MRM respectively lead to lower (7–19% lower for mature forests and 25–32% lower for overmature forests) and higher (17–18% higher for mature forest

Table 1
Mean biomass density and mean biomass expansion factor (BEF) and its corresponding parameters in Eq. (1) for China's major forest types.

Forest type	Parameters for equation: $\mathrm{BEF}=a+b/x$					Biomass density (Mg/ha)			Mean BEF (Mg/m^3)		
	a	b	n	r^2	p	n	Mean	SD	n	Mean	SD
Abies, Picea	0.5519	48.861	24	0.7764	<0.001	36	215.8	260.5	25	0.89	0.28
Cunninghamia lanceolata	0.4652	19.141	90	0.9401	<0.001	106	90.2	57.8	90	0.73	0.50
Cypress	0.8893	7.3965	19	0.8711	<0.001	29	85.4	67.7	16	1.05	0.29
Larix	0.6096	33.806	34	0.8212	<0.001	34	127.2	68.2	34	0.90	0.22
Pinus koraiensis	0.5723	16.489	22	0.9326	<0.001	28	120.5	74.5	22	0.98	0.77
P. armandii	0.4581	32.666	10	0.7769	<0.001	10	74.2	15.8	10	0.87	0.20
P. massoniana, P.yunnanensis	0.5034	20.547	51	0.8676	<0.001	61	101.0	53.2	51	0.69	0.21
P. sylyestris var.*mongolica*	1.112	2.6951	15	0.8478	<0.001	26	51.8	41.0	15	1.22	0.29
P. tabulaefomis	0.869	9.1212	112	0.9063	<0.001	127	98.1	58.4	112	1.00	0.25
Other pines and conifer forests	0.5292	25.087	18	0.8622	<0.001	39	112.4	68.1	18	0.89	0.34
Tsuga, Cryptomeria, Keteleeria	0.3491	39.816	30	0.7899	<0.001	26	98.7	54.5	10	0.69	0.36
Mixed conifer and deciduous	0.8136	18.466	10	0.9953	<0.001	11	91.6	84.5	10	1.31	0.67
Betula	1.0687	10.237	9	0.7045	<0.005	11	108.4	55.1	9	1.21	0.29
Casuarina	0.7441	3.2377	10	0.9549	<0.001	11	73.9	60.0	10	0.94	0.24
Deciduous oaks	1.1453	8.547	12	0.9795	<0.001	14	122.2	89.1	15	1.47	0.36
Eucalyptus	0.8873	4.5539	20	0.802	<0.001	20	127.8	88.3	20	0.90	0.26
Lucidophyllous forests	0.9292	6.494	23	0.8259	<0.001	32	185.4	137.4	23	0.95	0.26
Mixed deciduous and *Sassafras*	0.9788	5.3764	32	0.9333	<0.001	44	101.0	76.2	27	1.12	0.36
Nonmerchantable woods	1.1783	5.5585	17	0.9483	<0.001	20	48.8	29.2	20	1.31	0.32
Populus	0.4969	26.973	13	0.9183	<0.001	30	84.8	53.9	13	0.90	0.58
Tropical forests	0.7975	0.4204	18	0.8715	<0.001	26	88.3	54.9	18	0.85	0.21

where a and b are constants for a forest type and x (m^3/ha) is mean timber volume per unit area, the unit of BEF is Mg/m^3; n is number of samples and SD is standard deviation. The values in Table 1 which have been corrected are a little different from those in the previous study (Fang et al., 2007).

Table 2
Forest biomass carbon stocks in China estimated by three methods.

Period	Area (10^4 ha)	Volume (10^8 m^3)	Volume density (m^3/ha)	CBM-C (Tg C)	MBM-C (Tg C)	MRM-C (Tg C)	MBM/CBM (%)	MRM/CBM (%)
1984–1988	10,219	80.9	79.2	4020	5707	4189	142	104
1989–1993	10,864	90.9	83.6	4454	6032	4711	135	106
1994–1998	12,920	100.9	78.1	5024	7113	5210	142	104
1999–2003	14,279	121.0	84.7	5862	7726	6211	132	106
Net increment for two decades	4,060	40. 1	5.5	1842	2020	2023	110	110
Net increment for early decade	645	10.0	4.5	433	325	522	75	120
Net increment for late decade	1,359	20.1	6.7	839	613	1001	73	119

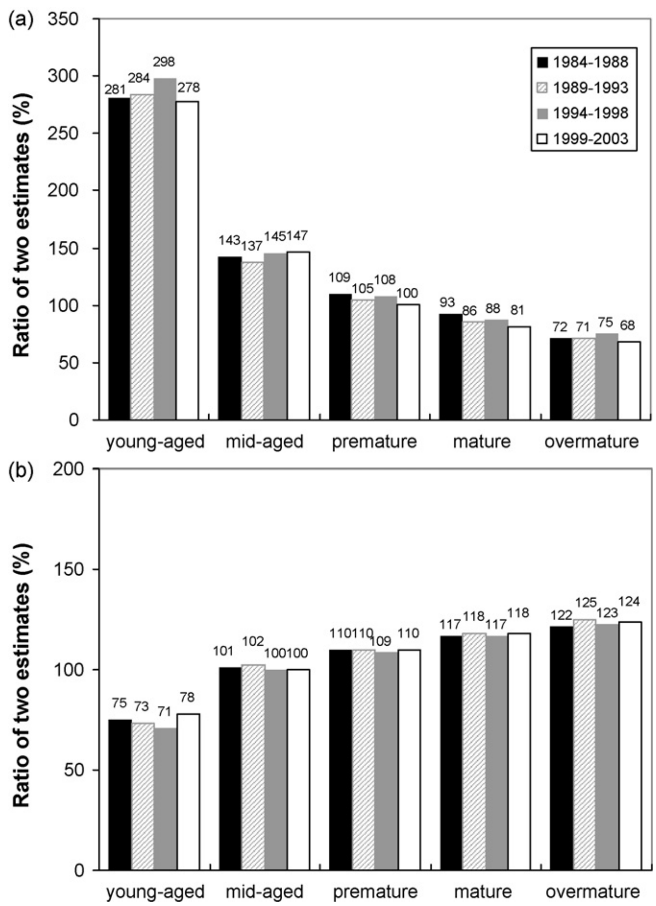

Fig. 2. Comparison of estimates of forest biomass C stocks for each age class for four inventory periods (1984–1988, 1989–1993, 1994–1998, and 1999–2003), using three methods. The comparison uses the CBM-derived estimates as a base. (a) Ratio of the MBM- to CBM-derived estimates, and (b) ratio of the MRM- to CBM-derived estimates.

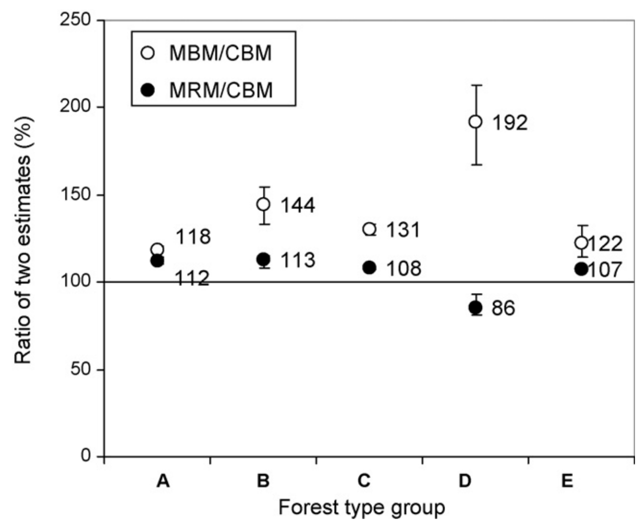

Fig. 3. Comparison of method-generated estimates for five forest groups, using the ratios of the estimates from MBM to CBM and from MRM to CBM. Forest groups, A, B, C, D, and E correspond to those in Table 3.

and 22–25% higher for overmature forests) estimates, relative to CBM (Fig. 2).

It is interesting to note that, if we use the CBM-derived estimates as the base, then the ratios of MBM- and MRM- to CBM-derived estimates change greatly with age classes. The MBM/CBM ratios (%) decrease sequentially from 278–298% for young-aged to 137–147% for middle-aged, to 100–109% for premature, and to 81–93% for mature forests and 68–75% for overmature forests, suggesting that MBM overestimates biomass C stocks for young forests but underestimates those for old-aged forests. The reverse is true for the MRM/CBM ratios, revealing that MRM underestimates biomass C stocks (71–78% of that from CBM) for young forests but overestimates those for older forests (ranging from 110% to 125%, Fig. 2).

Table 3
Forest biomass carbon stocks of different forest groups in China (Tg C).

Forest group	1984–1988			1989–1993			1994–1998			1999–2003		
	CBM	MBM	MRM	CBM	MBM	MRM	CBM	MBM	MRM	CBM	MBM	MRM
Boreal forest (A)	1075	1299	1183	1208	1378	1374	1326	1575	1483	1263	1505	1409
Temperate conifer forest (B)	235	358	267	288	393	332	300	464	323	410	548	466
Temperate deciduous forest (C)	1251	1668	1342	1370	1816	1479	1566	2016	1696	1628	2073	1762
Temperate/subtropical mixed forest (D)	625	1333	507	802	1547	680	1016	1974	841	1256	2095	1173
Evergreen broadleaf forest (E)	834	1049	890	786	897	845	816	1084	867	1305	1506	1402
Total	4020	5707	4189	4454	6032	4711	5024	7113	5210	5862	7726	6211

The forest types were divided into five groups (based on Fang, 2000): Boreal forest group: *Abies*, *Picea* and *Larix* forests; temperate coniferous forest group: *Pinus koraiensis*, *P. sylvestris* var. *monoglica*, *P. tabulaeformis*, *P. armandii* and other pine forests, *Cypress*, *Tsuga*, and other coniferous forests; temperate deciduous forest group: *Populus*, *Betula*, *Quercus*, *Tilia*, and *Casuarina* forests; temperate/subtropical mixed forest group: *Pinus massoniana*, *P. yunnanensis*, *Cunninghamia lanceolata*, *Cryptomeria*, *Sassafras* and *Keteleeria* forests, and other mixed conifer and deciduous forests; Evergreen broadleaf forest group: lucidophyllous forests, *Eucalyptus*, and tropical forests.

3.3. Biomass C stock by forest type

In order to compare effects of methodology on estimating of biomass C stocks of different forest types, we divided all major forest types into five forest groups which correspond to vegetation zone (Fang, 2000), and then used the three methods to estimate total biomass C stocks for each forest group for four inventory periods (Table 3). According to the results, CBM and MRM generate similar estimates (the ratios of the estimates from MRM to those from CBM are between 86% and 113%) for all the five forest groups, but MBM overestimates the C stocks, especially for temperate/subtropical mixed forest group (92% higher than the result estimated by CBM) (Fig. 3, Table 3).

4. Discussion

We estimated forest biomass C stocks for four inventory periods using the three methods, MBM, MRM, and CBM, and found that the different methods could result in highly variable estimates when disaggregated by age and forest group. CBM uses timber volume as a function of BEF and involves effects of forest age, forest density and forest site quality and thus it could more accurately estimate forest biomass than other methods (Fang et al., 2002a,b; Teobaldelli et al., 2009). Therefore we used the CBM-derived estimates as a base to compare estimates derived from the other two methods. Our results show that MBM results in the highest estimates of total national C stocks (32–42% higher than those from CBM), while MRM generates values close to those by CBM. Further investigation indicates that forest age significantly influences estimates derived from MBM and MRM: the former overestimates the C stocks for young forests and underestimates those for old forests, and the latter underestimates the C stocks for young forests and overestimates those for old forests.

Our analysis also shows that MBM generates considerably different estimates from CBM among forest groups, while MRM does not result in a substantial difference in the estimates (Fig. 3). Actually, the effect of the forest group is attributed to the effect of forest age structure as illustrated in Fig. 4 which shows percentage of area of each aged forests for each forest group. For example, MBM overestimates C stocks especially for temperate/subtropical mixed forest group (92% higher than from CBM) (Fig. 3, Table 3) because about a half (49%) of the total area is composed of young-aged forests (Fig. 4). Further, we calculated the ratios of the MBM- to CBM-derived estimates and the proportion of young-aged forest area for the four inventory periods (1984–2003) and found that the ratios

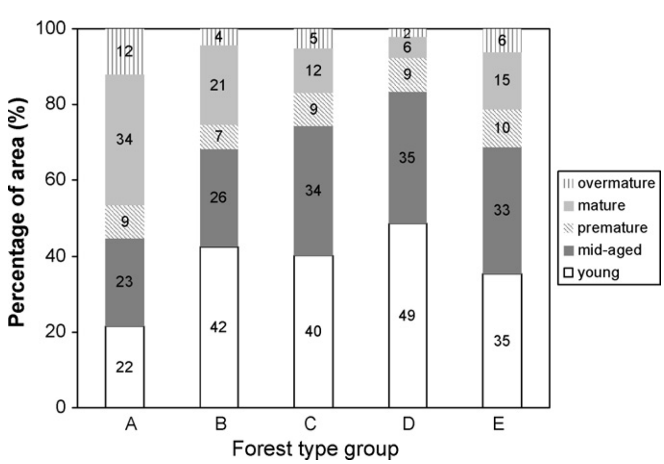

Fig. 4. Area percentage of each age class for each forest group (period 1984–1988). The similar trends are also exhibited for the other inventory periods, but are emitted for saving space. A, B, C, D, and E correspond to forest groups in Table 3.

Table 4
Total biomass C stocks of China's forests estimated by different authors.

Method	Period	C stock (Pg C)	Source
MBM	1984–1988	6.9	Fang et al. (1998)
MBM	1989–1993	6.9	Zhou et al. (2000)
Age-specific MBM	1989–1993	6.6	Pan et al. (2004)
MRM	1984–1988	3.8	Fang et al. (1998)
Regional-averaged MRM	1989–1993	4.2	Wu et al. (2008)
Regional-averaged MRM	1994–1998	4.6	Wu et al. (2008)
CBM	1984–1988	4.3	Fang et al. (1998)
CBM	1984–1988	4.1	Liu et al. (2000)
CBM	1989–1993	4.2	Liu et al. (2000)
Age-specific CBM	1984–1988	3.7	Pan et al. (2004)
Age-specific CBM	1989–1993	4.0	Pan et al. (2004)
Hyperbolic function	1989–1993	3.8	Zhao and Zhou (2006)
Age-specific CBM	1984–1988	3.8	Xu et al. (2007)
Age-specific CBM	1989–1993	4.1	Xu et al. (2007)
Age-specific CBM	1994–1998	4.7	Xu et al. (2007)
Age-specific CBM	1999–2003	5.5	Xu et al. (2007)
CBM	1984–1988	4.0	This study
CBM	1989–1993	4.5	This study
CBM	1994–1998	5.0	This study
CBM	1999–2003	5.9	This study

All the estimates are based on China's forest inventory data but different methods are used.

were strongly correlated with the proportion of the area ($r^2 = 0.61$, $n = 20$, $p < 0.0001$), suggesting importance of age structure in affecting the method-induced discrepancy of the estimates.

Next we compare our estimates of China's biomass C stocks with the previous studies which are based on the same forest inventory data sources (Table 4). In the last decade, several authors have estimated biomass C stocks for China's forests. For example, Liu et al. (2000) estimated China's forest biomass C stocks to be 4.1 and 4.2 Pg C for 1984–1988 and 1989–1993, respectively, using linear relationships between forest biomass and timber volume which is similar to CBM used in our study. Their estimates are very close to ours, though there are small differences because of less field sampling used in their study. Pan et al. (2004) used an age-specific CBM method (volume-biomass relationship by age class) to estimate C stocks of China's forest at 3.7 and 4.0 Pg C for the periods of 1984–1988 and 1989–1993. Their results are similar to, but a little smaller than, our CBM-derived estimates. Xu et al. (2007) also applied age-specific CBM method to estimate China's forest biomass. Their estimates were 3.8, 4.1, 4.7, and 5.5 Pg C for the periods of 1984–1988, 1989–1993, 1994–1998, and 1999–2003, respectively. Zhao and Zhou (2006) used a hyperbolic relationship between biomass and volume to obtain an estimate of 3.78 Pg C for 1989–1993, 15.2% smaller than the CBM-based estimate in this study. However, a nonlinear relationship between biomass and volume derived from field measurements cannot be scaled-up to a regional estimation, as pointed out by Fang et al. (2002a). Wu et al. (2008) used regional-averaged BEFs to perform their estimation and obtained the estimates of 4.22 and 4.65 Pg C for 1989–1993 and 1994–1998, which are quite close to our CBM-based ones.

In addition, Pan et al. (2004) used mean biomass density by age class to estimate the C stock at 6.62 Pg C for 1989–1993, slightly larger than our highest estimate (6.03 Pg C) based on MBM. Another study using mean biomass density generated an estimate of 6.20 Pg C for the same period using a ratio of 0.45 for converting biomass to C (Zhou et al., 2000). If applying a ratio of 0.5 that is commonly used in others, then we obtain an estimate of 6.89 Pg C, the highest estimate among all the previous studies.

Finally, we discuss the effect of forest age on the BEF and CBM method. The BEF varies with forest age, site class and forest density (Brown and Lugo, 1992; Turner et al., 1995; Fang et al., 1998); however, the CBM defines BEF as a function of stem volume which integrates the effects of forest age, site quality, and other biotic and abiotic factors on forest biomass. Therefore, with CBM it becomes possible to accurately calculate forest biomass without using age class, site class, and other information (Brown and Lugo, 1992; Schroeder et al., 1997; Brown and Schroeder, 1999; Fang et al., 2001, 2002b, 2005; Teobaldelli et al., 2009). In other words, the relationship between BEF and stem volume could independently stand for forest age and site quality because stem volume has already reflected the effects of forest age, as well as site quality and stem density (Fang et al., 2001, 2002b, 2005). Although Pan et al. (2004) and Xu et al. (2007) considered that the age-specific CBM was more appropriate than the consistent CBM developed by Schroeder et al. (1997), Brown and Schroeder (1999) and Fang et al. (2001, 2005), we suspect that possible different relationships between stem volume and biomass by age classes might be merely the consequence of different sampling size and data range for the different age classes. A recent global analysis on BEF vs. growing stock relationships also suggests that BEFs are almost independent with forest age class and site quality for a forest category (Teobaldelli et al., 2009). As an evidence, we illustrate the relationships between total biomass and stem volume for two forest types with relatively large sampling size and wide ranges of age, *Larix* forest (n = 42, 30–195 years) and *Pinus yunnanensis* and *P. Khasya* forest (n = 44, 20–150 years) (Fig. 5). It shows no significant difference to be found in the relationships across forest age classes

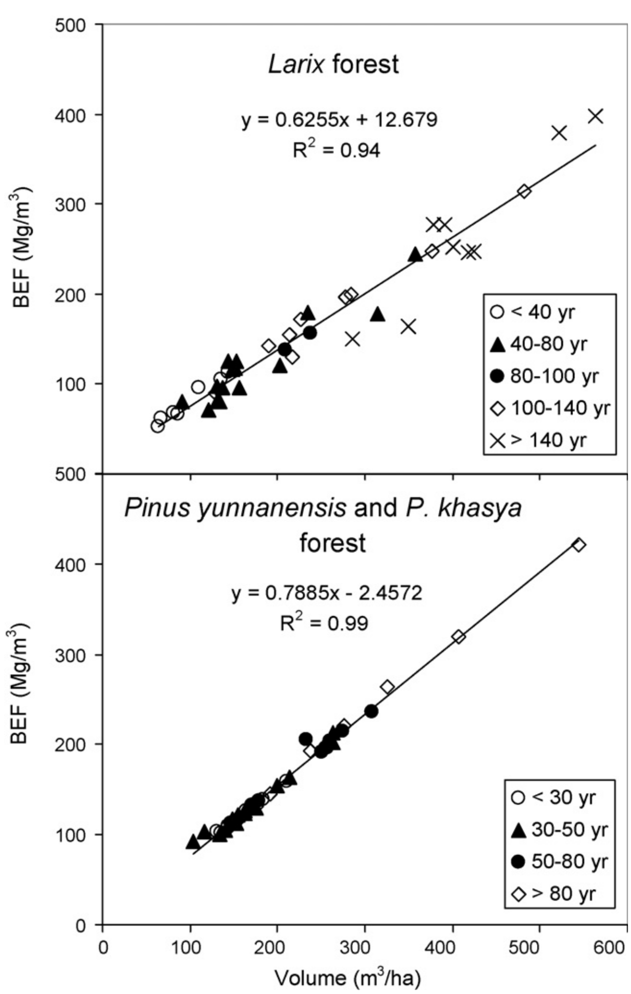

Fig. 5. Relationships between total biomass and stem volume for two forest types, *Larix* forest and mixed forest of *Pinus yunnanensis* and *P. Khasya*, by forest age class. No significant difference can be seen in the relationships for each age class. Block lines are overall regression curve across all the ages. Data are from Luo (1996).

for both forest types, supporting our claim that the relationship between BEF and growing stock can be independent of forest age.

However, we should note that the data requirement of CBM is stricter than the other two methods, because CBM can be applied only when forest area, growing-stock volume, and continuous functions of BEF are available. Compared with CBM, MRM does not need continuous functions of BEF, and just requires two variables, forest growing-stock volume and constant BEF value. Similarly, MBM can be used to estimate regional forest biomass when forest area and mean biomass density are available.

5. Conclusions

The three different methods generated different estimates for China's forest biomass C stocks: the lowest (4.0–5.9 Pg C) from CBM and the highest (5.7–7.7 Pg C) from MBM, with a middle value (4.2–6.2 Pg C) from MRM. Because CBM estimates biomass as a function of timber volume and thus incorporates effects of forest age, forest density and forest site quality, it can accurately estimate forest biomass without considering forest age, density, site and other factors. Compared with CBM, MBM overestimates the C stocks, while MRM generates close to, but slightly larger than values from CBM. Forest age significantly influences estimates derived from MBM and MRM: the former overestimates biomass C stocks for young forests and underestimates those for old forests, but the reverse is true for the latter. The various estimates derived from the methods within a forest group are also actually related to age structure.

Since the data requirement of CBM is stricter than the other two methods, which method to be selected may be determined by existing data. When there is sufficient forest inventory data, as well as field measurement data, which include forest area, growing-stock volume, and continuous functions of BEF, it is better to select CBM to estimate regional forest biomass. If there is not enough data, MRM is another selection, and MBM could be chosen only when there is no data but forest area. CBM is the best method to estimate biomass for all age classes. For which age classes MBM and MRM can be applied to estimate forest biomass depends on which age classes or site classes the mean biomass density and the mean BEF value derived from. In our study, MBM and MRM are suitable to estimate biomass for premature and mid-aged forests, respectively.

The results of this study have significance for reporting of greenhouse gas inventory statistics at the country level under the United Nations Framework Convention on Climate Change (UNFCCC, 1997). In situations where the proportion of young forests is changing, for example during periods of afforestation or extensive harvesting, a method that take good account of age-class distribution will perform better over short reporting cycles. To the extent that countries may eventually modify their forest age-class distributions in response to international climate treaties, short reporting cycles will be required to have an accurate accounting of the progress of management actions. In addition, to obtain accurate estimates of regional and national C stocks, it is necessary to collect more samples which cover large range of age classes and site quality to improve parameters involved in CBM. Also, uncertainty analysis for estimates of regional forest biomass is necessary in the future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2009.09.047.

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