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Forest Carbon Storage and Tree Carbon Pool Dynamics under Natural Forest Protection Program in Northeastern China

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Abstract: The Natural Forest Protection (NFP) program is one of the Six Key Forestry Projects which were adopted by the Chinese Government since the 1980s to address important natural issues in China. It advanced to protecting and restoring the structures and functions of the natural forests through sustainable forest management. However, the role of forest carbon storage and tree carbon pool dynamics since the adoption of the NFP remains unknown. To address this knowledge gap, this study calculated forest carbon storage (tree, understory, forest floor and soil) in the forest region of northeastern (NE) China based on National Forest Inventory databases and field investigated databases. For tree biomass, this study utilized an improved method for biomass estimation that converts timber volume to total forest biomass; while for understory, forest floor and soil carbon storage, this study utilized forest type-specific mean carbon densities multiplied by their areas in the region. Results showed that the tree carbon pool under the NFP in NE China functioned as a carbon sink from 1998 to 2008, with an increase of 6.3 Tg C/yr, which was mainly sequestrated by natural forests (5.1 Tg C/yr). At the same time, plantations also acted as a carbon sink, reflecting an increase of 1.2 Tg C/yr. In 2008, total carbon storage in forests covered by the NFP in NE China was 4603.8 Tg C, of which 4393.3 Tg C was stored in natural forests and 210.5 Tg C in planted forests. Soil was the largest carbon storage component, contributing 69.5%–77.8% of total carbon storage; followed by tree and forest floor, accounting for 16.3%–23.0% and 5.0%–6.5% of total carbon storage, respectively. Understory carbon pool ranged from 1.9 to 42.7 Tg C, accounting for only 0.9% of total carbon storage.

Keywords: biomass-volume linear regression models; mean carbon density method; national forest inventory; Key Forestry Projects; northeastern China

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1 Introduction

Forest ecosystems play a crucial role in regional and global carbon cycles and are valued globally for the services they provide to society (Pan *et al*., 2011). They store large quantities of carbon (over 40% of below-ground and 80% of aboveground carbon) (Bousquet *et al*. 2000), and exchange more than 90% of terrestrial carbon with the atmosphere through photosynthesis and respiration (Houghton *et al*., 2001). Forests cover an area of more than 1.96×10^8 ha in China, ranging from tropical forests in the south to boreal forests in the north

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(7th National Forest Inventory). Numerous studies have demonstrated that forest ecosystems in China have in recent decades acted as a carbon sink, especially since the Six Key Forestry Projects were implemented in the 1980s (Liu *et al*., 2000; Fang *et al*., 2001; Pan *et al*., 2004; Piao *et al*., 2005). These were adopted by the Chinese Government to protect forest resources through sustainable forest management. However, to date no studies have thoroughly assessed the carbon pool size of the forests covered by the Six Key Forestry Projects and evaluated their role in forest ecosystem sustainability in China (Hu and Liu 2006; Wu *et al*., 2008).

The Natural Forest Protection (NFP) program, one of the Six Key Forestry Projects aimed at protecting the natural forest resources and achieving sustainable forests, has been implemented since 1998. It covers about 6.0×10^7 ha of the natural forest land which account for 50% of the total natural forest area in China (7th National Forest Inventory). Although many studies have been conducted on forest carbon storage at regional scales (Fang *et al*., 1996; Liu *et al*., 2000; Pan *et al*., 2004; Piao *et al*., 2005), unfortunately their results differ substantially. The reasons for these differences could be: 1) the carbon storage estimation methods were different; 2) the available forest resource data sources were different; 3) the number of plots directly investigated for some forest types was very small; and 4) the relationship between climatic factors and forest types on regional scales was ignored (Zhao and Zhou, 2004a). Moreover, most of these studies focused primarily on tree biomass, while understory, forest floor and soil carbon storage remain poorly understood on a regional scale, particularly in light of the fact that some studies have found that both soil and forest floor carbon pools play crucial role in controlling forest carbon storage in boreal and temperate forests (Wei *et al*., 2013).

To address this important need, this study focused on the major forest types in the temperate and boreal forests of northeastern China. Focusing on biomass and carbon storage, the study estimates forest carbon storage (tree, understory, forest floor and soil) of the NFP in 2008 and tree biomass dynamics from 1998 to 2008 during its first decade in NE China. This would provide a good basis for calculating forest carbon storage on regional scales and contribute to a more thorough evaluation of the ecological effectiveness of the Key Forestry Projects.

2 Materials and Methods

2.1 Site descriptions

This study was conducted in the forest region of northeastern China (NE China), which includes Heilongjiang and Jilin provinces, and the eastern four leagues of the Inner Mongolia Autonomous Region (41°42′–53°34′N, 115°37′–135°05′E) (Fig. 1). Three major mountain systems are situated within these regions: Da Hinggan Mountains, Xiao Hinggan Mountains and Zhangguangcai-Changbai mountains. The climate is controlled by the high latitude East Asian monsoon, creating a zonal shift from warm temperate to temperate and cool temperate along an increasing latitudinal gradient. Mean annual temperature and precipitation range from –2.5℃ (north) to 4.8℃ (south) and 350 mm (west) to 1100 mm (east), respectively.

The total forest area of the region is 3.59×10^7 ha. The NFP has been in effect in NE China since 1998, and the major measurements of most forests under its purview are managed by state-owned forestry industry groups: Jilin (Changbai Mountains), Heilongjiang (Xiao Hinggan Mountains), Inner Mongolia (Da Hinggan Mountains) and Da Hinggan Ling Prefecture of Heilingjiang Province (Da Hinggan Mountains) from south to north, respectively. The temperate coniferous and broadleaved mixed forest is most prevalent in the Changbaishan Mountains and Xiao Hinggan Mountains

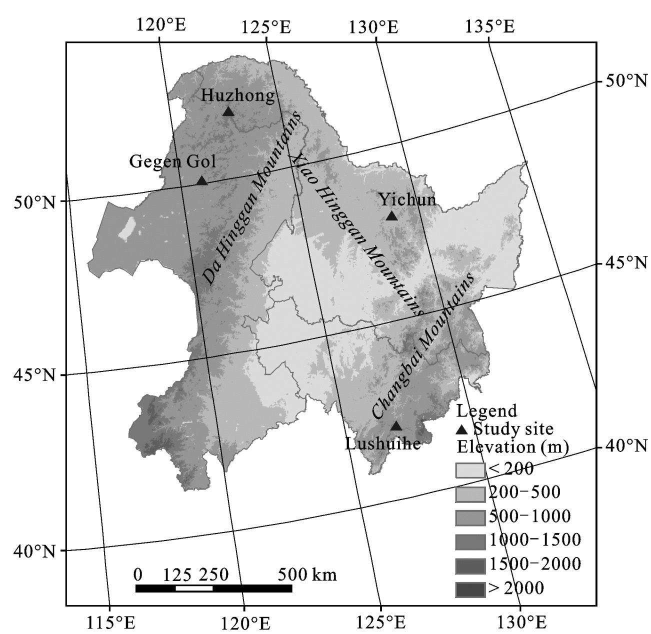

Fig. 1 Geographic location of study sites in northeastern China

while boreal coniferous forest predominate in the northern Da Hinggan Mountains.

2.2 Data sources

Databases were collected for the three provinces (Heilongjiang Province, Jilin Province, and Inner Mongolia Autonomous Region) from five continuous national forest inventories (1984–1988, 1989–1993, 1994–1998, 1999–2003, and 2004–2008). In addition, three databases (1994–1998, 1999–2003, 2004–2008) for the four state-owned forestry groups of Da Hinggan Ling Prefecture, Inner Mongolia, Heilongjiang and Jilin were also acquired. At the same time, databases obtained from direct field measurements for the main forest types of the temperate forest and boreal forest in NE China (Wang, 2011; Wei, 2013) were also utilized. Data from national forest inventories, which are complied every five years by aggregating provincial and prefectural forest management inventories, focus primarily on timber volume and forest area by age class (young, mid-aged, premature, mature and over mature). Data from direct filed investigation included datasets on tree biomass and volume, understory biomass (shrubs and herbs), forest floor biomass (woody debris, surface litter, organic matter horizons above the mineral soil and un-differentiable organic matter), and soil profile organic carbon by four age classes (young, mid-aged, mature and over mature).

Since there was no available information on timber volume and forest areas by age class for the main tree species under the NFP in NE China, this study defined the forest area under the NFP in NE China as the sum of the areas managed by the four state-owned forestry groups, and utilized the 5th National Forest Inventory database (1994–1998) as the beginning, and the 7th National Forest Inventory (2004–2008) as the end of the first implemented phase of the NFP.

2.3 Carbon storage calculation

Forest carbon storage is the synthesis of C pools in the tree, understory, forest floor and soil components. In this study, forest carbon storage of these different components were estimated at a regional scale. Since only timber volume and forest area were obtainable from the forest resources inventory databases, the biomass expansion factor (BEF) (defined as the ratio of all stand biomass to timber volume) which converts timber volume to mass (accounting for noncommercial components, such as branches, roots, and leaves) had to be obtained for different forest types (Fang *et al*., 1996; Fang and Chen, 2001). Many studies have suggested that BEF is not constant, and varies with forest age, site class, stand density, and other factors. It can be expressed as a function of timber volume (Fang and Chen, 2001):

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

where x is forest stand volume (m^3/ha); and a and b are constants which were determined from the datasets obtained from direct field measurements for the main forest types in NE China (Table 1). Therefore, the tree biomass for each forest type at a provincial scale can be calculated by the following formula:

$$B = \sum_{i=1}^{k} A_i \times BEF_i \times V_i / 100 \quad (2)$$

where B is the tree biomass (Tg); A_i is forest area of the major tree species group i (10^4 ha); BEF_i is the biomass expansion factor of the major species group i (Mg/m^3); V_i is the volume density of the major tree species group i (m^3/ha).

Tree biomass for the three northeastern provinces were obtained through Equation (2) utilizing the national forest inventory dataset. Because only total timber volume and forest area for each age class were obtained from inventory data and not more detailed information about timber volume for the major forest types, Equation (2) could not utilized to directly estimate biomass of NFP forests. Fang and Chen (2001) have demonstrated that the relationship between forest biomass and volume is addressed relatively well at the provincial scale within a linear regression framework, and is not altered by forest age. Thus, this study obtained mean biomass and volume densities at the provincial level utilizing the national forest inventory databases for the three northeastern provinces (1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008) to establish a new formula for biomass-volume linear regression models at the provincial scale in NE China. The equation is as follows:

$$Y = \mathrm{a} \times V + \mathrm{b} \quad (3)$$

where Y is tree biomass density at the provincial scale (Mg/ha); V is timber volume density at the provincial scale (m^3/ha); and a and b are constants (Fig. 2a). Then, tree C storage at the provincial scale was obtained through tree biomass multiplied the usual biomass–C storage transform coefficient of 0.5.

To verify the accuracy of Equation (3), this study estimated tree C storage of the natural and planted forests for the three northeastern provinces during 2004–2008 through equations (2) and (3), respectively. Results showed that the values of tree C storage from these two equations are similar, with relative errors < 6%, with the exception of forest plantations in Inner Mongolia, with a relative error of 30% (Fig. 2b). Thus, Equation (3) was deemed acceptable for estimating tree C storage of forests under the NFP in NE China.

For understory, forest floor and soil C storage of NFP forests in NE China, this study utilized the mean carbon density methods. First, the carbon densities of understory, forest floor and soil for the main forest types were obtained from many directly-investigated plots in the Da Hinggan Mountains, Xiao Hinggan Mountains and Changbai mountains. Then carbon storage of the understory, forest floor and soil were estimated by multiplying mean carbon density by forest area for each of these forest components.

3 Results

3.1 Change of forest area and tree carbon storage

3.1.1 In three northeastern provinces

Forest area increased from 1988 to 2008 in the three northeastern provinces. Concurrently, tree carbon storage of each province also increased, with an average carbon storage accumulation rate of 2.6–7.1 Tg C/yr (Table 2). The greatest tree carbon storage was in Heilongjiang Province (582.1–656.6 Tg C), while the smallest was in Jilin Province (314.1–366.4 Tg C). Conversely, tree carbon densities were the largest in Jilin Province (49.9–51.4 Mg C/ha), while in Inner Mongolia and Heilongjiang Province were of 29.8–31.4 and 33.8–37.4 Mg C/ha, respectively. Totally, tree carbon density has constantly decreased from 1988 to 2008 in the three northeastern provinces (Table 2).

Table 1 Parameters of biomass-volume models for major tree species in northeastern China

Tree species group	Parameter		Determination coefficient	Number of plots
	a	b	(R^2)	(n)
Coniferous mixed forest	0.708	26.000	0.859**	46
Coniferous and broadleaved mixed forest	0.788	–8.839	0.898**	239
Broadleaved mixed forest	0.803	–0.289	0.815**	236
Birch forest	0.744	3.989	0.812**	96
Larch forest	0.722	12.280	0.778**	157
Korean pine forest	0.634	7.134	0.990**	88
Mongolian Oak forest	1.207	–2.989	0.997**	26
Poplar forest	0.635	20.570	0.899**	99
Scotch pine forest	0.405	51.800	0.606**	82

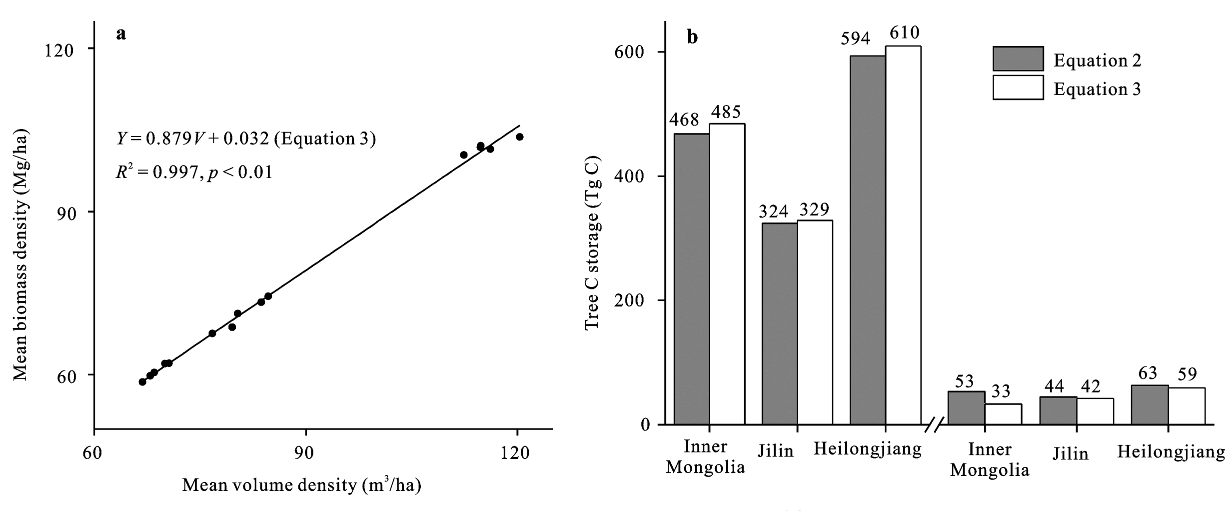

Fig. 2 Linear regression model for forest biomass and timber volume on provincial scales (a); and comparison between results of equations 2 and 3 for three northeastern provinces (b)

Table 2 Forest area, tree biomass carbon density, carbon storage and its change from 1988 to 2008 in three northeastern provinces

Province	Period	Forest area (10^4 ha)	Carbon storage (Tg C)	Carbon density (Mg C/ha)	Carbon storage change (Tg C/yr)
Inner Mongolia	1984–1988	1294.3	385.5	29.8	
	1989–1993	1320.0	400.1	30.3	2.9
	1994–1998	1390.3	436.9	31.4	7.3
	1999–2003	1608.2	490.4	30.5	10.7
	2004–2008	1681.3	526.5	31.3	7.2
Jilin	1984–1988	618.8	314.1	50.8	
	1989–1993	630.5	324.1	51.4	2.0
	1994–1998	699.9	349.5	49.9	5.1
	1999–2003	711.6	360.6	50.7	2.2
	2004–2008	726.7	366.4	50.4	1.2
Heilongjiang	1984–1988	1555.2	582.1	37.4	
	1989–1993	1610.9	593.4	36.8	2.3
	1994–1998	1755.6	627.8	35.8	6.9
	1999–2003	1792.2	606.2	33.8	–4.3
	2004–2008	1912.6	656.6	34.3	10.1
Total	1984–1988	3468.4	1281.7	37.0	
	1989–1993	3561.3	1317.6	37.0	7.2
	1994–1998	3845.8	1414.2	36.8	19.3
	1999–2003	4112.0	1457.3	35.4	8.6
	2004–2008	4320.6	1549.5	35.9	18.5

3.1.2 Under Natural Forest Protection program in northeastern China

For forests under the Natural Forest Protection Program in NE China, both the natural forest area and total forest area increased from 1998 to 2008, while the area of planted forest decreased from 1.47×10^6 to 1.22×10^6 (Table 3). Tree carbon storage also increased from 1998 to 2008, with an average carbon storage accumulation rate of 5.1, 1.2 and 6.3 Tg C/yr in natural forests, planted forests and in total forest, respectively. In addition, tree carbon density of natural forests was much higher than that of planted forests, while the latter showed an increasing trend from 15.1 to 28.0 Mg C/ha during this decade.

Table 3 Forest area, tree carbon density, carbon storage and its change from 1998 to 2008 under Natural Forest Protection program in northeastern China

Forest type	Period	Forest area (10^4 ha)	Carbon storage (Tg C)	Carbon density (Mg C/ha)	Carbon storage change (Tg C/yr)
Natural forest	1994–1998	2280.3	959.9	42.1	
	1999–2003	2412.7	967.6	40.1	1.5
	2004–2008	2427.4	1010.7	41.6	8.6
Planted forest	1994–1998	147.0	22.1	15.1	
	1999–2003	127.5	32.2	25.2	2.0
	2004–2008	122.4	34.3	28.0	0.4
Total	1994–1998	2427.3	982.1	40.5	
	1999–2003	2540.2	999.8	39.4	3.5
	2004–2008	2549.8	1045.1	41.0	9.1

3.2 Existing forest carbon storage under Natural Forest Protection program

Forest carbon storage under the NFP in NE China was 4603.8 Tg C, of which 4393.3 Tg C was stored in natural forests and 210.5 Tg C in planted forests in 2008 (Fig. 3). The largest carbon storage component was soil, which was of 3054.6 Tg C (69.5%), 163.7 Tg C (77.8%) and 3218.2 Tg C (69.9%) in natural forest, planted forest and total forest, respectively. Tree carbon storage was smaller than that of soil and contributed from 16.3% to 23.0% of total carbon storage. Carbon storage on the forest floor was of 287.2 Tg C (6.5%), 10.6 Tg C (5.0%), 297.8 Tg C (6.5%) in natural forest, planted forest, and total forest, respectively. The understory carbon pool was the smallest among storage components (1.9–42.7 Tg C), accounting for only 0.9% of total forest carbon storage in forests under the NFP in NE China (Fig. 3).

4 Discussion

4.1 Uncertainty analysis for carbon storage estimation

Appropriate biomass estimation methods and available forest data sources are two crucial factors for accurate calculation of forest biomass (Fang and Wang, 2001). This study selected the same forest types with similar climate conditions to establish biomass-volume regression models for the major tree species in NE China, and calculated biomass carbon storage on a regional scale utilizing national forest inventory databases. Moreover, we compared our estimation of biomass carbon storage with previous estimates for the same region and time period at the provincial scale (Table 4). Fang *et al*. (1996) estimated biomass carbon storage from 1984–1988 utilizing national forest inventory databases and reported results that were 19.4%–26.8% higher than our results for Jilin, Heilongjiang, and Inner Mongolia provinces, which was consistent with a conclusion in a later study that Fang *et al*. (1996) overestimated biomass carbon storage at regional scales (Pan *et al*., 2004). This was likely due to the relatively small number of plots for some forest types that were directly investigated, and also to the biomass-volume regression models that did not consider the relationship between climatic factors and tree species in China (Zhao and Zhou, 2004a).

Similarly, Liu *et al*. (2013) estimated forest biomass carbon storage in China for the period of 1999–2003 based on remote sensing and downscaling techniques and also reported results that were from 16.5%–28.7% higher than those of this study results for Jilin, Heilongjiang and Inner Mongolia. This is also likely attributable to the fact that Liu *et al*. (2013) did not consider the same forest types that under different climate conditions in China. On the other hand, our estimates were similar to Zhao and Zhou (2004b), who calculated biomass carbon storage via the relationship between stand biomass and volume for different forest types.

Some studies have found soil depth to be the key factor governing soil carbon storage (Jobbágy and Jackson, 2000; Wiesmeier *et al*., 2012). Same situation appeared in our study. Soil thickness, meanwhile, has been found to be about 40 cm in the Da Hinggan Mountains, and about 100 cm in the Xiao Hinggan Mountains and Changbai Mountains (Qi *et al*., 2013; Wei *et al*., 2013).

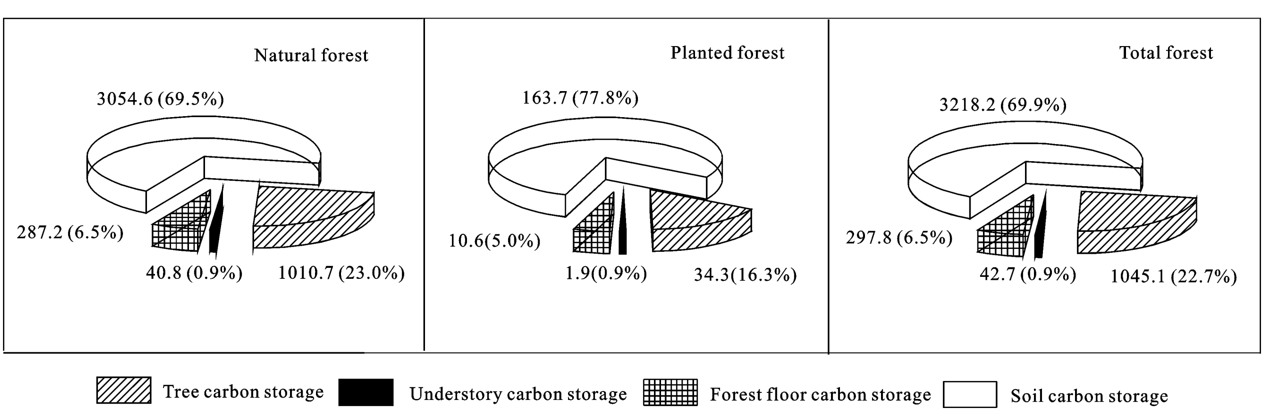

Fig. 3 Carbon storage (Tg C) of different forest components and their accounts for total forest carbon storage in parentheses under Natural Forest Protection Program in northeastern China in 2008

Table 4 Comparisons of tree carbon storage between this study and former studies in northeastern China

Province	Tree carbon density (Mg C/ha)	Tree carbon storage (Tg C)	Investigation time	Data sources
Jilin	63.0	390.2	1984–1988	Fang *et al*., 1996
	50.8	314.1	1984–1988	This study
		353.2	1989–1993	Zhao and Zhou, 2004b
	51.4	324.1	1989–1993	This study
	56.5	420.0	1999–2003	Liu *et al*., 2013
	50.7	360.6	1999–2003	This study
Heilongjiang	47.5	738.2	1984–1988	Fang *et al*., 1996
	37.4	582.1	1984–1988	This study
		591.6	1989–1993	Zhao and Zhou, 2004b
	36.8	593.4	1989–1993	This study
	39.5	780.0	1999–2003	Liu *et al*., 2013
	33.8	606.2	1999–2003	This study
Inner Mongolia	35.6	460.1	1984–1988	Fang *et al*., 1996
	29.8	385.5	1984–1988	This study
		408.3	1989–1993	Zhao and Zhou, 2004b
	30.3	400.1	1989–1993	This study
	39.0	600.0	1999–2003	Liu *et al*., 2013
	30.5	490.4	1999–2003	This study

Furthermore, this study has improved the estimation accuracy for soil carbon storage based entirely on the direct field plots investigation which established in the region according to the distribution of dominant forest types.

In addition, in this study the ratios of soil carbon to tree carbon for forests under the NFP in NE China range from 3.0–4.8, which is consistent with previous studies that indicated the world average ratio as approximately 3.0 (Prentice and Fung, 1990), and the ratio for temperate and boreal forest to be in the range of 2.0–6.4 (Alexeyev *et al*., 1995; Turner *et al*., 1995).

4.2 Role of Natural Forest Protection Program in forest ecosystem sustainability in China

The forest region of NE China had experienced continued extensive harvesting before the 1990s, which resulted in the loss of large areas of primary forests such as deciduous coniferous forest and temperate mixed coniferous broadleaved deciduous forest. When the Chinese Government launched the NEP at the end of the 1990s, logging was restricted and forest ecological resources were protected in NE China (Dai *et al*., 2011; Yu *et al*., 2011). Results of this study found that forest under the NFP in NE China acted as a carbon sink during the first stage of the program from 1998 to 2008, with an accumulated carbon storage of 6.3 Tg C/yr; and about 80.7% of total carbon storage sequestration were occurred in the natural forest (Table 3). In China, some studies have reported that forest carbon sinks in the country have increased primarily due to the expansion of planted forests (Liu *et al*., 2000; Fang *et al*., 2001; Piao *et al*., 2009); while in the United States the long-term net carbon uptake by forests has been attributed to forest regrowth after disturbance and from abandoned agriculture (Birdsey *et al*., 2006). This study suggests that protecting natural forests and improving their ecosystem functioning would also constitute effective measures to increase the carbon sink and mitigate increasing atmospheric CO_2.

Although the area of planted forest under the NFP in NE China decreased from 1998 to 2008, they also acted as a carbon sink, with an accumulation of 1.2 Tg C/yr. This may likely be attributed to improved tree carbon density on these forests. On an overall basis, the forest area and biomass carbon storage under the NFP in NE China accounted for 59.0% and 67.4% of total forest area and biomass carbon storage, respectively, of the three northeastern provinces. Moreover, tree biomass density of the NFP forest was also higher than that of the NE China (Table 2 and Table 3). All of the above suggests that the NFP plays an important role in forest ecosystem sustainability in China.

5 Conclusions

Forest ecosystems subject to the NEP in NE China acted as a carbon sink during the period of 1998–2008. Natural forests accounted for 80.7% of total carbon sequestration during this period, while planted forests also acted as a carbon sink, although area of plantation forests decreased during this time. As of 2008, carbon storage in forest under the NFP in NE China was 4603.8 Tg C, of which 4393.3 Tg C was stored in natural forests and 210.5 Tg C in forest plantations. Soil was the largest carbon storage component, contributing 69.5%–77.8% of total carbon storage; while tree and forest floor carbon pools accounted for 16.3%–23.0% and 5.0%–6.5% of total C storage. Understory ranging from 1.9 to 42.7 Tg C, accounted for only 0.9% of total carbon storage under the NFP in NE China.

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