The relative contributions of forest growth and areal expansion to forest biomass carbon

Peng Li[a#], Jiangling Zhu[a#], Huifeng Hu[b], Zhaodi Guo[a,c], Yude Pan[d], Richard Birdsey[d], Jingyun Fang[a]*

[a] Department of Ecology, College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes, Ministry of Education, Peking University, Beijing 100871, China

[b] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

[c] National Satellite Meteorological Center, China Meteorological Administration, Beijing 100081, China

[d] U.S. Department of Agriculture Forest Service, Newtown Square, PA 19073, USA

[#] Both authors equally contributed to this work

Corresponding author:
Name: Jingyun Fang
E-mail: jyfang@urban.pku.edu.cn
TEL: 86-10-62765578
FAX: 86-10-62756560

ABSTRACT

Forests play a leading role in regional and global terrestrial carbon (C) cycles. Changes in C sequestration within forests can be attributed to areal expansion (increase in forest area) and forest growth (increase in biomass density). Detailed assessment of the relative contributions of areal expansion and forest growth to C sinks is crucial to reveal the mechanisms that control forest C sinks and is helpful for developing sustainable forest management policies in the face of climate change. Using the Forest Identity concept and forest inventory data, this study quantified the spatial and temporal changes in the relative contributions of forest areal expansion and increased biomass growth to China’s forest biomass C sinks from 1977 to 2008. Over the last 30 years, the areal expansion of forests was a larger contributor to C sinks than forest growth for planted forests in China (62.2% *vs.* 37.8%). However, for natural forests, forest growth made a larger contribution than areal expansion (60.4% *vs.* 39.6%). For all forests (planted and natural forests), growth in area and density contributed equally to the total C sinks of forest biomass in China (50.4% vs. 49.6%).The relative contribution of forest growth of planted forests showed an increasing trend from an initial 25.3% to 61.0% in the later period of 1998 to 2003, but for natural forests, the relative contributions were variable without clear trends owing to the drastic changes in forest area and biomass density over the last 30 years. Our findings suggest that afforestation can continue to increase the C sink of China's forests in the future subject to sustain forest growth after establishment of plantation.

Keywords:

biomass density, biomass expansion factor, carbon sink, forest area, forest growth, forest identity

1. Introduction

As the largest terrestrial ecosystem, forests occupy around 30% of the global land surface area (Bonan, 2008; Pan et al., 2013) and play a dominant role in regional and global carbon (C) cycles because of their huge capacity for C storage and high productivity (Leith and Whittaker, 1975; Malhi et al., 2002; Pan et al., 2011). Forests can be sources of atmospheric CO_2 following anthropogenic and natural disturbances, but can also function as C sinks to sequester or conserve large quantities of C during regrowth after disturbances (Brown et al., 1996, 1999; Brown and Schroeder, 1999; Hu and Wang, 2008; Pan et al., 2011). Therefore, investigation of the possible mechanisms of forest C dynamics is of scientific and political importance (Watson et al., 2000; Fang et al., 2001, 2014a, b; Janssens et al., 2003; Nabuurs et al., 2003; Birdsey et al., 2006; McKinley et al., 2011).

China has the fifth-largest forest area of any country in the world (Ministry of Forest of China, 2009) and encompasses a variety of forest biomes, from boreal forests in the north to subtropical/tropical evergreen broadleaf forests in the south (Fang et al., 2010). With the implementation of national afforestation and reforestation programs since the late 1970s, such as the Three-north Protective Forest Program, the Natural Forest Conservation Program, and the Wetland Restoration Program, forest ecosystems in China are credited with making a significant contribution to regional and global C sinks in recent decades (Fang et al., 2001, 2014a; Fang & Chen, 2001; Lei, 2005; Xu et al., 2010; Pan et al., 2011; Guo et al., 2013). Based on the biomass expansion factor (BEF) method and China’s forest inventory data, Guo et al. (2013) estimated the spatio-temporal changes in the forest biomass C sink from 1977 to 2008 and concluded that the annual biomass C sink (70.2 Tg C year^{-1}, 1 Tg = 10^{12} g) offset 7.8% of the contemporary CO_2 emissions in the country.

In general, increased forest biomass C sinks are driven by forest areal expansion and forest regrowth. The Forest Identity concept, developed for separating the variables of change in forest area, biomass and C densities (Kauppi et al. 2006, Waggoner, 2008) , is useful to develop the method to estimate the change in forest biomass C stock driven by different causes. Using the Forest Identity concept, Shi et al. (2011) evaluated the status of change in China's forests and showed that the increase in C sequestration was attributable to the increase in forest area and growing stock density over the last three decades. More recently, to explore the mechanisms that drive forest C sinks in East Asia, Fang et al. (2014a) used the Forest Identity approach to estimate the relative contributions of changing forest area and forest C density to the forest biomass C sink in China, Japan and South Korea. These studies found that the relative contributions of the changing factors varied among countries and forest origin (planted vs. natural forests). Specifically, it was reported that forest areal expansion made a larger contribution to C sinks than increased biomass density for all forests. However, the study of Fang et al. (2014a) did not analyze the spatial and temporal variability in the relative contributions of forest areal expansion and increased biomass density to China's forest C sinks. In this study, we used the Forest Identity concept and forest inventory data to quantify in detail the spatial and temporal difference in the relative contributions of forest areal expansion and increased biomass density to China's forest C sinks during the past 30 years. Furthermore, we discussed the primary reasons for reduced biomass C stocks of natural forests in some provinces of China.

2. Data and Methods

2.1. Forest inventory data

China's forest inventory data (CFID) for the periods 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, and 2004–2008 were used in this study (Chinese Ministry of Forestry, 1983, 1989, 1994, 2000, 2005, 2010). These inventories were compiled from more than 250,000 plots (160,000 permanent sample plots plus 90,000 temporary sample plots) across the country. Systematic sampling with a grid of 2 km by 2 km or 4 km by 4 km and an area of 10 m by 10 m was used depending on forest region. In CFID, China's forests were classified into three categories: stands (including natural and planted forests), economic forests (woods with the primary objective of production of fruits, edible oils, drinks, flavorings, industrial raw materials, and medicinal materials), and bamboo forests (Guo et al. 2013). In the present study, "forest" refers only to a "forest stand" with canopy coverage ≥ 20% and therefore excludes economic and bamboo forests (Fang et al., 2007). At the provincial level, the inventories documented detailed information on age class, area, and volume for each forest type, in which forest area was estimated by the "ratio method" in the systematic sampling across each province (see Appendix E). To investigate spatial variation, we divided the national land area into six broad regions—North, Northeast, East, South Central, Southwest, and Northwest—consistent with the method of Fang et al. (2001) (Fig. 1c).

2.2. Calculation of forest biomass C stocks

In this study, we used the continuous biomass expansion factor (BEF, defined as the ratio of stand biomass to timber volume) method with parameters for each forest type taken from Guo et al. (2013) to calculate forest biomass in China, because the CFID only report the forest area and timber volume for each forest type. The BEF method was firstly developed from the allometric relationships between forest biomass and forest timber volume (Fang et al 1998; Brown and Schroeder, 1999), then evolved to be the continuous BEF method based on the reciprocal equation expressing BEF−timber volume relationship (Fang et al. 1998, 2001, 2005):

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

In Eq. (1), x is the timber volume per unit area (m^3 ha^{-1}), and a and b are constants for each specific forest type. With this simple BEF approach, one can easily calculate regional or national forest biomass based on direct field measurements and forest inventory data. Calculations with the BEF method are well documented by Fang et al. (2001, 2014a) and the BEF method has been applied previously to estimate China's forest stand biomass (Fang et al., 2007; Guo et al., 2013). In this study, the ratio of 0.5 was used to convert biomass to C stock (Fang et al., 2001).

2.3. Calculation of the relative contributions of forest areal expansion and increased biomass density

Using the Forest Identity concept (Kauppi et al., 2006; Waggoner, 2008), Fang et al. (2014a) proposed the method to separate relative contribution of forest areal expansion and forest growth to changes in forest biomass stock (or biomass C sink/source). According to Fang et al. (2014a), the relationships among forest area (*A*), biomass C density (*D*), and total biomass C stock (*M*) can be formulated by Eq. (2), and their respective rates of change (*a*, *d*, and *m*) over time (*t*) can be derived- from Eqs. (3) and (4).

$$M = A \times D\,. \tag{2}$$

Because $\ln(M) = \ln(A) + \ln(D)$,

the relative change rates of *M*, *A*, and *D* over time (*m*, *a*, and *d*) are the direct result of differentiating the equation over time

$$\frac{1}{M}\frac{dM}{dt} = \frac{1}{A}\frac{dA}{dt} + \frac{1}{D}\frac{dD}{dt}\text{, or }\frac{d\ln(M)}{dt} = \frac{d\ln(A)}{dt} + \frac{d\ln(D)}{dt} \tag{3}$$

Let the real change rate (*m*, *a* and *d*) among two inventory periods approximately equal to the change rate of its natural logarithm:

$$m \approx \frac{d\ln(M)}{dt}, a \approx \frac{d\ln(A)}{dt}, d \approx \frac{d\ln(D)}{dt}$$

Then, $m = a + d$

where *M*, *A*, and *D* represent total biomass C stock (Tg C or Pg C, 1Tg =10^{12} g, 1Pg = 10^{15} g), forest area (ha), and biomass C density (Mg C ha^{-1}, 1Mg =10^{6} g), respectively; and *m*, *a*, and *d* are the corresponding derivatives (or rate of change) of these attributes over time (*t*). The rates (*m*, *a*, and *d*) can be approximately calculated by the following formulas (Eq. 4):

$$Change\,rate(\%\ \mathrm{yr}^{-1}) \approx \frac{2\left(X_2 - X_1\right)}{\left(X_2 + X_1\right)\left(t_2 - t_1\right)} 100\% \qquad (4)$$

where X_1 and X_2 represent the forest area (*A*) or biomass C density (*D*) in the forest inventory period going from t_1 and t_2, respectively.

Thus, the relative contribution of change in forest area (R_a, %) and change in biomass density (R_d, %) to the change in forest biomass C stock can be expressed as Eq. (5):

$$R_a\ (\%) = a/m\ \times 100;\ R_d\ (\%) = d/m\ \times 100 \qquad (5)$$

The carbon sinks attributing to areal expansion (M_a) or growth in forest density (M_d) was derived from the multiplication of the relative contribution (%) and the total carbon sinks (ΔM)

$$M_a = R_a\ (\%)\ \times \Delta M\ ; \quad M_d = R_d\ (\%)\ \times \Delta M \qquad (6)$$

For all forests, the relative contributions (*R*, %) of areal expansion or growth in density were calculated by the ratio of carbon sinks in planted and natural forests to the carbon sinks of all forests (Eq.7).

$$R_a\ (\%) = \{M_a\ (planted)+M_a\ (natural)\}\ \times 100\ /\ \Delta M\ ;$$

$$R_d\ (\%) = \{M_d\ (planted)+M_d\ (natural)\}\ \times 100\ /\ \Delta M\ ; \qquad (7)$$

3. Results

3.1. Spatial pattern of the relative contributions of forest area and biomass density to C sinks

Figure 1 shows the results of the national and regional relative contributions of forest areal expansion (*a*) and increased biomass C density (*d*) to the C sinks planted, and natural forests between the late 1970s (1977–1981) and the 2000s (2004–2008)

Planted forests have functioned as C sinks (817.6 Tg C) in the past three decades (Appendix A), and areal expansion made a larger contribution to the C sink than did change in biomass density in all regions (Fig. 1a). At the national level, the area of planted forests increased at a mean rate of 3.18% year^{-1} and contributed 62.2% to biomass C sinks of planted forests between 1977 and 2008. Among the six regions, the largest contribution of areal expansion (78.2%) was in the Southwest, followed by the North (71.2%), South Central (60.4%) and East (57.1%) regions. The contributions of areal expansion and increased biomass density were approximately equal to 50% in the Northeast and Northwest regions.

In contrast to planted forests, areal expansion of natural forests was found to be a smaller contributor to the C sink (892.1 Tg C) than increased biomass density (39.6% vs. 60.4%) at the national level, with a and d of 0.27 and 0.41% year^{-1}, respectively (Fig. 1b). However, the patterns were not consistent at the regional level: forest areal expansion made a larger contribution to the C sink than did increased biomass density in the Southwest (63.2% vs. 36.8%) and South Central (58.0% vs. 42.0%) regions, and in the East region areal expansion was responsible for all of the C sink (104.0%), because the C density of natural forests has shrunk by 0.49% over the last 30 years (d = –0.02% year^{-1}) (also see Appendix B). Conversely, in North and Northwest China, increased C density dominated the C sinks, with contributions of 98.4% and 107.0%, respectively. In the Northeast region, the area of natural forest has decreased at a mean rate of 0.27% year^{-1}, which exceeds the increase in C density (d = 0.24% year^{-1}), and has ultimately contributed fully to the C source of the natural forest in this region.

On the whole, for all forests (planted and natural forests), the biomass C sink attributing to areal expansion and growth in density was 862.3 Tg C and 847.5 Tg C , respectively, indicating an equal relative contribution to the total forest biomass C sinks from this two driving agents in study period (50.4% vs. 49.6%, Table 1)..

3.2 Temporal dynamics of the relative contributions of forest area and biomass density to C sinks

We further explored changes of the relative contributions of forest areal expansion and biomass density to C sinks of Chinese forests from 1977 to 2008 (Fig. 2), by calculating the change rates (*a* and *d*) and the relative contribution rates for the six forest inventory periods.

For planted forests, the rate of change in forest area was highest in the 1980s (1981–1988; Fig. 2a) with a mean increase of 5.45% year^{-1}, then decreased until the late 1990s (1993–1998), and thereafter increased in the 2000s. Over the same period, forest biomass C density has experienced slow but relatively steady enhancement from the early 1980s to the early 2000s (Fig. 2a), reaching the highest rate of increase in the period 1998–2003 (d = 2.33% yr^{-1}), and then decreased abruptly to a low rate of increase (0.60% year^{-1}) in the late 2000s (2003–2008). The relative contribution of areal expansion declined from 74.4% between 1981 and 1988 to 39.0% between 1998 and 2003, whereas the contribution of increased C density increased from 25.6% to 61.0% over the same period (Fig. 2c). After 2003, on account of the rapid growth in forest area (Fig. 2a), the contribution of areal expansion increased and became the dominant contributor to the C sink of China's planted forest (87.7% vs. 12.3% for 2003–2008).

In contrast to planted forest, the areal expansion and increase of C density in natural forests were more dynamic, having relatively lower rates of change less than 1.5% year^{-1} over the study period (Fig. 2b). Furthermore, negative growth was observed in forest area (a = −1.80% year^{-1} for 1993–1998) and biomass C density (d = −0.08 and −0.20% year^{-1} for 1981–1988 and 1998–2003, respectively) in natural forest over the study period. Aligning with dynamic rates of change, the relative contribution of forest areal expansion showed a generally decreasing trend from 1981 (366.7%) to 2008 (70.2%), in contrast to the increase in C density (Fig. 2d). In addition, areal expansion always made a greater impact on the carbon sink than did the change in C density in most of the inventory periods, except for the period of 1988–1993, when increased C density made a slightly larger contribution than areal expansion

(51.1% vs. 48.9%).

3.3 Causes of C loss of natural forests at the provincial level

Over past three decades, planted forests have functioned as C sinks in all provinces of China (Appendix C). However, three provinces showed a distinct C loss in their natural forests over the study period (Appendix D): Heilongjiang (located in Northeast), Gansu (Northwest), and Fujian (East). Among these provinces, Heilongjiang contained the largest area of natural forest (1817.9 10^4 ha; 1977–1981) in China, of which the biomass C stock has shrunk by 47.2 Tg C (783.7 Tg C during 1977 –1981 to 736.5 Tg C in the 2000s). The C stocks of natural forest in Gansu and Fujian also underwent a decline from 87.0 and 132.8 Tg C in the 1970s to 82.4 and 128.9 Tg C in the 2000s, respectively. Here, we focused on these three provinces to explore the reasons for the declines in C stock of the natural forests over the past 30 years by quantifying the relative contributions of changes in forest area and C density.

Among the three provinces, biomass C density of natural forests increased more or less from 1977 to 2008; the rate of change was highest in Gansu (d = 0.66% year^{-1}), whereas only slight increases were observed in Heilongjiang and Fujian (Fig. 3, Appendix E). Conversely, the forest area in these provinces experienced more obvious decreases. The forest area in Heilongjiang decreased dramatically by 133.6 10^4 ha (a = −0.28% year^{-1}) over the last 30 years, followed by that of Gansu (41.1 10^4 ha, a = −0.85% year^{-1}) and Fujian (12.9 10^4 ha, a = −0.14% year^{-1}). Detailed analysis of the temporal dynamics of change rates in these provinces demonstrated that most of the decline in forest area occurred between 1981 and 1998 (Fig. 4a, c and e), whereas the contributions of forest area to the C stock change of these provinces increased rapidly, attaining their highest values (Fig. 4b, d and f). Overall, the rapid decline in forest area has exceeded the contribution of increased C density, and ultimately caused the C loss in these provinces (Figs. 3 and 4).

4. Discussion

4.1. Relative contributions of changes in forest area and biomass density to the C sink in China's forests

Over the past three decades, areal expansion and forest growth have increased C stocks in both planted (817.6 Tg C) and natural (892.1 Tg C) forests. However, the mechanisms underlying the C sinks differed markedly with various effects from these two driving agents (Fig. 5).

For planted forests, areal expansion made a larger contribution than did biomass growth at both national and regional levels (Fig. 1a). Benefiting from the implementation of national afforestation and reforestation projects since the 1970s (Fang et al., 2001; Li, 2004; FAO, 2006; Wang et al., 2007), the area of planted forest in China has expanded dramatically from 16.95 10^6 ha to 24.05 10^6 ha over the last 30 years (Appendix B). Meanwhile, the growth of these young forests also made a significant contribution to C sequestration; the biomass density of planted forest has increased by 71.2% from an initial density of 15.6 Mg C ha^{-1} to 26.7 Mg C ha^{-1} in the late 2000s (2004–2008), which indicates that planted forest could still sequester additional C through future growth (Guo et al., 2010; Xu et al., 2010).

Compared to planted forests, growth of existing natural forests was a larger contributor to the C sink than areal expansion at the national level (60.4% vs. 39.6% for density change vs. area change), because the biomass density has increased more rapidly, with a net gain of 4.8 Mg C ha^{-1} (11.6%), than did forest area (7.4%). Regional disparities were also apparent. Forest growth dominated the C sink in the North and Northwest regions, but made a smaller contribution in the Southwest, South Central and East regions (Fig. 1b). The inconsistent patterns in the contributions of forest growth and areal expansion may be associated with differences in forest management policies, harvest intensity, and climatic factors (e.g., the warming climate, increasing summer precipitation, elevated CO_2, and natural nitrogen deposition) among these regions (Fang et al., 2004; Du et al., 2014; Also see in Fang et al. 2014b). For instance, southern and southwest China has experienced drier and hotter climate in the last 3 decades while northern China became wetter and had longer growing seasons (Peng et al., 2011), which may effectively contribute to the enhanced C densities in the northern regions

4.2. Dynamics of areal expansion and forest growth in planted and natural forests

It is generally recognized that areal expansion and forest growth are closely associated with the intensity of reforestation and loss of forest cover (e.g. deforestation, industrial harvest or natural disturbance). Therefore, implementation of forest management policies may have a strong impact on forest C sequestration via the introduction of a variety forest projects in a country (Brown et al., 1997; Fang et al., 2001; Birdsey et al., 2006; Kauppi et al., 2006). Naturally, different forest management policies and projects would alter the rate of change in forest expansion and growth at different levels, ultimately leading to mechanisms regulating C sequestration among natural and planted forests.

The decline followed by an increasing trend in the areal expansion in planted forests was strongly associated with the stages of forest restoration projects conducted in China (Fig. 2a). The nationwide reforestation projects in China can be divided into two stages. Aiming to provide resistance to harsh weathers and environmental protection, the first stage was initiated in the 1970s and peaked in the 1980s; the forests established in this period were specifically targeted for environmental protection in some regions or provinces (Li, 2004; Wang et al., 2007). The second stage, initiated from the late 2000s, included six major forestry projects: Natural Forest Conservation Projects (2000), Three-North Protection Forest System (2000), Wild Life and Nature Reserve Construction Projects (2001), Grain for Green Project (2002), Fast-growing Forests in Key Areas Projects (2002), and the Beijing-Tianjin-Hebei Sandstorm

Source Treatment Project (2002) (Lei, 2005; Liu, 2006; Wang et al., 2007). Compared with the first stage, the second stage covered more than 97% of counties in the country, and was designed for a broader range of ecosystem services and multiple goals (e.g., biodiversity conservation and development of fast-growing plantations for industry). Rapid and concentrated afforestation projects would indeed enlarge the forest area and enhance the relative contribution of areal expansion to the C sink in a short period (i.e., in the periods 1981–1988 and 2003–2008; Fig. 2c). However, once the projects were slowed down or finished, forest growth would take over, accelerating under favorable growth conditions and effective management and leading to improvement in the relative contribution of C density to the C sink over a longer time frame (Fig. 2c).

The natural forests in China constitute a large C stock, of which its proportion to total forest biomass C stock was 83.40% in the late 2000s (2004–2008). However, natural forests have faced long-term logging pressure (e.g. timber extraction and farming) (Li, 2004; Lei, 2005), in addition to other degrading factors, such as increased wildfires or extreme weather events (Shi, 2011). In the present study, owing to the drastic changes in forest area and biomass density over the last 30 years (Fig. 2b), the relative contributions were variable without clear trends (Fig. 2d). For instance, in the period 1993–1998 biomass density increased from 43.2 Mg C ha^{-1} to 46.0 Mg C ha^{-1} (d = 1.25% year^{-1}), but forest area decreased by 0.97×10^6 ha ($a = -1.79\%$ year^{-1}) in the same period (Appendix C, Fig. 2b). Thus, areal contraction was responsible for the net C loss in the late 1990s. Analysis of C sinks at the provincial level also revealed that forest area declined at a relatively higher rate than the increase in biomass density in some provinces, making areal reduction the primary reason for C loss in natural forests (Fig. 3). Notably, since the late 1990s (1994–1998), natural forests in China have functioned as a persistent C sink, probably owing to implementation of the nationwide Natural Forest Conservation Project starting in 1998 (Appendix C) (Shen, 2000; Lei, 2005; Ministry of Forestry of China, 2009; Guo, 2013). Subsequently, the relative contribution of changes in biomass has shown a constantly increase (Fig. 2d).

4.3 Uncertainty of estimates

Uncertainties in our studies mainly arise from the quality of forest area and timber volume data in the forest inventories and the estimation of national biomass stocks using the BEF method. On the one hand, precision in the forest area and timber volume data was required to be >90% in almost all provinces (>85% in Beijing, Shanghai, and Tianjin) (Xiao, 2005). On the other hand, the R^2 values of the BEF equations used to convert timber volume to biomass for most dominant tree species or forest types exceeded 0.8 (Fang et al., 2014a). Therefore, the data and method used in the present study show relatively high precision. Previous studies have reported that the estimation error of biomass stocks at the national level are expected to be less than 3% in China (Fang et al., 1996).

Conclusions

With the implementations of national afforestation and reforestation programs since the late 1970s, China is credited with making a significant contribution to regional and global C sinks in recent decades. Using forest identity and CFID, this study quantified in detail the relative contributions of forest areal expansion and increased biomass density to China’s forest C sinks during the past 30 years. Our findings suggested that the mechanisms underlying the C sinks for natural and planted forests differed markedly with various effects from these two driving agents. The areal expansion of forests was a larger contributor to C sinks than forest growth for all forests and planted forests while forest growth (e.g. increased biomass density) made a larger contribution for natural forests. For all forests, growth in area and density each contributed equally to the total C sinks in forest biomass in China (50.4% vs. 49.6%).Furthermore, the increasing trend in the relative contribution of forest growth to C sinks for planted forests highlight that afforestation can continue to increase the C sink of

China's forests in the future subject to persistently-increasing forest growth after establishment of plantation.

Author contributions

J. F., J.Z., and P.L. designed the research; P. L., J.Z., H.H., Z.G., and J.F. performed the research; P.L., J.Z., and J.F analyzed data; J.F., Y.P. and R.B. contributed new analytic tools; P.L. and J.Z. prepared the manuscript with contributions from all co-authors.

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Table 1. Summary of forest variables for planted, natural and all forests between the forest inventory periods of 1977-1981 and 2004−2008

	1977−1981			2004−2008								
Forest type	Area (10^4 ha)	Density (Mg C ha^{-1})	Carbon stock (Tg C)	Area (10^4 ha)	Density (Mg C ha^{-1})	Carbon stock (Tg C)	a (% yr^{-1})	d (% yr^{-1})	R_a (%)	R_d (%)	M_a (Tg C)	M_d (Tg C)
Planted forests	1595	15.6	249.5	3999	26.7	1067.1	3.18	1.93	62.2	37.8	508.8	308.8
Natural forests	10755	41.5	4467.8	11559	46.4	5360.0	0.27	0.41	39.6	60.4	353.5	538.7
All forests	12350	38.2	4717.4	15558	41.3	6427.1	0.85	0.29	50.4	49.6	862.3	847.5

*a , change rate of forest area, d , change rate of forest density, R(a), relative contribution of areal expansion to carbon sink, R(d), relative contribution of forest regrowth to carbon sink， M_a carbon sinks attributing to areal area expansion, M_d carbon sinks attributing to growth in density

Fig. 1. Rate of change and relative contributions of forest area and biomass density to carbon sinks in planted (a) and natural (b) forests in six broad regions of China for the period 1977–2008. The division of these six broad regions are indicated as (c). Bars and numbers above represent the change rates and their relative contributions of forest area (in black color) and carbon density (in red color), respectively.

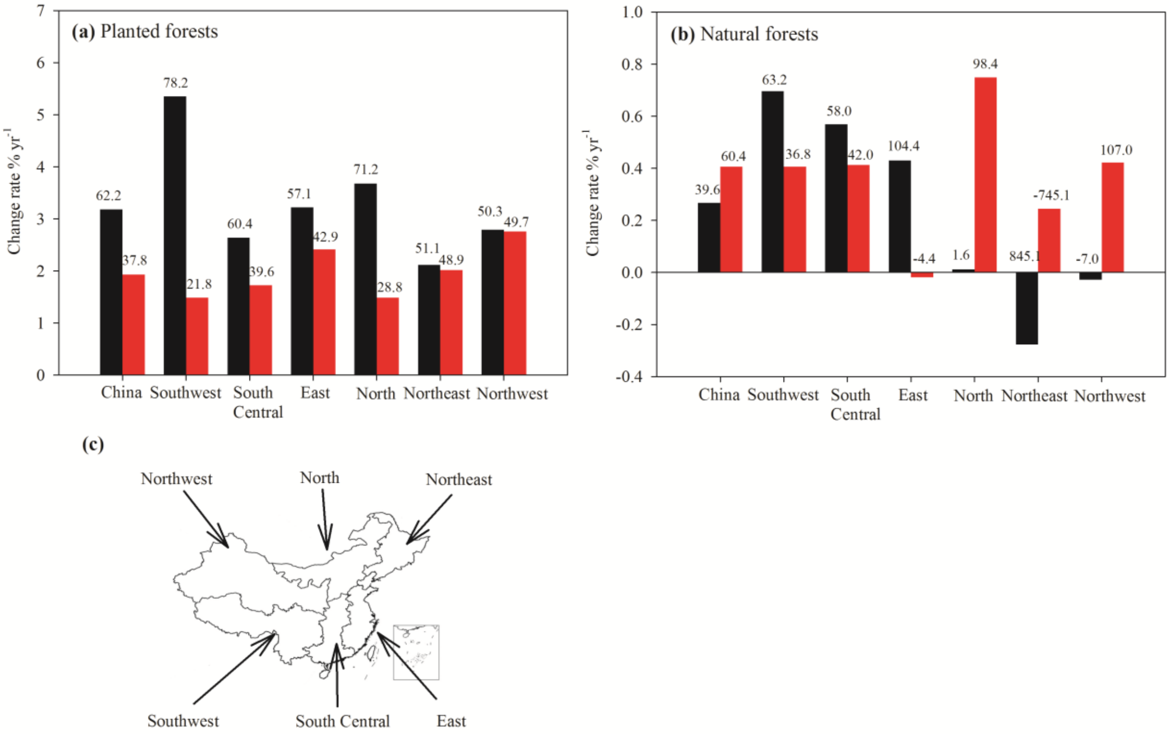


Fig. 2. Relative contributions and the dynamics of areal expansion and forest growth to carbon sinks in planted (a and c) and natural (b and d) forests of China in the period 1977–2008. Bars and points represent the rates of change and relative contributions of forest area (in black color) and carbon density (in red color), respectively.

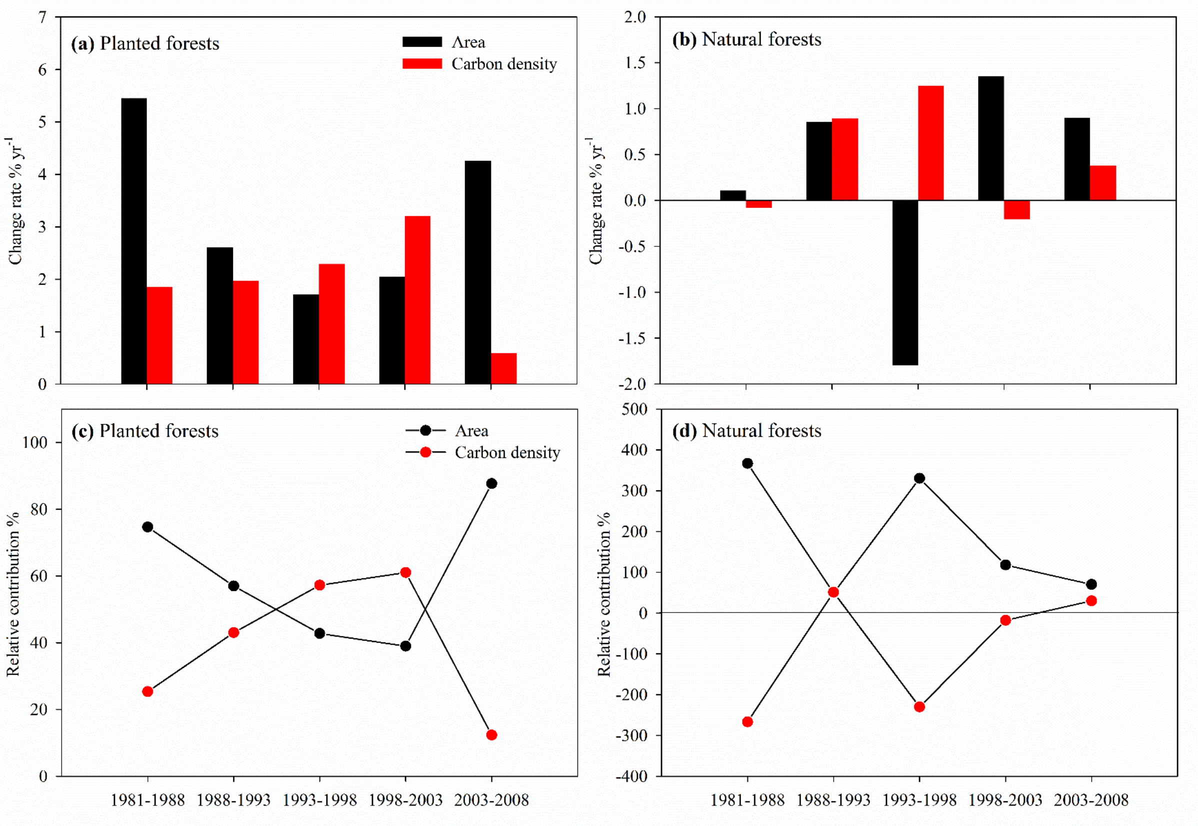


Fig. 3. Rate of change and the relative contributions of changes in forest area and carbon density of natural forests to carbon loss in three provinces of China in the period 1977–2008. Bars and numbers above represent the change rates and their relative contributions of forest area (in black color) and carbon density (in red color), respectively

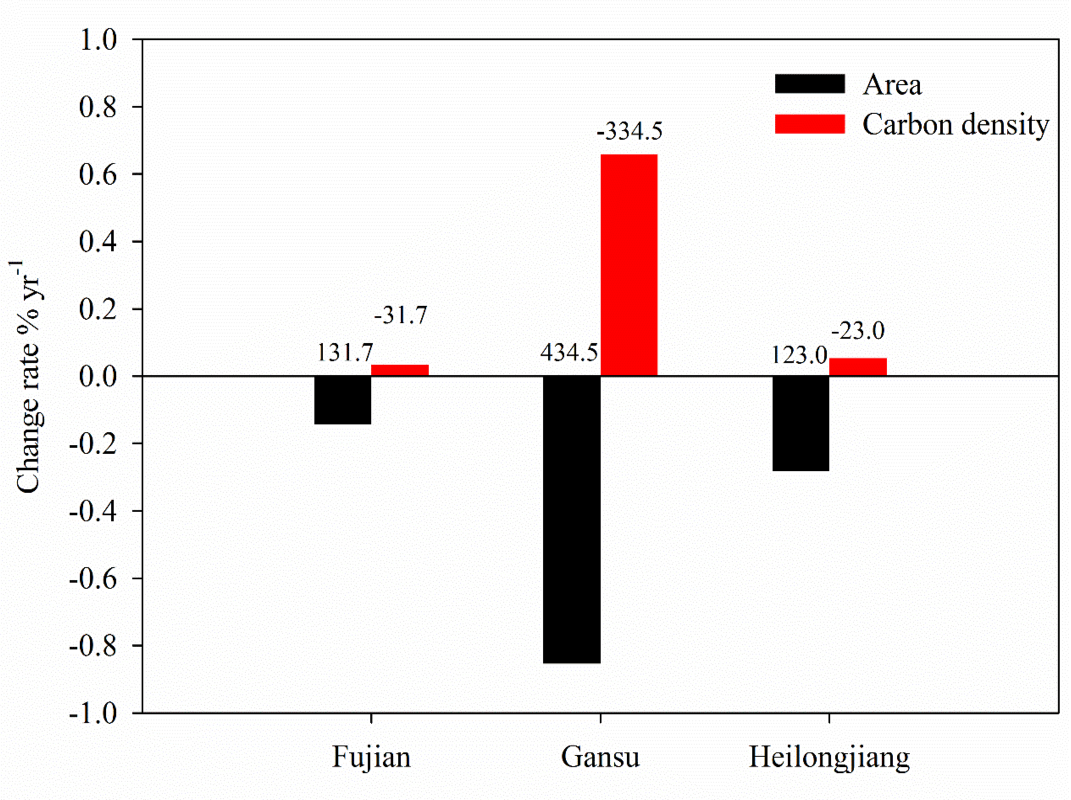


Fig. 4. Rate of change (a, c and e) and relative contributions of changes (b, d and f) in forest area and carbon density of natural forests to carbon loss in three provinces of China in the period 1977–2008. Bars and points represent the rates of change and relative contributions of forest area (in black color) and carbon density (in red color), respectively.

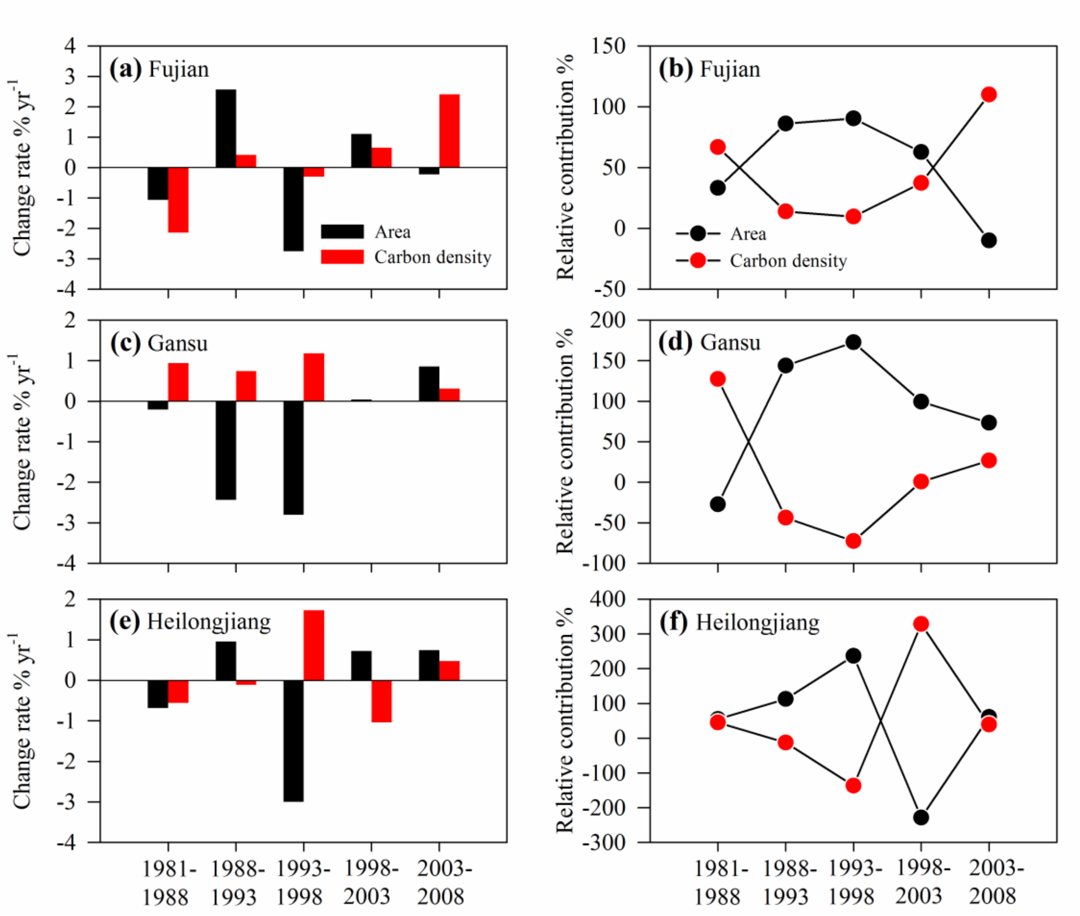
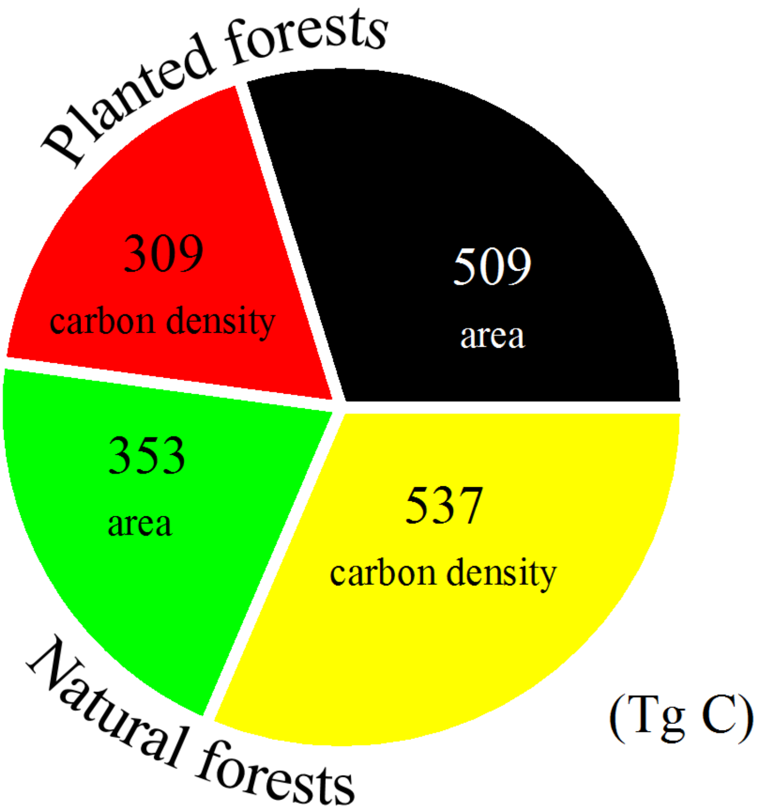


Fig. 5. Summary of the forest biomass carbon sinks attributing to areal expansion and increase in carbon density for planted and natural forests of China in the period 1977–2008.



Appendix A. Forest area, carbon stock, and carbon sinks of planted forests for six regions in China from 1977 to 2008

Period	China	North	Northeast	East	South Central	Southwest	Northwest
Area (10^4 ha)							
1977–1981	1595.2	166.2	298.2	365.4	586.1	101.9	77.3
1984–1988	2347.2	244.7	497.8	583.0	595.9	277.1	148.7
1989–1993	2675.2	308.7	456.8	680.8	761.9	339.1	127.9
1994–1998	2914.4	309.5	474.4	717.5	878.5	396.7	137.9
1999–2003	3229.4	386.2	461.9	769.2	976.3	495.9	139.8
2004–2008	3999.9	494.4	536.6	928.8	1235.8	633.3	170.9
Net change	2404.6	328.2	238.3	563.4	649.6	531.4	93.6
C stock (Tg C)							
1977–1981	249.5	23.5	57.1	52.2	88.2	18.5	10.1
1984–1988	418.0	41.4	105.7	105.0	96.5	47.1	22.3
1989–1993	525.8	55.6	105.5	136.0	138.1	62.1	28.4
1994–1998	642.4	63.0	130.7	153.2	171.0	87.3	37.2
1999–2003	836.1	82.5	150.3	203.7	231.0	130.8	37.7
2004–2008	1067.1	104.8	179.9	261.4	299.0	173.0	49.1
Net change	817.6	81.4	122.8	209.2	210.8	154.5	39.0
C density (Mg C ha^{-1})							
1977–1981	15.6	14.1	19.1	14.3	15.0	18.1	13.1
1984–1988	17.8	16.9	21.2	18.0	16.2	17.0	15.0
1989–1993	19.7	18.0	23.1	20.0	18.1	18.3	22.2
1994–1998	22.0	20.4	27.5	21.4	19.5	22.0	27.0
1999–2003	25.9	21.4	32.5	26.5	23.7	26.4	27.0
2004–2008	26.7	21.2	33.5	28.1	24.2	27.3	28.7
Net change	11.0	7.1	14.4	13.9	9.2	9.2	15.6
C sink (Tg C $year^{-1}$)							
1981–1988	24.1	2.6	6.9	7.5	1.2	4.1	1.7
1988–1993	21.6	2.8	0.0	6.2	8.3	3.0	1.2
1993–1998	23.3	1.5	5.0	3.4	6.6	5.0	1.7
1998–2003	38.7	3.9	3.9	10.1	12.0	8.7	0.1
2003–2008	46.2	4.5	5.9	11.5	13.6	8.4	2.3

Appendix B. Forest area, carbon stock, and carbon sinks of natural forests for six regions in China from 1977 to 2008

Period	China	North	Northeast	East	South Central	Southwest	Northwest
Area (10^4 ha)							
1977–1981	10755.0	1682.8	2655.6	1160.5	1587.2	2837.3	831.5
1984–1988	10822.0	1655.1	2556.5	1140.3	1546.4	3055.9	867.9
1989–1993	11296.2	1688.3	2673.6	1223.3	1684.1	3193.5	833.3
1994–1998	10326.1	1451.6	2295.5	1186.4	1620.3	3012.9	759.5
1999–2003	11049.3	1617.0	2364.4	1257.5	1743.7	3306.2	760.4
2004–2008	11559.1	1688.5	2464.1	1303.8	1851.5	3425.9	825.4
Net change	804.1	5.7	−191.5	143.2	264.3	588.5	−6.1
C stock (Tg C)							
1977–1981	4467.8	533.2	1192.8	332.3	368.2	1701.2	340.0
1984–1988	4466.8	552.2	1150.8	272.0	331.5	1810.2	350.3
1989–1993	4876.5	573.7	1203.2	292.8	367.3	2089.4	350.0
1994–1998	4745.5	558.3	1126.4	282.0	374.5	2058.0	346.3
1999–2003	5026.4	618.6	1122.5	311.9	422.0	2195.7	355.7
2004–2008	5360.0	655.3	1182.3	371.5	480.3	2292.3	378.3
Net change	892.1	122.0	−10.5	39.2	112.1	591.1	38.3
C density (Mg C ha^{-1})							
1977–1981	41.5	31.7	44.9	28.6	23.2	60.0	40.9
1984–1988	41.3	33.4	45.0	23.9	21.4	59.2	40.4
1989–1993	43.2	34.0	45.0	23.9	21.8	65.4	42.0
1994–1998	46.0	38.5	49.1	23.8	23.1	68.3	45.6
1999–2003	45.5	38.3	47.5	24.8	24.2	66.4	46.8
2004–2008	46.4	38.8	48.0	28.5	25.9	66.9	45.8
Net change	4.8	7.1	3.1	−0.1	2.7	7.0	4.9
C sink (Tg C year^{-1})							
1981–1988	−0.1	2.7	−6.0	−8.6	−5.3	15.6	1.5
1988–1993	81.9	4.3	10.5	4.2	7.2	55.8	0.0
1993–1998	−26.2	−3.1	−15.4	−2.2	1.4	−6.3	−0.7
1998–2003	56.2	12.1	−0.8	6.0	9.5	27.5	1.9
2003–2008	66.7	7.3	12.0	11.9	11.7	19.3	4.5

Appendix C. Changes in forest area, carbon density, and carbon stock for planted forests in provinces of China for the period 1977–2008

Province	Area (10^4 ha)			Carbon density (Mg C ha^{-1})			Carbon stock (Tg C)		
	1977–1981	2003–2008	Net Change	1977–1981	2003–2008	Net Change	1977–1981	2003–2008	Net Change
Beijing	2.6	19.3	16.8	11.5	18.1	6.6	0.3	3.5	3.2
Tianjin	0.6	5.0	4.4	11.4	21.4	10.0	0.1	1.1	1.0
Hebei	43.1	122.2	79.0	12.5	20.7	8.2	5.4	25.3	19.9
Shanxi	12.5	57.2	44.7	13.2	21.9	8.7	1.6	12.5	10.9
Neimenggu	107.5	290.7	183.2	14.9	21.5	6.5	16.1	62.4	46.4
Liaoning	129.9	166.8	36.8	15.4	26.8	11.4	20.0	44.7	24.7
Jilin	88.1	141.5	53.3	21.6	39.7	18.1	19.0	56.1	37.2
Heilongjiang	80.2	228.4	148.2	22.6	34.6	12.0	18.1	79.0	60.9
Shanghai	0.0	3.4	3.4	0.0	16.9	16.9	0.0	0.6	0.6
Jiangsu	18.6	71.1	52.4	12.5	25.0	12.5	2.3	17.7	15.4
Zhejiang	63.5	118.5	55.1	12.6	24.6	12.0	8.0	29.2	21.2
Anhui	53.8	136.8	83.0	13.4	25.5	12.2	7.2	34.9	27.8
Fujian	108.6	239.8	131.2	18.8	37.3	18.4	20.5	89.4	68.9
Jiangxi	61.7	213.1	151.4	13.6	26.1	12.5	8.4	55.6	47.2
Shandong	59.2	146.0	86.8	9.9	23.3	13.4	5.9	34.0	28.1
Henan	37.7	164.6	126.9	12.7	25.4	12.8	4.8	41.9	37.1
Hubei	79.5	110.4	30.9	11.4	21.8	10.4	9.1	24.1	15.0
Hunan	115.5	290.8	175.3	13.1	25.4	12.2	15.2	73.8	58.6
Guangdong	***183.8***	343.5	159.7	***14.9***	20.0	5.1	***27.3***	68.5	41.2
Guangxi	148.7	293.1	144.4	19.6	28.1	8.5	29.1	82.4	53.3
Hainan	***19.4***	33.4	14.0	***18.0***	25.1	7.0	***2.4***	8.4	5.9
Sichuan	37.2	332.6	295.4	16.0	26.2	10.2	5.9	87.0	81.1
Guizhou	34.1	143.5	109.4	21.0	28.7	7.7	7.1	41.1	34.0
Yunnan	30.5	154.5	124.0	17.7	28.6	10.8	5.4	44.2	38.7
Xizang	0.2	2.8	2.6	0.0	24.4	24.4	0.0	0.7	0.7
Shaanxi	33.2	77.1	43.8	12.8	21.1	8.3	4.3	16.3	12.0
Gansu	19.2	55.7	36.4	12.8	24.4	11.7	2.5	13.6	11.2
Qinghai	2.3	4.1	1.8	23.6	36.5	12.9	0.5	1.5	1.0

Ningxia	6.8	5.9	-0.9	12.2	21.3	9.1	0.8	1.3	0.4
Xinjiang	15.7	28.2	12.5	13.1	58.4	45.3		2.1	2.1

Bold italic font refers to the values in Hainan and Guangdong acquired from the forest inventory data in the period of 1984–1988, because these two provinces were not separated administratively until 1988 and their separate inventory data was lacked for the period of 1977–1981.

Appendix D. Changes in forest area, carbon density, and carbon stock for natural forests in provinces of China for the period 1977–2008

Province	Area (10^4 ha)			Carbon density (Mg C ha^{-1})			Carbon stock (Tg C)		
	1977–1981	2003–2008	Net Change	1977–1981	2003–2008	Net Change	1977–1981	2003–2008	Net Change
Beijing	5.8	16.2	10.4	15.5	17.9	2.4	0.9	2.9	2.0
Tianjin	0.5	0.4	−0.1	14.4	18.2	3.9	0.1	0.1	0.0
Hebei	103.0	166.1	63.0	16.1	17.5	1.3	16.6	29.0	12.4
Shanxi	77.1	115.2	38.1	27.2	28.5	1.3	21.0	32.8	11.9
Neimenggu	1496.3	1390.5	−105.8	33.1	42.5	9.4	494.7	590.4	95.8
Liaoning	172.6	194.6	22.0	29.3	35.2	5.9	50.6	68.6	18.0
Jilin	665.2	585.3	−79.9	53.9	64.5	10.5	358.6	377.2	18.7
Heilongjiang	1817.9	1684.3	−133.6	43.1	43.7	0.6	783.7	736.5	−47.2
Shanghai	0.2	0.0	−0.2	8.8	0.0	−8.8	0.0	0.0	0.0
Jiangsu	2.9	3.4	0.4	12.5	18.4	5.9	0.4	0.6	0.3
Zhejiang	227.7	275.1	47.4	19.2	21.5	2.3	43.8	59.2	15.4
Anhui	135.7	134.0	−1.7	20.4	25.2	4.8	27.6	33.8	6.1
Fujian	339.1	326.2	−12.9	39.2	39.5	0.4	132.8	128.9	−3.8
Jiangxi	442.0	555.0	113.0	28.7	26.6	−2.1	126.7	147.5	20.9
Shandong	12.9	10.1	−2.8	8.0	13.8	5.8	1.0	1.4	0.4
Henan	101.1	118.7	17.6	19.7	25.6	5.9	19.9	30.4	10.5
Hubei	317.9	397.4	79.5	18.4	23.1	4.7	58.6	91.8	33.2
Hunan	379.7	435.8	56.1	21.5	21.8	0.3	81.8	95.0	13.2
Guangdong	***320.0***	335.3	15.3	***19.7***	27.1	7.4	***62.9***	90.8	27.9
Guangxi	394.9	513.6	118.7	26.3	27.9	1.6	103.8	143.5	39.6
Hainan	***49.5***	50.7	1.3	***49.4***	56.7	7.3	***24.4***	28.8	4.3
Sichuan	765.8	1014.7	248.9	60.5	62.3	1.8	463.7	632.3	168.6
Guizhou	225.6	254.6	29.0	28.6	28.4	−0.1	64.5	72.4	7.9
Yunnan	1056.7	1318.2	261.5	52.2	53.4	1.2	551.2	703.6	152.4
Xizang	789.2	838.4	49.1	78.8	105.4	26.6	621.9	884.0	262.1
Shaanxi	487.6	490.0	2.3	32.4	36.0	3.6	158.0	176.5	18.6
Gansu	198.9	157.8	−41.1	43.7	52.3	8.5	87.0	82.4	−4.5
Qinghai	21.9	31.4	9.6	41.9	52.1	10.2	9.2	16.4	7.2
Ningxia	4.1	5.2	1.1	22.6	31.3	8.7	0.9	1.6	0.7

Xinjiang	119.1	141.1	22.0	71.4	71.8	0.5	85.0	101.3	16.3

Bold italic font refers to the values in Hainan and Guangdong acquired from the forest inventory data in the period of 1984–1988, because these two provinces were not separated administratively until 1988 and their separate inventory data was lacked for the period of 1977–1981.

Appendix E. The estimation methods for forest area and stand volume in CFID.

a) Forest area estimation

In forest inventory of China, the systematic sampling was conducted at the provincial level.

Based on the sampling method, the ratio of forest area (P_i) for a certain forest type (i) can be expressed as:

$$p_i = \frac{m_i}{n} \tag{1}$$

$$S_{p_i} = \sqrt{\frac{p_i(1-p_i)}{n-1}} \tag{2}$$

where n represents the number of all the sampling plots, m_i represents the number of plots classified as type i (including various types of land categories , vegetation types, forest types and other land classification attributions), S_{pi} represents the standard deviation of P_i.

then, the area of forest i （$\hat{A}_i$） can be estimated by the following equation

$$\hat{A}_i = A \cdot p_i \tag{3}$$

where A means the overall area in the forest inventory for one province, and the total area equals to the sum area of all kinds of forests.

The limit of error for the area estimation is calculated by the following equation

$$\Delta_{A_i} = A \cdot t_\alpha \cdot S_{p_i} \tag{4}$$

where t_a is the reliability index, the estimation interval can be expressed as $\hat{A}_i \pm \Delta_{A_i}$.

The sampling precision (P_{Ai}) can be expressed as:

$$P_{A_i} = (1 - \frac{t_a \cdot S_{p_i}}{p_i}) \cdot 100\% \tag{5}$$

b) Forest volume estimation

The mean stand volume for forest i can be expressed as:

$$\overline{V_i} = \frac{1}{n}\sum_{j=1}^{n} V_{ij} \tag{6}$$

Where V_{ij} represents the stand volume of plot j for forest i.

The sampling variance is calculated as

$$S_{V_i}^2 = \frac{1}{n-1}\sum_{j=1}^{n}(V_{ij} - \overline{V}_i)^2 \tag{7}$$

$$S_{\overline{V_i}} = \frac{S_{V_i}}{\sqrt{n}} \tag{8}$$

The overall stand volumes for forest *i* can be estimated as:

$$\hat{V}_i = \frac{A}{a} \cdot \overline{V_i} \tag{9}$$

where *A* means the overall area in the forest inventory for one province, *a* means the area of the sampling plot.

The limit of error for the overall estimation of forest *i* can be calculated by the following equation:

$$\Delta_{V_i} = \frac{A}{a} \cdot t_a \cdot S_{\overline{V_i}} \tag{10}$$

where t_α is the reliability index, the estimation interval can be expressed as $\hat{V}_i \pm \Delta_{V_i}$.

The sampling precision (P_{vi}) can be expressed as:

$$P_{V_i} = (1 - \frac{t_a \cdot S_{V_i}}{\overline{V_i}}) \cdot 100\% \tag{11}$$