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ORIGINAL PAPER

Dynamics of forest biomass carbon stocks from 1949 to 2008 in Henan Province, east-central China

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Abstract We estimated forest biomass carbon storage and carbon density from 1949 to 2008 based on nine consecutive forest inventories in Henan Province, China. According to the definitions of the forest inventory, Henan forests were categorized into five groups: forest stands, economic forests, bamboo forests, open forests, and shrub forests. We estimated biomass carbon in forest stands for each inventory period by using the continuous biomass expansion factor method. We used the mean biomass density method to estimate carbon stocks in economic, bamboo, open and shrub forests. Over the 60-year period, total forest vegetation carbon storage increased from 34.6 Tg (1 Tg = 1 × 10^{12} g) in 1949 to 80.4 Tg in 2008, a net vegetation carbon increase of 45.8 Tg. By stand type, increases were 39.8 Tg in forest stands, 5.5 Tg in economic forests, 0.6 Tg in bamboo forests, and −0.1 Tg in open forests combine shrub forests. Carbon storage increased at an average annual rate of 0.8 Tg carbon over the study period. Carbon was mainly stored in young and middle-aged forests, which together accounted for 70–88% of the total forest carbon storage in different inventory periods. Broad-leaved forest was the main contributor to forest carbon sequestration. From 1998 to 2008, during implementation of national afforestation and reforestation programs, the carbon storage of planted forest increased sharply from 3.9 to 37. 9 Tg. Our results show that with the growth of young planted forest, Henan Province forests realized large gains in carbon sequestration over a 60-year period that was characterized in part by a nation-wide tree planting program.

Keywords Forest biomass carbon stock · Forest resource inventory · Henan Province

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Introduction

Forest ecosystems store the greatest amounts of carbon in terrestrial ecosystems and are important in global C cycling and climate change (Dixon et al. 1994; Pan et al. 2011). Forest ecosystem carbon storage has been reported at global, national and regional scales (Durán et al. 2015; Holdaway et al. 2014; Kohl et al. 2015; Pan et al. 2011; Poorter et al. 2015). China as the largest developing country in the world has the largest area of plantation forests (Streets et al. 2001). After the new social system was established in 1949, rapidly increasing population and economic development have resulted in increased forest exploitation and environmental degradation across the country, especially 1949–1963 and 1976–1980. In order to reduce environmental degradation, China's government launched a series of national key forest programs beginning in the late 1980s, including: "Natural Forest Protection Program", "Desertification and Dust Storms Control Program in the vicinity of Beijing and Tianjin Municipalities", "Forest Shelterbelt Development Program in key environmentally fragile regions", "Wildlife Conservation and Nature Reserves Development Program" and "Fast-growing and High-yield Timber Plantations Program", in the late 1990s, Grain for Green Program has played an important role in the restoration of vegetation. (Sylvie et al. 2009). These programs increased forest area and the amounts of carbon stored in China's forest ecosystems.

China's forest vegetation carbon storage, carbon density and spatial distribution have been quantified using various methods at regional and national scales (Fang et al. 2001; Piao et al. 2005; Ren et al. 2011, 2013, 2014). Differences in the regional distribution of forests, field data collection methods, and analytical methods have resulted in varying estimates of forest vegetation carbon storage in China. For example, Wang et al. (2001) estimated forest vegetation carbon storage based on the 38 dominant tree species in China at 3724 Tg. In contrast, Fang et al. (1998) estimated China's forest ecosystem carbon storage at 4300 Tg while Dixon et al. (1994) estimated 17,000 Tg. Forest carbon sequestration is closely related to forest area, forest age structure and forest species (McKenney et al. 2004). Many studies showed that carbon density varies by forest vegetation type and by forest age class (Guan et al. 2015; Fang et al. 1998; Ren et al. 2013; Wang et al. 2015). To account for regional variation in carbon storage estimates caused by forest type and research methods, it is necessary to estimate China's forest carbon storage using a regional approach.

In China, Ren et al. (2011) used forest inventory data to determine that total forest vegetation carbon storage increased in Fujian Province from 136.5 Tg in 1978 to 229.3 Tg in 2008. Guan et al. (2015) estimated carbon storage increased from 83.1 Tg in 1979 to 100.7 Tg in 2006 in Gansu Province, depending on the relevant forest inventory data and empirical factors. These estimations of forest carbon stocks covered short time spans.

Henan Province, in east-central China, supports 359.1×10^4 ha of forest land that covers 21.5% of the province. Forest inventory data for Henan Province cover the years 1949–2008 yet the dynamics of forest biomass carbon stocks during this time period have not been reported. In this study we analyzed these forest inventory data (FID; field data collected by Henan Province Forestry Bureau) to estimate carbon storage by forest vegetation from 1949 to 2008. Our objectives were to: (1) estimate carbon storage and density by forest type, age class, forest category, and forest origin; and (2) to describe forest carbon storage dynamics in Henan Province over this 60-year period.

Materials and methods

Study area

Henan Province is located in east-central China at 31°23′ to 36°22′N and 110°21′ to 116°39′E, in the middle and lower reaches of the Yellow River. The total land area is 1670×10^4 ha, including 720×10^4 ha of farmland and 740×10^4 ha of hilly area. Henan Province is a transitional zone between subtropical and warm temperate regions of China, with a humid and semi-humid monsoon climate. Annual rainfall ranges from 500 to 900 mm and annual average temperature is 12–16 °C. Based on the Soil Taxonomy of China (Henan Province Soil Survey Office 2004), Henan soil types are mainly brown, cinnamon, yellow–brown, yellow-cinnamon, fluvo-aquic, lime-concretion black, and saline-alkali soils. Southern warm temperate deciduous broad-leaved forests and northern subtropical evergreen broad-leaved forests are the main vegetation types in the region. Henan supports 197 plant families represented by 1191 genera and 4473 species, accounting for 12.2% of China's flora.

Data source

Henan's forest resource inventory database spans nine periods: 1949, 1950–1963, 1973–1976, 1977–1980, 1984–1988, 1989–1993, 1994–1998, 1999–2003 and 2004–2008. Inventory data were recorded using a systematic sampling method implemented by Henan Province Forestry Department. Mapped forest areas were overlaid with a 4×4 km grid and square plots covering 28.28×28.28 m were systematically sampled within each grid cell. Sampling methods were adjusted depending on the type of forest cover. The forest resource survey data of 1949 and 1963 were estimated by Henan Province forestry department in 1990 by using the predict equation (Li 1999). There are over 5399 permanent sample plots spread across Henan Province that have been systematically sampled for forest resource inventory from 1980 to 2008.

China's forest resource inventory defined five distinct forest groups or categories: forest stands, economic forests, bamboo forests, open forests and shrub forests. For each of these forest groups, the forest inventory documented the areas and timber volumes for dominant tree species for forest stands by five age classes (young, middle-aged, premature, mature and post-mature), four forest categories (timber, shelter, fuelwood, special use forest) and two sources of forest origin (plantations and natural forests). For the nine listed forest inventory periods, only total forest area was calculated for economic, bamboo, open, and shrub forests.

In 1994, the definition of forest stands in China's forest resource inventory was changed from >30% canopy coverage to >20% canopy coverage. In order to make our results comparable among different periods, Guo et al. (2013) modified the equations of the two criteria for the forest area and biomass C stocks at the provincial level for achieving more accurate conversion between 20 and 30% canopy coverage. In this study, we used their equations as follows to produce better estimates (Guo et al. 2013).

$$\mathrm{AREA}_{0.2} = 1.290 \times \mathrm{AREA}_{0.3}^{0.995} \quad (1)$$

$$\mathrm{CARBON}_{0.2} = 1.147 \times \mathrm{CARBON}_{0.3}^{0.996} \quad (2)$$

AREA and CARBON are the forest stand area (10^4 ha) and biomass C stock (Tg) in a province, respectively; subscripts 0.3 and 0.2 represent the criterion of >30 and 20% canopy coverage, respectively.

We calculated carbon storage of forest vegetation by multiplying the amount of forest biomass by the carbon coefficient. We estimated forest biomass carbon stocks for each inventory period by using the continuous BEF method for forest stands, and the mean biomass density method for economic forests, bamboo forests, open forests and shrub forests. The coefficient of carbon of dominant tree species of the forest stands was obtained by the formula:

$$C = C_1 \times 44.4\% + C_2 \times 45.5\% + C_3 \times 82.2\% \quad (3)$$

where C_1 represents the cellulose content, C_2 is the hemicellulose content, C_3 is the lignin content. Cellulose, hemicellulose and lignin content for various species were obtained from the literature (Jiang and Peng 2001; Wang and Ding 1985) (Table 1). We used a ratio of 0.5 to convert biomass to carbon stock for bamboo forests, economic forests, open forests and shrub.

Estimating the biomass of forest stands

The biomass of trees was calculated using the continuous BEF method (Fang et al. 2001) with a regression equation as follows:

$$B = aV + b \quad (4)$$

where B is the biomass per hectare (Mg ha^{-1}), V is the volume per hectare (m^3 ha^{-1}), and a and b are parameters converting from volume to biomass for given tree species.

Henan Province forest resources inventory data included 12 dominant tree species. Where the biomass of *Larix*, *Cunninghamia lanceolata*, poplar, and *Paulownia* in Henan Province have been quantified (Feng et al. 1992; Wang 1999; Zeng 2005; Zhao 1989; Zhao et al. 1999), we used the estimated parameters derived from these studies. Fang et al. (2001) derived formulae for converting volume to biomass for 21 dominant forest types in China. Five of the derived formulae were suited for Henan Province forests and were used in this study (Table 1). The parameters for three additional forest species groups including mixed conifer forest, mixed conifer and broadleaved forest and mixed broadleaved forest were taken from Zeng (2005), and these were suited for Henan Province.

Estimating the biomass of economic forests and bamboo forests

We estimated biomass carbon stocks by multiplying the mean biomass density by the area of economic forests in each inventory period. For mean biomass density we use the value of 23.7 Mg ha^{-1} (Fang et al. 1996).

Henan's forest inventory documented the areas of moso bamboo and other bamboo forests. We estimated bamboo forest biomass carbon stocks by using the mean biomass

Table 1 Parameters used to calculate biomass of forest stands and carbon fraction for different dominant tree species

Dominant tree species	a	b	N	R^2	References	Carbon fraction (CF)
Platycladus orientalisb	0.6129	46.1451	11	0.98	Fang et al. (2001)	0.5034
Larix	0.5442	16.1235	35	1.00	Zhao et al. (1999)	0.5211
Pinus tabulaeformis	0.7554	5.0928	82	0.98	Fang et al. (2001)	0.5207
Pinus massoniana	0.5101	1.0451	12	0.92	Fang et al. (2001)	0.4596
Cunninghamia lanceolata	0.5371	11.9858	29	1.00	Wang (1999)	0.5201
Quercus	1.1453	8.5473	12	0.98	Fang et al. (2001)	0.5004
Hardwood forests	0.7564	8.3103	11	0.98	Fang et al. (2001)	0.4834
Populus	0.981	0.004	10	0.99	Zhao (1989)	0.4956
Paulownia	0.8956	0.0048	22	0.99	Feng et al. (1992)	0.4695
Mixed conifer forests	0.5894	24.5151	–	–	Zeng (2005)	0.5101
Mixed broadleaf forests	0.8362	9.4157	–	–	Zeng (2005)	0.4900
Mixed conifer and broadleaf forests	0.7143	16.9654	–	–	Zeng (2005)	0.4978

density for each bamboo type multiplied by the area. We used the estimates of Guo et al. (2013) for the mean biomass density of moso bamboo and other bamboo forests (81.9 and 53.1 Mg ha^{-1}, respectively).

Estimating the biomass of open forests and shrub forests

The Qinling Mountains–Huaihe River form the geographical boundary between south and north China. The distribution area of open forests and shrub forests in China are divided into three regions, viz. south Qinling Mountains–Huaihe River Line, northeast of Qinling Mountains–Huaihe River Line, and northwest China. In these three districts the mean biomass densities are 19.76, 13.14 and 13.9 Mg ha^{-1} (Fang et al. 1996). Henan Province is located northeast of the Qinling Mountains–Huaihe River Line so we adopted a mean biomass density of 13.14 Mg ha^{-1} to estimate the open forest and shrub-forest biomass density. The total biomass of open forests and shrub-forest was calculated by multiplying the average biomass density by the total area (calculated by Forestry Department of Henan Province).

Results

Change in forest area, forest biomass carbon storage and carbon sink

The total forest area increased from 231.9 × 10^4 ha in 1949 to 404.5 × 10^4 ha in 2008. During the periods 1950–1963 and 1977–1980 total forest area decreased (Fig. 1). Beginning in 1980, forested area increased steadily. Notably, the area of afforestation increased significantly from 339.2 × 10^4 to 404.5 × 10^4 ha in 1999–2008. From 1949 to 2008, total vegetation carbon storage increased by 132% from 34.6 to 80.3 Tg, while forest vegetation carbon density increased by 30% from 14.9 to 19.9 Mg ha^{-1} (Fig. 1). The forest vegetation biomass carbon sinks varied greatly by time period: the carbon sinks in 1950–1963 and 1977–1980 were negative, implying forest vegetation had been damaged in these two periods. The forest biomass carbon sink increased from −2.782 Tg a^{-1} in 1977–1980 to 4.120 Tg a^{-1} in 2004–2008.

During the period 1949–2008, carbon storage and carbon density dynamics varied by forest type (Table 2). Accounting for 53–72% of total forested area, forest stands stored 72–86% of total biomass carbon storage and net accumulated carbon of 39.7 Tg over the 60-year period, at an average carbon accumulation rate of 0.674 Tg a^{-1}. This accounted for 87% of total biomass carbon sink during 1949–2008. The area-weighted mean of biomass carbon density also increased from 18.6 Mg ha^{-1} in 1949 to 24.4 Mg ha^{-1} in 2008. Maximum forest stand carbon sink was estimated for 2004–2008 at 4.576 Tg a^{-1}. These results confirm that carbon stored in forest stands had the most influence on total forest vegetation carbon storage. Over the past six decades, the increase of carbon storage in economic forests, bamboo forests, open forests and shrub-forests was mainly due to the increase in forested area and tree growth. The sum of carbon storage of economic forests, bamboo forests, open forests and shrub-forests accounted for 14–28% of total forest vegetation carbon storage in different inventory periods.

Biomass carbon storage and density of forest stands by age class

Forest carbon is closely related to forest age composition (Liu et al. 2000). In the early forest resource inventory

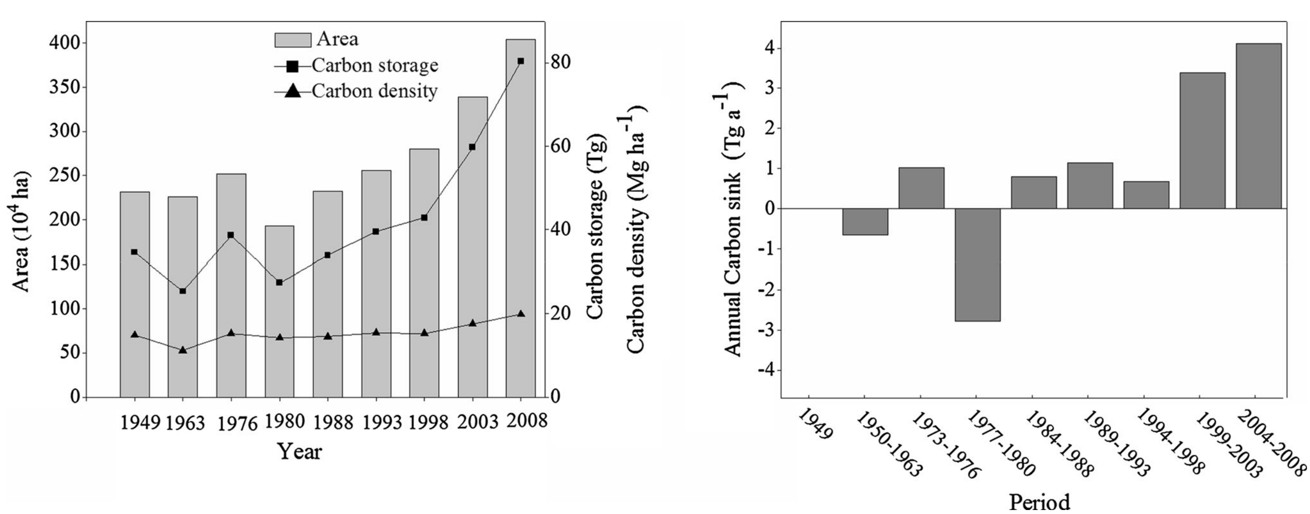

Fig. 1 The change of area and carbon stocks in Henan Province's forests during 1949–2008

Table 2 The area and carbon stocks changes for different forest types in Henan Province from 1949 to 2008

Period	Forest stands				Economic forests			Bamboo forests			Open forests and shrub forests		
	Area (10^4 ha)	Carbon storage (Tg)	Carbon density (Mg ha^{-1})	Carbon sink (Tg a^{-1})	Area (10^4 ha)	Carbon storage (Tg)	Carbon sink (Tg a^{-1})	Area (10^4 ha)	Carbon storage (Tg)	Carbon sink (Tg a^{-1})	Area (10^4 ha)	Carbon storage (Tg)	Carbon sink (Tg a^{-1})
1949	158.0	29.4	18.6		5.1	0.6		0.1	0.02		68.7	4.5	
1950–1963	139.3	19.4	13.9	−0.716	3.41	0.4	−0.014	0.4	0.11	0.006	83.1	5.5	0.067
1973–1976	148.4	28.1	19.0	0.672	58.1	6.9	0.498	3.0	0.80	0.053	42.9	2.8	−0.203
1977–1980	139.2	22.2	15.9	−1.485	31.1	3.7	−0.799	0.7	0.19	−0.151	21.8	1.4	−0.347
1984–1988	156.0	26.9	17.2	0.586	32.8	3.9	0.026	0.7	0.19	−0.001	43.0	2.8	0.174
1989–1993	165.4	31.0	18.7	0.824	42.9	5.1	0.239	1.3	0.34	0.031	46.2	3.0	0.042
1994–1998	149.8	30.8	20.6	–0.042	57.3	6.8	0.341	1.9	0.56	0.044	71.2	4.7	0.328
1999–2003	197.7	46.3	23.4	3.098	70.8	8.4	0.320	1.8	0.52	−0.008	68.9	4.5	−0.031
2004–2008	283.4	69.2	24.4	4.576	51.1	6.1	−0.466	2.1	0.63	0.022	67.9	4.4	−0.012
1949–2008				0.674			0.092			0.010			−0.001

data, forest stands only were grouped into three forest age classes (young, middle-aged, mature). After the inventory period of 1984–1988, forest stands were grouped into five age classes (young, middle-aged, premature, mature and post-mature). To enable comparison of all inventory data, we included premature, mature, and post-mature forest into a single age class we named old–aged forest. The temporal change of area, carbon storage, and carbon density among three age classes of forest stands are shown in Fig. 2. Carbon storage was mainly distributed in the young and middle-aged forests, whose area accounted for 87–97% of the province's total forest area in different periods. Carbon storage in various periods accounted for 70–88% of total forest stand carbon storage. Old-aged forest area accounted for 3–13% of the total forest stand area and carbon storage accounted for 12–30% of total forest stand carbon (Fig. 2). Carbon densities ranked by age class in descending order as: old-aged > middle-aged > young (Fig. 2).

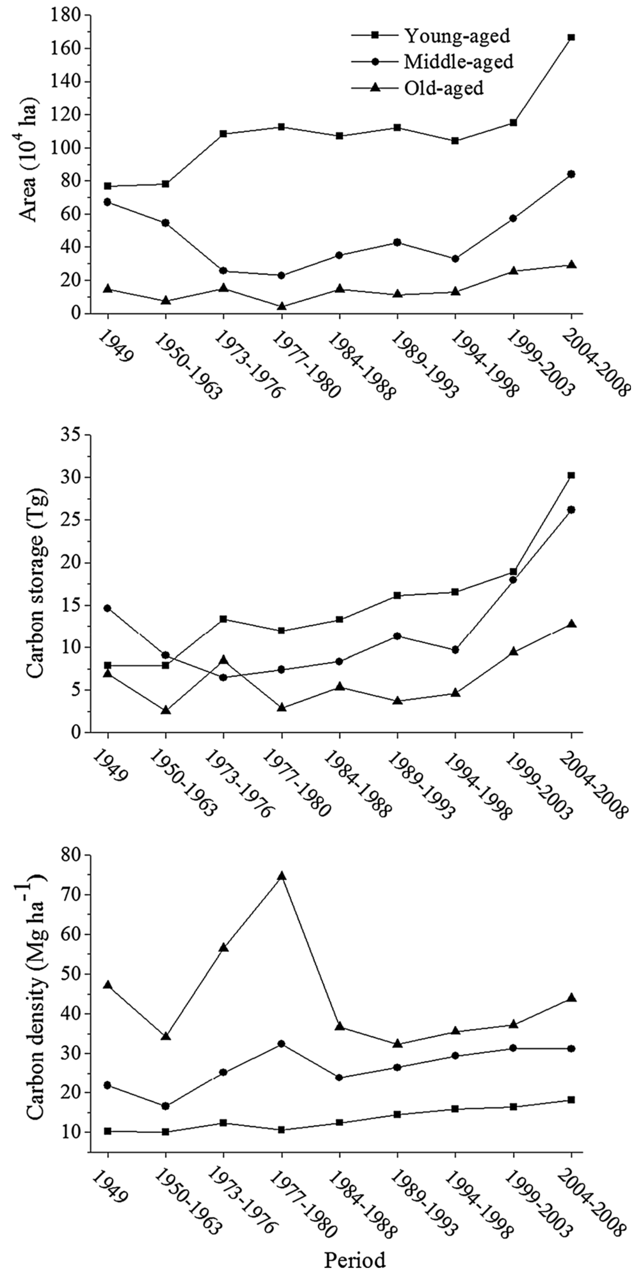

Fig. 2 Area, carbon storage and carbon density of Henan Province's forest stands among different age classes during 1949–2008

Biomass carbon storage and density of forest stands in planted and natural forests

We analyzed data by forest origin (natural versus planted) for the inventory periods after 1963 (previous records made no distinction). Temporal changes in forest area, carbon storage, and carbon density under planted and natural forests are shown in Fig. 3.

From 1976 to 2008, the area, carbon storage and carbon density of natural forest changed little. Natural forest area increased from 95.9×10^4 to 118.7×10^4 ha, accounting for 42–73% of the total forest stand area. Carbon storage was between 18.3 and 31.3 Tg accounting for 45–85% of the total forest stands carbon storage, meanwhile, the carbon density ranged from 18.0 to 26.3 Mg ha^{-1}. Compared to natural forests, planted forests increased in area, carbon storage and carbon density remarkably. The area of planted forest increased from 38.1×10^4 to 160.8×10^4 ha, accounting for 27–58% of the total forest stand area. From 1998 to 2008 the area of planted forest increased from 53.9×10^4 to 160.8×10^4 ha. From 1976 to 2008, carbon storage of planted forest increased from 3.9 Tg to 37.9 Tg, accounting for 15–55% of the total forest stand carbon storage. Increased carbon storage was 33.7 Tg, or 82% of the total forest stand carbon storage increment (41.0 Tg), and average annual sequestration of 1.1 Tg of carbon. The carbon density of planted forest increased from 8.9 Mg ha^{-1} in 1976 to 23.6 Mg ha^{-1} in 2008.

Biomass carbon storage and density of different forest types in forest stands

We categorized forest stands as coniferous and broad-leaved forests. Coniferous forest area accounted for 8.4, 43.1, 19.3, 19.5, 19.5, 24.2, 24.5, 17.8 and 12.1%, respectively, of Henan Province's total area of forest stands in the nine inventories from 1949 to 2008. Carbon storage estimates for the nine periods were 2.3, 9.1, 4.6, 4.1, 5.1, 7.2, 7.5, 4.9 and 5.7 Tg, accounting for 7.7, 46.9, 16.4,18.6, 18.8, 23.4, 24.3, 10.5 and 8.2%, respectively, of total forest stand carbon storage in the corresponding inventory periods (Fig. 4).

Broad-leaved forests area accounted for 92, 57, 81, 80, 81, 76, 76, 82 and 88% of the Henan Province's total area of the forest stands in the nine periods from 1949 to 2008.

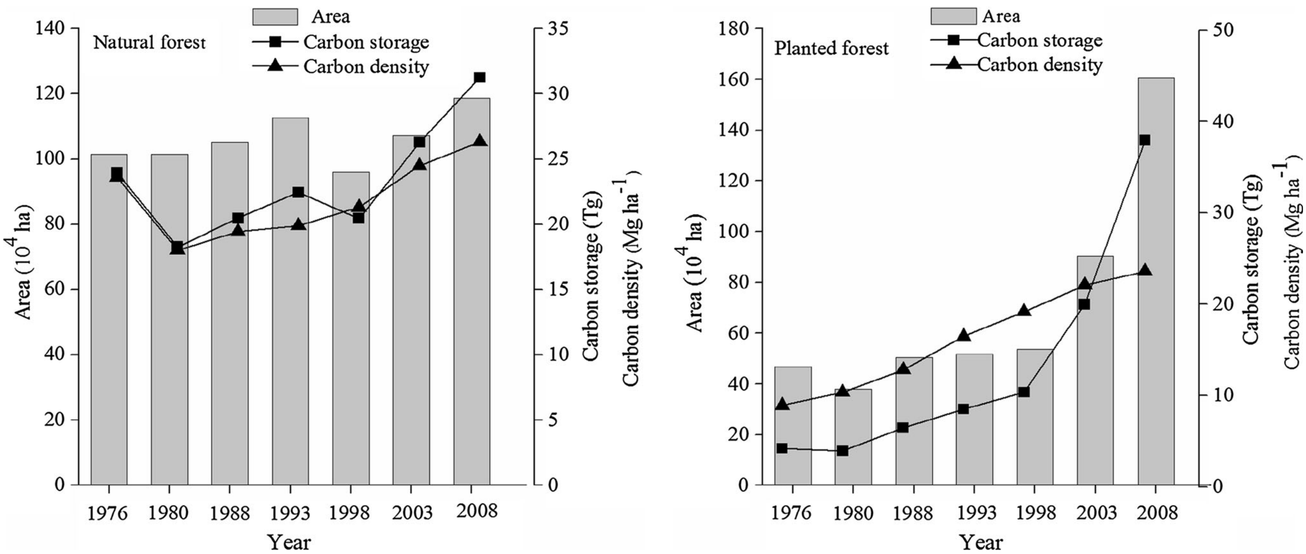

Fig. 3 Area, carbon storage and carbon density of Henan Province's forest stands in natural forest and planted forest during 1949–2008

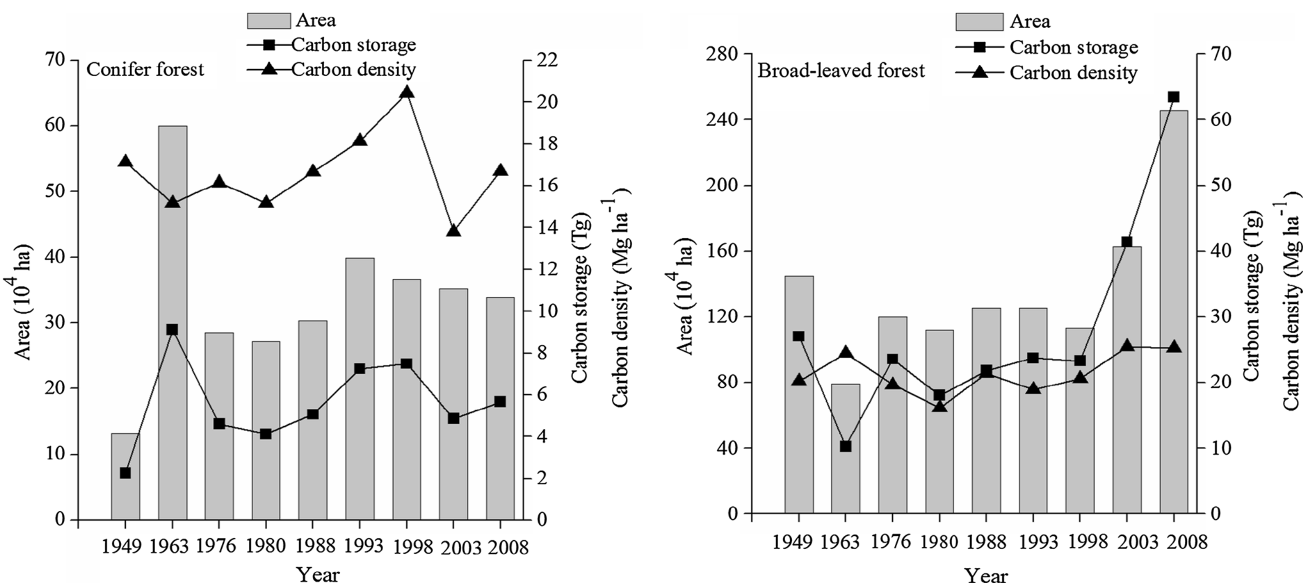

Fig. 4 Area, carbon storage and carbon density of Henan Province's forest stands in conifer forest and broad-leaved forest during 1949–2008

And carbon storage amounts in the nine periods were 27.0, 10.3, 23.6, 18.1, 21.8, 23.8, 23.3, 41.4 and 63.5 Tg, accounting for 92, 53, 84,81, 81, 77, 76, 90 and 92%, respectively, of the total forest stands carbon storage in the corresponding time. Forest biomass carbon was accumulated mainly in broad-leaved forests. During 1949–2008, the mean carbon density of broad-leaved forests was between 16.1 and 25.5 Mg ha^{-1} and conifer forests ranged from 13.8 to 20.4 Mg ha^{-1} (Fig. 4). The broad-leaved forests had high carbon storage mainly attributed to the large broad-leaved forest area and high biomass density. Broad-leaved forest was the main contributor to forest carbon sequestration in Henan Province.

Biomass carbon storage and density of forest stands by forest category

Based on the goals of forest management, Henan's forest stands can be divided into four forest categories: timber, shelter, fuelwood, and special use. But the forest stands were not divided into these four categories between 1949 and 1976. From 1949 to 1998 the area of timber forest was greater than other forest categories, accounting for 96%, 95%, 91%, 64%, 61%, 64%, 67% of the total forest stand area (Table 3). The area of shelter forest surpassed that of timber forest in 2003 and 2008, reaching 48% of total area in both years. Reforestation and afforestation programs

Table 3 Area, carbon storage and carbon density of different forest categories for nine periods from 1949 to 2008 in Henan Province, China

Period	Forest category	Area (10^4)	Carbon storage (Tg)	Carbon density (Mg ha^{-1})
1949	Timber forest	151.8	27.7	18.3
	Shelter forest	6.4	1.6	25.2
	Total	158.1	29.3	18.5
1950–1963	Timber forest	132.5	18.2	13.7
	Shelter forest	7.0	1.2	17.5
	Total	139.5	19.4	13.9
1973–1976	Timber forest	135.9	26.8	19.7
	Shelter forest	9.0	1.3	14.3
	Fuelwood forest	3. 8	0.2	4.7
	Total	148.7	28.2	19.0
1977–1980	Timber forest	89.2	13.4	15.1
	Shelter forest	35.2	7.7	21.9
	Fuelwood forest	15.2	1.1	6.9
	Forest for special use	0.3	0.1	15.4
	Total	139.8	22.2	15.9
1984–1988	Timber forest	94.9	16.0	16.9
	Shelter forest	43.4	9.0	20.7
	Fuelwood forest	15.0	0.9	6.2
	Forest for special use	3.6	1.1	29.4
	Total	156.9	27.0	17.2
1989–1993	Timber forest	105.6	19.3	18.3
	Shelter forest	39.8	9.5	23.8
	Fuelwood forest	16.9	1.2	6.8
	Forest for special use	3.9	1.2	29.2
	Total	166.2	31.2	18.7
1994–1998	Timber forest	100.4	19.4	19.4
	Shelter forest	36.8	9.4	25.6
	Fuelwood forest	8.7	0.6	7.2
	Forest for special use	3.9	1.3	33.4
	Total	149.8	30.7	20.6
1999–2003	Timber forest	87.7	17.7	20.2
	Shelter forest	94.7	24.0	25.4
	Fuelwood forest	6.0	0.3	4.6
	Forest for special use	9.4	4.3	45.8
	Total	197.7	46.3	23.4
2004–2008	Timber forest	126.1	29.5	23.4
	Shelter forest	134.4	32.9	23.9
	Fuelwood forest	2.4	0.1	5.0
	Forest for special use	16.7	6.7	38.9
	Total	279.5	69.2	24.7

focus on conservation of water and soil, causing the increasing area of shelter forest. The dynamic of carbon storage in different forest categories was consistent with the changing area of different forest categories. Carbon densities varied by forest category during the period 1949 to 2008: The carbon density of fuelwood forest was the lowest of all forest categories. In 2008, the carbon densities ranked by category as special use forest > shelter forest > timber forest > fuelwood forest.

Discussion

The increase of total forest vegetation carbon storage in Henan Province during 1949–2008 mainly resulted from a net increase of forest coverage rate by more than 74% over 60 years (Table 2). In 2008, the total forest vegetation carbon storage in Henan Province was 80.3 Tg, or 1% of the forest vegetation carbon storage of 7811.5 Tg in China. The forest vegetation carbon density in Henan Province in

2008 was lower than that of 40.0 Mg ha^{-1} in China (Li and Lei 2010). This was due to the dominance of young and middle-aged forests in Henan Province at the time of the survey. Li et al. (2012) reported that the carbon storage and carbon density of Henan Province's forest stands were 88.0 Tg and 31.0 Mg ha^{-1}, respectively, both estimates exceeding ours. The main reason was the use of different methods to estimate forest carbon. The total carbon storage of Henan Province's forest vegetation in 2008 was equivalent to 58% of Henan Province carbon emission in 2010 (Li et al. 2011) and 3.7% of China's total carbon emission (estimated at 2200 Tg in 2010 (Durban conference)).

During the period of 1949 to 2008, the forest carbon storage dynamics showed a trend of increasing. However, the forest carbon storage in 1950–1963 and 1977–1980 decreased, because of the government economic policy and lack of the regulatory measures for forests. From 1998 to 2008, the forest area and carbon storage increased drastically, this was significantly due to the Grain for Green Program was carried out in Henan Province. These results have demonstrated that reforestation and afforestation programs are important measures to increase the forest carbon sequestration. These results are consistent with previous studies (Ren et al. 2013; Zhang et al. 2009).

Broad-leaved forests stored more carbon than did coniferous forests in nine inventories from 1949 to 2008, due mainly to the greater area of broad-leaved forest and its higher carbon density. From 1998 to 2008, forest carbon storage increased sharply in plantations. This was because: (1) Many trees were planted during this period by the Grain for Green Program; and (2) good management practices were applied to the planted forests. The result of carbon density in natural forest is higher than in planted forest is consistent with the study from Guo et al. (2013), mainly because species diversity and productivity are greater in the former (Deng and Shangguan 2013).

Analyses is data sets covering 60 years are often subject to various sources of error. First, the most important errors may come from forest inventory data and the model parameters (regression coefficients a, b) converting forest volume to biomass. Forest inventory data used in our study specified the precision requirement in sampling design: the forest area and volume precision were required to be >90% in Henan Province. In addition, the R square values of the equations used to convert timber volume to biomass were above 0.9 for most dominant tree species (Table 1). Therefore, the data and method used in this study have relatively high precision. Ren et al. (2013) analyzed the error in estimates of forest carbon storage in Guangdong Province, southern China. In their study, the forest area and volume only contributed a small error to forest C storage estimate. Larger errors were mainly caused by model parameters (regression coefficients a, b), which accounted for 97, 97, and 96% of the total error in 1992, 1997, and 2002, respectively. To improve the accuracy of model predictions, it is necessary to develop conversion parameters that are adjusted to fit regional forest conditions.

For the economic forests, bamboo, open forests and shrub, the major error can be generated from the use of mean biomass density. In this study, we used a mean biomass density estimate that is a universal value abstracted from the literature. This might have introduced error due to the influences of climate, site conditions, or management practices. To remove this source of error, it is necessary to develop regionally accurate estimates of mean biomass density for representative forest vegetation types.

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