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Forest biomass carbon storage from multiple inventories over the past 30 years in Gansu Province, China: implications from the age structure of major forest types

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Abstract We used the forest inventory data of Gansu Province, China to quantify carbon storage and carbon density changes by regional forest cover and by typical forest types in 1979–2006. Total forest area increased from 1.77×10^6 ha in 1979 to 2.32×10^6 ha in 2006, and the forest carbon storage, estimated by the continuous biomass expansion factor method, increased from 83.14 to 100.66 Tg, equivalent to a carbon accumulation rate of 0.0071 Tg per year during the period. Mean carbon densities were 44.83–48.50 t ha^{-1} and the values decreased slightly over the time period. Natural forests generated greater carbon storage and density than did plantations. By regression analysis, forest stand age was an important parameter in carbon density studies. We developed various regression equations between carbon density and stand age for major types of natural forests and plantations in the region. Our results can be used for proper selection of re-forestation species and efficient management of young and middle-aged forests, offering great potential for future carbon sequestration, especially in arid and semi-arid regions.

Keywords Age class · Carbon density · Forest carbon storage · Forest inventory data · Gansu Province · Reforestation

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Introduction

Globally, forests cover about 4.1×10^9 ha, approximately 38 % of land area, accounting for 76–98 % of the above-ground, and 40 % of the below-ground global organic carbon (Cao and Woodward 1998; Dixon 1994). Forest ecosystems are critical to global terrestrial carbon cycling and storage. Human activities and/or natural events, such as land management (Houghton 2003; Hunter 2001), air pollution (Canadell et al. 2007a), insect attacks (Kurz and Apps 1999), N deposition (Vetter et al. 2005), and climate change, have a noticeable effect on carbon storage. The net balance of carbon exchange, due to combinations of events and activities, has resulted in forests acting as either carbon sources or carbon sinks (Noble and Dirzo 1997; Wang et al. 2007). Assessing carbon storage at large scales, either global, national and/or regional, has been a focus on carbon cycling for the past several decades (Brown and Lugo 1982; Fang et al. 2001; Zhang et al. 2012). Consequently, estimating the spatial and temporal variations in carbon storage has been considered of great importance for understanding the impacts of climate change and human

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activities (King et al. 1997; Ni 2001; Parks and Bernier 2010; Zaehle et al. 2007).

China is a signatory to the Kyoto Protocol and the United Nations Framework Convention on Climate Change, and has planned to reduce the intensity of CO_2 emissions per unit of GDP in 2020 by 40–45 % compared with the level of 2005 (Xinhua 2009). To achieve this target, China has launched a series of nationwide afforestation and reforestation projects. Such approaches are inextricably linked to the evaluation of carbon storage and flux. Species and stand age structure, inevitably, are the prominent determinants of timber production and carbon storage (Garcia-Gonzalo et al. 2007; Ren et al. 2011; Schulze et al. 2000) since young stands acquire carbon from dead materials and litterfall (Kashian et al. 2006; Wang et al. 2007). Furthermore, stand age can provide clues about past disturbances while aiding assessment of carbon storage dynamics (Hicke et al. 2007). Due to intensive deforestation and reforestation over the last century, stand age structure has been significantly modified in China, especially in the western region. Therefore, successive inventories of the forest resources can provide a scientific basis for assessing the vegetation carbon storage and possible drivers affecting the dynamics of carbon storage (Ren et al. 2011; Shi et al. 2011).

Since China is one of the largest countries with a wide north–south gradient in temperature and a west-east gradient in precipitation, ecosystem carbon storage can be studied on either large- or small-scale climatic and geographic units (Hou 1983; Wang et al. 2007). China contains diverse ecosystems, including all major forest types of the northern hemisphere, from boreal forests in the north to evergreen tropical forests in the south (Hou 1983; Houghton and Hackler 2003; Li 2004). Forest inventory data (FID) in China is a valuable tool in monitoring the macro-changes of forest resources and biomass, as it includes natural and anthropogenic impacts on forests at regional and national levels, and has been conducted every 5 years for more than 30 years. The inventory is carried out by specially-designed standards formulated by the State Forestry Administration, focusing on the area and volume of each forest stand type (Lei et al. 2009; Liu and Cossalter 2006).

Gansu Province in northwest China covers about 4.7 % of the country, ranking it the 7th largest of 34 administrative divisions of China. Compared with the eastern and southern regions, Gansu is ecologically fragile with large areas of arid and semiarid land. There are 2.32×10^6 ha of forest, approximately 5.11 % of land area, and a total timber volume of 1.94×10^8 m^3 according to the recent National Forest Inventory (Fig. 1). Forest cover has been increasing due to implementation of national projects, such as the "Natural Forest Protection" and "Grain-for-Green"
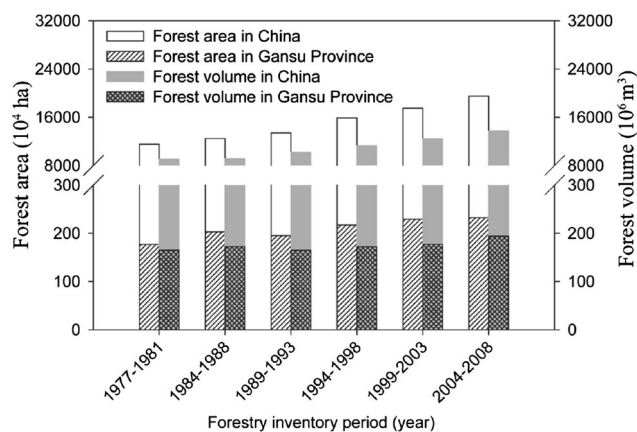

Fig. 1 Changes in forest area and forest volume in China and Gansu Province since 1977. Each period refers to a working time-span of the national forest inventory. The corresponding surveys in Gansu Province were finished in 1979, 1988, 1991, 1996, 2001, and 2006

(converting cropland to forest or grassland). During the past 3 decades, forest area and volume in Gansu Province have increased by 31.39 and 17.15 %, respectively. Although plantations contribute only a small fraction to global forest carbon (1.4×10^8 ha of current forests, 3.8 % of the total (FAO 2006)) their potential capacity for accumulating carbon and mitigating climate change in the future has been recognized (Canadell et al. 2007b; Pregitzer and Euskirchen 2004). Therefore, an assessment of carbon dynamics is urgently needed for properly evaluating and predicting present and future capacity for carbon sequestration in forests of each region (Chen et al. 2009). Since forest area has been increasing in the province, we hypothesized that forest carbon storage also increased. Given that forest age is an important determinant of carbon density (Pan et al. 2004; Xu et al. 2010), we predicted that forest age structure strongly affect the changing trend of carbon density and storage.

Based on multiple FID from 1979 to 2006, we aimed to estimate the status of carbon storage and density and their dynamic changes within Gansu Province, to quantify the dynamics of carbon allocation in both natural forests and plantations, and to determine the effect of forest type, forest age, and forest origin on forest carbon density.

Materials and methods

Study area

Gansu Province is located in the upper reaches of the Yellow River in northwest China, at 32°11′–42°57′N and 92°13′–108°46′E, with a total geographic area of 4.54×10^5 km^2 (Fig. 2). The climate is categorized as continental monsoon, with long cold winters and short
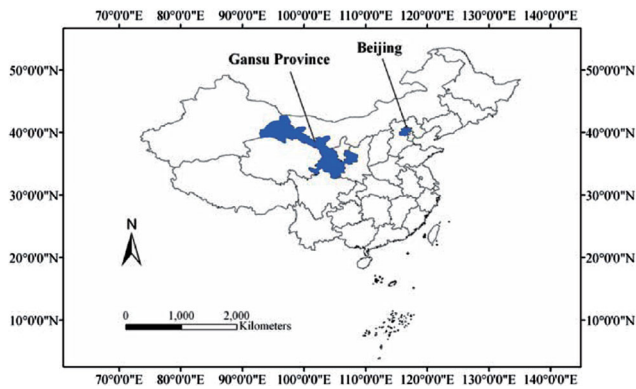
Fig. 2 Map of China showing the location of Gansu Province

warm summers. Most of the precipitation is concentrated in summer with average annual totals of 40 mm in the northwestern arid desert and 540 mm in the southern sub-humid forest. Average temperatures ranged from 0 to 15 °C, according to recent 50-year data from meteorological stations (CMDSSS). Because of the uneven precipitation distribution (a minimum of 30 mm to a maximum of 860 mm), ecosystems change from forest to steppe to desert from southeast to northwest Gansu. The geographic features are narrow and long, going from southeast to northwest, with an interlaced distribution of mountain, plateau, plain, valley and desert. More than 70 % of the area consists of mountains and plateau and most elevations are over 1000 m. Forest types include sub-tropical broad-leaved evergreen and deciduous forest, warm-temperate deciduous forest, cold-temperate deciduous forest, cold-temperate coniferous forest, and coniferous and broad-leaved mixed forest (GFEB 1998).

Data sources

The State Forestry Administration has conducted 6–7 systematic surveys in most provinces since the 1970s (Lei et al. 2009). The first survey in Gansu Province was conducted in 1979 and the 6th survey was finished in 2006. In the inventories, detailed information about forest type (species and origin), area, volume, extent, age class, forestry program type (e.g. shelter forest, timber production forest, fuelwood forest, special purpose forest) and ecological status is collected in systematically-distributed permanent sample plots (each with an area of 800 m^2 in Gansu Province). On a nationwide scale, forests include three large categories, i.e. general forest stands (both natural and planted forests), economic forests (plantations which are used for the production of fruits, edible oils, medicine, flavorings and industrial raw materials), and bamboo forests. As few economic and bamboo forests occur in Gansu Province, the forest inventory data in this study only cover general forest stands, including natural forests and plantations.

In 1979, a total of 6855 sample plots were surveyed, and sample plot numbers increased in later surveys. There were 17,702 permanent sample plots in the surveys of 2001 and 2006. In these plots, we measured the height and diameter at breast height (DBH) of all trees with DBH > 5 cm, and calculated the stem volume of each measured tree by a volume table in accordance with species and region (FAC 1977). Stand timber volume of each plot was calculated by adding the volume of all individual trees within a plot. The differences in forest types and age classes were not separated in the 1979 inventory. Natural forests and plantations were separately recorded from the inventory of 1988. Since 1991, all forests have been recorded by category of origin and age. To obtain relatively precise biomass and carbon estimates, we used the data from the later 4 inventories for most of the analyses in our study.

Defining forest age class

The age classes of dominant trees recorded in the inventory are based on national guidelines of forest resource surveys (MOF 1982). Five age classes were used to classify forest age: young forest, middle-aged forest, pre-mature forest, mature forest and over-mature forest. The full definition of each age class with respect to different species is shown in Table 1.

Forest biomass estimation

We used the consistent function of stem volume, i.e., the continuous biomass expansion factor (BEF) method, which is widely recommended as it uses timber volumes that are closely related to forest biomass and it involves forest age, density, site and other factors. (Brown and Lugo 1982; Fang et al. 2001; Guo et al. 2010). The relationship between biomass and stem volume of a specific forest type (species group) can be described as:

$$B = aV + b, \tag{1}$$

where, B is the total (including above and below ground) dry biomass per hectare (t ha^{-1}), V is the stem volume per hectare (m^3 ha^{-1}), and a and b are parameters which are constants for a specific forest type when stand volume is large enough. For estimating provincial biomass of all forests, the calculation can be expressed as:

$$B_{\text{total}} = \sum_{i}^{n} (A_i \times B_i), \tag{2}$$

where, B_{total} is the total biomass, A_i and B_i are total area and biomass per unit area of each species group.

In the calculation of forest biomass using FID, forests were categorized into 21 species groups according to

Table 1 Criteria of forest age classification for major species in Gansu Province, China

Forest type	Original	Age class (year)					Deadline
		Young	Middle-aged	Pre-mature	Mature	Over-mature	
Abies, *Cupressus*	Natural	1–60	61–100	101–120	121–160	≥161	20
	Planted	1–40	41–60	61–80	81–120	≥121	20
Picea	Natural	1–40	41–80	81–100	101–140	≥141	20
	Planted	1–20	21–30	31–40	41–60	≥61	10
Pinus, *Larix*	Natural	1–30	31–50	51–60	61–80	≥81	10
	Planted	1–20	21–30	31–40	41–60	≥61	10
Populus, *Betula platyphylla* and other softwood species	Natural	1–20	21–30	31–40	41–60	≥61	10
	Planted	1–10	11–15	16–20	21–30	≥31	5
Quercus and other hardwood species	Natural	1–40	41–60	61–80	81–120	≥121	20
	Planted	1–20	21–40	41–50	51–70	≥71	10

dominant species. Parameters of forest volume-biomass for the tree species were developed by Fang et al. (2001). For tree species with unknown parameters, biomass estimation was based on the parameters of the other known species according to their morphological similarity.

Forest carbon storage and carbon density

The calculated total biomass was converted into forest vegetation carbon storage by multiplying biomass by percentage of carbon content. Carbon content can vary from 45 to 55 % of total biomass, differing between tree components (e.g. stems, branches, leaves and roots), species, age, and community structure of forest types (Brown and Lugo 1984; Fang et al. 2001; Potter et al. 2008). We used the generally-accepted average carbon content of 50 % (Fang et al. 2001; Karjalainen 1996). Carbon density of a forest type is the ratio of its total carbon storage to its area and varies according to forest type, area and age class.

Because the definition of forest in China's national inventories has been changed from a canopy density of 30–20 % since 1994, forest areas calculated in earlier inventories can be lower, especially for young plantations that may contain stands with density of 20–30 %. In order to compare data before and after 1994, we used a linear model constructed by Fang et al. (2007) to calibrate the data of forest area and carbon storage, and the corresponding forest carbon density was calculated using the same criteria.

Results

Dynamics in forest carbon storage

The provincial total amount of forest carbon storage increased from 83.14 to 100.66 Tg, while forest carbon density decreased from 47.29 to 45.00 t ha^{-1} from 1979 to 2006 (Fig. 3). Though the forest carbon storage showed a mean carbon accumulation rate of 0.0071 Tg per year during the whole period, there was a decrease that occurred in 1988–1991. A rapid increase occurred after 1991 with a mean carbon accumulation rate of 0.0123 Tg per year by 2006.

Natural forests and plantations showed remarkable differences in both the amounts and trends of forest carbon storage (Fig. 4). Natural forests accounted for 68.14 and 79.98 % of the total forest area and carbon storage, respectively, according to the recent inventory. The highest proportion of carbon storage has always been in natural forests and followed a pattern similar to that of total carbon storage as documented by inventories over time. Plantations showed lower carbon density than natural forests. Carbon storage in plantations increased in a fluctuating pattern since 1988.

Due to afforestation and reforestation, there have been two large increases of 25.98 × 10^4 and 22.55 × 10^4 ha in forest area in 1979–1988 and 1991–1996, leading to jumps in forest carbon storage of 7.05 and 7.83 Tg, respectively. Compared with the baseline that was set by the first
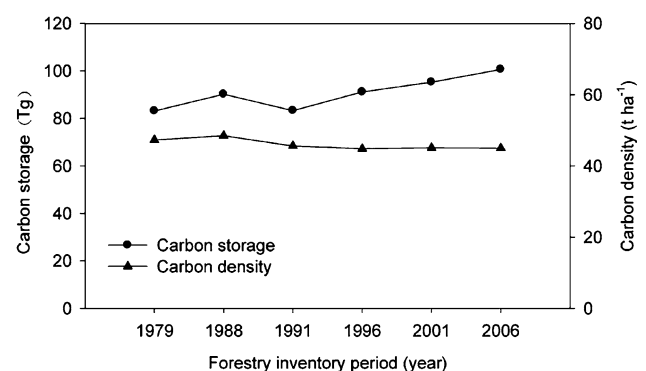

Fig. 3 Changes in forest carbon storage and carbon density in Gansu Province since 1979
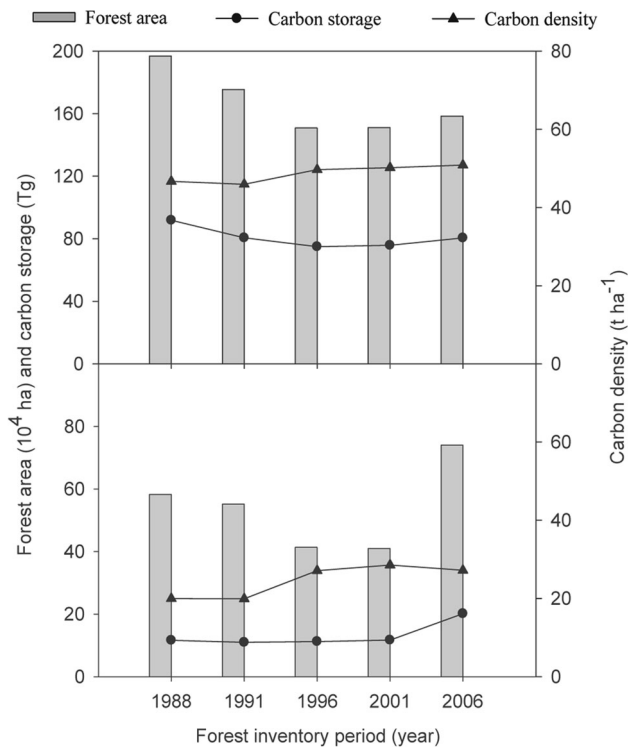
Fig. 4 Changes in forest area and carbon storage of natural forests and plantations in Gansu Province since 1988 (natural forests and plantations were not separated in the inventory in 1979)

inventory, forest carbon storage increased by 17.52 Tg in the whole province.

Carbon storage distribution by forest age class

Forest carbon storage was greatly affected by the age class and the contributions by different age classes were different between natural forests and plantations, coinciding with the variations in their areal extent (Fig. 5). The middle-aged forest class contributed the most to carbon storage in natural forests, whereas for plantations, both young and middle-aged forest classes contributed most to carbon storage. Apparently, afforestation and reforestation programs affected age structure and carbon storage proportions of plantations. Natural forests maintained relatively stable proportions of age classes although the general trend of carbon storage was an increase over the study period.

Carbon storage and carbon density in typical forest types

The dominant tree species of major forests in Gansu Province can be defined as *Abies sp* and *Picea* spp., *Pinus tabuliformis*, *Quercus* spp., and *Populus* spp. These four groups of tree species accounted for 40 % of the total forest area, and their carbon storage accounted for 50 % of the

total according the recent FID. We selected these four forest types and analyzed their carbon storage dynamics over the period 1979–2006 (Fig. 6). Over the study period, the mean area, carbon storage and carbon density of *Abies/Picea* were consistantly higher than for the other three types. The carbon density of 4 forest types showed fluctuating increases over the whole period. The data confirm that the *Abies/Picea* forest was logged extensively before the implementation of Natural Forest Protection in 1990s.

### Relationship between forest carbon density and age class

Regression analyses showed forest carbon density was significantly correlated with stand age (Figs. 7, 8). Between 4 types of forests, *Pinus*, *Quercus*, and *Populus* showed quadratic regressions, whereas *Abies/Picea* showed a positive linear regression, or the ascending phase of a parabola. Separating the data into natural (Fig. 7) and planted (Fig. 8) forests revealed differences in the regression equations. For the forest types dominated by *Pinus* and *Populus*, natural forests reached their maximum value of carbon density at around the age of 90 and 70 years, respectively, whereas, plantations reached a maximum at around 40 and 25 years, respectively. *Abies/Picea* forests showed gradual increases in carbon density with increasing age, without reaching their maxima at the ages reached during the study. In Gansu Province, all *Quercus* forests were natural and maximum carbon density was reached at around 90 years according to the fitted equations.

Discussion

Characteristics of forest carbon storage and carbon density

Total forest carbon storage in Gansu Province decreased from 90.19 Tg in 1988 to 83.31 Tg in 1991, and then increased to 100.66 Tg in 2006, most likely due to changes in land use. There have been studies suggesting that growth of human population and economic policy changes during the past decades in China resulted in significant changes in land use, forest volumes, and, accordingly, in carbon storage. The construction of Three-North Shelterbelt in the north, northeast and northwest of China was started in the late 1970s, resulting in a small increase in plantations in Gansu Province. The implementation of Natural Forest Protection and Grain-for-Green projects in the late 1990s totally banned deforestation and resulted in conversion of much farmland back to forest. The increasing trend of carbon accumulation shown in the later inventories demonstrated the effects of reforestation programs.

Fig. 5 Changes in forest area and forest carbon storage of different age groups in natural forests and plantations since 1991 (forests of different age classes were not separated in the inventories in 1979 and 1988)
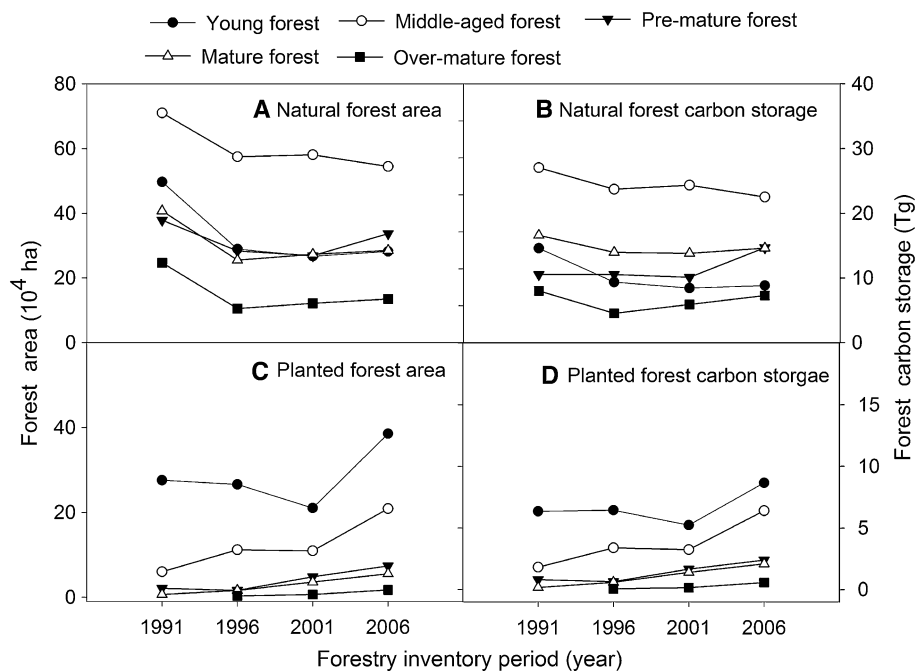
Plantations contributed more to the temporal changes of forest cover in the province. With an increasing proportion of mature forest, carbon density of plantations, in addition to carbon storage, is expected to increase. This suggests that plantations will be a considerable sink for carbon sequestration in the next decade. However, given that the distribution of plantations covers various climatic and geographic sites in Gansu Province, the average potential for carbon sequestration in plantations should be much lower than in natural forests. Over our study period, carbon density of natural forests was invariably 1.75 to 2.13 times higher than for plantations. This is mainly because forest types in this province are predominantly high biomass subalpine coniferous natural forests, which account for about 44 % of the area and 66 % of the volume of the whole province. Furthermore, the higher carbon density in natural forest is consistent with the national case (Fang and Chen 2001). In northwestern China, with many areas of arid and semi-arid land, forest types and distributions differ from those in other regions, resulting in lower total carbon storage but higher carbon densities (Wang et al. 2002, 2001).

Compared with other northwestern provinces, carbon density over the three decades in this study was lower than the estimates for Xinjiang (65.34 t ha^{-1}) and Qinghai (51.01 t ha^{-1}), but was higher than reported for Shaanxi (40.51 t ha^{-1}) and Ningxia (37.4 t ha^{-1}) (Fang and Chen 2001). Meanwhile, carbon density in Gansu was higher than the nation-wide average (Fang et al. 2001), which can

be attributed to the large proportion of subalpine coniferous forests with high biomass.

Species difference in the relationship between forest age class and carbon density

For different forest types and species, forest ages that correspond to a stage of maturity are not equal. For example, it takes more than 120 years to reach maturity for natural *Abies* forests; however, natural *Pinus* forests only require 60 years to reach maturity. The productivity dynamics within a generation are thus specific to forest types and dominant species. For most forest types, forest carbon density increases with forest age (Yang and Guan 2008). Analyses in this study support this general trend (Figs. 7, 8). However, differences in the regressive relationships were also detected among species and between natural forests and plantations. *Abies/Picea* and *Quercus* forests represented the largest areas of natural coniferous and broadleaved forests in the province, and the former constituted a major proportion of regional carbon storage. The estimated ages when these two types of forest reach their highest carbon density are more than 160 years and about 100 years, respectively (Fig. 7A, D). Our analyses also showed that the maximum carbon densities of these natural forests can be more than 100 and 60 t ha^{-1}, respectively. These results suggest that the present composition of age structures for both types has considerable potential for carbon accumulation. The other two types of
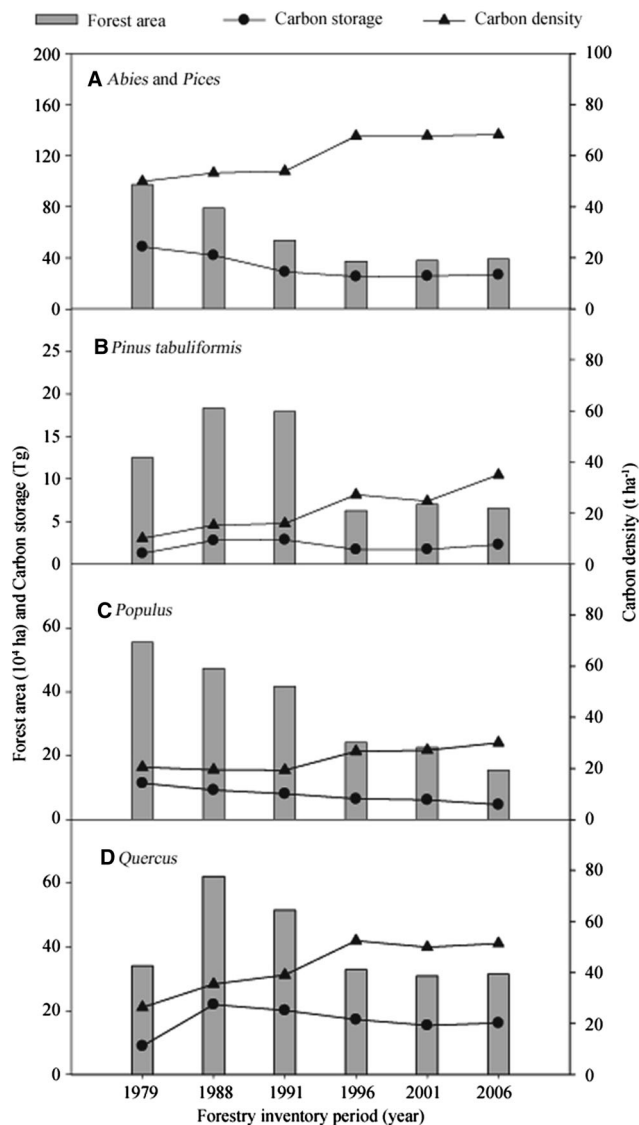
Fig. 6 Changes in forest area, carbon storage, and carbon density of four typical forests in Gansu Province since 1979

natural coniferous and broadleaved forests, *Pinus* and *Populus*, though accounting for smaller proportions of overall forest distribution, also showed increasing trends in carbon storage with respect to their carbon density peaks (Fig. 7B, C).

Dynamics of carbon density for plantations also varied with age. As plantations have shorter life spans and lower peaks of carbon density than natural forests of corresponding species, their contribution to the regional carbon storage is also lower. Nevertheless, the two types of coniferous plantations still have considerable potential for carbon accumulation (Fig. 8A, B).

The area and carbon storage in different forest types and age classes reflect the major characteristics of regional forest distribution and trends. According to the recent FID, middle-aged, premature and mature classes accounted for

74.92 % of natural forest carbon storage, whereas 74.82 % of plantation carbon storage was stored in young and middle-aged classes (Fig. 5). This suggests that prohibition of deforestation and management of plantations play crucial roles in carbon accumulation in regional forests. The contribution of age classes might be different in other regions due to different land-use histories. Reports for several southern regions showed that large proportions of carbon storage were in young and middle-aged forests, for example 76.32 % in Pearl River Delta, 71.6 % in Hainan Province (Yang and Guan 2008), 65 % in Yunnan Province (Pei and Li 2012), and 81.19 % in Fujian Province (Ren et al. 2011). However, the nationwide average showed that carbon storage was mainly distributed in middle-aged and mature forests that accounted for 85.3 % of the total (Fang and Chen 2001; Yang and Guan 2008). This suggests large variations in forest types and carbon storage distribution throughout the country based on differing natural conditions and management histories.

Potential of forest carbon storage in the province

It is commonly expected that increasing CO_2 emissions from fossil fuel consumption will be partly offset by afforestation and reforestation (Steffen et al. 1998). Several researchers estimated that about 0.3 Pg C has been sequestrated by forest plantations in China since the mid-1970s and this greatly contributed to global terrestrial carbon sinks (Fang et al. 2001, Zhang et al. 2000). Hence, with about 38.54×10^4 ha of young plantations, this region has considerable potential to accumulate additional biomass. Baishya et al. (2009) reported that plantation forests of sal (*Shorea robusta*) in northeastern India had higher aboveground biomass (406.4 t ha^{-1}) than the natural tropical semi-evergreen forests (323.9 t ha^{-1}), with carbon density approximating 203 and 162 t ha^{-1}, respectively. He suggested that plantation forests had an advantage over the natural forest because of better silvicultural practices (Baishya et al. 2009). In our study region, forest productivity is generally at a magnitude of tens of t ha^{-1}, with plantations 50 % lower than natural forests (Figs. 7, 8). This corresponds with the nature of many arid and semiarid areas in the province, and the general distribution of natural forests in sub-humid mountainous areas. Nevertheless, if scientific management is applied to young and middle-aged forests, they may play important roles in mitigating increasing CO_2 concentration in the atmosphere in the region.

This study focused on the vegetation carbon storage dynamics without inclusion of soil carbon sequestration. Soil carbon generally accounts for two thirds of the total carbon storage in a forest (Dixon 1994). Chronosequence studies showed that converting arable land to forest

Fig. 7 Relationship between
forest carbon density and forest
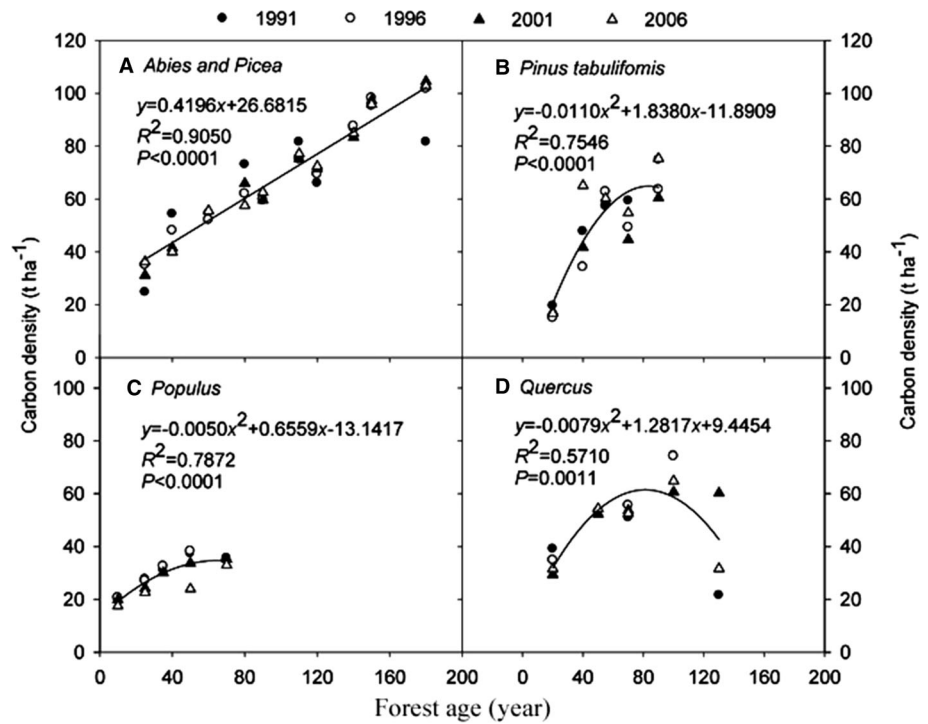age for four natural typical
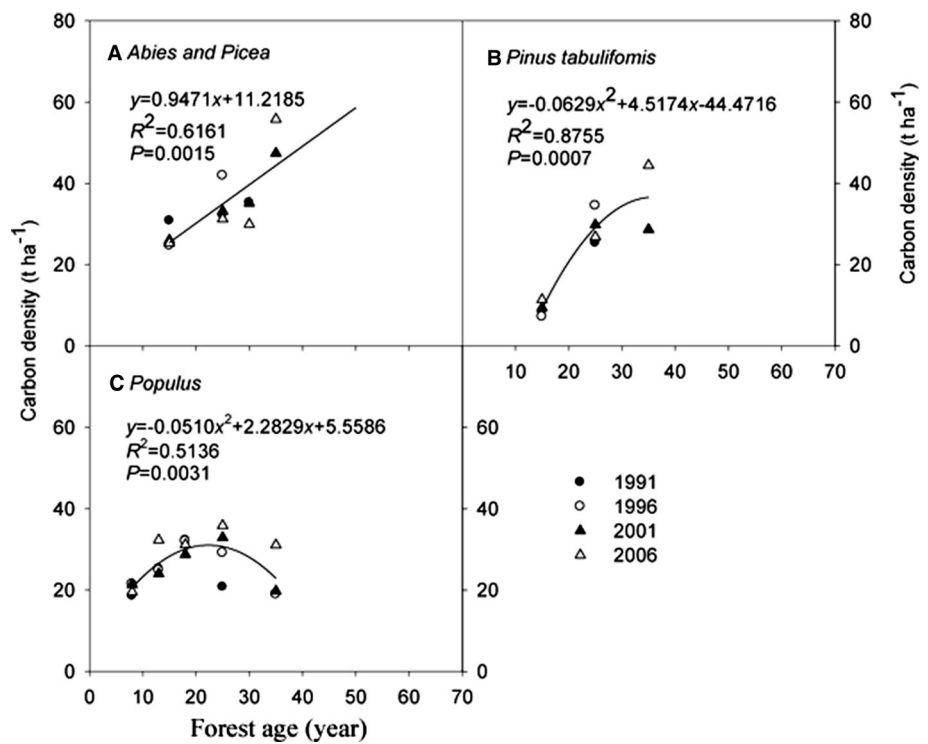forests in Gansu Province

Fig. 8 Relationship between
forest carbon density and forest
age for three typical plantations
in Gansu Province (There are no
plantation *Quercus* forests in
Gansu Province)

resulted in increases in soil carbon storage with stand age, especially in the upper soil layers (Johnson 1992; Lugo et al. 1986; Wilde 1964). Due to increasing areas of plantations on abandoned farmland resulted from national ecological projects in recent years, it is expected that not only vegetation biomass but also soil organic carbon in young and middle-aged forests will contribute considerably to carbon sequestration. Proper forest management strategies are needed in order to promote either the accumulation of soil carbon storage or forest ecosystem productivity.

Uncertainties in estimation of biomass and carbon storage based on FID

Several uncertainties and errors in estimation of biomass and carbon storage can result from this inventory-based method. Due to varying geographical conditions, the same species at different sites frequently show conspicuously different heights and diameters. This may cause bias in the estimated forest biomass of each species/age class (Zhao and Zhou 2005). Another problem is that trees with DBH < 5 cm were excluded in the inventory, which leads to an uncertainty in approaches to analyzing carbon storage potential (i.e., carbon sink in the future), especially for young forests. Biomass of belowground, shrub, grass, litter and dead wood of understory were also excluded. Some estimates showed that downed and dead wood can be 14 % of the total ecosystem carbon storage in US forest and that litter can be 5 % in global forest carbon storage (Pan et al. 2011, Woodall et al. 2008). In the future, inventories for carbon storage monitoring should be expanded to include both above- and below-ground carbon because both are important contributors to total carbon dynamics.

Conclusion and management implication

The marked increase in carbon storage in Gansu Province over the period 1979–2006 provides evidence that some national ecological programs have made a positive contribution to carbon sequestration. Considering the large proportions of young and middle-aged forests in the province, age structure effects on ecosystem carbon sequestration will be more prominent in the near future, especially if effective strategies are applied. The dynamics of forest productivity and carbon density during the life cycle of a stand varies by forest type/species and origin (natural or planted). Natural forests, coniferous forests in particular, are major forest types in the region and have a relatively high carbon densities and long life-spans. These forests have considerable potential for carbon accumulation due to their carbon density peaks at older ages. With rapid increases in area, plantations are also making an increasing contribution to regional carbon storage, especially young plantations established during implementation of various ecological programs. On the other hand, for higher precision of regional carbon storage estimates, it is necessary to collect more samples that cover a large range of age classes and site conditions. Moreover, future surveys should cover every component within the ecosystem, including more vegetation layers and the soil. In addition, remote sensing technology may also contribute to the survey of forest resources.

The present study not only provides a provincial summary of forest carbon storage over the past 30 years but also reveals the differences in age-related changes of carbon density among major forest types and species. The results suggest that future forest management should emphasize the selection of reforestation species and proper silvicultural practice with respect to the development stage so that carbon sequestration potentials can be maximized.

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