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Abstract Inconsistent estimates of forest biomass carbon stocks (BCS) in China have been reported in recent decades using inventory data. This study was to update China's forest biomass carbon sink based on seven forest inventories from 1973 to 2008 and to identify the relative contributions to such sink from changes in forest area and biomass carbon density (BCD) as a result of growth, plantation and harvests in different regions. Our results indicated that total BCS of all forest types, including forest stands and other forest types (economic forests, woodlands, shrub forests, bamboo forests and trees on non-forest lands), increased by 65 % from 1973 to 2008 and recently reached 8.12 PgC. Total BCS and BCD of forest stands (canopy coverage >20 %) increased from 4.11 PgC and 35.10 $MgC\,ha^{-1}$ to 6.24 PgC and 40.12 $MgC\,ha^{-1}$ during the study period, respectively. Forest stands acted as a biomass carbon sink of 0.17 $PgC\,year^{-1}$, which accounts for 84.4 % of the total sink of all forest types from 1999 to 2008 and have great potential to absorb more biomass carbon in the future due to large fractions of young and middle aged forests, which are increasing BCD. BCS of forest stands increased in all regions but the northeast region. Their biomass carbon sink was mainly driven by the BCD increase in the densely populated south and east regions and by the expansion of forest areas in the north, northwest, and southwest regions with abundant land resources.

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1 Introduction

In the past few decades, studies indicated that forest ecosystems in the mid-high latitudes of the Northern Hemisphere function as a large carbon sink owing to enhanced growth of forests (Dixon et al. 1994; Pan et al. 2011), changes in forest age (Myneni et al. 2001; Pan et al. 2011), reforestation and afforestation (Fang et al. 2001; Goodale et al. 2002; Piao et al. 2005), and CO_2 fertilization and nitrogen deposition (Chen et al. 2000). Up to 2010, China's forests make up 5 % of the global total (FAO 2010). Recent studies indicated that forests in China were acting as a carbon sink during the past decades (Fang et al. 2001; Piao et al. 2005; Wang et al. 2007; Ju et al. 2007). However, the estimates of the carbon sink in China's forests are still inconsistent.

The mean biomass density, volume-derived, and remote sensing methods are three commonly used methods for estimating forest biomass carbon stocks (BCS). In the International Biological Program period, the first method was widely used. However, it tends to overestimate BCS because the results based on field measurements are usually greater than the average levels in a region or a country (Dixon et al. 1994; Guo et al. 2010). Remote sensing images can provide spatial information on BCS at large scales. Great efforts are still needed to tackle many challenges, such as atmospheric and background noises, similar spectral characteristics of different vegetations, saturation of remote sensing signals in dense vegetations. The volume-derived method is recognized as the most effective and reliable method for estimating BCS at large scales (Fang et al. 1998, 2001).

China has implemented a nationwide forest resources inventory once every 5 years since the 1970s. With these data, dynamics of BCS at various levels have been studied (Fang et al. 2001, 2007; Pan et al. 2004; Xu et al. 2007; Wang et al. 2009; Ren et al. 2011). However, the outputs from these studies are inconsistent. Pan et al. (2004) indicated that 83 % of the plots used by Fang et al. (2001) to develop models estimating BCS from volume were classified as younger stands, leading to overestimates of BCS of older forests. Tree species grouping also has significant effects on forest BCS calculation owing to its effects on determining model parameters. Ren et al. (2011) declared that above 98 % of uncertainties in estimated BCS were related to model parameters. Improving BCS calculation equations can better the estimation of forest BCS (Goodale et al. 2002), which can be implemented by increasing the number of samples used to develop the equations (Smith et al. 2002).

In this study, we collected biomass measurements at 3543 forest plots across China from literature to establish models for calculating biomass for 30 types of tree species. With these models, forest BCS in China was calculated using seven inventories from 1973 to 2008. The major objectives of this study are: (1) to update forest BCS in China from 1973 to 2008; (2) to explore the effects of the changes in forest area and biomass carbon density (BCD) resulting from forest growth, plantation and harvests on forest BCS in China; and (3) to compare estimated forest BCS using different methods.

2 Data and methods

2.1 Forest inventory data

The forest inventory data used were compiled by the Chinese Ministry of Forestry in seven periods: 1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003 and 2004–2008 (Chinese Ministry of Forestry 1977, 1982, 1989, 1994, 1999, 2004, 2009). Each inventory consists of permanent and temporary plots distributed evenly across China. The numbers of permanent plots and trees account for above 98 % and 95 % in each inventory period, respectively. Inventories in all provinces were regularly implemented in 5-year intervals. One inventory was finished in a single year for a specific province and in 5 years for the whole country, documenting forest areas and timber volume by age classes and forest types. Each forest type is divided into young, middle-aged, premature, mature and overmature age groups. According to Forest Resource Statistics of China, forests are divided into forest stands (including natural and planted forests), economic forests, woodlands, shrub forests, bamboo forests, and trees on non-forest lands.

2.2 Field measurement data

Luo (1996) compiled data from 1266 sample plots published from 1979 to 1994. We reviewed almost all related publications in China from 1979 to 2011 and recorded information of sampling plots on locations, forest types, stand age, stand density, stand volume, mean tree height and diameter at breast height (DBH) for trees with DBH>4 cm, the sizes of sampling plots, and biomass of different organs and whole trees. In total, data from 3543 sampling plots were successfully collected (Appendix S1). Some plots are missing stand volume or belowground biomass measurements, which were estimated following Fang et al. (1998) (Appendix S2) and Wang et al. (2008) (Table 1), respectively.

2.3 Biomass estimation of forest stands

The biomass of forest stands was calculated using the continuous biomass expansion factor (CBEF) method (Fang et al. 1998, 2001):

$$B = aV + b \tag{1}$$

where B is the total stand biomass (Mg ha^{-1}); V is the stand volume (m^3 ha^{-1}); and a and b are the coefficients for a specific forest type.

The total biomass of a forest type (B_f) or a province (B_p) was calculated as:

$$B_f = \sum_{i=1}^{31} \sum_{j=1}^{5} S_{ij}\left(aV_{ij} + b\right) \tag{2}$$

$$B_p = \sum_{m=1}^{30} \sum_{j=1}^{5} S_{mj}\left(aV_{mj} + b\right) \tag{3}$$

where V_{ij} and S_{ij} are the stand volume and total area of age group j (j=1, 2, 3, 4, 5) for province i (excluding Taiwan province due to lacking data) (i=1, 2, …, 31); V_{mj} and S_{mj} are the stand volume and total area of age group j for forest type m (m=1, 2, …, 30).

Fang et al. (1998, 2001) determined parameters a and b in Eq. 1 for 21 groups of tree species using data from 758 plots. For some groups, the numbers of plots are small and skewed at young ages, possibly inducing uncertainties in calculated BCD (Pan et al. 2004). In this study, we classified dominant tree species into 30 groups and refined parameters a and b using measured biomass and volume at 3543 plots (Table 1).

Since 1994, the canopy coverage criterion of forest stands in China has been changed from >30 % to >20 %. In order to correct the effect of changing the definition of forest stands from 20 % to 30 % canopy coverage in 1994 on the temporal dynamics of forest area and BCS, Fang et al. (2007) developed a method to correct the areas and BCS of forest stands in

Table 1 Biomass statistics for 30 forest types in China based on field measurements

Forest type	Belowground/Aboveground biomass*								Parameters in Eq. 1				
	Natural				Planted								
	N_1	Mean	SD	Age range	N_2	Mean	SD	Age range	*a*	*b*	*n*	R^2	Age range
Abies, *Picea*	199	0.22	0.06	40–317	16	0.18	0.04	6–100	0.3933	56.65	173	0.8015	20–317
Cunninghamia lanceolata	7	0.22	0.04	22–53	123	0.23	0.08	4–55	0.4553	17.552	132	0.9214	3–51
Platycladus and *Cupressus*	12	0.17	0.06	29–220	33	0.19	0.07	15–50	0.4904	30.427	31	0.9608	10–220
Hardwoods, Softwoods[a]	241	0.24	0.08	3–200	26	0.30	0.12	4–52	0.8918	28.441	245	0.8103	3–200
Pinus armandi	22	0.22	0.06	20–80	22	0.16	0.03	16–30	0.6217	12.96	38	0.8994	13–80
Pinus koraiensis	39	0.33	0.14	26–238	48	0.20	0.06	19–101	0.4691	24.659	45	0.8511	19–238
Pinus yunnanensis, *Pinus kisiya*	46	0.17	0.05	20–150	7	0.18	0.03	4–35	0.737	3.276	51	0.9768	4–150
Pinus tabulaeformis	179	0.25	0.04	15–106	140	0.26	0.06	18–35	0.7709	8.8631	751	0.9254	12–106
Pinus taeda	–	–	–	–	5	0.32	0.01	4–21	0.8136	7.0371	11	0.9849	4–21
Cryptomeria fortunei, *Tsuga chinensis*, *Keteleeria*	–	–	–	–	18	0.20	0.08	5–26	0.5334	12.431	21	0.9669	5–26
Tropical forests	16	0.25	0.07	5–110	5	0.54	0.20	19–70	0.9745	12.068	21	0.9655	5–110
Metasequoia glyptostroboides	–	–	–	–	20	0.29	0.13	3–30	0.496	3.6048	25	0.899	3–30
Acer,*Tilia*, *Ulmus*[b]	–	–	–	–	–	–	–	–	0.7564	8.3103	11	0.98	–
Davidia[c]	–	–	–	–	–	–	–	–	0.8956	0.0048	22	0.99	–
Betula	93	0.31	0.08	5–75	93	0.31	0.08	5–75	0.8101	11.682	221	0.8815	5–75
Casuarina	–	–	–	–	40	0.17	0.06	3–30	0.8142	50.53	26	0.7179	3–30
Quercus	18	0.31	0.07	26–232	2	0.23	0.01	26–36	0.7848	16.715	157	0.9542	12–232
Eucalyptus	48	0.18	0.10	1–12	–	–	–	–	0.5631	10.835	64	0.7574	1–12
Larix	91	0.29	0.14	22–195	87	0.20	0.06	7–61	0.6079	17.062	368	0.8948	7–195
Phoebe, *Cinnamomum*	–	–	–	–	12	0.29	0.06	8–37	0.5381	41.881	13	0.7357	8–37
Mixed coniferous and broadleaf forest	42	0.24	0.14	17–238	97	0.23	0.10	4–220	0.4385	52.905	105	0.7179	4–460
Sassafras	7	0.16	0.02	17–51	9	0.23	0.06	5–19	0.8354	4.5822	13	0.9277	5–51

Table 1 (continued)

Forest type	Belowground/Aboveground biomass*								Parameters in Eq. 1				
	Natural				Planted								
	N_1	Mean	SD	Age range	N_2	Mean	SD	Age range	*a*	*b*	*n*	R^2	Age range
Pinus sylvestris, *Pinus densifolia*	11	0.24	0.04	53–180	40	0.24	0.16	5–47	0.5162	18.293	41	0.8357	8–180
Mixed coniferous[d]	2	0.20	0.01	28–33	40	0.36	0.20	4–35	0.7442	26.806	31	0.7026	4–33
Populus	43	0.23	0.09	6–58	67	0.20	0.09	4–32	0.6251	11.462	100	0.8537	5–58
Mixed broadleaf forest	26	0.29	0.14	20–130	13	0.26	0.12	3–48	0.7393	43.21	36	0.7314	3–130
Fraxinus, *Juglans*, *Phellodendron*	–	–	–	–	20	0.30	0.06	5–39	1.0394	2.3728	18	0.7516	5–39
Pinus densata	18	0.18	0.07	20–108	–	–	–	–	0.4508	29.099	18	0.9041	20–108
Acacia	–	–	–	–	13	0.22	0.05	1.5–21	0.572	49.996	12	0.5784	1.5–21
Pinus massoniana	36	0.18	0.07	16–101	84	0.17	0.07	4–70	0.6632	7.2656	123	0.7959	4–101

"–" means no value

[*] The ratio of belowground/aboveground biomass was calculated from the measured data with the consideration of forest types and origins, i.e., separate models were used for natural and planted forests following Wang et al. (2008)

[a] Hardwoods include *Ulmus pumila*, *Schima superba*, *Liquidambar taiwaniana*, *Tilia amurensis* and other hardwoods. Softwoods include willow, chinaberry tree and other softwoods

[b] Fang et al. 1998, 2001

[c] Feng et al. 1999

[d] Mixed coniferous include coniferous mixed forest and other pines, such as *Pinus elliotii*, *Pinus tbunbergii*, *Pinus qviffithii*, and exotic pine

Table 2 Areas, volume, calculated biomass carbon stocks and density of forests in seven inventory periods

	Total	Forest stands	Economic forests	Bamboo	Woodlands	Shrub forests	Trees on non-forest lands
Area (10^6 ha)							
1973–1976	173.88	117.12	8.52	3.04	15.63	29.57	–
1977–1981	175.12	116.64	11.28	3.20	17.20	26.80	–
1984–1988	189.57	124.53	13.74	3.55	19.64	28.12	–
1989–1993	199.78	132.16	16.10	3.79	18.03	29.71	–
1994–1998	195.27	129.20	20.22	4.21	7.20	34.45	–
1999–2003	220.32	142.79	21.39	4.84	6.00	45.30	–
2004–2008	239.86	155.59	20.41	5.38	4.82	53.65	–
Volume (10^9 m^3)							
1973–1976	7.68	7.55	–	–	0.56	–	0.13
1977–1981	9.21	7.98	–	–	0.54	–	0.69
1984–1988	9.52	8.09	–	–	0.55	–	0.89
1989–1993	10.74	9.09	–	–	0.55	–	1.10
1994–1998	11.31	10.09	–	–	0.14	–	1.09
1999–2003	13.26	12.10	–	–	0.13	–	1.03
2004–2008	14.55	13.36	–	–	0.11	–	1.08
Carbon stocks (Pg C)							
1973–1976	4.93	4.11	0.10	0.15	0.15	0.29	0.12
1977–1981	5.32	4.21	0.13	0.18	0.17	0.27	0.37
1984–1988	5.53	4.18	0.16	0.27	0.19	0.28	0.45
1989–1993	6.00	4.52	0.19	0.27	0.18	0.29	0.55
1994–1998	6.06	4.50	0.24	0.39	0.07	0.34	0.55
1999–2003	7.10	5.41	0.25	0.43	0.06	0.45	0.50
2004–2008	8.12	6.24	0.24	0.52	0.05	0.53	0.54
Carbon stock changes (Pg C $year^{-1}$)							
1973–1976							
1977–1981	0.099	0.025	0.008	0.008	0.005	–0.005	0.063
1984–1988	0.030	−0.004	0.004	0.013	0.003	0.001	0.011
1989–1993	0.094	0.068	0.006	0.000	−0.002	0.002	0.020
1994–1998	0.012	−0.004	0.010	0.024	−0.022	0.010	0.000
1999–2003	0.207	0.182	0.002	0.008	−0.002	0.022	−0.010
2004–2008	0.204	0.166	−0.002	0.018	−0.002	0.016	0.008
Carbon density (Mg C ha^{-1})							
1973–1976	28.33	35.10	–	–	–	–	–
1977–1981	30.40	36.11	–	–	–	–	–
1984–1988	29.18	35.53	–	–	–	–	–
1989–1993	30.04	34.21	–	–	–	–	–
1994–1998	31.04	34.84	–	–	–	–	–
1999–2003	32.22	37.89	–	–	–	–	–
2004–2008	33.85	40.12	–	–	–	–	–

"–" means no value. Carbon content is converted from biomass using a factor of 0.5. To evaluate historical changes in biomass carbon stocks (BCS) during the seven forest inventory periods, the areas and BCS of forest stands before 1994 were corrected to the values corresponding canopy coverage >20 % following Fang et al. (2007)

each province before 1994 to the values corresponding to canopy coverage >20 % based on the concurrent values of forest areas and BCS with canopy coverage >30 % and 20 % calculated from the fifth inventory data. This method was adopted this study to correct the forest areas and calculate BCS before 1994 for studying temporal dynamics of BCS.

2.4 Biomass calculation of other forest types

BCS of economic forests, woodlands and shrub forests was calculated as the product of average BCD and their total area (Ren et al. 2011). BCD was assumed to be 23.7 $Mg\,ha^{-1}$ for economic forests (Iwaki 1983) and 19.76 $Mg\,ha^{-1}$ for woodlands and shrub forests (Jin et al. 1990) without spatial variations considered.

BCS of bamboo was calculated as the average biomass per bamboo stem multiplied by the total number of bamboo stems. The former was assumed to be 22.5 kg for bamboos with DBH≥2.5 cm and Height≥3.5 m and 11.25 kg for other bamboos (Nie 1994). The density was assumed to be 3255 bamboos per hectare when bamboo density data are not available (Fang et al. 1996).

BCS of trees on non-forest lands was calculated as the volume of these trees multiplied by the average conversion parameters, which equals the total of calculated biomass divided by the total volume of forest stands in a province in the same period.

The fraction of carbon in biomass is assumed to be 0.5 for all forest types, although it varies slightly for different forests. Since one forest inventory spans 5 years for the whole country in China, the biomass carbon sink during two inventory periods was calculated as the BCS change divided by the interval between their middle years.

3 Results

3.1 Biomass carbon sink of forest stands

With the correction following Fang et al. (2007), the change in the definition of forest stands from 30 % to 20 % canopy coverage in 1994 has no noticeable effect on the progressions of forest area and BCS (Table 2). The area and BCS of forest stands increased from 117.12×10^6ha and 4.11 PgC during 1973 to 1976 to 155.59×10^6ha and 6.24 PgC during 2004 to 2008, respectively, indicating a biomass carbon sink of 0.07 $PgC\,year^{-1}$. About 38 % and 62 % of this sink were contributed by planted and established forests stands (Appendix S3). From 1973 to 1981, the area of forest stands decreased owing to the harvest of mature forests. The increase in BCS of middle-aged forests caused by the growth of young and middle-aged forests compensated for this timber harvest. Total BCS of forest stands increased from 4.11 to 4.21 PgC. From 1999 to 2008, BCS of forest stands increased significantly, owing to considerable increases in the area and BCD (Table 2), related to the implementation of the "Grain for Green" project initiated in 1998.

3.2 Biomass carbon sink of other forest types

The total areas of other types of forests accounted for 32.6–35.2 % of the total forest area from 1973 to 2008 (Table 2). BCS in woodlands decreased obviously while those of economic forests, bamboo, shrubs and trees on non-forestry land increased considerably. In total, BCS of these types of forests increased by 1.06 PgC from 1973 to 2008, indicating a biomass carbon sink of 0.03 $PgC\,year^{-1}$.

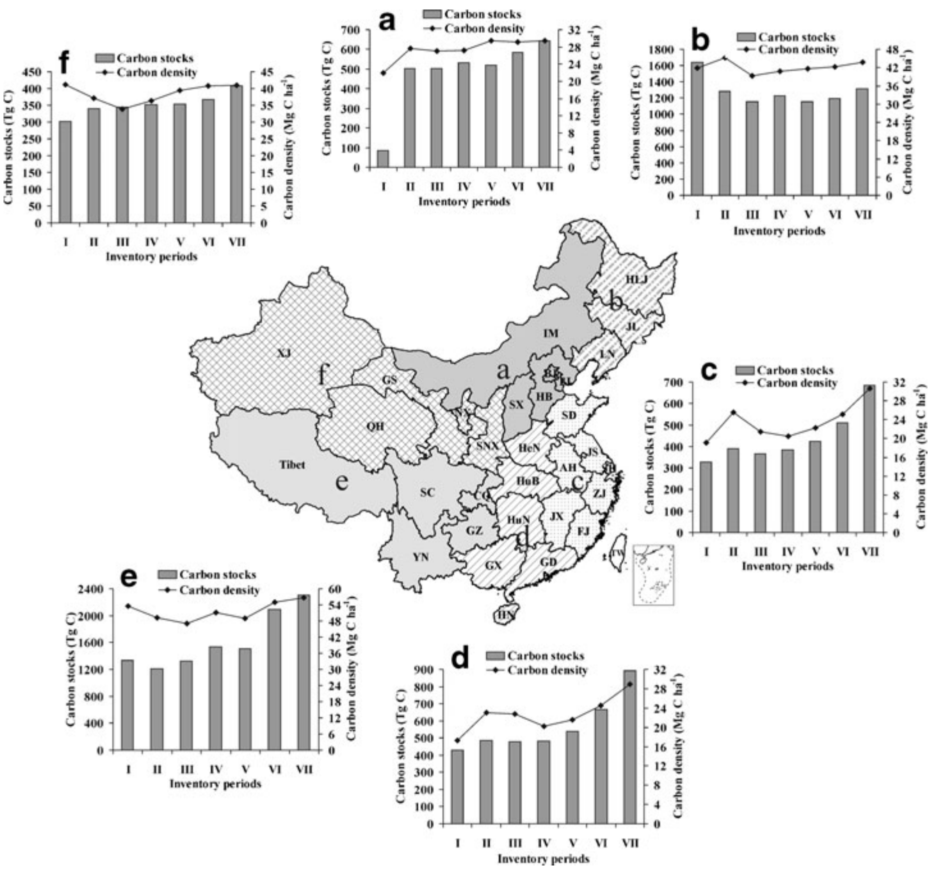

Fig. 1 Changes in biomass carbon stocks (BCS) and density of forest stands in different regions of China (not including Taiwan, Hongkong and Macao) from 1973 to 2008. The biomass carbon stocks (BCS) prior to 1994 were corrected using the method of Fang et al. (2007). Northern China (**a**) (including Beijing (BJ), Tianjin (TJ), Hebei (HB), Shanxi (SX), and Inner Mongolia (IM)); Northeastern China (**b**) (including Liaoning (LN), Jilin (JL) and Heilongjiang (HLJ); Eastern China (**c**) includes Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), Anhui (AH), Fujian (FJ), Jiangxi (JX) and Shandong (SD); Southern China (**d**) includes Henan (HeN), Hubei (HuB), Hunan (HuN), Guangdong (GD), Guangxi (GX) and Hainan (HN); Southwestern China (**e**) includes Chongqing (CQ), Sichuan (SC), Guizhou (GZ), Yunnan (YN) and Tibet; Northwestern China (**f**) includes Shannxi (SNX), Gansu (GS), Qinghai (QH), Ningxia (NX) and Xinjiang (XJ)

The total area and BCS of all types of forests in China increased from 173.88×10^6ha and 4.93 PgC during 1973 to 1976 to 239.86×10^6ha and 8.12 PgC during 2004 to 2008, respectively, indicating an average biomass carbon sink of 0.10 PgCyear^{-1}, with 66.7 % contributed by forest stands and 33.3 % by other types of forests. From 1999 to 2008, forest stands and other types of forests in China acted as biomass carbon sinks of 0.17 and 0.04 PgC year^{-1}, respectively (Table 2).

3.3 Biomass carbon sinks in different age groups of forest stands

In all inventory periods, BCS of mature forests (including premature, mature and overmature) accounted for the largest BCS fraction (~50 %) of forest stands (Appendix S4). During 1973–1981, BCS of mature forest stands decreased from 2.39 to 2.01 PgC. This loss of BCS was sufficiently compensated by the increase in BCS of middle-aged forest stands (0.44 PgC). BCS of young, middle-aged and mature forest stands steadily increased by 0.35, 0.61 and 1.10 PgC from 1984 to 2008, respectively, mainly driven by the increase in BCD for young stands and by the area expansion of middle-aged and mature forest stands.

From 1973 to 2008, BCD of young forest stands increased significantly from 13.12 to 22.22 $MgCha^{-1}$, while BCD of middle-aged forest stands slightly increased from 34.63 to 36.6 $MgCha^{-1}$. BCD of mature forest stands even showed a slight downward trend. Extensive plantation campaigns have been implemented since the 1970s in China. Currently, BCD of mature forest stands is 1–2 times higher than those of young and middle-aged forest stands, implying that China's forests can sequester more biomass carbon in the near future since young and middle-aged forests account for 34 % and 33 % of the total area of forest stands in 2004–2008.

3.4 Spatial and temporal patterns of biomass carbon sinks of forest stands

BCS and BCD of forest stands show substantial spatial and temporal variations (Fig. 1). About 28–39 % and 21–40 % of BCS of forest stands existed in the southwestern region and northeastern region, respectively. BCS of forest stands in other regions accounted only for a small fraction of the national total. BCD was also high in the southwest and northeast regions (40–57 $MgCha^{-1}$), in which productive subalpine coniferous forests and boreal forests are dominantly distributed. Forest stands in the southern and eastern regions are mainly plantations and have lower BCD (<30 $MgCha^{-1}$), owing to young stand age and greater human disturbances here (Fang et al. 2001).

From 1973 to 2008, forest stands in China were biomass carbon sinks in all regions except the northeast region (Fig. 1) (Appendix S5), in which BCS of forest stands decreased from 1636.8 to 1313.3 TgC. The decrease in BCS here occurred mainly from 1973 to 1988 and then BCS increased thereafter. BCS of forest stands in the southwestern region increased from 1332.6 TgC during 1973 to 1976 to 2300.3 TgC during 2004 to 2008. The increase in BCS of forest stands mainly occurred from 1994 to 2008, mostly driven by the increase of forest area (from 31.69×10^6 to 40.59×10^6ha). BCS of forest stands in the north region increased from 84.1 to 644.3 TgC from 1973 to 2008. This increase of BCS mainly occurred during the periods from 1973–1976 to 1977–1981 and from 1994–1998 to 2004–2008. In the east region, forest stands accumulated 356.7 TgC of BCS (from 328.1 to 648.8 TgC) from 1973 to 2008. The increase in BCS of forest stands showed an increasing rate after 1984 and equaled 175.3 TgC during 1999–2008. BCS of forest stands in the south region increased from 427.9 TgC during 1973 to 1976 to 890.9 TgC during 2004 to 2008 and showed a temporal pattern very similar to that in the east region. In the northwest region, BCS of forest stands increased at a similar magnitude in the periods from 1973–1976 to 1977–1981 (13.0 %) and from 1999–2003 to 2004–2008 (11.0 %). From 1999 to 2008, BCS of forest stands increased above 10 % in all regions of China.

BCD of forest stands increased in all regions except the northwest region from 1973 to 2008. The largest magnitude of increase in BCD occurred in the south region (67.3 %) while it slightly decreased by 0.5 % in the northwest region (Appendix S6). The south and east regions exhibited very similar temporal variations in BCD of forest stands, significantly increased during the periods from 1973–1976 to 1977–1981 and from 1994–1998 to 2004–2008. The latter large increase in BCD here was mainly due to the initiation of South China

Timber Production Program in the middle 1980s and growth of mature forests (Fang et al. 2001; Piao et al. 2005). In the north region, the increase in BCD of forest stands mainly occurred in the periods from 1973–1976 to 1977–1981 (25.7 %) and from 1989–1993 to 1994–1998 (8.5 %). In the northeast region, the BCD of forest biomass decreased during the period from 1977–1981 to 1984–1988 (−13.2 %) and then increased slightly. In the southwest region, BCD of forest stands showed a bimodal increasing trend during the entire study period. During 2004 to 2008, the southwest region had the highest BCD of forest stands (56.7 $MgCha^{-1}$) and the south region had the smallest one (28.9 $MgCha^{-1}$).

From 1973 to 2008, the increases of BCS were mainly driven by the area expansion in the north, northwest, southwest regions with abundant land resources and by the increase of BCD in the densely populated south and east regions. The reduction of forest area caused BCS to decrease in the northeast region.

4 Discussion

4.1 Comparison of calculated BCS of forest stands

4.1.1 The comparison of BCS calculated using the same method

Fang et al. (2001, 2007) and Guo et al. (2010) calculated BCS of forest stands in China using the same CBEF method and inventory data. However, the grouping of dominant tree species differs between these previous and our current studies, being 21 and 30 groups, respectively. The number of plots used to determine model parameters also differs, being 758 and 3543 plots, respectively. Fang et al. (2001) estimated that BCS of forest stands (canopy coverage >30 %) in China was 4.44, 4.38, 4.45, and 4.63 PgC for the periods of 1973–1976, 1977–1981, 1984–1988, and 1989–1993, respectively. With refined model parameters, Fang et al. (2007) and Guo et al. (2010) estimated that BCS of forest stands was 5.01 and 5.85 PgC for the periods of 1994–1998 and 1999–2003, respectively. Our BCS values (canopy coverage >30 % before 1994 and then >20 %) (Appendix S7) were 7.5–18.2 % lower. When calculated using the same grouping scheme of tree species and parameters as Fang et al. (2001), calculated BCS increased by 4.7–10.0 % relative to the values calculated using the new grouping scheme and parameters determined in this study for 1977–1981 to 1999–2003, but still slightly lower than the corresponding values of Fang et al. (2001, 2007).

The difference in calculated BCS in our study and in Fang et al. (2001, 2007) is mainly due to the difference in estimated BCD, which is significantly affected by the parameters a and b in Eq. 1. After just refining parameters a and b, Guo et al. (2010) reported the BCS values 9.7 % and 3.8 % lower than those of Fang et al. (2001) in the periods of 1984–1988 and 1989–1993, respectively. Pan et al. (2004) pointed out that BCS might be overestimated above 35 % by Fang et al. (2001) due to small datasets used to fit model parameters and a skewed age distribution of sample plots towards younger ages. The samples of some deciduous forest types (*Betula*, *Casuarina*, and *Quercus*) in Fang et al. (2001, 2007) were too small due to data availability, possibly resulting in uncertainties in estimated BCS. Fortunately, we were able to collect more data from literature to refine model parameters and constrain uncertainties in calculated BCS, mainly due to the intensive studies on forest biomass in China in recent years.

4.1.2 Comparison of BCS calculated using different methods

With an age-specific CBEF method, Pan et al. (2004) estimated that BCS of forest stands in China was 3.51, 3.60, 3.69, and 4.02 PgC for the periods of 1973–1976, 1977–1981, 1984–1988, and 1989–1993, respectively (Appendix S7). With the same method, Xu et al. (2007) estimated that BCS of forest stands in China ranged from 3.70 to 5.51 PgC during the periods 1977–1981 to 1999–2003. Our calculated BCS and BCD are very close to the values of Pan et al. (2004) and slightly lower than the values of Xu et al. (2007). Our numbers were about 6.0 % higher than the values reported by Zhao and Zhou (2004, 2006) for the periods of 1984–1988 and 1989–1993 and by Wang et al. (2010) for the period of 1999–2003 using a hyperbolic function.

BCS of forest stands estimated using the same inventory datasets differed to some extent in previous and current studies, mainly caused by the differences in methods and parameters. Most studies assumed linear relationships between volume and biomass, which were derived from field measurements. This treatment makes the calculation of BCS using provincial-level statistical volume data feasible. Parameters a and b in Eq. 1 significantly affect estimated BCS. Data used to fit these two parameters are usually not enough or skewed to certain age classes. They were determined only for 21 groups of tree species in Fang et al. (2001, 2007) and 13 groups of tree species in Pan et al. (2004) and Xu et al. (2007), respectively. In addition, most field biomass and volume data used in previous studies were collected by Luo (1996), in which, approximately 88 % of the plots are natural forests while natural forests only accounted for 70–82 % of total forest stands in the inventory data. Above limitations might induce biases in estimated BCS. In this study, we update this dataset by adding planted plots of some forest types. In total, data from 3543 plots were used to determine a and b for 30 tree groups which cover most dominant tree species in the inventory datasets.

4.2 Effect of stand age distribution in field data on estimated BCS

BCS increases greatly with forest age. Pan et al. (2004) demonstrated that higher percentage of data from young and middle-aged field plots used to develop the model might lead to BCS overestimation of old forests. In current study, we tried to collect data of forests at various ages to avoid this problem. For most tree species, the percentages of plots in different age categories are close to the area percentages of different ages in the inventory data from 1973 to 2008 (Table 3). However, the percentages of premature and/or mature stands of *Cunninghamia lanceolata*, *Quercus*, mixed coniferous and broadleaf forest, *Pinus yunnanensis*, and *Pinus kisiya* in the field dataset are slightly higher than the corresponding values in the inventory datasets. For *Betula*, *Cunninghamia lanceolata*, and *Quercus*, the percentages of plots in young groups are lower than those in the inventory datasets.

Pan et al. (2004) and Xu et al. (2007) considered that the age-specific CBEF method is more applicable than the CBEF method ignoring age effects. The fitted model parameters a and b show an opposite changing trend with ages (Pan et al. 2004). We established the relationships between biomass and volume for widely distributed tree species with large number of samples in wide ranges of ages. Estimated BCS did not show any obvious bias in any age groups (Fig. 2), supporting our inference that BCS can be estimated using inventory data with one set of model parameters for all age groups if sample plots used to fit model parameters are enough and evenly distributed in different age groups. This is due to the linear relationship between BCS and volume. A similar conclusion has been indicated by

Table 3 Percentages of forests in different age groups in the inventory and field datasets

	Young	Middle-aged	Premature	Mature	Overmature
Area percentage (%) in inventory data					
Betula	21.18–32.54	36.01–46.14	7.35–20.56	9.68–14.95	5.26–7.39
Cunninghamia lanceolata	23.58–59.02	26.58–50.71	8.25–15.16	6.26–9.27	0.96–1.28
Quercus	39.91–45.56	23.50–37.52	8.90–13.96	10.92–11.75	4.79–6.07
Larix	21.74–35.28	15.73–43.48	8.31–12.18	12.51–22.92	7.63–9.73
Mixed coniferous and broadleaf forest	15.20–37.67	24.89–43.90	11.55–13.37	8.21–15.77	1.57–5.16
Softwood, softwood	33.81–64.47	27.26–37.88	7.34–13.29	8.04–10.01	3.03–4.07
Mixed broadleaf forest	22.40–37.27	31.94–46.75	11.10–20.48	10.72–18.43	2.04–6.30
Pinus massoniana	32.52–70.18	22.19–44.06	6.45–17.24	1.40–5.73	0.20–0.45
Populus	29.38–46.08	22.37–36.45	10.62–18.07	12.38–16.24	4.10–8.75
Abies, *Pieca*,	3.65–8.57	12.86–18.72	9.09–14.11	32.77–51.05	18.48–36.64
Pinus tabulaeformis,	26.79–70.68	23.26–45.49	3.81–20.63	1.52–14.42	1.37–10.33
Pinus yunnanensis, *Pinus kisiya*	27.01–39.27	28.35–40.79	15.43–19.83	11.15–17.86	4.54–7.43
Percentage of plots in field data (%)					
Betula	11.76	36.20	21.27	22.17	8.60
Cunninghamia lanceolata	16.67	44.70	20.45	15.15	3.03
Quercus	24.84	35.03	31.21	7.01	1.91
Larix	35.05	17.66	10.60	25.00	11.68
Mixed coniferous and broadleaf forest	21.00	27.00	25.00	17.00	10.00
Softwood, softwood	51.84	30.20	8.16	8.57	1.22
Mixed broadleaf forest	55.56	19.44	5.56	13.89	5.56
Pinus massoniana	37.40	43.90	9.76	7.32	1.63
Populus	35.00	24.00	9.00	17.00	15.00
Abies, *Pieca*,	1.73	14.45	13.29	34.10	36.42
Pinus tabulaeformis,	23.30	39.68	8.66	20.64	7.72
Pinus yunnanensis, *Pinus kisiya*	31.37	29.41	7.84	13.73	17.65

Teobaldelli et al. (2009) and Guo et al. (2010) and is also supported by the close values of estimated BCS in Pan et al. (2004) and this study.

4.3 Comparison of biomass carbon sinks by forests in China with other countries

Estimated BCS of all types of forests in China increased from 4.93 to 8.12 PgC from 1973 to 2008 while estimated BCS of forest stands increased from 4.11 to 6.24 PgC (Table 2). Forest stands contributed to 87.9 % and 81.4 % of total biomass carbon sink of forests in China in 1999–2003 and 2004–2008, respectively.

Pan et al. (2011) estimated that forest biomass carbon sink in China, United States, Europe, Japan, South Korea, Russia, and Canada (with a total forest area of 1619×10^{6}ha) was 0.59 PgC$\,$year^{-1} during 1999–2008. According to this study, China's forest stands are the biggest contributor (about 29.3 %) of the biomass carbon sink of forests in these regions

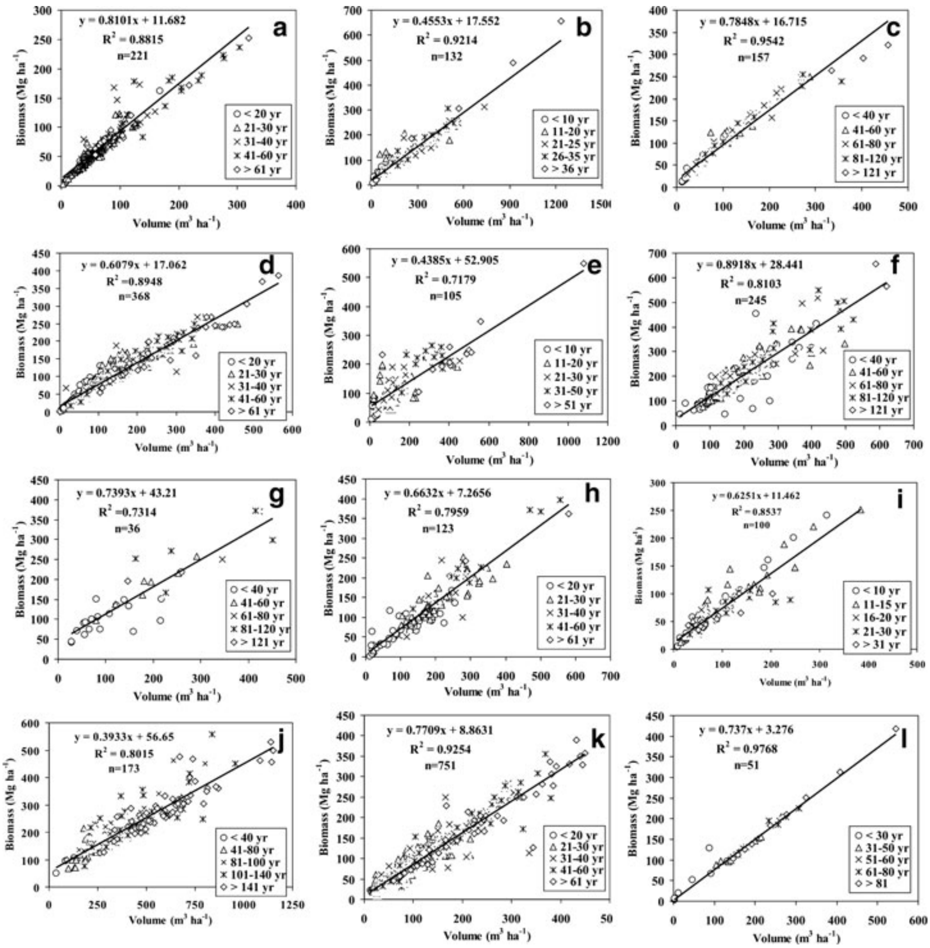

Fig. 2 Relationships between biomass and volume for major forest types. The *solid black lines* are the regression lines fitted using data in all age groups. **a** *Betula*, **b** *Cunninghamia lanceolata*, **c** *Quercus*, **d** *Larix*, **e** mixed coniferous and broadleaf forest, **f** softwood and hardwood, **g** mixed broadleaf forest, **h** *Pinus massoniana*, **i** *Populus*, **j** *Abies* and *Pieca*, **k** *Pinus tabulaeformis*, and **l** *Pinus yunnanensis* and *Pinus kisiya*

although their area only accounted for 9.2 % of the total (Appendix S8). The biomass carbon sink strength of forest stands in China was 1.17 $\text{MgC ha}^{-1}\text{year}^{-1}$, second only to the value of South Korea (1.89 $\text{MgC ha}^{-1}\text{year}^{-1}$) (Li et al. 2010). The biomass carbon sink strength of planted and natural forest stands in China was 1.27 and 1.13 $\text{MgC ha}^{-1}\text{year}^{-1}$ from 1999 to 2008, respectively. The latter was larger than those of forest stands in United States, Russia, and Canada, and slightly higher than those of forest stands in Europe and Japan (Appendix S3 and S8). The large biomass carbon sink of forest stands in China primarily resulted from the change in stand age structure, the consequence of intensive national afforestation and reforestation programs in the last few decades (Appendix S4, Fang et al. 2001, 2007). The planted forests were a biomass carbon sink of 46 TgC year^{-1} during 1999 to 2008 (Appendix S3).

4.4 Uncertainties and limitations in currently estimated BCS

BCS were estimated from inventory data using the empirical relationships between volume and biomass, which were developed using limited field measurements. Smith et al. (2002) indicated that if the number of samples used to develop a biomass model is inadequate, the error of estimated BCS might reach 10 %. We tried to collect almost all data published in recent decades in China. The number of plots for some forest types is still too small. In addition, the field data might be collected with different methods, dates, and plot sizes. At some plots, the belowground biomass was estimated from aboveground biomass and the ratio of belowground biomass to aboveground biomass of same tree species. Uncertainties in field biomass data might induce errors in estimated BCS.

Only a few previous studies calculated BCS of all types of forests at national (Fang et al. 1998; Pan et al. 2004) and provincial (Ren et al. 2011) levels. This study estimated BCS of all types of forests in China for all seven inventory periods using approximation methods. Uncertainties in BCS for non-forest stands need further assessment.

It is currently impossible to analyze the detailed spatial patterns of BCS and BCD using inventory datasets. The relationship between volume and biomass only represents the impact of biotic factors on forest growth and biomass carbon accumulation, which are also influenced by abiotic factors, such as climate change, atmospheric CO_2, and nitrogen deposition (Zhao and Zhou 2006; Hyvonen et al. 2007; Ju et al. 2007). The response of forest carbon sequestration to these factors and its future trends need to be investigated using modeling approaches (Ju et al. 2007).

5 Conclusions

In this study, BCS of forests in China was calculated using seven inventory datasets from 1973 to 2008 and the refined CBEF model. The effects of forest area and BCD changes on BCS dynamics in different regions were explored. Following conclusions can be drawn:

(1) During the period from 1973 to 2008, total BCS of all types of forests in China increased from 4.93 PgC to 8.12 PgC with increases of 2.13 PgC by forest stands and 1.06 PgC by other types of forests, respectively. Total BCS of forest stands increased by 51.8 %, mainly driven by area expansion.
(2) Forest stands in China acted as an average biomass carbon sink of 0.17 $PgC year^{-1}$ from 1999 to 2008. BCD of young and middle-aged forests is largely smaller than the value of mature forests. Currently, about 67 % of forest stands in China are at young and middle ages and will have a large carbon sequestration potential in the future.
(3) BCS of forest stands increased in all regions but the northeast region during the study period. The increase of BCS in the densely populated south and east regions was mainly driven by the increase in BCD while it was mainly due to the area expansion in the north, northwest, and southwest regions with relatively abundant land resources. BCS increased in all regions from 1999 to 2008.

In this study, we refined the estimates of forest BCS and sinks in China. However, other carbon pools in forest ecosystems were not examined. The results from this study would be a basis for completely evaluating carbon budget in forest ecosystems related to dynamics of soil organic matter and detritus and emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) caused by forest fires using modeling approaches and the IPCC method.

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