Responses to comments

Reply to Dr. Williams, Associate Editor

(1) There appears to be an error in the abstract's statement: "... areal expansion of forests was a larger contributor to C sinks than forest growth for all forests... (74.6% vs. 25.4% for all forests, ..)". This cannot be correct given the numbers in Figure 5. Density and area each contribute equally to the total C sink in forest biomass in China (49.6% vs. 50.4%). The same error appears at line 161 to 164. I wonder if percentages were added over regions with different forested areas instead of adding absolute C numbers over regions and then calculating percentages, which is the correct way of computing total contributions. Whatever the case, this must be corrected before the work can be accepted for publication.

Tg C per 30 yrs	density	area	total
planted	309.1	508.5	817.6
natural	538.8	353.3	892.1
all	**847.9**	**861.8**	**1709.7**
% of relative contributions	density	area	Total
planted	37.8%	62.2%	100%
natural	60.4%	39.6%	100%
all	**49.6%**	**50.4%**	**100%**

Reply: Sorry for the confusions about Fig. 5 .

Using CFID and BEF method, the areas and carbon stocks of China's forests were firstly estimated at provincial level, and then the provincial estimates were accumulated for each region (6 regions in Fig. 1) and for the whole country, while the carbon density was carbon stock per forest area (defined as the value of carbon stock divided by forest area). The relative contributions (%) were calculated by adding absolute C numbers over regions instead of adding percentages over regions. Consistently, for all forests (natural forest and planted forest), the relative contributions were also calculated by adding C numbers of planted and natural forests instead of averaging their percentages.

For details, the relative contributions (%) were calculated by the change rates of forest area (a) and carbon density (d) (Eq.1)

$$R_a (\%) = a/m \times 100; R_d (\%) = d/m \times 100 \tag{1}$$

Then, 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) (Eq.2). Using this method, we calculated the relative contributions of areal expansion and growth in density to carbon sinks for all, planted and natural forests of China (Table 1).

$$M_a = R_a\,(\%) \times \Delta M; \quad M_d = R_d\,(\%) \times \Delta M \tag{2}$$

However, for all forests, the carbon sinks attributing to areal area expansion (M_a) or growth in density (M_d) are not equal to the sum of which in planted and natural forest, because while adding the variables (i.e., area, C stock) of these two forest types together, the relative contributions (%) would change along with the variation of **a and d** (Table 1).

Over the study period, China's forests had increased in both forest area and biomass carbon density, and for planted and natural forests, the size of **a vs. d** were 3.18 %yr^{-1} vs. 1.93 yr^{-1} and 0.27 %yr^{-1} vs. 0.41% yr^{-1}, respectively (Table 1). However, compared with planted forests, natural forests were much larger in forest area (10755×10^{4}ha vs. 1595×10^{4}ha), but lower in the relative contribution of areal expansion (39.6% vs. 62.2%). Besides the fast areal expansion of planted forests, all these factors had contributed to a much slower increase in forest density than forest area (0.29 %yr^{-1} vs. 0.85 %yr^{-1}) for all forests, thus resulted in a higher relative contribution in areal expansion than growth in density to carbon sinks (74.6% vs.25.4%)(Table 1).

Similarly, for all forests, the relative contribution was not equal to the average of which in planted and natural forests as you have commented, where areal expansion and growth in density had contributed equally to the forest biomass carbon sink of China (49.6% vs. 50.4%)(Eq. 3).

$$R_a\,(\%) = 100*(62.23+37.77)/2; \qquad R_d\,(\%) = 100*(39.62+60.38)/2;$$

or

$$R_a\,(\%) = 100*(508.83+353.45)/2; \qquad R_d\,(\%) = 100*(308.78+538.69)/2 \tag{3}$$

In the early version of MS, the pie chart of Fig. 5 may bring some confusions. So following you suggestions, we changed this pie chart with the histogram in the revised MS. We have also carefully checked the figures of the revised MS to avoid errors.

Fig. 5. Summary of the forest biomass carbon accumulation induced by areal expansion and increase in carbon density for natural and planted forests of China in the period 1977–2008.
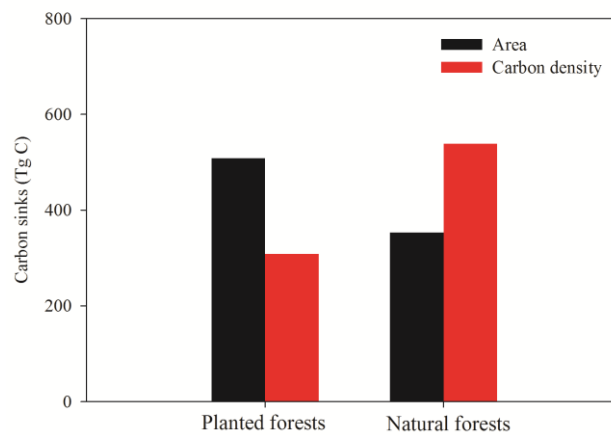
Table 1. Summary of forest variables for all, planted and natural forests between the forest inventory periods of 1977-1981 and 2004-2008

	1977-1981			2004-2008		
	Area (10^4ha)	Density (Mg C ha^{-1})	Carbon stock (Tg C)	Area (10^4ha)	Density (Mg C ha^{-1})	Carbon stock (Tg C)
All forests	12350	38.2	4717.4	15558	41.3	6427.1
Planted forests	1595	15.6	249.5	3999	26.7	1067.1
Natural forests	10755	41.5	4467.8	11559	46.4	5360.0
	a (% yr^{-1})	d (% yr^{-1})	R_a (%)	R $_d$ (%)	M_a (Tg C)	M_d (Tg C)
All forests	0.85	0.29	74.6	25.4	1275.5	434.2
Planted forests	3.18	1.93	62.2	37.8	508.8	308.8
Natural forests	0.27	0.41	39.6	60.4	353.5	538.7

*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

List of changes

1. Line 34, change the number 62.4% to 62.2%。
2. Line 488， replace the pie chart with the revised histogram (Fig.5)

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

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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 all forests and planted forests in China (74.6% *vs.* 25.4% for all forests, and

62.24% *vs.* 37.8% for plantations). However, for natural forests, forest growth made a larger

contribution than areal expansion (60.4% *vs.* 39.6%). 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.

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

70 forest area, biomass and C densities (Kauppi et al. 2006, Waggoner, 2008) , is useful to

71 develop the method to estimate the change in forest biomass C stock driven by different

72 causes. Using the Forest Identity concept, Shi et al. (2011) evaluated the status of change in

73 China's forests and showed that the increase in C sequestration was attributable to the

74 increase in forest area and growing stock density over the last three decades. More recently, to

75 explore the mechanisms that drive forest C sinks in East Asia, Fang et al. (2014a) used the

76 Forest Identity approach to estimate the relative contributions of changing forest area and

77 forest C density to the forest biomass C sink in China, Japan and South Korea. These studies

78 found that the relative contributions of the changing factors varied among countries and forest

79 origin (planted vs. natural forests). Specifically, it was reported that forest areal expansion

80 made a larger contribution to C sinks than increased biomass density for all forests. However,

81 the study of Fang et al. (2014a) did not analyze the spatial and temporal variability in the

82 relative contributions of forest areal expansion and increased biomass density to China's

83 forest C sinks. In this study, we used the Forest Identity concept and forest inventory data to

84 quantify in detail the spatial and temporal difference in the relative contributions of forest

85 areal expansion and increased biomass density to China's forest C sinks during the past 30

86 years. Furthermore, we discussed the primary reasons for reduced biomass C stocks of natural

87 forests in some provinces of China.

88

89 **2. Data and Methods**

90 *2.1. Forest inventory data*

91   China's forest inventory data (CFID) for the periods 1977–1981, 1984–1988, 1989–1993,

92 1994–1998, 1999–2003, and 2004–2008 were used in this study (Chinese Ministry of Forestry,

93 1983, 1989, 1994, 2000, 2005, 2010). These inventories were compiled from more than

94 250,000 plots (160,000 permanent sample plots plus 90,000 temporary sample plots) across

95   the country. Systematic sampling with a grid of 2 km by 2 km or 4 km by 4 km and an area of

96   10 m by 10 m was used depending on forest region. In CFID, China's forests were classified

97   into three categories: stands (including natural and planted forests), economic forests (woods

98   with the primary objective of production of fruits, edible oils, drinks, flavorings, industrial

99   raw materials, and medicinal materials), and bamboo forests (Guo et al. 2013). In the present

100   study, "forest" refers only to a "forest stand" with canopy coverage $\geq 20\%$ and therefore

101   excludes economic and bamboo forests (Fang et al., 2007). At the provincial level, the

102   inventories documented detailed information on age class, area, and volume for each forest

103   type, in which forest area was estimated by the "ratio method" in the systematic sampling

104   across each province (see Appendix F). To investigate spatial variation, we divided the

105   national land area into six broad regions—North, Northeast, East, South Central, Southwest,

106   and Northwest—consistent with the method of Fang et al. (2001) (Fig. 1d).

107

108   *2.2. Calculation of forest biomass C stocks*

109   In this study, we used the continuous biomass expansion factor (BEF, defined as the ratio of

110   stand biomass to timber volume) method with parameters for each forest type taken from Guo

111   et al. (2013) to calculate forest biomass in China, because the CFID only report the forest area

112   and timber volume for each forest type. The BEF method was firstly developed from the

113   allometric relationships between forest biomass and forest timber volume (Fang et al 1998;

114   Brown and Schroeder, 1999), then evolved to be the continuous BEF method based on the

115   reciprocal equation expressing BEF−timber volume relationship (Fang et al. 1998, 2001,

116   2005):

117   BEF= $a + b/x$ (1)

118   In Eq. (1), x is the timber volume per unit area (m^3 ha^{-1}), and a and b are constants for each

119   specific forest type. With this simple BEF approach, one can easily calculate regional or

120   national forest biomass based on direct field measurements and forest inventory data.

121   Calculations with the BEF method are well documented by Fang et al. (2001, 2014a) and the

122   BEF method has been applied previously to estimate China's forest stand biomass (Fang et al.,

123   2007; Guo et al., 2013). In this study, the ratio of 0.5 was used to convert biomass to C stock

124   (Fang et al., 2001).

125   *2.3. Calculation of the relative contributions of forest areal expansion and increased biomass*

126   *density*

127   Using the Forest Identity concept (Kauppi et al., 2006; Waggoner, 2008), Fang et al. (2014a)

128   proposed the method to separate relative contribution of forest areal expansion and forest

129   growth to changes in forest biomass stock (or biomass C sink/source). According to Fang et al.

130   (2014a), the relationships among forest area (A), biomass C density (D), and total biomass C

131   stock (M) can be formulated by   Eq. (2), and their respective rates of change (a, d, and m)

132   over time (t) can be   derived- from Eqs. (3) and (4).

133    $M = A \times D$.   (2)

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

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

136   differentiating the equation over time

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

138   Let the real change rate (m, a and d) among two inventory periods approximately equal to the

139   change rate of its natural logarithm:

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

141   Then, $m = a + d$

142   where M, A, and D represent total biomass C stock (Tg C or Pg C, $1\mathrm{Tg} = 10^{12}$ g, $1\mathrm{Pg} = 10^{15}$ g),

143   forest area (ha), and biomass C density (Mg C ha^{-1}, $1\mathrm{Mg} = 10^6$ g), respectively; and m, a, and

144　　*d* are the corresponding derivatives (or rate of change) of these attributes over time (*t*).

145　　The rates (*m*, *a*, and *d*) can be approximately calculated by the following formulas (Eq. 4):

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

147　　where X_1 and X_2 represent the forest area (*A*) or biomass C density (*D*) in the forest inventory

148　　period going from t_1 and t_2, respectively.

149　　Thus, the relative contribution of change in forest area (R_a, %) and change in biomass density

150　　(R_d, %) to the change in forest biomass C stock can be expressed as Eq. (5):

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

152

153　　**3. Results**

154　　*3.1. Spatial pattern of the relative contributions of forest area and biomass density to C sinks*

155　　Figure 1　shows the results of the national and regional relative contributions of forest areal

156　　expansion (*a*) and increased biomass C density (*d*) to the C sinks for all, planted, and natural

157　　forests between the late 1970s (1977–1981) and the 2000s (2004–2008). For all forests in

158　　China, the mean rates of change in forest area and biomass density were 0.85% year^{-1} and

159　　0.29% year^{-1}, respectively, with a larger contribution by the former than that of the latter

160　　(74.6% vs. 25.4%) to the net change of carbon stock (1709.7 Tg C) (Fig. 1a, Appendix A). As

161　　shown in Fig. 1a, forest stands in all regions have increased in area and C density, and

162　　functioned as C sinks during the period 1977–2008 (also see Appendix A), but the relative

163　　contributions differed considerably among regions. Within the Southwest, South Central and

164　　East regions, forest area increased remarkably, and thus areal expansion made a larger

165　　contribution than that of increased biomass density to the C sinks (the relative contributions of

166　　forest area in these regions were 89.6%, 65.4%, and 76.2%, respectively). In addition, forest

167　　C sinks within these three regions were much larger than those of other regions in China

(Appendix A). The relative contributions of changes in forest area and biomass density were similar in the North (53.3% vs. 56.7%) and Northwest (46.1% vs. 53.9%) regions. However, in the Northeast region forest area increased only slightly, with a mean change of 0.06% year^{-1}, and thus made a small contribution (18.3%) to the regional C sink over the past 30 years.

Planted forests have functioned as C sinks (817.6 Tg C) in the past three decades (Appendix B), and areal expansion made a larger contribution to the C sink than did change in biomass density in all regions (Fig. 1b). 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. 1c). 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 C). 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

193   this region.

194   *3.2 Temporal dynamics of the relative contributions of forest area and biomass density to C*

195   *sinks*

196   We further explored changes of the relative contributions of forest areal expansion and

197   biomass density to C sinks of Chinese forests from 1977 to 2008 (Fig. 2), by calculating the

198   change rates (*a* and *d*) and the relative contribution rates for the six forest inventory periods.

199   For planted forests, the rate of change in forest area was highest in the 1980s (1981–1988;

200   Fig. 2a) with a mean increase of 5.45% year^{-1}, then decreased until the late 1990s

201   (1993–1998), and thereafter increased in the 2000s. Over the same period, forest biomass C

202   density has experienced slow but relatively steady enhancement from the early 1980s to the

203   early 2000s (Fig. 2a),   reaching the highest rate of increase in the period 1998–2003 (*d* =

204   2.33% yr^{-1}), and then decreased abruptly to a low rate of increase (0.60% year^{-1}) in the late

205   2000s (2003–2008). The relative contribution of areal expansion declined from 74.4%

206   between 1981 and 1988 to 39.0% between 1998 and 2003, whereas the contribution of

207   increased C density increased from 25.6% to 61.0% over the same period (Fig. 2c). After

208   2003, on account of the rapid growth in forest area (Fig. 2a), the contribution of areal

209   expansion increased and became the dominant contributor to the C sink of China's planted

210   forest (87.7% vs. 12.3% for 2003–2008).

211   In contrast to planted forest, the areal expansion and increase of C density in natural

212   forests were more dynamic, having relatively lower rates of change less than 1.5% year^{-1} over

213   the study period (Fig. 2b). Furthermore, negative growth was observed in forest area (*a* =

214   −1.80% year^{-1} for 1993–1998) and biomass C density (*d* = −0.08 and −0.20% year^{-1} for

215   1981–1988 and 1998–2003, respectively) in natural forest over the study period. Aligning

216   with dynamic rates of change, the relative contribution of forest areal expansion showed a

217   generally decreasing trend from 1981 (366.7%) to 2008 (70.2%), in contrast to the increase in

218 C density (Fig. 2d). In addition, areal expansion always made a greater impact on the carbon

219 sink than did the change in C density in most of the inventory periods, except for the period of

220 1988–1993, when increased C density made a slightly larger contribution than areal expansion

221 (51.1% vs. 48.9%).

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

223   Over past three decades, planted forests have functioned as C sinks in all provinces of

224 China (Appendix D). However, three provinces showed a distinct C loss in their natural

225 forests over the study period (Appendix E): Heilongjiang (located in Northeast), Gansu

226 (Northwest), and Fujian (East). Among these provinces, Heilongjiang contained the largest

227 area of natural forest (1817.9 10^4 ha; 1977–1981) in China, of which the biomass C stock has

228 shrunk by 47.2 Tg C (783.7 Tg C during 1977 –1981 to 736.5 Tg C in the 2000s). The C

229 stocks of natural forest in Gansu and Fujian also underwent a decline from 87.0 and 132.8 Tg

230 C in the 1970s to 82.4 and 128.9 Tg C in the 2000s, respectively. Here, we focused on these

231 three provinces to explore the reasons for the declines in C stock of the natural forests over

232 the past 30 years by quantifying the relative contributions of changes in forest area and C

233 density.

234   Among the three provinces, biomass C density of natural forests increased more or less

235 from 1977 to 2008; the rate of change was highest in Gansu ($d = 0.66\%$ year^{-1}), whereas only

236 slight increases were observed in Heilongjiang and Fujian (Fig. 3, Appendix E). Conversely,

237 the forest area in these provinces experienced more obvious decreases. The forest area in

238 Heilongjiang decreased dramatically by 133.6 10^4 ha ($a = -0.28\%$ year^{-1}) over the last 30

239 years, followed by that of Gansu (41.1 10^4 ha, $a = -0.85\%$ year^{-1}) and Fujian (12.9 10^4 ha, $a =$

240 -0.14% year^{-1}). Detailed analysis of the temporal dynamics of change rates in these provinces

241 demonstrated that most of the decline in forest area occurred between 1981 and 1998 (Fig. 4a,

242 c and e), whereas the contributions of forest area to the C stock change of these provinces

243 increased rapidly, attaining their highest values (Fig. 4b, d and f). Overall, the rapid decline in

244 forest area has exceeded the contribution of increased C density, and ultimately caused the C

245 loss in these provinces (Figs. 3 and 4).

246

247 **4. Discussion**

248 *4.1. Relative contributions of changes in forest area and biomass density to the C sink in*

249 *China's forests*

250   Over the past three decades, areal expansion and forest growth have increased C stocks in

251 both planted (817.6 Tg C) and natural (892.1 Tg C) forests (Appendices B and C). However,

252 the mechanisms underlying the C sinks differed markedly with various effects from these two

253 driving agents (Fig. 5).

254   For planted forests, areal expansion made a larger contribution than did biomass growth

255 at both national and regional levels (Fig. 1b). Benefiting from the implementation of national

256 afforestation and reforestation projects since the 1970s (Fang et al., 2001; Li, 2004; FAO,

257 2006; Wang et al., 2007), the area of planted forest in China has expanded dramatically from

258 16.95 10^6 ha to 24.05 10^6 ha over the last 30 years (Appendix B). Meanwhile, the growth of

259 these young forests also made a significant contribution to C sequestration; the biomass

260 density of planted forest has increased by 71.2% from an initial density of 15.6 Mg C ha^{-1} to

261 26.7 Mg C ha^{-1} in the late 2000s (2004–2008), which indicates that planted forest could still

262 sequester additional C through future growth (Guo et al., 2010; Xu et al., 2010).

263   Compared to planted forests, growth of existing natural forests was a larger contributor to

264 the C sink than areal expansion at the national level (60.4% vs. 39.6% for density change vs.

265 area change), because the biomass density has increased more rapidly, with a net gain of 4.8

266 Mg C ha^{-1} (11.6%), than did forest area (7.4%). Regional disparities were also apparent.

267 Forest growth dominated the C sink in the North and Northwest regions, but made a smaller

268   contribution in the Southwest, South Central and East regions (Fig. 1c). The inconsistent

269   patterns in the contributions of forest growth and areal expansion may be associated with

270   differences in forest management policies, harvest intensity, and climatic factors (e.g., the

271   warming climate, increasing summer precipitation, elevated CO_2, and natural nitrogen

272   deposition) among these regions (Fang et al., 2004; Du et al., 2014; Also see in Fang et al.

273   2014b). For instance, southern and southwest China has experienced drier and hotter climate

274   in the last 3 decades while northern China became wetter and had longer growing seasons

275   (Peng et al., 2011), which may effectively contribute to the enhanced C densities in the

276   northern regions

277   *4.2. Dynamics of areal expansion and forest growth in planted and natural forests*

278   It is generally recognized that areal expansion and forest growth are closely associated

279   with the intensity of reforestation and loss of forest cover (e.g. deforestation, industrial

280   harvest or natural disturbance). Therefore, implementation of forest management policies may

281   have a strong impact on forest C sequestration via the introduction of a variety forest projects

282   in a country (Brown et al., 1997; Fang et al., 2001; Birdsey et al., 2006; Kauppi et al., 2006).

283   Naturally, different forest management policies and projects would alter the rate of change in

284   forest expansion and growth at different levels, ultimately leading to mechanisms regulating C

285   sequestration among natural and planted forests.

286   The decline followed by an increasing trend in the areal expansion in planted forests was

287   strongly associated with the stages of forest restoration projects conducted in China (Fig. 2a).

288   The nationwide reforestation projects in China can be divided into two stages. Aiming to

289   provide resistance to harsh weathers and environmental protection, the first stage was initiated

290   in the 1970s and peaked in the 1980s; the forests established in this period were specifically

291   targeted for environmental protection in some regions or provinces (Li, 2004; Wang et al.,

292   2007). The second stage, initiated from the late 2000s, included six major forestry projects:

293　　Natural Forest Conservation Projects (2000), Three-North Protection Forest System (2000),

294　　Wild Life and Nature Reserve Construction Projects (2001), Grain for Green Project (2002),

295　　Fast-growing Forests in Key Areas Projects (2002), and the Beijing-Tianjin-Hebei Sandstorm

296　　Source Treatment Project (2002) (Lei, 2005; Liu, 2006; Wang et al., 2007). Compared with

297　　the first stage, the second stage covered more than 97% of counties in the country, and was

298　　designed for a broader range of ecosystem services and multiple goals (e.g., biodiversity

299　　conservation and development of fast-growing plantations for industry). Rapid and

300　　concentrated afforestation projects would indeed enlarge the forest area and enhance the

301　　relative contribution of areal expansion to the C sink in a short period (i.e., in the periods

302　　1981–1988 and 2003–2008; Fig. 2c). However, once the projects were slowed down or

303　　finished, forest growth would take over, accelerating under favorable growth conditions and

304　　effective management and leading to improvement in the relative contribution of C density to

305　　the C sink over a longer time frame (Fig. 2c).

306　　　　The natural forests in China constitute a large C stock, of which its proportion to total

307　　forest biomass C stock was 83.40% in the late 2000s (2004–2008). However, natural forests

308　　have faced long-term logging pressure (e.g. timber extraction and farming) (Li, 2004; Lei,

309　　2005), in addition to other degrading factors, such as increased wildfires or extreme weather

310　　events (Shi, 2011). In the present study, owing to the drastic changes in forest area and

311　　biomass density over the last 30 years (Fig. 2b), the relative contributions were variable

312　　without clear trends (Fig. 2d). For instance, in the period 1993–1998 biomass density

313　　increased from 43.2 Mg C ha^{-1} to 46.0 Mg C ha^{-1} ($d = 1.25\%$ year^{-1}), but forest area

314　　decreased by 0.97×10^6 ha ($a = -1.79\%$ year^{-1}) in the same period (Appendix C, Fig. 2b).

315　　Thus, areal contraction was responsible for the net C loss in the late 1990s. Analysis of C

316　　sinks at the provincial level also revealed that forest area declined at a relatively higher rate

317　　than the increase in biomass density in some provinces, making areal reduction the primary

318 reason for C loss in natural forests (Fig. 3). Notably, since the late 1990s (1994–1998), natural

319 forests in China have functioned as a persistent C sink, probably owing to implementation of

320 the nationwide Natural Forest Conservation Project starting in 1998 (Appendix C) (Shen,

321 2000; Lei, 2005; Ministry of Forestry of China, 2009; Guo, 2013). Subsequently, the relative

322 contribution of changes in biomass has shown a constantly increase (Fig. 2d).

323 *4.3 Uncertainty of estimates*

324 Uncertainties in our studies mainly arise from the quality of forest area and timber volume

325 data in the forest inventories and the estimation of national biomass stocks using the BEF

326 method. On the one hand, precision in the forest area and timber volume data was required to

327 be >90% in almost all provinces (>85% in Beijing, Shanghai, and Tianjin) (Xiao, 2005). On

328 the other hand, the R^2 values of the BEF equations used to convert timber volume to biomass

329 for most dominant tree species or forest types exceeded 0.8 (Fang et al., 2014a). Therefore,

330 the data and method used in the present study show relatively high precision. Previous studies

331 have reported that the estimation error of biomass stocks at the national level are expected to

332 be less than 3% in China (Fang et al., 1996).

333 **Conclusions**

334 With the implementations of national afforestation and reforestation programs since the late

335 1970s, China is credited with making a significant contribution to regional and global C sinks

336 in recent decades. Using forest identity and CFID, this study quantified in detail the relative

337 contributions of forest areal expansion and increased biomass density to China's forest C

338 sinks during the past 30 years. Our findings suggested that the mechanisms underlying the C

339 sinks for natural and planted forests differed markedly with various effects from these two

340 driving agents. The areal expansion of forests was a larger contributor to C sinks than forest

341 growth for all forests and planted forests while forest growth (e.g. increased biomass density)

342 made a larger contribution for natural forests. Furthermore, the increasing trend in the relative

343   contribution of forest growth to C sinks for planted forests highlight that afforestation can

344   continue to increase the C sink of China's forests in the future subject to

345   persistently-increasing forest growth after establishment of plantation.

346

347   **Author contributions**

348   J. F., J.Z., and P.L. designed the research; P. L., J.Z., H.H., Z.G., and J.F. performed the

349   research; P.L., J.Z., and J.F analyzed data; J.F., Y.P. and R.B. contributed new analytic tools;

350   P.L. and J.Z. prepared the manuscript with contributions from all co-authors.

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460 **Fig. 1.** Rate of change and relative contributions of forest area and biomass density to carbon
461 sinks in all (a), planted (b) and natural (c) forests in six broad regions of China for the period
462 1977–2008. The division of these six broad regions are indicated as (d). Bars and numbers
463 above represent the change rates and their relative contributions of forest area (in black color)
464 and carbon density (in red color), respectively.

465

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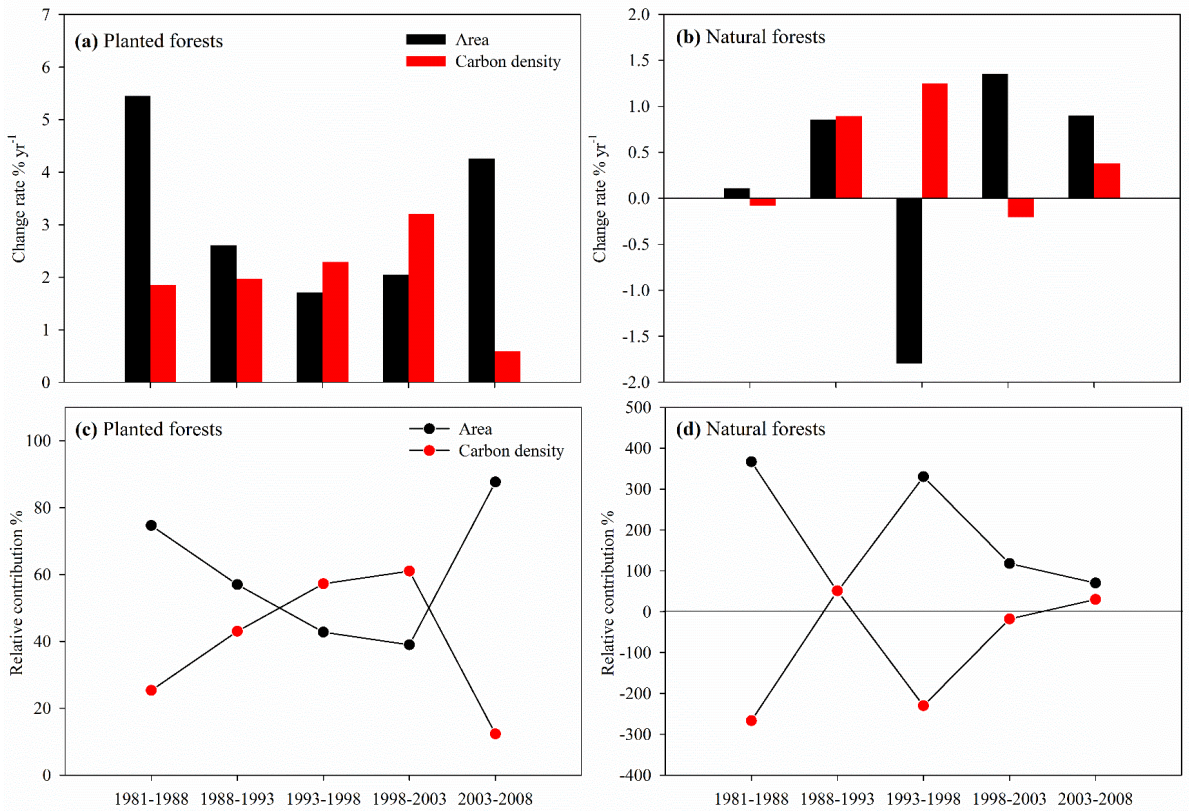
Fig. 3. Rate of change and the relative contributions of changes in forest area and carbon density of natural forests to carbon loss in three provinces of China in the period 1977–2008. Bars and numbers above represent the change rates and their relative contributions of forest area (in black color)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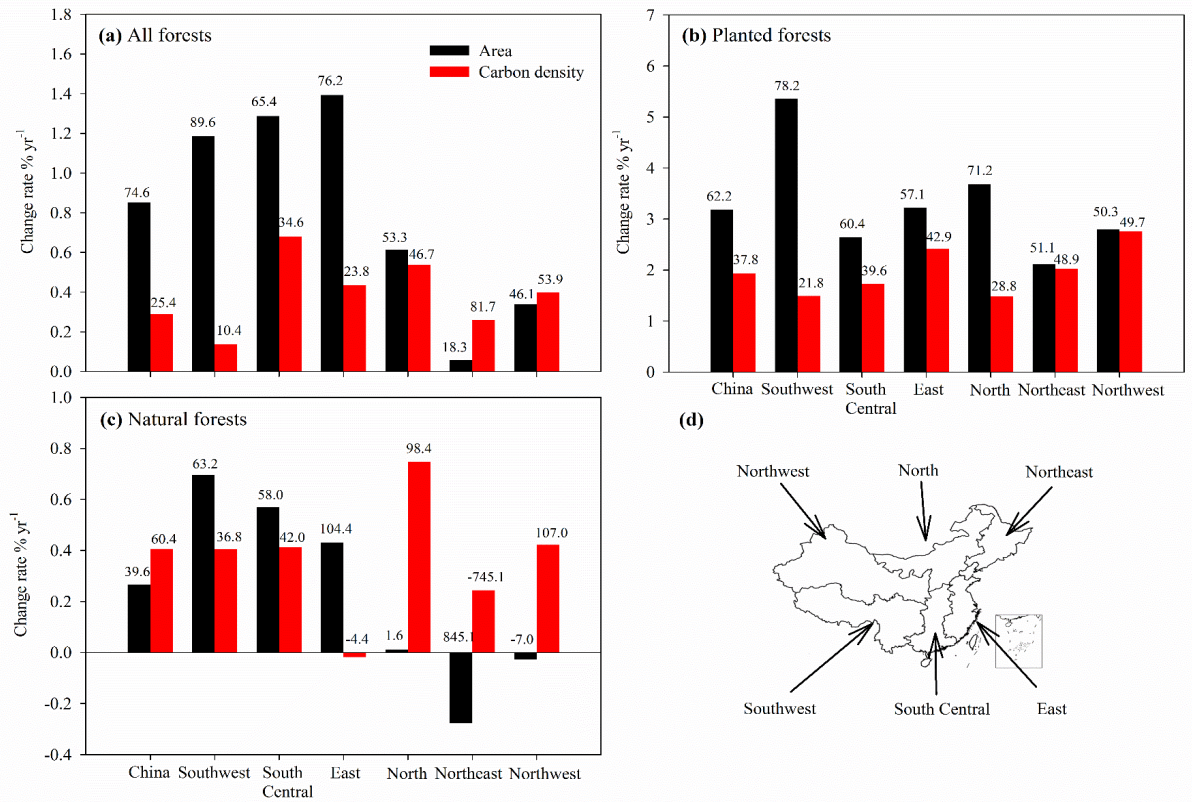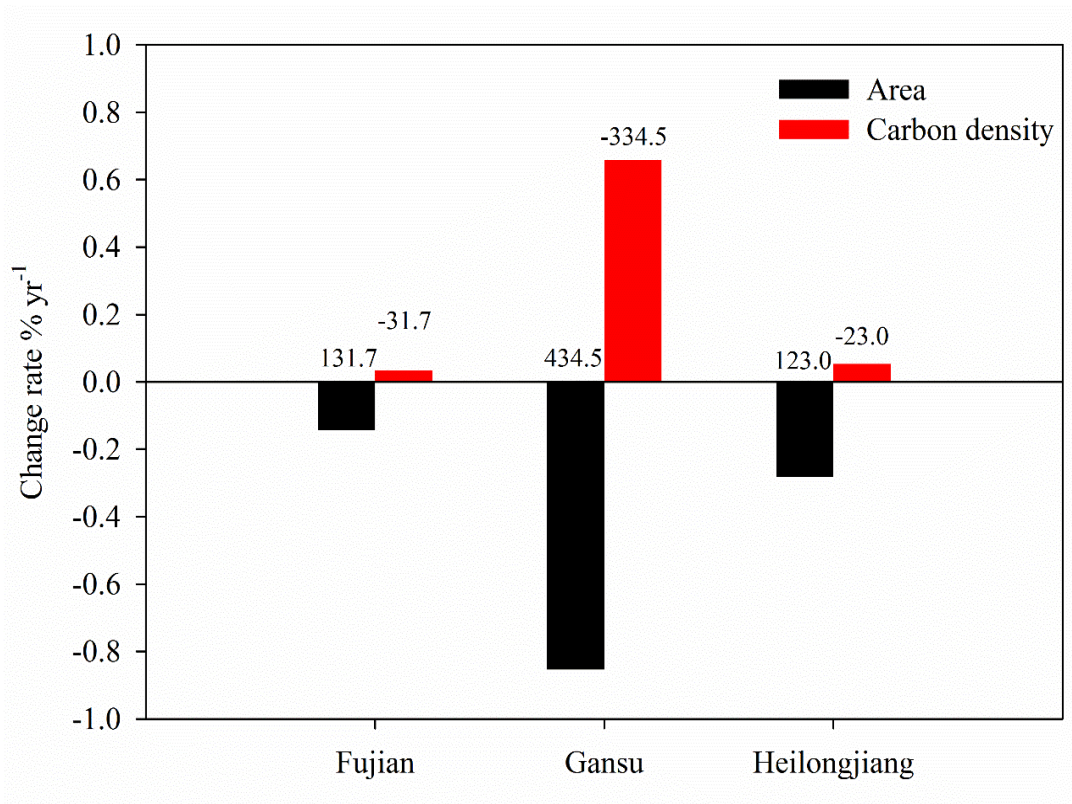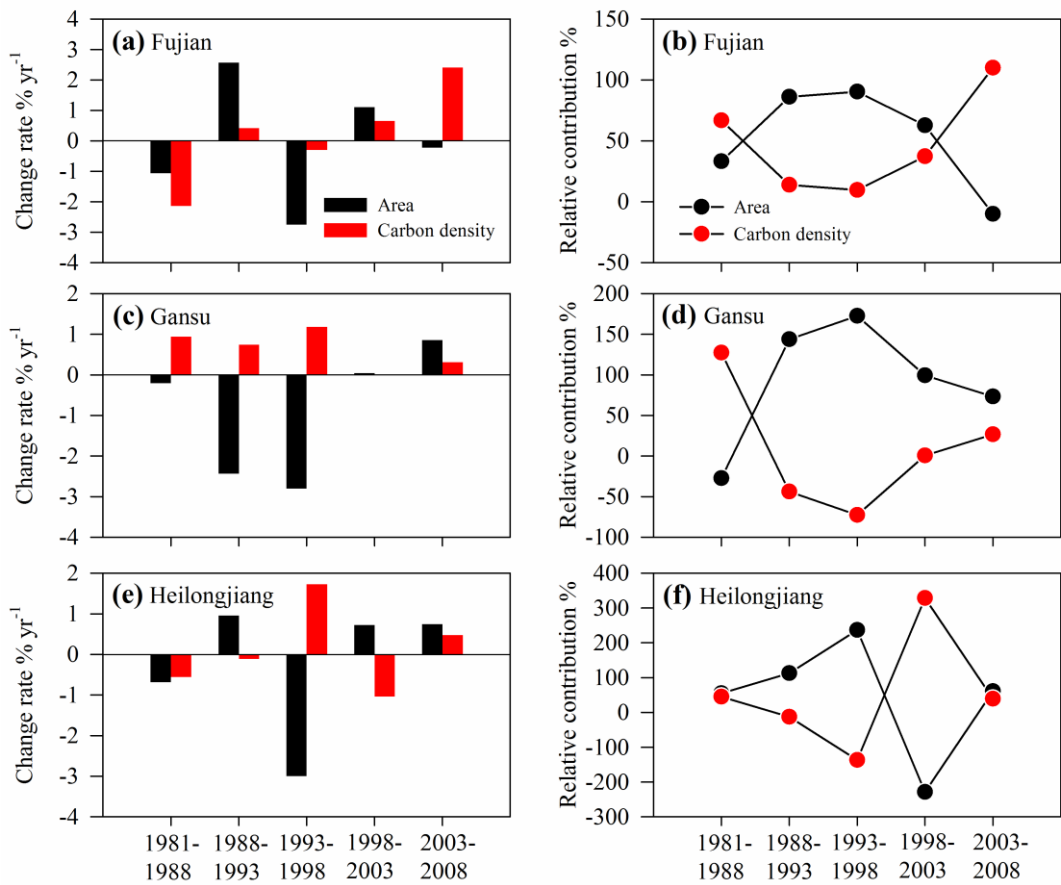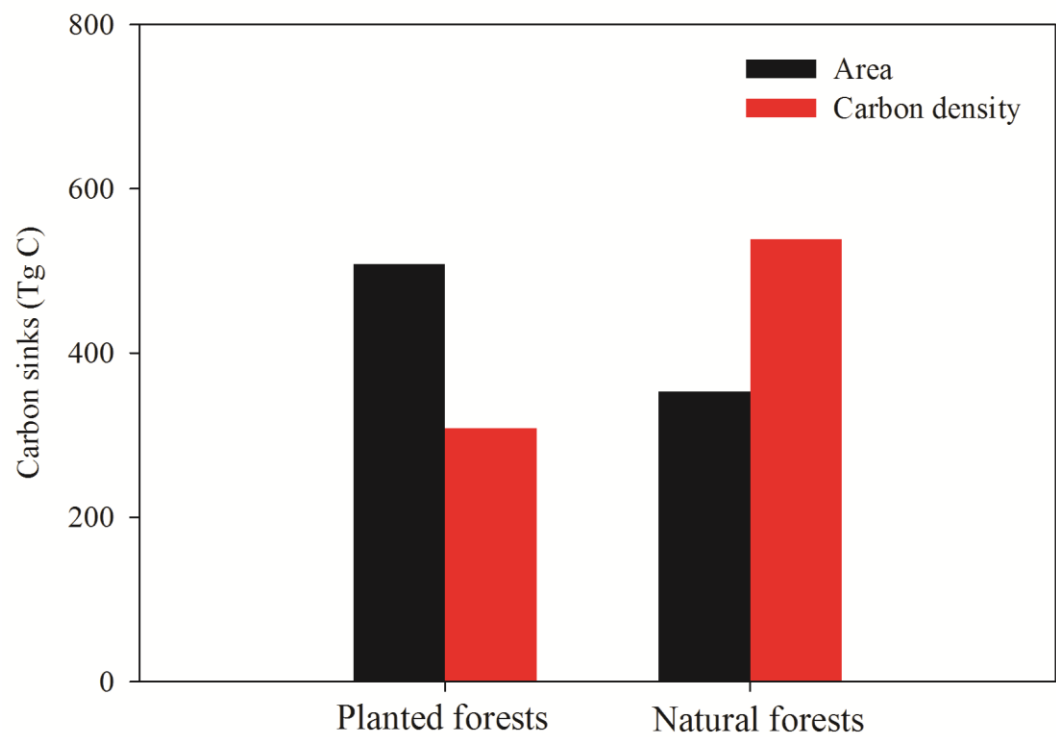respectively.

486 **Fig. 5.** Summary of the forest biomass carbon accumulation induced by areal
487   expansion and increase in carbon density for planted and natural forests of China in
488   the period 1977–2008.

489

490
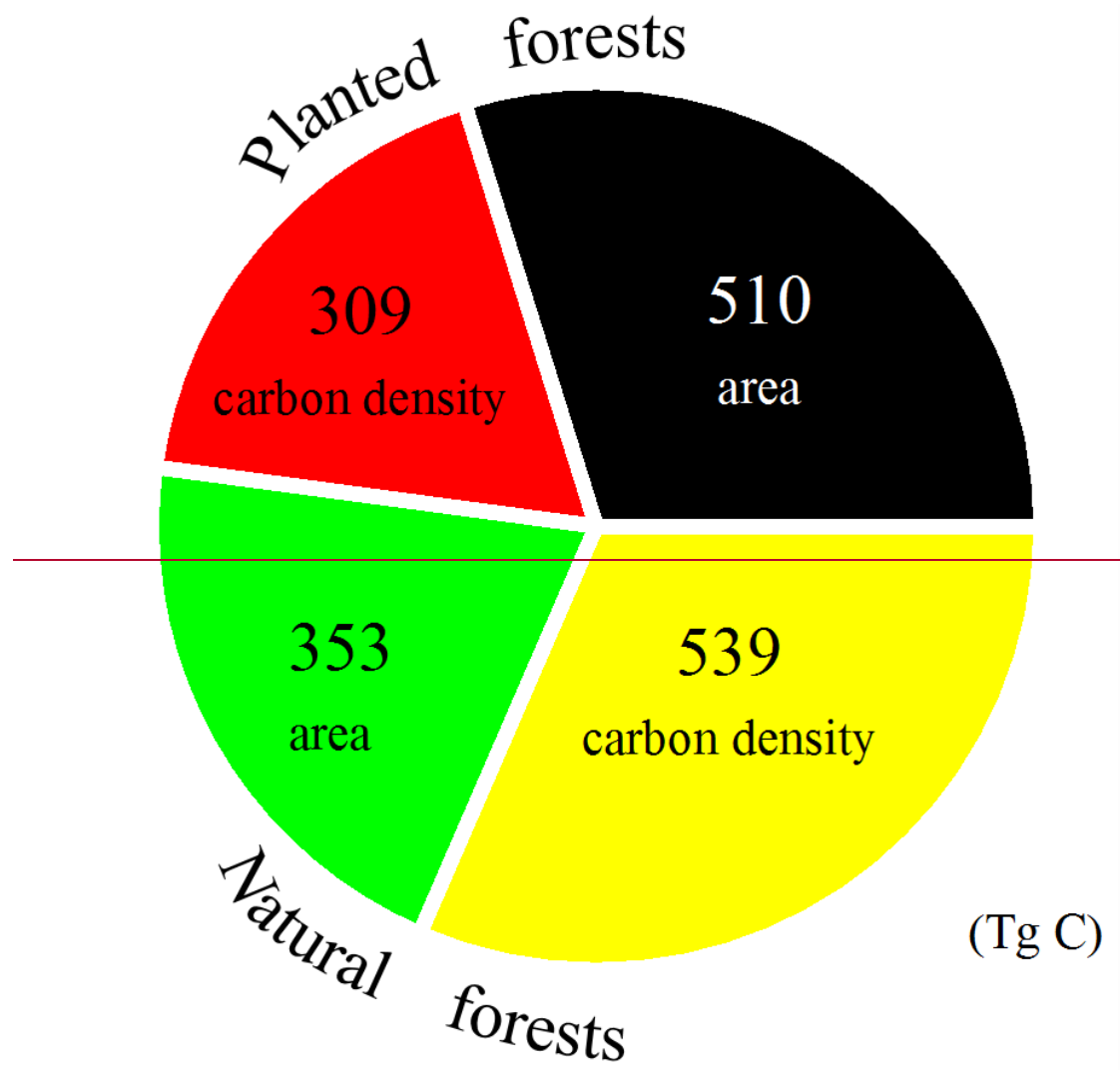
Appendix A. Forest area, carbon stock, and carbon sinks for six regions in China from 1977 to 2008

Period	China	North	Northeast	East	South Central	Southwest	Northwest
Area (10^4 ha)							
1977–1981	12350.3	1849.1	2953.9	1525.9	2173.3	2939.3	908.8
1984–1988	13169.1	1899.8	3054.2	1723.2	2142.3	3333.0	1016.6
1989–1993	13971.5	1997.1	3130.5	1904.2	2446.0	3532.6	961.2
1994–1998	13240.6	1761.0	2769.8	1903.9	2498.8	3409.7	897.4
1999–2003	14278.7	2003.3	2826.3	2026.7	2720.0	3802.2	900.3
2004–2008	15559.0	2182.9	3000.7	2232.6	3087.3	4059.2	996.3
Net change	3208.7	333.9	46.8	706.7	914.0	1119.9	87.5
C stock (Tg C)							
1977–1981	4717.4	556.7	1249.9	384.5	456.4	1719.7	350.2
1984–1988	4884.8	593.6	1256.4	377.0	428.0	1857.3	372.6
1989–1993	5402.3	629.3	1308.7	428.8	505.4	2151.5	378.5
1994–1998	5387.9	621.3	1257.1	435.2	545.5	2145.4	383.5
1999–2003	5862.5	701.1	1272.8	515.7	653.0	2326.6	393.4
2004–2008	6427.1	760.1	1362.2	632.8	779.3	2465.3	427.4
Net change	1709.7	203.4	112.3	248.4	322.9	745.6	77.2
C density (Mg C ha^{-1})							
1977–1981	38.2	30.1	42.3	25.2	21.0	58.5	38.5
1984–1988	37.1	31.2	41.1	21.9	20.0	55.7	36.6
1989–1993	38.7	31.5	41.8	22.5	20.7	60.9	39.4
1994–1998	40.7	35.3	45.4	22.9	21.8	62.9	42.7
1999–2003	41.1	35.0	45.0	25.4	24.0	61.2	43.7
2004–2008	41.3	34.8	45.4	28.3	25.2	60.7	42.9
Net change	3.1	4.7	3.1	3.1	4.2	2.2	4.4
C sink (Tg C year^{-1})							
1981–1988	23.9	5.3	0.9	−1.1	−4.1	19.6	3.2
1988–1993	103.5	7.2	10.5	10.4	15.5	58.8	1.2
1993–1998	−2.9	−1.6	−10.3	1.3	8.0	−1.2	1.0
1998–2003	94.9	16.0	3.1	16.1	21.5	36.2	2.0
2003–2008	112.9	11.8	17.9	23.4	25.3	27.8	6.8

Appendix B. 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 C. 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

504 **Appendix D.** 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

505 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
506 two provinces were not separated administratively until 1988 and their separate inventory data was lacked for the period of 1977–1981.
507

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

Province	Area (10⁴ 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

509   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

510   two provinces were not separated administratively until 1988 and their separate inventory data was lacked for the period of 1977–1981.

Appendix F. 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

536
$$S_{V_i}^2 = \frac{1}{n-1}\sum_{j=1}^{n}(V_{ij} - \overline{V}_i)^2 \tag{7}$$

537
$$S_{\overline{V}_i} = \frac{S_{V_i}}{\sqrt{n}} \tag{8}$$

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

539
$$\hat{V}_i = \frac{A}{a} \cdot \overline{V}_i \tag{9}$$

540 where A means the overall area in the forest inventory for one province, a means the area of

541 the sampling plot.

542 The limit of error for the overall estimation of forest i can be calculated by the following

543 equation: $\Delta_{V_i} = \frac{A}{a} \cdot t_a \cdot S_{\overline{V}_i}$

544
$$\tag{10}$$

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

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

547
$$P_{V_i} = (1 - \frac{t_a \cdot S_{V_i}}{\overline{V}_i}) \cdot 100\% \tag{11}$$

548