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Changes in Forest Biomass Carbon Storage in China Between 1949 and 1998

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The location and mechanisms responsible for the carbon sink in northern mid-latitude lands are uncertain. Here, we used an improved estimation method of forest biomass and a 50-year national forest resource inventory in China to estimate changes in the storage of living biomass between 1949 and 1998. Our results suggest that Chinese forests released about 0.68 petagram of carbon between 1949 and 1980, for an annual emission rate of 0.022 petagram of carbon. Carbon storage increased significantly after the late 1970s from 4.38 to 4.75 petagram of carbon by 1998, for a mean accumulation rate of 0.021 petagram of carbon per year, mainly due to forest expansion and regrowth. Since the mid-1970s, planted forests (afforestation and reforestation) have sequestered 0.45 petagram of carbon, and their average carbon density increased from 15.3 to 31.1 megagrams per hectare, while natural forests have lost an additional 0.14 petagram of carbon, suggesting that carbon sequestration through forest management practices addressed in the Kyoto Protocol could help offset industrial carbon dioxide emissions.

Recent studies have shown that the mid- and high-latitude forests in the Northern Hemisphere are functioning as a significant sink for C (*1–4*). These findings have been confirmed by several studies, mainly from North America and European countries using forest inventories (*5–8*). A long history of agricultural exploitation, forest management practice, and changing land use and forestry policies suggest that China, too, plays an important role in the global C cycle (*9, 10*). China has 133.7 million hectares of forested land (*11*) that range from tropical forests in the south to boreal forests in the north. Nationwide afforestation and reforestation programs have been in effect since the 1970s. To reduce the uncertainty in estimating C sinks, well-designed and statistically sound national forest inventories over the long term, combined with direct field measurements of C stocks from local sample plots, may provide the best data sources for accurately quantifying C sinks and their dynamics at large scales.

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Here, we used the National Forest Resource Inventory database for China collected from 1949 to 1998 for 5- to 10-year periods (*11, 12*) and a forest biomass database obtained from direct field measurements (*13, 14*) to estimate forest biomass C storage and its spatiotemporal distributions. The forest inventory database is based on the Forest Resource Inventory of China (FRIC), which spans seven periods: 1949, 1950–62, 1973–76, 1977–81, 1984–88, 1989–93, and 1994–98 (*11, 12, 15*). These inventories, excluding FRIC from 1949 which was derived from an assessment report (*11, 16*), were compiled from more than 250,000 plots (160,000 permanent sample plots plus 90,000 temporary sample plots) across the country. Systematic sampling with a grid of 2 km by 2 km or 4 km by 4 km and an area of 10 m by 10 m was used depending on forest region. Forest area and timber volume by age class as well as by forest type were documented at provincial levels. Unfortunately, these forest inventories do not provide detailed information about forest biomass; only the commercial portion (such as timber volume) is available. To use timber data to estimate all forest biomass, a biomass expansion factor (BEF, defined as the ratio of all stand biomass to growing stock volume), which converts timber volume to mass and accounts for noncommercial components, such as branches, roots, and leaves, must be calculated. The forest biomass database obtained from direct field measurements (*17*) was used to determine BEF values for each forest type using a literature review of forest biomass studies in China (*14*).

Recent studies (*8, 13, 18, 19*) suggest that BEF is not constant, but varies with forest age, site class, stand density, and other biotic and abiotic factors that are closely associated with relative stand density, and can be expressed as a function of timber volume. Here, we used a function expressed as $BEF = a + b/x$, to obtain a variable BEF value for each forest type, where x is timber volume and a and b are constants for a forest type (*13*) (Table 1). Using the method published by Fang *et al.* (*13*), forest inventory data, and parameters listed in Table 1, forest biomass (including all living trees and shrubs) for each forest type was calculated at both provincial and national levels for all seven periods (*20*).

Total forest biomass C (Table 2) decreased from 5.06 Pg of C (Pg C) in 1949 to 4.38 Pg C in 1977–81, and then increased by 4.75 Pg C over the period 1980–98, mainly due to changes in land use, population growth, and economic policy changes. Since the new social system was established in 1949, rapidly increasing population and economic development have resulted in increased forest exploitation across the country (*11*). By 1949, Chinese forests accumulated the largest C storage (5.06 Pg C) and area-weighted mean C density (49.45 Mg ha^{-1}), due to a larger area of primary forests that have high biomass density. Since then, forest C storage has significantly decreased by 0.68 Pg C, with a mean rate of 0.022 Pg C year^{-1} (ranging from 0.01 to 0.04 Pg C year^{-1}) from 1949 to the end of the 1970s. For this period, the policy of forest exploitation led to soil erosion, widespread desertification, loss of biodiversity, land degradation, and catastrophic flooding (*21*). Since the 1970s, however, the Chinese government has implemented several ecological restoration projects, including the Three-North Protective Forest Program, South China Timber Production Program, Rivers Protection Forest Program (*22*), and the Natural Forest Conservation Program (*21*). Consequently, forests in China have accumulated about 0.4 Pg C with an annual mean rate of 0.021 Pg C (ranging from 0.011 to 0.035 Pg C) during the past two decades (Table 2). The increasing C accumulation over this period is primarily the result of increased afforestation and reforestation (Table 2). Areas planted through afforestation and reforestation programs have expanded from 12.74 × 10^6 to 17.39 × 10^6 ha for the period 1970–80 to 23.11 × 10^6 ha in 1994–98, and forest C sequestration has increased from 0.27 to 0.72 Pg C, with a total C uptake of 0.45 Pg and a mean increased rate of 0.020 Pg C $year^{-1}$ (Table 2) during this time. Forest C density during this period has increased linearly from 15.32 Mg C ha^{-1} for 1973–76 to 31.11 Mg C ha^{-1} during the 1994–98 period, with a mean increased C uptake of 0.72 Mg ha^{-1} $year^{-1}$.

To compare the contribution of planted and natural forests to C accumulation or loss, we also present total area and C content of natural forests (Table 2), which are the differences between those of all forests and planted forests since the mid-1970s. No clear changes in the area (ranging from 82.70 × 10^6 to 87.30 × 10^6 ha) and C storage (ranging from 3.9 to 4.2 Pg C) of natural forests were evident during this period, compared to planted forests. Because over this period all forests and planted forests have sequestered 0.31 Pg C (Table 2) and 0.45 Pg C (Table 2), respectively, natural forests have lost an additional 0.14 Pg C. However, natural forests have become a small C sink of 0.1 Pg during the past decade (Table 2).

There is considerable spatial (or regional) and temporal variability in forest C storage and C densities in China (Fig. 1, A and B). About 28 to 35% of forest C storage occurs in the southwestern region (including the provinces of Sichuan, Tibet, Yunnan, Guangxi, and Guizhou), followed by 24 to 31% in the northeastern region (e.g., Helongjiang, Jilin, and Liaoning provinc-

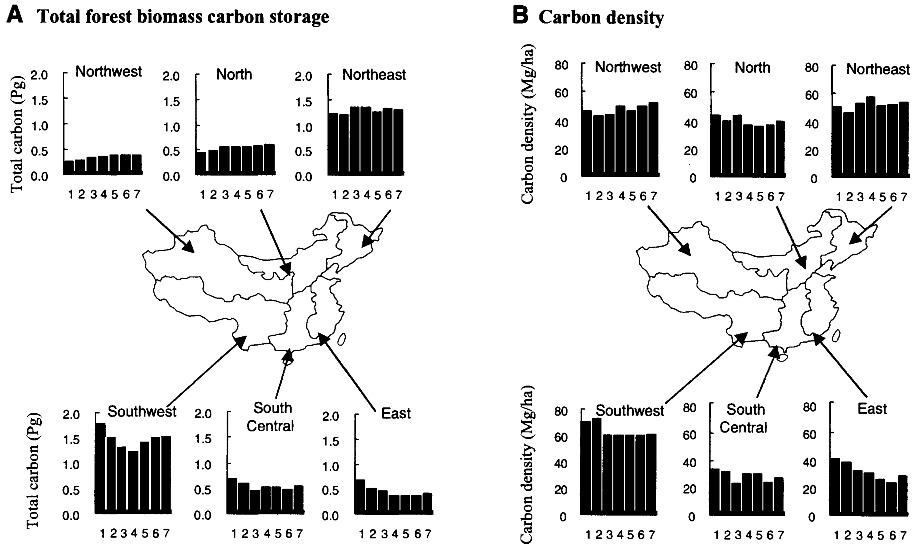

Fig. 1. Spatiotemporal distribution of (**A**) total forest biomass C storage and (**B**) C density in China. The numbers 1 through 7 represent the periods 1949, 1950–62, 1973–76, 1977–81, 1984–88, 1989–93, and 1994–98, respectively.

Table 1. Parameters used to calculate biomass expansion factor (BEF). BEF is expressed as a function of stand timber volume (*x*), $BEF = a + b/x$, where *a* and *b* are constants for a forest type. Data are based on direct field measurements.

Forest type	*a* (Mg m^{-3})	*b* (Mg)	*N*	R^2
Abies and *Picea*	0.4642	47.4990	13	0.98
Betula	1.0687	10.2370	9	0.70
Casuarina	0.7441	3.2377	10	0.95
Cunninghamia lanceolata	0.3999	22.5410	56	0.95
Cypress	0.6129	46.1451	11	0.96
Deciduous oaks	1.1453	8.5473	12	0.98
Eucalyptus	0.8873	4.5539	20	0.80
Larix	0.6096	33.8060	34	0.82
Lucidophyllous forests	1.0357	8.0591	17	0.89
Mixed conifer and deciduous forests	0.8136	18.4660	10	0.99
Mixed deciduous and *Sassafras*	0.6255	91.0013	19	0.86
Nonmerchantable woods	0.7564	8.3103	11	0.98
Pinus armandii	0.5856	18.7435	9	0.91
P. koraiensis	0.5185	18.2200	17	0.90
P. massoniana, *P. yunnanensis*	0.5101	1.0451	12	0.92
P. sylvestris var. *mongolica*	1.0945	2.0040	11	0.98
P. tabulaefomis	0.7554	5.0928	82	0.96
Other pines and conifer forests	0.5168	33.2378	16	0.94
Populus	0.4754	30.6034	10	0.87
Tsuga, *Cryptomeria*, *Keteleeria*	0.4158	41.3318	21	0.89
Tropical forests	0.7975	0.4204	18	0.87

Table 2. Area, total C, and C accumulation rate for all forests, and planted and natural forests for seven periods from 1949 to 1998 in China. The variables of natural forests were differences between those of all forests and planted forests. Carbon content is converted from biomass using a factor of 0.5. No information on planted forests is available before the mid-1970s. Data from Taiwan were not included in this study. Dashes indicate data that were not collected.

Period	All forests				Planted forests				Natural forests		
	Total area (10^6 ha)	Total C (Pg C)	C density (mg ha^{-1})	C accumulation rate (Pg C yr^{-1})	Total area (10^6 ha)	Total C (Pg C)	C density (Mg ha^{-1})	C accumulation rate (Pg C yr^{-1})	Total area (10^6 ha)	Total C (Pg C)	C accumulation rate (Pg C yr^{-1})
1949	102.34	5.06	49.45	–	–	–	–	–	–	–	–
1950–62	98.08	4.58	46.67	−0.040	–	–	–	–	–	–	–
1973–76	101.26	4.44	43.83	−0.010	17.39	0.27	15.32	–	83.87	4.17	–
1977–81	95.62	4.38	45.75	−0.013	12.74	0.33	25.55	0.012	82.88	4.05	−0.024
1984–88	102.19	4.45	43.53	0.011	18.74	0.52	27.48	0.027	83.45	3.93	−0.017
1989–93	108.63	4.63	42.58	0.035	21.37	0.61	28.69	0.020	87.26	4.02	0.018
1994–98	105.82	4.75	44.91	0.026	23.11	0.72	31.11	0.021	82.71	4.03	0.005

es). As expected, eastern and southeastern regions that have higher population densities and northern and northwestern regions that are arid have only a small portion of the C pool and low C density. In some regions, spatial patterns of C storage and density showed a large temporal variation. For example, forest C storage in the northwestern and northern regions has significantly increased (Fig. 1A), probably as a result of increased area afforested through the Three-North Protective Forest Program (*22*). Similar to C storage, higher C densities (e.g., 50 to 70 Mg ha^{-1}) were also found in the southwest and northeast of China, which are dominated by boreal forests or subalpine coniferous forests (including *Picea*, *Abies*, and *Larix*) with high biomass production. As expected, forests in the central and eastern regions, with a high proportion of plantations (31 to 40%) have lower C densities (e.g., 23 to 35 Mg ha^{-1}). This may reflect differing stand age factors (*23*) or perhaps greater human disturbance in these regions, which have dense population and are undergoing rapid economic development.

Although the mid- and high-latitude forests in the Northern Hemisphere greatly contribute to the terrestrial C sink, the magnitude of forest C sinks and their spatial distributions are still controversial (*2, 24–26*). Continental-scale comparison of C fluxes estimated using an atmospheric inverse model, terrestrial ecosystem models, and forest inventories often provide conflicting results. For example, analyses of the North American terrestrial C sink have indicated large annual variations, ranging from 0.05 to 0.17 (*25*) or 0.08 (*27*) to 1.7 Pg (*2*). Differences in data sources or parameters used for model simulation and estimation at different temporal and spatial scales are likely sources of uncertainty (*25, 28*). A narrow range of annual U.S. C sink from 0.08 to 0.35 Pg, which was estimated using inventory records (*4, 6*), indicates that inventory-based estimation of forest C at both regional and national scales may help to reduce the uncertainties in accurately evaluating the role of forests in regional and global C budgets. Our results, derived from 50-year monitoring at a national level, show that during the past two decades there is a mean C uptake of 0.021 Pg C $year^{-1}$ by Chinese forests, planted forests have accumulated 0.72 Pg total C, and their C densities have increased by about 0.72 Mg C ha^{-1} $year^{-1}$ (*29*). The estimated C sink in China is comparable to that of North American forests, because the area and total C pool of Chinese forests are only half and one-third of those of the conterminous United States, respectively (*30*).

In addition, our results provide evidence to support the proposal addressed by the Kyoto Protocol that C sequestered by afforestation or reforestation could partly offset CO_2 emissions from fossil fuel consumption, even though the increased C uptake is viewed as temporary reservoirs (*31, 32*). The Kyoto Protocol does not require commitments from developing countries, including China, but recent decreases in the rate of deforestation in China have already contributed to reduced CO_2 emissions (Table 2). We believe that continuing the practice of nationwide afforestation and reforestation projects could contribute significantly to global terrestrial C sinks.

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16. Forest inventory data for 1949 were not obtained from a direct survey across the country, but were derived from estimates of forest area and timber volume for major forest types for all provinces, based on forest resource statistics and forest timber records obtained from some regions, and literature reviews conducted by the Forestry Ministry of China (1996) (*11*).
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$$Y = \sum_{i=1}^{31}\sum_{j=1}^{3}\sum_{k=1}^{5} A_{ijk} \cdot BEF \cdot x_{ijk}.$$

The area-weighted mean biomass (y) of each forest type was calculated using the equation

$$y = \frac{1}{A}\sum_{i=1}^{31}\sum_{j=1}^{3}\sum_{k=1}^{5} A_{ijk} \cdot BEF \cdot x_{ijk},$$

where A is the total area of each forest type.
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