

# Biomass Carbon Storage and Its Sequestration Potential of Afforestation under Natural Forest Protection Program in China

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**Abstract:** Based on the data from China's Seventh Forest Inventory for the period of 2004–2008, area and stand volume of different types and age-classes of plantation were used to establish the relationship between biomass density and age of planted forests in different regions of the country. Combined with the plantation area in the first-stage of the Natural Forest Protection (NFP) program (1998–2010), this study calculated the biomass carbon storage of the afforestation in the first-stage of the program. On this basis, the carbon sequestration potential of these forests was estimated for the second stage of the program (2011–2020). Biomass carbon storage of plantation established in the first stage of the program was 33.67 Tg C, which was majority accounted by protection forests (30.26 Tg C). There was a significant difference among carbon storage in different regions, which depended on the relationship of biomass carbon density, forest age and plantation area. Under the natural growth, the carbon storage was forecasted to increase annually from 2011 to 2020, reaching 96.03 Tg C at the end of the second-stage of the program in 2020. The annual growth of the carbon storage was forecasted to be 6.24 Tg C/yr, which suggested that NFP program has a significant potential for enhancing carbon sequestration in plantation forests under its domain.

**Keywords:** Natural Forest Protection (NFP) program; afforestation; carbon storage; carbon sequestration; China

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## 1 Introduction

There is no overall consensus on the precise relationship of temperature to carbon dioxide (CO<sub>2</sub>) concentration in the atmosphere (Knee, 2009; Zahn, 2009). However, a worldwide political consensus has emerged that global CO<sub>2</sub> concentration should be controlled to a suitable level. Thus the status of atmospheric CO<sub>2</sub> concentration is not only one of the key foci of global change research, but also the important global political and diplomatic issue (Ding *et al.*, 2009). Forests account for 85%–90%

of the biomass of all global terrestrial vegetation, and for 90% of the carbon exchange with the atmosphere via photosynthesis and respiration, so forests play a key role in regional and global carbon cycles (Fang *et al.*, 2006; Bonan, 2008; Pan *et al.*, 2011; Guo *et al.*, 2013).

In recent years, there has been a considerable amount of researches on carbon storage in the forests of China. Results have suggested the importance of carbon storage in China's forests to regional and global carbon budgets, and have documented a continual increase in the carbon storage of planted forests (Xu *et al.*, 2010; Guo *et al.*,

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2013). This was the result from carrying out of a series of major forestry ecological engineering programs (Sloping Land Conversion program, Three-North Shelterbelt Forest program, the Changjiang (Yangtze) River Basin Forest Protection program, Beijing-Tianjin Sandstorm Source Control program, Natural Forest Protection program, and other programs) over the past 30 years (China Forestry Sustainable Development Strategy Research Group, 2002). Since most of the public welfare forests planted in these programs comprises young forests, the programs have a greater potential for carbon storage in China's forests (Deng *et al.*, 2014).

Since 1998, the Natural Forest Protection (NFP) program has been carried out to address the deterioration of ecological environment of China. By reclassifying natural forests of the country, adjusting the goal of the forest management and promoting the natural forest resource protection, cultivation and development, the program aims to sustain and improve the ecological environment while meeting the economic and social demands for forest products (Wei *et al.*, 2014). The objective of the program includes significantly decreasing and adjusting the timber yield in three regions of the Upper Changjiang River, the Upper and Middle Huanghe (Yellow) River, and the Key State-owned Forest Districts of Northeast China and Inner Mongolia Autonomous Region; prohibiting commercial logging of natural forests in the Upper Changjiang River and the Upper and Middle Huanghe River regions; and accelerating plantation establishment in degraded lands of the three aforementioned regions. The regions of the NFP program include 17 provincial-level administrative units. The Key State-owned Forest Districts covers Jilin, Heilongjiang, Hainan provinces, Uygur Autonomous Region of Xinjiang, and the eastern of Inner Mongolia; the Upper Changjiang River region includes Hubei, Sichuan, Guizhou, Yunnan provinces, Chongqing Municipality, and Tibet Autonomous Region; and the Upper and Middle Huanghe River region includes Henan, Shanxi, Shaanxi, Qinghai provinces, Midwest of Inner Mongolia, and Hui Autonomous Region of Ningxia. The area of natural forests covered by the program is 7 330 000 ha, and it is about 69% of the area of all natural forests in China (Wei *et al.*, 2014). The NFP program has significantly contributed to improving the ecological environment in China as well as the carbon sequestration

capacity of terrestrial ecosystems (Hu and Liu, 2006). However, there have been few precise estimates of the carbon storage and carbon sequestration potential of plantation forest established under the NFP program. The objectives of this study were: 1) to estimate the carbon storage of the planted forests under the NFP program at the end of the first stage of the program (1998–2010); and 2) to estimate the carbon sequestration potential of forests planted in the preceding stage at the end of second stage (2011–2020).

## 2 Materials and Methods

### 2.1 Data sources

The data used in this study come from China's Seventh Forest Inventory (2004–2008) (Chinese Ministry of Forestry, 2010), China Forest Statistical Yearbook of 1998–2010 (Chinese Ministry of Forestry, 2011), and forest area covered by the NFP program in each province. Inventory data on age-class and stand volume were used to establish the relationship between biomass density and age of plantation forests. When calculating the planted forest area under the NFP program in each region only the areas of the timber, protection and special forests were included; but the areas of fuelwood forest and economic forest were not evaluated. That was because the fuelwood forest as energy sources has a lower carbon sequestration capacity, and the economic forests, used for growing the fruit, has shorter growth periods and thus short periods of carbon sequestration.

### 2.2 Calculation of biomass density

The biomass density of China's Seventh Forest Inventory for the period of 2004–2008 was evaluated with the method of biomass expansion factor (Fang *et al.*, 2001). First, timber density was calculated based on the data on the area and timber of different forest types in different age-classes. The biomass expansion factor (BEF) method was then used to calculate the biomass density. The equation is as follows:

$$BEF = a + b / x \quad (1)$$

$$B = BEF \times x \quad (2)$$

where *BEF* is a biomass expansion factor, *x* is timber volume of a given age of a forest type, *a* and *b* are constants for a given forest type, and *B* is biomass density.

### 2.3 Model of biomass carbon density and forest age

According to the 'Technical Regulations for Forest Resources Planning and Designing' (China Forestry Sustainable Development Strategy Research Group, 2002), five stand ages (initiation, young, medium, mature and old) with ages 10 years, 20 years, 35 years, 50 years and 70 years, respectively were identified in the program regions of the Upper Changjiang River and the Upper and Middle Huanghe River. In the Key State-owned Forest Districts of the Northeast-Inner Mongolia, stand ages were set as 20 years, 35 years, 50 years, 70 years and 90 years, while for the Key State-owned Forest Districts in Hainan, the stand ages were set as the same as those for the Changjiang and Huanghe River regions, considering the climate and forest types in Hainan.

The logistic function was used to fit the relationship of planted forest biomass density and age. The equation is as follows (Xu *et al.*, 2010):

$$B = \frac{w}{1 + ke^{-at}} \quad (3)$$

where  $B$  is the stand biomass density,  $t$  is the stand age, and  $a$ ,  $w$  and  $k$  are parameters.

The equation was fitted by nonlinear regression analysis by using SPSS 16.0 (2008, v.16.0; SPSS Inc., USA).

### 2.4 Estimation of biomass carbon potential of plantation forests

According to the plantation areas of timber, protection and special use forests in NFP program regions in each year (1998–2010), the total carbon sequestration for these forests for 2011–2020 was evaluated. The equation is as follows:

$$C_t = c \times \sum_{t=1}^{12} f(t) \times S_t \quad (4)$$

where  $t$  is the age of the forest;  $C_t$  is the amount of carbon sequestration at the age of  $t$ ;  $c$  is the conversion coefficient of carbon, taken as 0.5 in this study;  $S_t$  is plantation area at the age of  $t$ ; and  $f(t)$  is the stand growth curve.

## 3 Results

### 3.1 Relationship between biomass carbon density and forest age

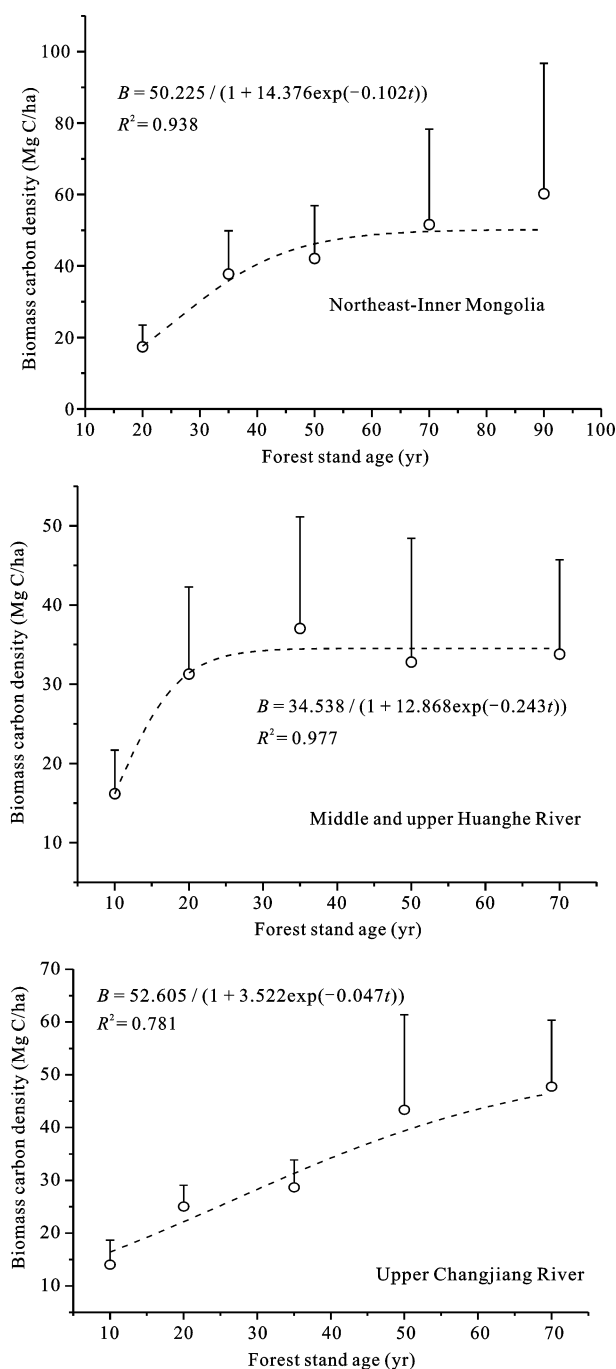
In Key State-owned Forest Districts of Northeast-Inner

Mongolia, Upper Changjiang Rivers and Upper and Middle Huanghe River area, the logistic curve model is the best to fit the relationship between biomass carbon density and forest age, with the  $R^2 > 0.780$ . It suggests that the logistic curve model could effectively simulate the natural growing process of plantation forests in the three regions (Fig. 1).

### 3.2 Planting areas and carbon storage under the first stage of NFP program in each province

The NFP program not only improved forest quality by protecting the natural forest, but also aided in developing non-commercial forests by the planting trees to decrease soil erosion. During 1998–2010, forest area planted had changed annually, ranging from  $220.85 \times 10^3$  ha in 2006 to  $1294.35 \times 10^3$  ha in 2009. From 1998 to 2010, the plantation area in the first stage of the NFP program reached  $8453.7 \times 10^3$  ha, of which the areas of timber, protection and special forests were  $611.95 \times 10^3$  ha,  $7798.34 \times 10^3$  ha and  $43.45 \times 10^3$  ha, respectively (Fig. 2). Protection forests were obviously the major forest category, which comprised 63.4%–97.4% and averaged 90.5% of the planted forests (Table 1). Plantation forests were concentrated in the Upper Changjiang River and the Upper and Middle Huanghe River regions. Plantation areas in Sichuan, Inner Mongolia and Shaanxi were  $2877.4 \times 10^3$  ha,  $1251.5 \times 10^3$  ha and  $1196.2 \times 10^3$  ha, respectively. Decreased timber production occurred mainly in Key State-owned Forest Districts in the northern-Inner Mongolia and Hainan, where the area of planted forests was relatively small. Plantation areas in Jilin, Heilongjiang, Xinjiang and Hainan were  $112.5 \times 10^3$ ,  $134.4 \times 10^3$ ,  $4.0 \times 10^3$  and  $10.1 \times 10^3$  ha, respectively. The plantation area of all Key State-owned Forest Districts accounted for only 3.1% of whole planted area under the NFP program.

Carbon storage of the plantation established each year depended primarily on the relationship of plantation area and biomass carbon density with forest age. The forest planted in 2001 was not the largest one in area ( $922.22 \times 10^3$  ha), but with the largest carbon storage of 7.18 Tg C due to the longer growth time until 2010. In addition, the planted forest in 2009 showed the largest area with the carbon storage of 2.38 Tg C due to the shorter growth time. Given that the starting time of the program and the above relationships differed in different provinces, it was not surprising that carbon storage of



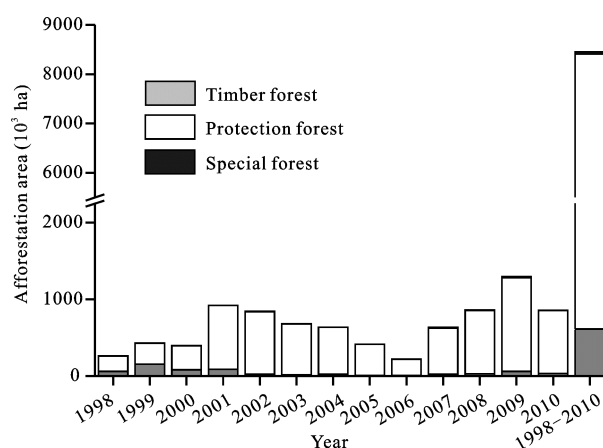
**Fig. 1** Logistic curve between biomass carbon density and forest age of plantation forests in Natural Forest Protection (NFP) program regions

planted forests varied in different provinces at the end of the first stage of the NFP program (2010) (Table 1). The plantation carbon storage in Shaanxi, Inner Mongolia, Gansu, Shanxi and Sichuan were 8.78 Tg C, 6.85 Tg C, 3.47 Tg C, 3.33Tg C and 2.48 Tg C, respectively, which together accounted for 81.1% of carbon storage in the whole program. Hainan had the lowest of carbon storage

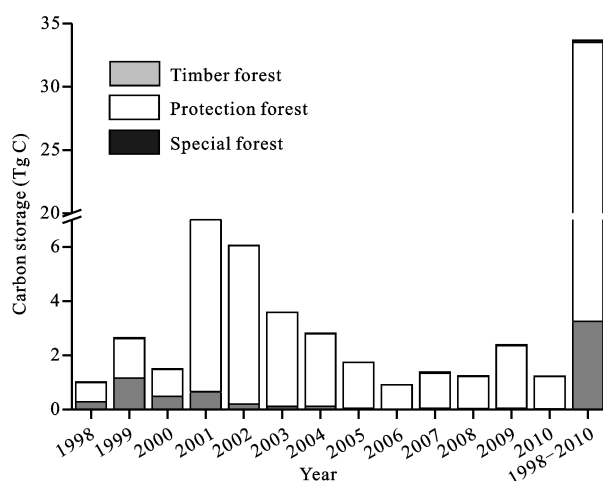
of 0.01 Tg C. At the conclusion of the first stage (1998–2000) of the NFP program, the carbon storage of the planted forest during this period reached 33.67 Tg C (Fig. 3).

### 3.3 Biomass carbon sequestration potential of afforestation under NFP program

Based on the model components of age, carbon density and plantation area under the NFP program from 1998 to 2010, we predicted the change of carbon storage of those plantation forests over the next 10 years. If logging and tree mortality were not considered, the carbon storage of the plantations in the first stage of the program increased with the time, reaching 96.03 Tg C at the end of the second stage in 2020. Compared to 33.67 Tg C in 2010 (Fig. 3), storage increased by 62.36 Tg C, reflecting an increase of 6.24 Tg C/yr from 2010 to 2020 (Fig. 4d).



**Fig. 2** Area of afforestation under Natural Forest Protection (NFP) program in China (1998–2010)



**Fig. 3** Forest biomass carbon stocks of different afforestation time in 2011



**Table 1** Plantation area and carbon sequestration of forest plantations under Natural Forest Protection (NFP) program (1998–2010)

Province	Plantation area (10 <sup>3</sup> ha)				Carbon sequestration (Tg C)			
	Timber forest	Protection forest	Special forest	Total	Timber forest	Protection forest	Special forest	Total
Shanxi	3.1	408.1	0.3	411.5	0.04	3.29	0.00	3.33
Shaanxi	99.0	1096.7	0.5	1196.2	1.09	7.68	0.01	8.78
Gansu	10.5	401.3	20.7	432.4	0.14	3.26	0.07	3.47
Qinghai	0.0	104.3	0.0	104.3	0.00	0.62	0.00	0.62
Ningxia	0.0	109.3	0.0	109.3	0.00	0.93	0.00	0.93
Henan	4.1	49.7	0.7	54.5	0.02	0.40	0.01	0.42
Inner Mongolia	32.9	1209.2	9.4	1251.5	0.28	6.53	0.04	6.85
Jilin	90.9	20.7	0.9	112.5	0.78	0.17	0.01	0.96
Heilongjiang	54.0	76.9	3.6	134.4	0.48	0.68	0.03	1.19
Xinjiang	2.5	1.5	0.0	4.0	0.02	0.01	0.00	0.03
Hubei	16.9	169.1	0.3	186.3	0.02	0.22	0.00	0.24
Hainan	0.7	8.4	1.0	10.1	0.00	0.01	0.00	0.01
Chongqing	50.8	357.5	0.0	408.3	0.06	0.34	0.00	0.40
Sichuan	142.5	2732.4	2.6	2877.4	0.13	2.35	0.00	2.48
Guizhou	38.7	317.7	3.3	359.7	0.03	0.31	0.00	0.34
Yunnan	65.3	678.5	0.3	744.2	0.05	0.57	0.00	0.62
Tibet	0.0	57.1	0.0	57.1	0.00	0.04	0.00	0.04

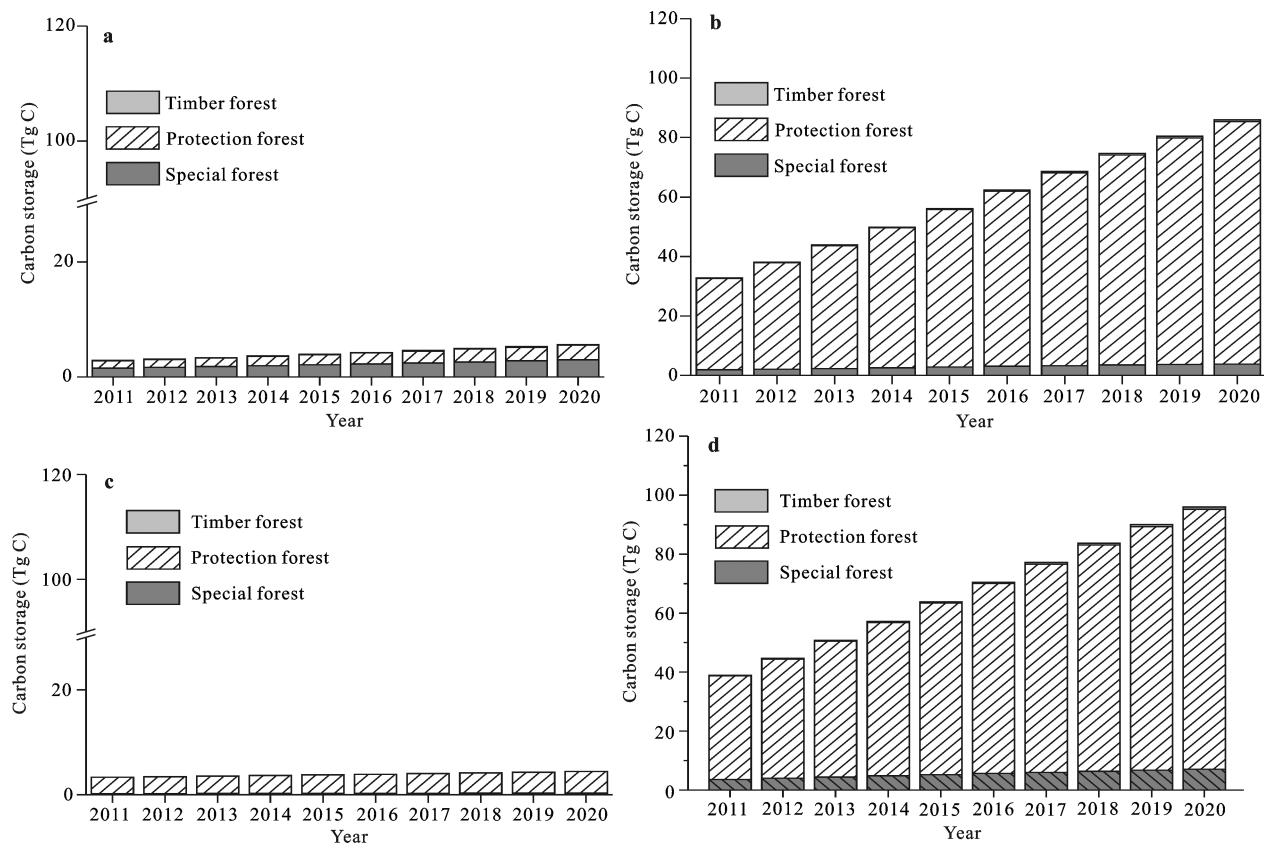
Carbon storage of plantations showed an increasing trend in the different program regions (Fig. 4a, Fig. 4b, and Fig. 4c). At the same time, the potential of carbon sequestration varied in different regions for the differences in the relationship of plantation area and carbon density with forest age (Fig. 4). In 2020, carbon storage in the Northeast- Inner Mongolia, the Upper Changjiang River and the Upper and Middle Huanghe River forest regions were 5.6 Tg C, 85.9 Tg C and 4.4 Tg C, respectively, which accounted for 5.9%, 89.5% and 4.6% of the total storage under the NFP program. Protection forests accounted for 91.8% of overall carbon storage under the program, about 88.1 Tg C. Carbon storage of timber and special forests was lower in comparison, about 7.1 Tg C and 0.7 Tg C, respectively. The carbon sequestration potential of different forest categories varied in different program regions. In the Upper Changjiang River and the Upper and Middle Huanghe River forest regions, protection forests accounted for the bulk of carbon sequestration potential. In the Northeast-Inner Mongolia forest region, both protection and timber forests showed the highest potential, with 54% and 45% of the regional total, respectively.

## 4 Discussion

### 4.1 Carbon sequestration potential of plantation under NFP program

It is generally agreed that forests, one of the important kinds of terrestrial ecosystems, play a key role in carbon sequestration (Ding *et al.*, 2009). According to China's Seventh Forest Inventory, the total carbon storage of forest biomass in China is 6427 Tg C (Guo *et al.*, 2013). Forests under the NFP program, one of the key forestry programs in the country covering 45% the total forest area in China, play a crucial role in regulating forest carbon sequestration in China (Chinese Ministry of Forestry, 2010).

From 1998 to 2010, the total area of plantations under the NFP program was  $8.45 \times 10^6$  ha, but biomass carbon storage of these forests only accounted for 1.3% of total forest biomass carbon storage in China, thus playing a minor role in sequestering carbon dioxide. On the other hand, the plantations under the NFP program not only represented a clean development mechanism under the Kyoto Protocol, but also served to reduce soil erosion and accompanying carbon losses (Ramos *et al.*, 2006). In

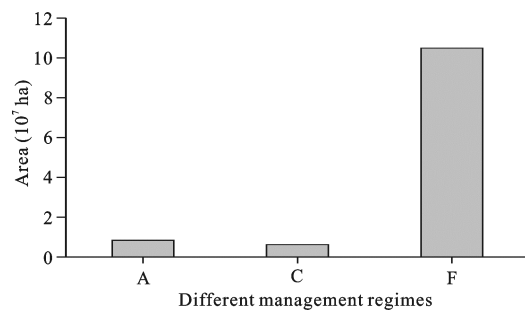


**Fig. 4** Carbon sequestration potential of plantation forests under Natural Forest Protection (NFP) program from 2011–2020. a, North-east-Inner Mongolia; b, Middle and Upper Huanghe River; c, Upper Changjiang River; d, NFP program

this light, the amount of carbon storage for plantations under the NFP program was underestimated in this study.

Pan *et al.* (2004) reported that the relationship between forest biomass carbon density and forest age was one of logarithmic growth, indicating that forest age is an important factor in calculating forest biomass. However, this study only estimated biomass carbon storage of plantations for the first stage of the NFP program (1998–2010), and the continuing protection of these forests under the program should enhance their capacity for carbon sequestration during the second stage (2010–2020) (Fig. 1).

In addition, there are many other protection and management patterns in ecological welfare forest construction in addition to plantations, i.e., closed forest, forest administration and protection, and so on, that are encompassed by the NFP program. Actually, the area of plantations under the NFP program only accounted for 7.1% of total ecological welfare forest area (Fig. 5). If the rate of carbon sequestration for plantations under the NFP program continues, the program will make a significant impact on the carbon sequestration potential of



**Fig. 5** Area of different forest management regimes for public welfare forests under Natural Forest Protection (NFP) program in 2010. A, afforestation; C, closed forest; F, forest administration and protection

the forest in China (Xu *et al.*, 2010).

## 4.2 Uncertainty analysis for carbon storage calculation

There are many methods to estimate the forest biomass carbon storage on a regional scale (Piao *et al.*, 2005; Guo *et al.*, 2010; Xiao *et al.*, 2011), and ecological model was usually used to forecast the trend of the forest carbon pool change (Xu *et al.*, 2010). Because the

effects on forest biomass of some forest management activities (thinning, restoration planting, and so on) have been considered when calculating forest biomass on a regional scale by using forest inventory data from different periods, it was reasonable to calculate forest biomass through the relationship between forest biomass carbon density and forest age at regional and national scales. Moreover, this method was quite precise, yielding minor errors of  $-2.1\%$ – $3.6\%$  (Guo *et al.*, 2010; Chen *et al.*, 2012). So in this study, the relationship between the plantation forest biomass carbon density and forest age was established by using the Seventh National Forest Inventory. However, since the relationship was established on a provincial scale base, and the data from the national forest inventory just has one phase, it was easy to cause errors for estimation results. So it is necessary that the existing datasets should be updated to reduce this uncertainty for carbon calculations. This can be expected with the completion of the Eighth National Inventory in 2013.

In addition, the results of estimates generated in this study might be affected by the followed factors: 1) The area of plantations was uncertain due to the low survival rate of some plantations affected by the geographic and climate conditions. 2) The number of inventory plots is insufficient when they are used to establish the biomass volume equations on regional scales, which led to relatively higher errors for the results of our calculation. 3) Calculation of biomass carbon storage was under the hypothesis that plantation growth proceeded according to the growth equation in this study. In actuality, young forests are affected by many factors, including silvicultural activities, pest control measures, fire disturbance, and many other human activities which are difficult to quantify (Cai *et al.*, 2013). Thus, the results of this study might be overestimated. 4) There are even broader factors that may affect the accumulation of forest biomass carbon storage, i.e., climate change, an increase in the concentration of atmospheric CO<sub>2</sub>, nitrogen deposition, and so on (Piao *et al.*, 2009; Wang *et al.*, 2011). So the estimation results of forest biomass carbon storage could be affected if it was not considered all of the above factors.

## 5 Conclusions

The objectives of the NFP program are to protect the natural forest, construct the public welfare forest, and

achieve the sustainable development of forest. Afforestation under the NFP program not only improves the ecological environment of China, but also has a greater potential for the carbon storage in China's forests. So afforestation has been an important component of the NFP program. Based on the data from China's Seventh National Forest Inventory, the relationships between plantation forest biomass carbon density and forest age on regional scales are established in this study. And the logistic curve model fits relationship between biomass carbon density and forest age. Forest biomass carbon storage of plantation in the first stage of the NFP program (1998–2010) was estimated to be 33.67 Tg C. Carbon storage of the plantations established each year depended primarily on the relationship of plantation area and biomass carbon density with forest age. The accumulation of forest biomass carbon storage is increasing year by year in the afforestation of the NFP program from 2011 to 2020, which will be up to 96.03 Tg C in 2020. Although biomass carbon storage of afforestation in the first-stage of the NFP program just plays a minor role in offsetting the carbon emission of China. Because the afforestation is just a small part of the NFP program, so the carbon storage of the NFP program should be further studied.

## References

- Bonan G B, 2008. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320(7): 610–619. doi: 10.1126/science.1155121
- Cai W H, Yang J, Liu Z H *et al.*, 2013. Post-fire tree recruitment of a boreal larch forest in Northeast China. *Forest Ecology and Management*, 307(11): 20–30. doi: 10.1016/j.foreco.2013.06.056
- Chen Q Q, Xu W Q, Li S G *et al.*, 2012. Aboveground biomass and corresponding carbon sequestration ability of four major forest types in South China. *Chinese Science Bulletin*, 58(13): 1551–1557. doi: 10.1007/s11434-012-5100-8
- China Forestry Sustainable Development Strategy Research Group, 2002. *General View of China Forestry Sustainable Development Strategy Research*. Beijing: China Forestry Publishing House, 109–131. (in Chinese)
- Chinese Ministry of Forestry, 2011. *China Forestry Statistical Yearbook 1998–2010*. Beijing: China Forestry Publishing House. (in Chinese)
- Chinese Ministry of Forestry, 2010. *Forest Resource Statistics of China (2004–2008)*. Beijing: China Forestry Publishing House. (in Chinese)
- Deng L, Liu G B, Shangguan Z P, 2014. Land use conversion and changing soil carbon stocks in China's 'Grain-for Green' Pro-

- gram: A synthesis. *Global Change Biology*, (in press). doi: 10.1111/gcb.12508
- Ding Z L, Duan X N, Ge Q S et al., 2009. Control of atmospheric CO<sub>2</sub> concentrations by 2050: An calculation on the emission rights of different countries. *Science in China Series D: Earth Sciences*, 52(10): 1447–1469. doi: 10.1007/s11430-009-0155-3
- Fang J Y, Brown S, Tang Y H et al., 2006. Overestimated biomass carbon pools of the northern mid-and high latitude forests. *Climatic Change*, 74(1–3): 355–368. doi: 10.1007/s10584-005-9028-8
- Fang J, Chen A P, Peng C H et al., 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science*, 292(5525): 2320–2322. doi: 10.1126/science.1058-629
- Guo Z D, Fang J Y, Pan Y D et al., 2010. Inventory-based estimates of forest biomass carbon stocks in China: A comparison of three methods. *Forest Ecology and Management*, 259(7): 1225–1231. doi: 10.1016/j.foreco.2009.09.047
- Guo Z D, Hu H F, Li P et al., 2013. Spatio-temporal changes in biomass carbon in China's forests from 1977 to 2008. *Science China-Life Science*, 56(7): 661–671. doi: 10.1007/s11427-013-4492-2
- Hu Huifeng, Liu Guohua, 2006. Carbon sequestration of China's National Natural Forest Protection Project. *Acta Ecologica Sinica*, 26(1): 291–296. (in Chinese)
- Knee R A, 2009. What happened to global warming? Scientists say just wait a bit. *Science*, 326(10): 28–29. doi: 10.1126/science.326\_28a
- Pan Y, Birdsey R A, Fang J Y et al., 2011. A large and persistent carbon sink in the world's forests. *Science*, 333(8): 988–993. doi: 10.1126/science.1201609
- Pan Y, Luo T, Birdsey R et al., 2004. New estimates of carbon storage and sequestration in China's forests—Effects of age-class and method on inventory-based carbon estimation. *Climatic Change*, 67(2–3): 211–236. doi: 10.1007/s10584-004-2799-5
- Piao S L, Fang J Y, Ciais P et al., 2009. The Carbon balance of terrestrial ecosystems in China. *Nature*, 458(4): 1009–1013. doi: 10.1038/nature07944
- Piao S L, Fang J Y, Zhu B et al., 2005. Forest biomass carbon stocks in China over the past 2 decades: Estimation based on integrated inventory and satellite data. *Journal of Geophysical Research*, 110(G1): 1–10. doi: 10.1029/2005JG000014
- Ramos M C, Martinez-Casasnovas J A, 2006. Erosion rates and nutrient losses affected by composted cattle manure application in vineyard soils of NE Spain. *Catena*, 68(2–3): 177–185. doi: 10.1016/j.catena.2006.04.004
- Wang X H, Piao S L, Ciais P et al., 2011. Spring temperature change and its implication in the change of vegetation growth in North America from 1982 to 2006. *Proceedings of the National Academy of the Sciences of the United States of America*, 108(4): 1240–1245. doi: 10.1073/pnas.1014425108
- Wei Yawei, Zhou Wangming, Yu Dapao et al., 2014. Carbon storage of forest vegetation under the Natural Forest Protection Program in Northeast China. *Acta Ecologica Sinica*, (in press). (in Chinese)
- Xiao Y, An K, Xie G D et al., 2011. Carbon sequestration in forest vegetation of Beijing at subplot level. *Chinese Geographical Science*, 21(3): 279–289. doi: 10.1007/s11769-011-0469-x
- Xu B, Guo Z D, Piao S L et al., 2010. Biomass carbon stocks in China's forests between 2000 and 2050: A prediction based on forest biomass-age relationships. *Science China Life Science*, 53(7): 776–783. doi: 10.1007/s 11427-010-40304
- Xu X L, Li K R, 2010. Biomass carbon sequestration by planted forests in China. *Chinese Geographical Science*, 20(4): 289–297. doi: 10.1007/sl 1769-010-0401-9
- Zahn R, 2009. Climate change: Beyond the CO<sub>2</sub> connection. *Nature*, 460(7): 335–336. doi: 10.1038/460335a