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Carbon Stocks and Dynamics in the Three-North Protection Forest Program, China

Kohlenstoffvorräte und Kohlenstoffdynamiken im Three-North Protection Forest Programm, China

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Keywords: Three-North Protection Forest Program, carbon stocks, carbon density, carbon dynamics, agroforestry system

Abstract

The Three-North Protection Forest Program is a typical cross-regional agroforestry system in China meant to enhance the operation and management quality of the nation's forests with a particular goal of creating and enhancing large carbon sinks. Based on statistical data from phase I (1978–1985), phase II (1986–1995), phase III (1996–2000), and phase IV (2001–2010) of the Three-North Protection Forest Program and in combination with the region-scale volume-derived biomass model, we estimated the carbon density, and carbon stocks, and biomass at the beginning and the end of the period of four projects within the Three-North Protection Forest Program, analyzed dynamic changes in the carbon stocks and carbon density of forests of different types and stand ages. The results showed that in 1977, 1985, 1995, 2000 and 2010, the carbon stocks to be 176.22 Tg, 189.48 Tg, 238.82 Tg, 243.88 Tg, and 744.19 Tg (1 Tg = 10^{12} g) at the beginning of the project and at the end of each of its first four phases, respectively, and the carbon densities to be 15.06 t·hm^{-2}, 13.76 t·hm^{-2}, 12.70 t·hm^{-2}, 16.42 t·hm^{-2}, and 22.94 t·hm^{-2}. The quality of the forests in the Three-North Protection Forest Program increased gradually. Timber forests and the shelter forests were dominant. Over time, the proportion of the carbon stocks in shelter forests gradually became higher than that of timber forests. The carbon stocks of

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the half-mature forests were the greatest, followed by the mature forests. The young forests occupied the largest geographic area. As these young forests mature, the Three-North Protection Forest Program may become a huge carbon stocks.

Zusammenfasssung

Das Three-North Protection Forest Programm ist ein typisches überregionales Agroforstsystem in China, welches nicht nur die Verbesserung der Verwaltung und des Managements der nationalen Wälder zum Ziel hat, sondern vor allem auch der Schaffung und Vergrößerung von Kohlenstoffsenken dient. Basierend auf statistischen Daten des Three-North Protection Forest Programms von Phase I (1978–1985), Phase II (1986–1995), Phase III (1996–2000), und Phase IV (2001–2010) und der Kombination mit regionalen volumsbasierten Biomassemodellen wurden Kohlenstoffdichte, Kohlenstoffvorrat und Biomasse zu Beginn und Ende der vier Perioden abgeschätzt. Außerdem wurden dynamische Veränderungen in den Kohlenstoffvorräten und Kohlenstoffdichten von verschiedenen Waldtypen und dem Bestandesalter analysiert. Am Beginn des Projekts und am Ende der jeweiligen vier Phasen in den Jahren 1977, 1985, 1995, 2000 und 2010, ergaben sich Kohlenstoffvorräte von 176,22 Tg, 189,48 Tg, 238,82 Tg, 243,88 Tg, und 744,19 Tg (1 Tg = 10^{12}g) und Kohlenstoffdichten von 15,06 $t \cdot hm^{-2}$, 13,76 $t \cdot hm^{-2}$, 12,70 $t \cdot hm^{-2}$, 16,42 $t \cdot hm^{-2}$, und 22,94 $t \cdot hm^{-2}$. Im Zuge des Three-North Protection Forest Programms verbesserte sich die Beschaffenheit der Wälder -hauptsächlich Wirtschafts- und Schutzwälder - zunehmend. Es konnte gezeigt werden, dass im Laufe des Projektes die Kohlenstoffvorräte in den Schutzwäldern jene in Wirtschaftswälder überstiegen, und dass Altbestände nach mittleren Altersklassen die größten Kohlenstoffspeicher darstellten. Jungwälder hatten im Programm die größte geographische Ausbreitung und werden im Laufe der Zeit zu sehr großen Kohlenstoffvorräten heranwachsen.

1. Introduction

Increased atmospheric CO_2 concentration has been extensively recognized as a major contributor to global warming (*Wofsy 1993, IPCC 2007*). With the increasing attention being given to global changes, carbon sinks have become a hot issue in the scientific and political fields. Forest ecosystems do not only play an important role in maintaining the regional ecological environment. They also make a huge contribution to the global carbon balance. Organic carbon storage by forests accounts for 76–98 % of the total terrestrial ecosystem storage (*Wang and Fang 1995*). Against the background of global climate change, the forest ecosystem has become a subject of great interest in the study of carbon balance.

Under the Kyoto Protocol, developed countries can offset part of their greenhouse gas emissions by implementing forest carbon sink projects in the developing countries. In this way, the Kyoto Protocol may be considered official recognition of the leading position of forestry in ecological construction. China is the world's largest developing country and it has the largest forest plantation area in the world. Since the 1970s, China's forest area and percentage of forest cover have continued to increase. This can potentially improve not only ecological and economical conditions but also play an active role in the fixation of atmospheric CO_2 (*Fang et al. 2001*).

According to current correlative research, most studies of forest ecosystem carbon stocks have focused at global, regional and national levels. Dixon et al. (1994) estimated the global carbon stocks in forest ecosystems to be 1146 Pg. Hazel et al. (1980) concluded the annual net uptake of carbon in the world's temperate forests to be 0.17–0.35 Tg. The study conducted by Apps (1993) showed the northern temperate and boreal forests to be carbon sinks and the annual net carbon absorption capacity of boreal forests to be 0.4–0.6 Tg. In national level, Kolchugina et al. (1995) calculated that Russian forests sequester 0.36–0.45 Tg annually. The forest carbon sink value in the U.S. which used U.S. forest resource data was estimated to be 0.079–0.28 Pg. (*Houghton et al. 1999, Brown and Schroeder 1999, Houghton et al. 2000*).

China began studying forest biomass and carbon stocks in the late 1970s. The first study on the carbon stocks of fir plantations was conducted by Pan et al. (1979). Later, Feng et al. (1981) and Li et al. (1982) studied the masson pine artificial forest and Changbai Mountain temperate natural forests. China then progressed to the study of the biomasses of artificial and natural forests. Xu and Liu (1992) concluded that forests are the largest terrestrial ecosystem carbon stocks, with a carbon stocks per unit area forest 20–100 times that of farmland. Researchers established the relative growth equation for the determination of the biomasses of major forest tree species (*Chen et al. 1984, Liu et al. 1990, Dang et al. 1992*). In the mid-1990s, large-area, large-scale forest biomass studies were carried out. Fang et al. (2001) conducted a large-scale study of China's forest cover carbon stocks and carried out the first assessment of China's forest carbon sinks. Liu et al. (2001) evaluated forest biomass and carbon stocks using forest resource data. Then, Wang et al. (2008), following data from the sixth forest inventory, estimated that the carbon stocks in China's forest vegetation are 5.16 Pg. In addition, China's forest vegetation carbon stocks of various provinces have been estimated by many researchers (*Guo and Zhang 2002, Guo 2003, Jiao and Hu 2005, Zhang 2005, Wang et al. 2007, Wang 2008, Luo et al. 2009*).

As stated before, the focus is mainly on the estimates of forest carbon stocks on the national scale and on static reports on forest carbon stocks in certain areas using forest inventory data. These studies generally lack assessments of carbon stocks in the key forestry projects, especially large-span artificial forests. In addition, limited studies about carbon stocks of Three-North Protection Forest Program was based on national forestry inventory data, the results lack specific analysis about the region and periods of the project. Therefore, the systematical research on carbon stocks and its temporal dynamics of Three-North Protection Forest Program have not been carried out previously. That may restrict objective assessment of the ecological functions of the project.

The Three-North Protection Forest Program was China's first, most long-lasting, and largest protection forest project. It is known internationally as "China's Green Great Wall" and "the world's largest eco-engineering project"(fig.1). The Three-North Protection Forest Program is a large-scale protection forest program that began in 1978. This project crosses the western part of northeastern China and most of northern and northwestern China, starting in Bin County, Heilongjiang in the east and stretching to Wuzibieli Mountain in the Xinjiang Uygur Autonomous Region in the west, including 13 provinces (autonomous regions and municipalities) and 551 counties (including qi, city, district) in northern China. It stretches 4,480 km from east to west and is 560–1,460 km wide from north to south, with a total area of 4,069.000 km^2. It accounts for 42.4 % of total national land. The project planning and construction period is 73 years (from 1978 to 2050), divided into three stages and eight projects. Currently, the first phase (1978–1985), second phase (1986–1995), third phase (1996–2000), and fourth phase (2001–2010) have been completed. The fifth phase (2011–2020) is under way.

In this study, we conducted estimates of forest carbon stocks and carbon density of the Three-North Protection Forest Program during different stages and analyzed carbon sequestration and changes in the program with the goal of making an objective assessment of its carbon stocks contributions. Our results may also provide a scientific basis for the management and evaluation of the Three-North Forest Protection Forest Program in the future.

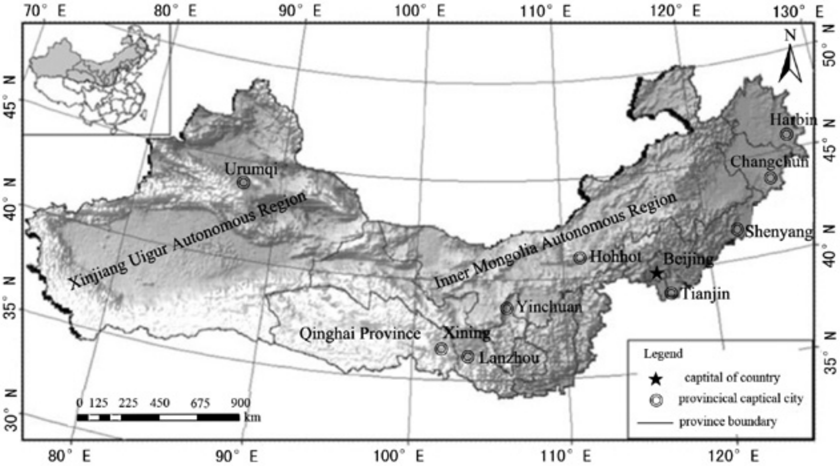

Fig. 1 Location of the Three-North Protection Forest Program

2. Research methods

2.1. Data sources

The basic data in this paper cover the Three-North Protection Forest master plan, 30 years of development reports on the Three-North Protection Forest, and resource inventory data collected at the beginning and the end of each phase of the project. Forest resource inventory data from each phase was provided by the Three-North Protection Forest Construction Bureau. These data include forest area, forest size, forest category, and forest age. The forest categories include shelter forests, special-purpose forests, timber forests, and fuelwood forests. Forest age categories include young forests, half-mature forests, near-mature forests, mature forests, and overmature forests.

2.2. Models for calculation of carbon stocks

2.2.1. Measurement of biomass

In this paper, the formula for forest stand biomass and volume proposed by Fang et al. (2001, 2002) were used to calculate the biomass of the Three-North Protection Forest.

[1] $B = 0.5751V + 38.706$ ($n = 120$, $r^2 = 0.83$)

where, B is the total average biomass ($t \cdot hm^{-2}$) and V is the total average stocks volume of forest stand ($m^3 \cdot hm^{-2}$).

2.2.2. Measurement of carbon stocks and carbon density

The biomass was calculated using formula (1) and the statistical data collected at the end of each phase. Then the forest carbon stocks were calculated as follows:

[2] $C = BCc$

where, C is the carbon stocks (t) and Cc is the carbon content.

[3] $\rho_c = C / S$

where, ρ_c is the carbon density (t/hm^2) and S is the regional forest area (hm^2).

After considering the results of relevant previous studies, we adopted 0.5 as the carbon content for the purpose of calculating carbon stocks (*Wang et al., 2001; Ma, 2002*). In this paper, the term "carbon stocks" refers to the living biomass carbon of the forest, not including the carbon in the understory, dead wood, litter layer, and forest soil.

3. Results and analysis

3.1. Carbon stocks and carbon density of the Three-North Protection Forest Program

Upon considering data collected in 1977, 1985, 1995, 2000, and 2010, including but not limited to statistical data concerning period resources during the early implementation of the Three-North Protection Forest Program and at the end of each of the first four phases as well as formula (1), we estimated the region's total biomass and calculated its total carbon stocks (Tg = 10^6 t) and biomass carbon density ($t \cdot hm^{-2}$) using a carbon rate conversion coefficient of 0.5. The results are shown in Figure 2 and Figure 3.

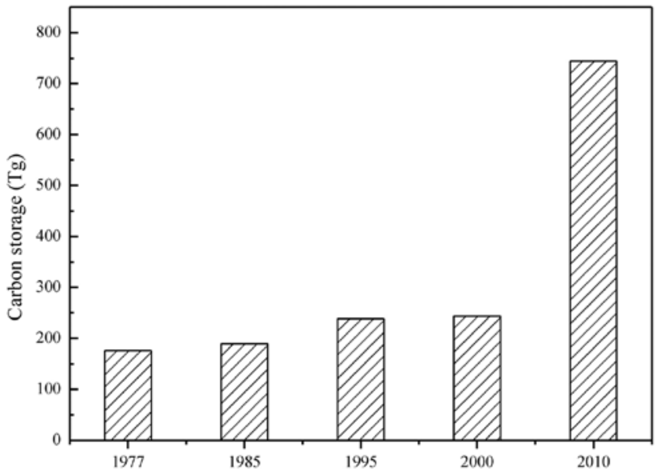

Fig. 2 Biomass carbon stocks in the Three-North Protection Forest during different periods

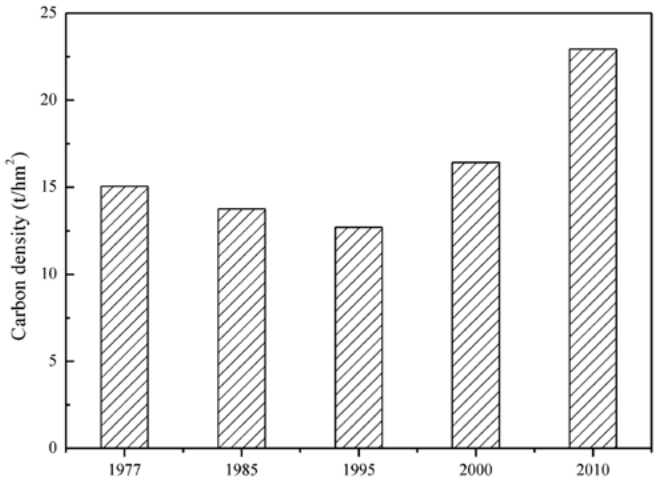

Fig. 3 Biomass carbon density in the Three-North Protection Forest during different periods

Figures 2 and 3 show that regional carbon stocks and density of the Three-North Protection Forest Program have different trends. Before the implementation of Phase III (1995), the forest area tended to increase much more dramatically than carbon stocks, which showed some slow decline during this period (1978–1995). The third phase was shorter in duration, and forest area decreased while carbon stocks grew slowly, so carbon density increased significantly. Carbon stocks and density during the fourth phase increased significantly. At the end of the fourth phase, carbon stocks were nearly twice than that of the end of the third phase. The rapid growth in carbon stocks was closely related to the increase in forest area and forest volume. Forest area and volume at the end of the forth phase (2001–2010) were 118.43 % and 205.15 % higher, respectively, than at the end of the third phase (1996–2000). The increase in forest volume was faster than the increase in forest area. The rapid growth of carbon stocks in the project region was not only due to the increase in forest area, but also due to the increase in forest volume caused by the growth of the project's own trees. The growth of carbon stocks was here consistent with changes in the carbon density of the project region. This demonstrates that the quality of the forest has been gradually improving, and carbon fixation capacity has been gradually increasing.

According to the final statistics from the fourth phase, carbon density in the Three-North Protection Forest Program region was 22.94 t/hm^2, which is far below the national average for that period 39.96 t/hm^2 (State Forestry Administration 2009). Figure 3 shows that carbon density had decreased significantly by 1995. In 1995, forest area and volume were 36.51 % and 26.03 % higher, respectively, than in 1985. Forest area grew faster than forest volume. This was found to be relevant to the expanding area of young forests, led by new forestation. During the second phase (1978–1985), we focused on arrangements for five key projects: Mu Us Sandland Sand-Fixing Forestry Project in the eastern and northwestern China and eastern Inner Mongolia; the Protection Forest Project of Beijing-Baotou-Lanzhou Railway across Beijing, 3 provinces and 2 autonomous regions, and Jilin Province; The Green Projects in and around Beijing and Tianjin; and Teenagers' Forest Protection Projects in the Yellow River area in northwestern and northern China. Before the implementation of the Three-North Protection Forest Program in 1977, young forests comprised only 40.2 % of the total forested area in China. This figure increased to 43.2 % in 1985 and to 45.5 % in 1995, while in the end of 2010 it was only 27.9 %. According to two studies, overall forest carbon density was negatively correlated with average annual temperature and positively correlated with average annual precipitation (*Zhao and Zhou 2004, Lin 2010*). Over the last 50 years, temperature in the northwest arid regions has risen. The year 1986 was a point of discontinuity of the average annual temperature. After 1986, temperature rapidly increased (Ren 2004). The overall downward trend that has been observed in carbon density in the Three-North Protection Forest System may be related to this. However, in the Three-North Protection Forest Program region, the main climatic factor that limited tree growth was lack of water, caused by lack of rainfall. Studies have shown that the average annual precipitation in these areas, 350–400 mm is the lower limit for forest growth. Below this, tree growth becomes difficult (*Zhu and Jiang 2006, Zhu and Li 2007*). The natural regeneration of high forest can only occur when annual precipitation is around 500–700 mm (*Shen and Zhang 1993*). The average annual precipitation in most areas in the Three-North Project Region is below 400 mm, especially west of Helan Mountain, which is in Ningxia in northwestern China. This area has very little capacity to store groundwater and cannot meet the needs of tree growth (*Shen 2000*). For this reason, during the first two phases of the Three-North Protection Forest Program, the decrease in forest carbon density may be less related to precipitation than to the low level of artificial tending. However, as trees in these projects gradually matured and as planting and maintenance techniques gradually improved, the carbon density also improved steadily.

3.2. Carbon stocks and carbon density of different kinds of forests in the Three-North Project

3.2.1. Carbon stocks analysis in different types of forests

The calculated results show that, at the end of each of the four phases, carbon stocks in shelter forest were 58.80 Tg, 67.35 Tg, 109.71 Tg, and 467.1 Tg, respectively. Carbon stocks in timber forest were 112.22 Tg, 115.13 Tg, 120.03 Tg, and 194.61 Tg, respectively (Fig. 4). At the ends of the first two phases (1985 and 1995), carbon stocks in timber forest were the highest of any type of forest and those in shelter forest were second. The two carbon stocks occupied 97 % of the total volume, while carbon stocks in special-purpose forests and fuelwood forests were a little lower. However, at the end of the fourth phase in 2010, shelter forests and special-purpose forests had increased in carbon stocks significantly, while timber forest had decreased significantly. Due to the shorter duration of the fourth phase, the data collected in 2000 were not classified by forest category as in previous years (*State Forestry Administration 2008*). They are not discussed here.

The relative amounts of carbon stocks in shelter forest changed over time, most notably from 1995 to 2010, when the relative amount of carbon stocks increased from 46 % to 63 %. That of timber forest decreased from 50 % to 26 % during this period. This change in forest category structure demonstrated that the purposes behind the forestation projects had also begun to gradually from a focus on simple economic benefits (such as construction, paper, wood, etc.) to ecological benefits (such as sand-fixing, CO_2 sequestration, water conservation, cleaning air).

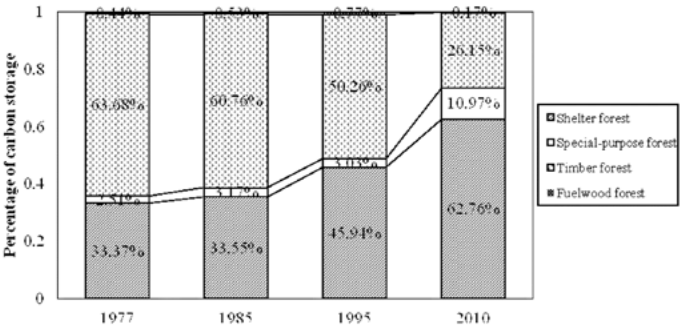

Fig. 4 Relative temporal variation in carbon stocks in four different types of forest

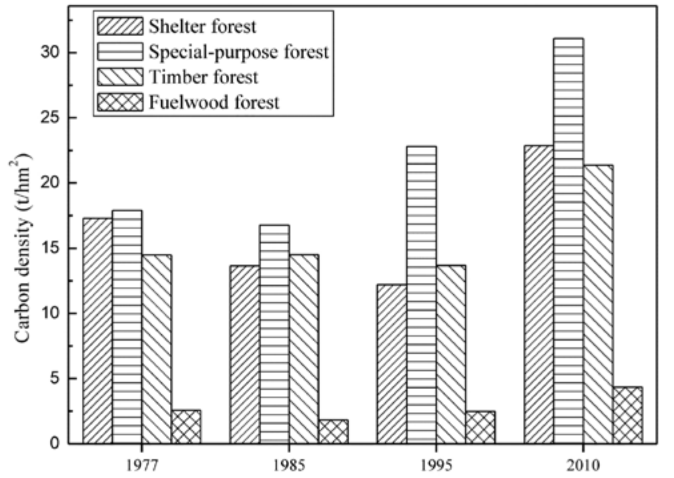

Fig. 5 Carbon density in different types of forest in the Three-North Protection Forest Program

3.2.2. Carbon density analysis of different types of forests

Figure 5 shows that, during the four phases, carbon density was highest in special-purpose forests and lowest in fuelwood forests. Timber forests and shelter forests showed about the same carbon density. Special-porpose forests are usually used for protecting and beautifying the environment, teaching, scientific experiments, seed breeding, and defense services. The quality and management of this type of forest land and forestation tend to be good, so these forests are usually of high quality. Carbon density in shelter forest increased because the relative amount of shelter forest increased, and this type of forest matures gradually. Overall, carbon density during the first two phases of the Three-North Protection Forest Program remained about the same, and the carbon density of different forest categories during the first four phases increased significantly. This shows that, in recent years, the improvement of forestation technology, forest maintenance, and the level of forest maturity contribute to carbon sequestration.

3.3. Carbon stocks and density of forests of different ages during different phases of the Three-North Protection Forest Program

3.3.1. Analysis of changes in carbon stocks of forests of different ages

Figure 6 shows that carbon stocks was highest in half-mature forests, and mature forests were second. The distribution of carbon stocks in forests of different ages shows that the Three-North Protection Forest Program has gradually aged from young to mature. Carbon stocks in mature forests are significantly higher than in young forests because the carbon density in mature forests is much higher than in young forest. Currently, young forests cover a larger geographic area than mature forests. As these young forests mature, their carbon sequestration capacity will gradually increase, potentially creating a huge carbon pool.

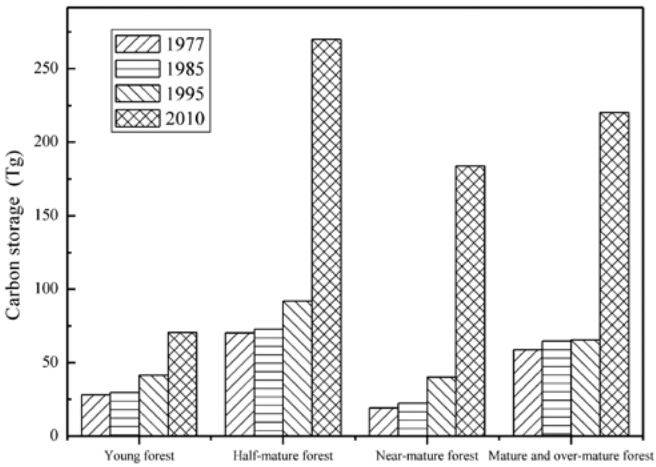

Fig. 6 Carbon stocks of forests of different ages during different periods of the Three-North Protection Forest Program

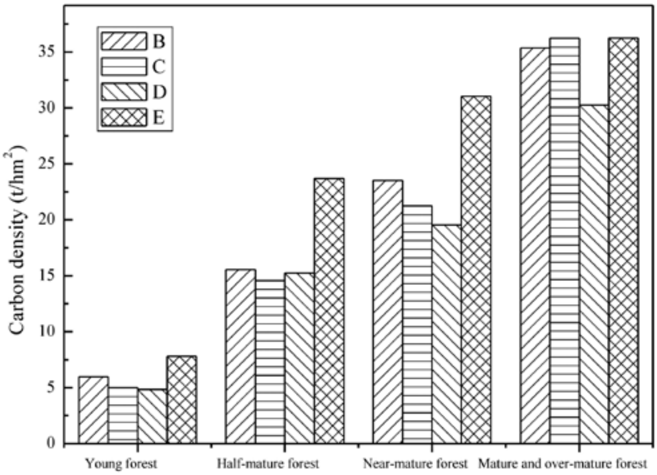

Fig. 7 Carbon density of forests of different ages during different phases of the Three-North Protection Forest Program

3.3.2. Carbon density analysis of different-age forests in different periods

Throughout the tree growing season, carbon stocks gradually increases. The carbon density of the Three-North Protection Forest Program increased as the forests aged (Fig. 7). The oldest forest showed a maximum carbon density of up to 30–36 t/hm^2, which is five times that of the youngest forests. From the beginning of construction to the end of the fourth phase of project, the carbon density of forests of all ages increased, but that of half-mature forest and near-mature forests increased most notably. This indicates that forest quality has increased steadily, that the management and maintenance of forest land have become stronger, and that the quality of forestland has increased gradually.

4. Discussion

4.1. Contribution of the Three-North Protection Forest Program to total forest carbon stocks in China

Fifteen years of data from the second, third, and fourth phases of the Three-North Protection Forest Program to fifteen years of data from the fourth through seventh national forest resource inventories (Table 1). Total carbon stocks at the end of the second phase (1995) and at the end of the fourth

Tab. 1 Area, volume, carbon stocks, and density of each type of forest during different periods

Region	Period	Area/10^4hm^2	Annual growth rate of area	Carbon stocks (Tg)	Annual growth rate of carbon stocks	Carbon density ($t \cdot hm^{-2}$)	Annual rate of increase in carbon density
Three-North Program	1995	1880.50	3.70% (1996–2010)	238.82	7.87% (1996–2010)	12.70	4.02% (1996–2010)
	2010	3243.43		744.19		22.94	
National average	1989–1993	13370.35	2.56% (1994–2008)	4930.70	3.12% (1994–2008)	36.87	0.54% (1994–2008)
	2004–2008	19545.22		7811.00		39.96	

phase (2010) were 238.82 Tg and 744.19 Tg, respectively, showing a increase of 505.37 Tg, a growth rate of 211.62 %, and an annual growth rate of 7.87 %. From 1989–1993 and 2004–2008, the carbon stocks across the country were 4930.70 Tg and 7811.00 Tg, respectively, showing an increase of 3508.40 Tg, a growth rate of 81.54 %, and an annual growth rate of 3.12 %. The annual growth rate of carbon stocks in the Three-North Protection Forest Program was twice the national growth rate.

With respect to increased area, the growth rate of the forested area in the Three-North Protection Forest Program was only 3.70 % during the period evaluated. This is less than half the annual growth rate of carbon stocks, which suggests that the rapid accumulation of total carbon stocks is not solely due to increased amounts of forested area but also to the growth of stocks volume as the forests mature. The change in carbon intensity in the Three-North Protection Forest Program region confirms this. During the 15 years from 1995 to 2010, the average annual growth rate of forest carbon density in the Three-North Protection Forest Program region was 4.02 %. During 15 years from 1993 to 2008, the national average annual growth rate was 0.54 %. This suggests that the quality of forest in the Three-North Protection Forest Program region has gradually increased and that carbon sequestration capacity is continuing to increase.

The carbon stocks assessed at the end of the fourth phase of the Three-North Protection Forest Program was 744.2 Tg. The national forest carbon stocks, according to the 7th national forest resource inventory (2004–2008), was 7811 Tg. The former is only 9.53 % of the latter. The national forest carbon stocks were higher in 2010 than in 2008, so the carbon stocks of forests (not including shrubs, commercial forest, or bamboo forest) of Three-North Protection Forest Program was less than one tenth of the total carbon stocks of the forests across the country. This is not promising for the Three-North Protection Forest Program, whose forested area makes up 16.59 % of the total national forest area. The forest carbon density of Three-North Protection Forest Program at the end of 2010 was only 22.94 t/hm^2, while the national forest carbon density at the end of 2008 was 39.96 t/hm^2. The former is only half of the latter, which may be attributed to water shortages, serious soil erosion in the Three-North regions, economic and technological backwardness, low levels of forest management, and low forest quality. However, with the continuous increase of the national ecological environmental maintenance, increased value will be placed on forest health management and the forest quality of the Three-North Protection Forest Program will increase, potentially increasing carbon stocks and density.

The carbon stocks of the Three-North Protection Forest Program increased by 505.37 Tg during 15 years from the beginning of the third phase to the end of the fourth, showing an average annual increase of 33.69 Tg. During the 15 years from the fourth to the seventh national forest resource inventory, carbon stocks increased by 2,880.30 Tg, showing an average annual increase of 192.02 Tg. This indicates that the contribution of the Three-North Protection Forests to the growth in national carbon stocks is 17.55 %, over one sixth. This suggests that the Three-North Protection Forest has had an enormous and beneficial ecological impact.

The Three-North Protection Forest is located in a mid-latitude zone in the northern hemisphere. The terrestrial ecosystems (forest ecosystems) in the middle and high latitude zones of the northern hemisphere are believed to have an important role in carbon sink activity (*Tans et al. 1990, Ciais et al. 1995, Keeling et al. 1996, Fan et al. 1998*). Since 2000, many studies have supported this conclusion through different research methods in different zones (*Fang et al. 1998, 2001, Battle et al. 2000, Janssens et al. 2003*). Recently, Piao et al. (2009) conducted a comprehensive study of the spatial and temporal pattern of China's land carbon sinks and sources. They found the carbon sinks in China's terrestrial ecosystems to be mainly associated with increases in artificial forest, regional climate change, carbon dioxide concentration, and fertilization, promoting vegetation growth and vegetation recovery, especially shrub recovery. The Three-North Protection Forest Program includes forests and a large tracts of shrubland and grassland. In this paper, we did not include the effects of bushes and commercial forests within the Three-North Protection Forest Program. Although the carbon stocks of the forests in the Three-North regions are relatively low, the areas of shrubland are about a third to half that of the forest stand area. The total area of shrubland and grassland in the Three-North Protection Forest Program is 42.4 % of China's national land area. If the carbon stocks of these types of vegetation are considered, then the carbon stocks of the Three-North Protection Forest Program are even higher than the values given above.

4.2. Potential for further carbon sequestration within the Three-North Protection Forest Program

Global climate change has motivated researchers and governments to look for low-cost methods of carbon sequestration. This is becoming an increasingly valued international objective. Agroforestry has been increasingly recognized for its potential in carbon sequestration and mitigation of the greenhouse effect. The Three-North Protection Forest Program zone is an agricultural and pastoral area within China. It has an arid and semi-arid climate, with dry sand, soil erosion, and other natural problems. These pose a serious threat to farmland and pastureland and are a major obstacle to the increase in forestry and agricultural production output. While the agroforestry systems of the Three-North Protection Forest Program have the advantages of resource sharing , so they can realize the intensive use of resources and enhance the productivity of the system.

Agroforestry systems have huge potential for carbon stocks and carbon sequestration through interactions between forest stands, crops, and soil (*Nair 1998*). This may offset the effects of greenhouse gases in the atmosphere (*Dixon 1995, Nair and Nair 2002*). In 1993, Dixon et al. conducted a large number of studies and estimated that every 1 km^2 of agroforestry model was sufficient to counter 5 km^2 of deforestation. In 2000, Sánchez concluded that less carbon is lost when forests are converted to agroforestry systems than when they are converted to arable land or pasture.

For all these reasons, the Three-North Protection Forest Program, a national-scale agroforestry system, has become an important means of reducing levels of atmospheric CO_2 and increasing carbon stocks. The construction of the Three-North Protection Forest Program can effectively curb the sand and wind hazards in these areas and mitigate soil erosion. This increases the soil carbon stocks in the Three-North regions. Studies show that soil contains the largest terrestrial carbon stocks (about 1.600 Pg), about twice that of atmospheric carbon stocks (750 Pg), and three times that of live plant carbon stocks (Dixon 1994). If the carbon stocks of soil, shrubs, and commercial forests are calculated together, the forest carbon stocks of the Three-North Protection Forest Program are even higher than otherwise estimated. As young forests mature and as planting and maintenance techniques improve, the Three-North Protection Forests will have an even greater impact on carbon sequestration.

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