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ORIGINAL ARTICLE

Carbon sequestration from China's afforestation projects

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Abstract Since the late 1970s, the Chinese government has implemented massive afforestation projects to address grievous environmental disasters, protect human health and provide long-term environmental security. Having a better understanding of the total carbon sink from the afforestation projects is fundamental to assess its global carbon benefit. Here, the sequestered carbon stock based on Chinese national forest inventory data is calculated by using three comparable volume-derived biomass models. Results show that the carbon sink contribution from these Chinese afforestation projects was 1.02 Pg C by the end of 2008 and 0.79 Pg C on average from 1981 to 2008 with a cumulative rate of 0.028 Pg C/a, which corresponds to 2 % of the total industrial carbon emissions from China during the same period. The financial value of carbon sequestration from these projects can be estimated by its value in carbon taxes of Finland and is potentially 190 billion RMB from 1981 to 2008, which is 43.4 % of the original investment. Hence although China's afforestation projects make only modest contributions to offsetting industrial growth in carbon, the carbon sequestered, if valued according to some markets, is a significant fraction of the total project costs.

Keywords Afforestation projects · China · Carbon sequestration · Climate change · Industrial emission · Economic input–output

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Introduction

Carbon exchange between the atmosphere, land and the oceans is important. The atmospheric concentrations of carbon dioxide has been steadily rising and projected to continue to rise in the future (Taub 2010). The range of atmospheric CO_2 depends both on human activities, biogeochemical and climatological processes and their interaction with the carbon cycle (Falkowski et al. 2000). Terrestrial biosphere plays an extremely important role in global carbon cycle (Pan et al. 2011; Raupach 2011), given that the terrestrial and marine environments are currently absorbing about half of the carbon dioxide that is emitted by fossil fuel combustion (Schimel et al. 2001) and even thought to be a major driver of the inter-annual CO_2 rate (Zhao and Running 2010). However, disturbed by natural and anthropogenic factors, the terrestrial biosphere may shift from carbon sinks to sources (Oechel et al. 1993). Previous studies have reported the significant impacts of droughts (Lewis et al. 2011; Zhao and Running 2010), fires (Harrison et al. 2010; Werf et al. 2010) on terrestrial ecosystem productivity in regional and global scale and a huge amount of CO_2 released into the atmosphere. Most of all, human activities-induced CO_2 emission ranks the first.

Nevertheless, in view of the likely climatic effects of increasing industrial CO_2 concentrations, the Kyoto protocol was negotiated with the aim of reducing fossil fuel emissions and the management of natural terrestrial carbon sinks, forest management (primarily afforestation and reforestation), cropland management, grazing land management and re-vegetation (Schulze et al. 2000; Smith 2004). As an important sink for carbon, terrestrial plants received great attention of the world. Reductions in terrestrial emissions are believed to be more cost-effective and environmentally beneficial than those in other sectors (Niu and Duiker 2006). Forest management could exploit NPP (Net primary productivity) for carbon sequestration in forests or biomass production for bio-energy through climate change mitigation (Karoshi et al. 2010). In this context, many countries carried out a series of terrestrial plant attempts, such as plantation of marginal agricultural land (Niu and Duiker 2006), conservation reserve program (CRP) (Gelfand et al. 2011) in the USA, afforestation of open woodlands (Boucher et al. 2012), afforestation of agricultural land (Arevalo et al. 2011) in Canada and forest restoration projects in China (Qin et al. 2013). In 2008, the United Nations launched the Reducing Emissions from Deforestation and forest Degradation Programme (REDD), which is among the most prominent of recent attempts to mitigate climate change (Agrawal et al. 2011). In the past decades, the global forest regions contained a large and persistent carbon sink of 2.4 ± 0.4 Pg C/a from 1990 to 2007 (Pan et al. 2011). Long-term monitoring and accurate assessment of the carbon sequestrations from these activities are essential for the understanding of the global carbon cycle.

China is an important region for the global carbon study because of its vast territory with various climate regimes, diverse ecosystems and long history of human modification of the natural environment (Ni 2013; Yu et al. 2013). China faces huge pressure in international climate change negotiations due to its current high level of carbon dioxide emissions from rapid industrial development (Ni 2013; Zhang et al. 2013). China is one of the few countries that has increased forest cover in recent decades (Fang et al. 2001). Even though forest coverage was still being debated before 1980s, Miao et al. (2013) agreed that the forest area expansion started to happen in the 1950s (Miao et al. 2013). From 1973, data on forestry has come from the Chinese National Forest Resource Inventory which is more reliable than estimates made from historical sources. From 1981 to 2000, the Chinese forest biomass carbon density increased from 36.9 Mg C/ha (1 Mg C = 10^6 g C) to 41.0 Mg C/ha, largely due to forest projects with an annual carbon sequestration rate of 0.075 Pg C/a (Fang et al. 2007).

The increase in forest area mainly occurred as a result of a series of ecological projects implemented by the Chinese government since 1978, particularly from the "9th five-year plan (1995–2000)" to the latest "12th five-year Plan (2011–2015)", when the government put the "Sustainable development of environment" strategy into practice. China's ecological projects were the largest elements in the plans and were implemented on a massive scale, encompassing 97 % of Chinese counties and planned investments will eventually exceed 700 billion RMB (Wang et al. 2010). Afforestation is one of the main activities of the ecological engineering. The main afforestation projects are: Three-Norths Protective Forest Program; Natural Forest Conversion Program; Grain for Green; Beijing–Tianjin Sand and Dust Engineering. However, not all planted forests resulted from those "large ecological projects". These projects were designed and have been shown to slow down and reverse land degradation by soil erosion (Liu et al. 2008; Peng et al. 2007; Zhang et al. 2007), improve local socioeconomic development (Liu et al. 2008) and help to alleviate poverty in rural communities (Sjögersten et al. 2013). During implementation of these projects, the planted area increased to 62 million ha according to the Chinese official statement. Internationally, Chinese afforestation area ranks first in the world, accounting for about a quarter of the total global afforestation area (264 million ha in 2010) (FAO 2011).

The increases of forest cover have largely contributed to terrestrial carbon sequestration, though this was not an object of these projects. The accumulated carbon sink from afforestation projects includes not only plant biomass (aboveground biomass, below-ground biomass, deadwood and litter), but also soil organic carbon (Paul et al. 2002). An earlier study suggested that plant biomass increase from the Natural Forest Conversion Program absorbed about 0.45 Pg C between 1980 and 1998 (Fang et al. 2001), which offset 28–37 % of China's fossil carbon emissions during that period (Piao et al. 2009). Several major afforestation projects have been implemented since 1998; therefore, this is an opportune moment to evaluate the terrestrial biological carbon sequestration from all these projects in China and quantify their individual contribution if possible.

Materials and method

The detailed information of planted forest of each project (including forest type, volume and area) is based on the official statistical data every 5 years of the National Forest Resource Inventory Database of China (FRIC) from 1977 to 2008 (six periods: 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003 and 2004–2008). We obtained the seven FRIC statistics from the Forest Resources Statistics of China provided by the Forest Resources Management Department of the Chinese Forestry Administration (Chinese Ministry of Forestry 1982, 1989, 1994, 1999, 2004, 2009). The FRIC is the most reliable record of the distribution and quantity of forest species during any particular period and has been used in many previous studies on forest-related calculation (Boucher et al. 2012; Fang et al. 2001; Piao et al. 2009). It provided the areas and timber volumes by individual tree species and stand ages in each province for forest stands (Du et al. 2014). Industrial carbon emissions data are from the Carbon Dioxide Information Analysis Center (http://cdiac.ornl.gov/trends/emis/overview.html) (Marland et al. 2003). Three comparable volume-derived biomass models were applied to qualify the aboveground biomass and carbon sequestration from planted forest areas. The carbon stock equivalent of the biomass used a conversion coefficient of 0.5 (Fang et al. 2001). The principle of the method is as follows:

$$B_{\text{total}} = V_{\text{total}} * \text{BEF}, \quad (1)$$

where B_{total} is the total biomass (Mg/ha) of a forest type, V_{total} the total volume of a forest type (m^3/ha) and BEF the biomass expansion factor.

IPCC models (intergovernmental panel on climate change models)

To implement monitoring and assessment of national forest biomass globally, the panel come up with this method. The central idea of the IPCC method is to build a relationship of the forest biomass with volume, density of wood, biomass expansion factor and the proportion of root and shoot in different climatic zones. In this assessment, China is divided into northern, temperate and tropical biological zones (Li and Lei 2010; Li et al. 2012). The formula is as follows:

$$B_{\text{total}} = V_{\text{total}} * D * \text{BEF2} * (1 + R), \quad (2)$$

$$\text{BEF} = D * \text{BEF2} * (1 + R), \quad (3)$$

where D is the density of wood for a forest type (Mg C/m^3), BEF the biomass expansion factor and R the proportion of root and shoot. D, BEF2 and R can be found from published species-specific tables (Li and Lei 2010). There are two IPCC models, both of which consider the climatic regionalization by forest species, but only model 2 considers the age of the trees (here, all the forest is treated as middle-aged timber).

BCF model (biomass conversion factor model)

This model seeks to capture the fact that forest carbon storage varies with age, site class, stand density, and other biotic and abiotic factors that are closely associated with relative stand density (Fang and Chen 2000; Fang et al. 2001). The model is calibrated using data from the FRIC database. The forest biomass database is obtained from 758 direct field measurements and divided the forest into 21 types to estimated forest biomass C storage and its spatiotemporal distributions from the sites to regions. Parameters required in the biomass conversion factor (BCF) model are taken from Fang et al. (2001). The following formulas are:

$$\text{BEF} = a + b/V_{\text{total}}, \quad (4)$$

$$B_{\text{total}} = aV_{\text{total}} + b, \quad (5)$$

$$B_{\text{all}} = B_{\text{total}} * A_{\text{total}} = (aV_{\text{total}} + b) * A_{\text{total}}, \quad (6)$$

where B_{all} is the biomass (Mg), B_{total} the biomass per ha (Mg/ha) and V_{total} the volume of a forest type (m^3/ha). The values of a (Mg C/m^3) and b (Mg C) are decided by the age and forest type and the location for each particular forest type.

According to Fang et al. (2007) the calculation of forest canopy density was based on 0.3 before 1994, and forest coverage record was with a canopy density standard of 0.3 before 1994. Since 1994, the definition of forest canopy density is transferred to 0.2. The total carbon should be updated as follows:

$$\text{TC}_{0.2} = 1.122 * \text{TC}_{0.3} + 1.157 \ (R2 = 0.995,\ N = 30), \quad (7)$$

where $\text{TC}_{0.2}$, $\text{TC}_{0.3}$ (Pg C) means the total carbon sink when the canopy is 0.2 and 0.3, respectively.

Economic input–output analysis

International carbon trading schemes exist such as EU ETS (the EU Emissions Trading System: the first international carbon emissions), New South Wales, Chicago Climate exchange, UK Emissions Trading Scheme and so on (Ellerman and Joskow 2008). The EU ETS was introduced as an alternative to a carbon tax with the aim of mitigating CO_2 emissions. It is based on a supply of carbon credits which may be purchased at auctions. Hence, carbon price is determined largely by supply and demand. The global recession since 2008 has reduced industrial production considerably in the EU, while carbon credits offered by governments have remained at pre-recession levels; hence by 2013 the carbon price had collapsed. Many European countries also apply carbon taxes aimed at fossil fuel emissions. Carbon tax was first introduced in Finland and since 1990 Finland's tax is \$30/t and Norway's tax on gasoline equates to \$62/t CO_2. France's proposed tax rate was modeled after prices for CO_2 allowances in the ETS and set at an equivalent of about \$25/t (Sumner et al. 2011). Here, this study uses Finland's value (\$30/t CO_2) and exchange rates (1\$ = 6.15 RMB yuan) on May 13, 2013.

Main afforestation projects in China

Three-Norths Protective Forest Program (Three-Norths, 1978–2050)

The project scope is mainly in the northwest, north and the northeast of China. The main aims are to stabilize land against sandstorms and mitigate serious water and soil loss problems in arid and semi-arid areas by increasing forest coverage (Wang et al. 2010). As the earliest afforestation project in China, it represents a turning point of China's environmental strategy from an era dominated by timber production to an era with a wider perspective on sustainability. The scheme has been planned to span 73 years from 1978 to 2050 when total area afforested will reach 534 million ha and bring the forest coverage in these regions from 5.05 % to 14.95 % (http://baike.baidu.com/view/102256.htm).

Natural Forest Conversion Program (NFCP, 1998–2010)

The NFCP is a nation-wide natural forest protection program, which aims to restrict radical deterioration of the ecological environment and improve socioeconomic sustainable development. This program has been implemented using a combination of policy tools, including technical training and education, land management planning, mandatory conversion of marginal farmlands to forest, resettlement and retraining of forest dwellers, and diversification of private ownership (Zhang et al. 2000). The government input reaches 96.2 billion RMB.

Grain for green (GFG, 1998–2010)

The GFG project is by far the most extensive project in China's forest construction history covering the whole of China. The project was designed to tackle the increasingly aggravated situation of soil erosion in China by paying farmers subsidies to convert their farmland to natural grassland or forest. It has had a positive impact on farmers' income, but more controversial impacts on employment and migration (Chen et al. 2011).The official payment was 220 billion RMB from 1998 to 2008.

Beijing–Tianjin sands and dust engineering (BTSDE, 2000–2012)

Beijing and Tianjin have suffered from spring sandstorms due to grassland degradation and their proximity to the deserts of Northern China. To improve ecological conditions in the sandstorm source region, the BTSDE Program included prohibition of animal grazing by enclosure of grassland; conversion of cropland to forest or grassland; enforced policies on crop rotation; and reforestation/afforestation by aerial seeding (Liu et al. 2013). Until 2008 the input was 41.2 billion (http://www.gov.cn/jrzg/2012-10/07/content_2238556.htm).

Results

Total carbon sequestration from all afforestation projects in China

Figure 1 shows the carbon sequestration from all the afforestation projects calculated by three different models with a normalized forest canopy density of 0.2 (See Methodology). It clearly demonstrates the tremendous increase in stored carbon from 0.12 to 0.37 Pg C in 1981 to 0.78–1.15 Pg C in 2008. The cumulative carbon sink calculated by the IPCC model 2 shows the highest value, while that of the IPCC model 1 is always the smallest. The BCF model modifies this constant biomass to volume ratio into a simple linear relationship via in situ experiments (Fang et al. 2001), while both IPCC models treat biomass to volume ratio as constant. The three models' estimate of total carbon sequestration from afforestation projects in China between 1981 and 2008 averaged 0.23 Pg C until 1981 and about 1.02 Pg C until 2008 with a cumulative rate of 0.028 Pg C/a on average. Afforestation engineering construction is the main reason for the increase of forest carbon sinks and amounts to about 13 % of total forest biomass storage in China (7.8 Pg C) (Li and Lei 2010).

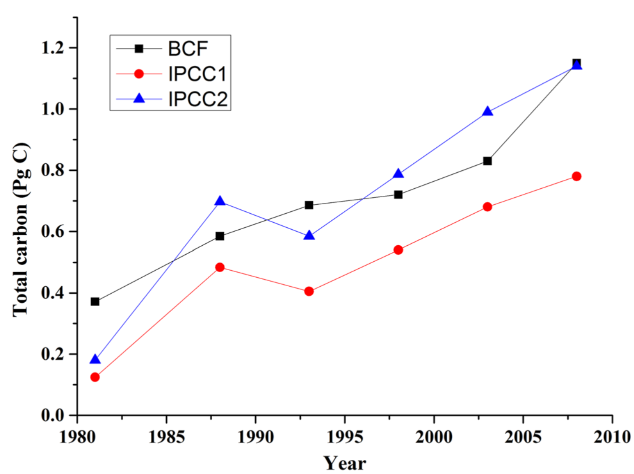

Fig. 1 Carbon storage by Chinese ecological engineering using three models; the result of BCF during 1977–1981, 1984–1988, 1989–1993, 1994–1998 are from (Piao et al. 2009)

Comparison of the results with previous studies

Different models based on different datasets provide different estimates for planted forest carbon sequestration (Table 1). The results from models 1–4 are similar in annual increasing rates, while those of models 8 and 9 are much higher than the others. Both BCS (biomass carbon stocks) and BCF are based on empirical equation between volume and biomass, but BCS uses 3543 statistical plots other than 758 in BCF (Fang et al. 2001). IPCC model 2 takes the age of forest into the calculation. Both models 1 and 5 use the BCF method but with different time series, 1981–2008 and 1949–1998. The total carbon sequestration in planted forest has decreased from 0.45 Pg C (1949–1998) calculated using model 4 by Fang to 0.34 Pg C (1998–2008) calculated from model 1 (Fang et al. 2001). The rate of carbon sequestration increased from 0.009 Pg C/a during 1949–1998 to 0.028 Pg C/a in the last two decades based on BCF. This is because almost all afforestation projects except the Three-Norths Program started from 1998. Satellite-based inventory estimation is based on measured biomass and soil carbon inventories combined with remotely sensed vegetation greenness index (Piao et al. 2009). The FID-based (forest inventory data) model also considers the area and volume by tree species and climate factors (precipitation and the intercepted net radiation) based on a new hyperbolic relationship between stand biomass and volume developed by Zhou and others (Boucher et al. 2012; Zhou et al. 2002).The climatic partition model (used in models 9, Table 1) in contrast does not rely on an inventory, but classes forest as cold temperate, warm temperate, subtropical or tropical (Wu et al. 2008).

Spatial pattern of planted forest carbon sink

Figure 2 illustrates the spatial carbon distribution calculated by models 1–3. Though the total numbers estimated by the models are similar nationally, there are quite large differences at the provincial scale. All three models illustrate that the northern (Inner Mongolia, Heilongjiang, Jilin, Liaoning) and southern (Sichuan, Yunnan, Guizhou, Guangxi, Guangdong, Jiangxi, Jiangsu, Fujian) parts of China are important regions for carbon stock, while the Tibet Autonomous Region, Xinjiang Autonomous Region, Qinghai Province and the middle part of China show less proportion of the national total. The regions with the highest potential are the most extensively forested and in areas associated with traditional forest and hence most suited to growth show larger storage in the models that take into account the age of trees (BCF model and IPCC model 2).

Ecological benefits of afforestation projects in China

The Chinese afforestation engineering could offset carbon emissions to some extent. Based on the industrial carbon emissions data from the Carbon Dioxide Information Analysis Center, Fig. 3 shows that Chinese industrial carbon emissions are increasing rapidly, with a dramatic acceleration after 2004, from 0.36 Pg C/a in 1977 to 1.92 Pg C/a in 2008. Total emissions are 27.35 Pg C and increased with an acceleration of 0.03 Pg C/a before 1997 and then accelerated even faster at 0.13 Pg C/a after 1998. The total carbon benefit from afforestation projects from 1981 to 2008 averaged 0.79 Pg C accounting for only 2 % of total industrial emissions (25.8 Pg C) during the same period, or approximately the industrial carbon emission in China in 2001 (0.95 Pg C). The total investment in afforestation projects in China from 2001 to 2010 is 436 billion RMB (http://www.igsnrr.ac.cn/xwzx/zhxw/200912/t20091221_2711977.html). The total carbon sink value (1.03 Pg C) by the end of 2008 when converted using a rate of $30/t carbon tax from Finland's value is about 190 billion RMB from 1981 to 2008. This is only about 43.4 % of the total investment in afforestation projects.

Table 1 Comparison of carbon storage estimates using different models

	Model	Periods	Total carbon (Pg C)	Annual rates (Pg C/year)	References
1	BCF	1981–2008	0.78	0.028	This study
2	IPCC model 1	1981–2008	0.66	0.024	This study
3	IPCC model 2	1981–2008	0.96	0.034	This study
4	BCS	1981–2008	0.83	0.030	(Zhang et al. 2013)
5	BCF	1949–1998	0.45	0.009	(Fang et al. 2001)
6	Inventory–satellite-based estimation	1982–1993	0.70 ± 0.31	0.058 ± 0.026	(Piao et al. 2009)
7	Inventory–satellite-based estimation	1994–2003	0.92 ± 0.44	0.092 ± 0.044	(Piao et al. 2009)
8	FID-based model	1989–1993	1.41	0.118	(Zhao et al. 2005)
9	Climatic partition	–2010	–	0.115	(Wu et al. 2008)

Zhao and Zhou (2005) only considered four major afforestation forest types

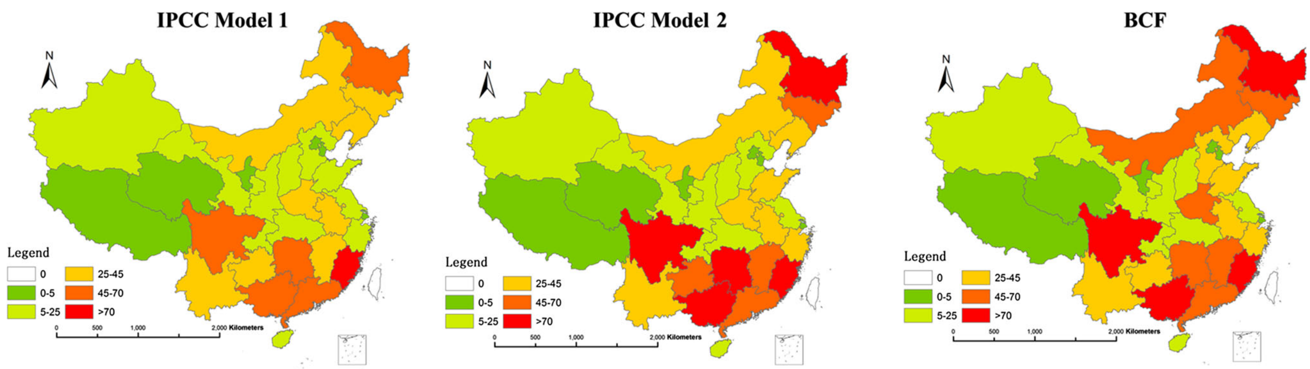

Fig. 2 Spatial distribution of total forest C sequestration based on three models before 2008 in China

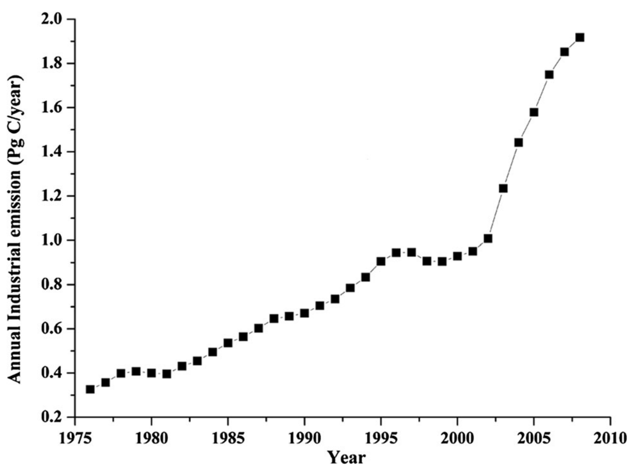

Fig. 3 Inter-annual variations of industrial emissions from China from 1977 to 2008

Discussion

Worldwide deforestation and forest degradation have been considered to be the second largest anthropogenic source of carbon dioxide to the atmosphere after fossil fuel combustion (Montagnini and Nair 2004; van der Werf et al. 2009). The value of forest afforestation in sequestering carbon and reducing carbon dioxide emission to the atmosphere has received increased worldwide attention (Montagnini and Nair 2004). Afforestation and reforestation have been recognized as a carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation (Montagnini and Nair 2004). Concerns have been raised that carbon sequestration in the biosphere is finite and not permanent, difficult to measure and monitor (Post et al. 2009) and related to forest age, forest species, climate division and stand density. This study had applied three comparable statistical models to evaluate the potential afforestation forest carbon storage in the past decades.

Chinese carbon contribution by anthropogenic afforestation amounts to 0.79 Pg C averaged from 1981 to 2008 according to this study. Carbon sequestration in protected areas of Canada (all the national parks including national park reserves and all Saskatchewan Provincial Parks) is 4431.76 Mg C in 2000 (Kulshreshtha et al. 2000). Urban planted trees in the coterminous areas around the USA currently store 0.7 Pg C carbon with a gross carbon sequestration rate of 0.023 Pg C/a based on field data from ten USA cities and national urban tree cover data (Nowak and Crane 2002). Another study in Tarai indicated that forest management carbon benefit is 36.13 Mg C/ha for Populous deltoids, wheat and lemon grass (Yadava 2010). Adopting cropland management practices such as optimization of cropping system and fertilization is another carbon sink as it annually sequesters 26.35 ± 10.22 Tg of carbon dioxide, and may contribute 40 ± 18 % of the global net cropland soil carbon sink (Rice 25 %, wheat 19 % and maize 23 %) for 1961–2100 by the main contributors Asia (49 %), North America (17 %) and Europe (16 %) (Song et al. 2013). The Chinese cropland sink represented approximately 18 % of world's croplands and sequestered 4.39 ± 1.56 Tg/a of carbon dioxide which is more than that of the USA or India (Song et al. 2014).

Different methods will result in different estimates of carbon storage depending on the different surveys applied in different periods. The age of the forest, species grouping considering the parameters, field measurement data and forest data resources may cause discrepancy in the results listed. When using a forest inventory-based BCF method to estimate forest carbon, separating age groups has been reported as potentially creating a 27 % difference in the carbon pool and an 89 % difference in carbon sequestration rate (Ni 2013) and will lead to underestimates of old forest as most of the volume were classified as younger stand (Guo et al. 2010). However, Fig. 1 shows a much smaller range between the three models used here, amounting to a 50 % spread in carbon storage estimates. The relationships between volume and biomass of natural forests and afforestation are not discussed separately by the BCF method (Fang et al. 2001).

In addition, this study only calculates the carbon sequestration of afforestation and reforestation of the forest stand, but neglect the economic trees (rely on by-product except the wood), shrub, bamboo and soil carbon storage. Soil organic carbon storage in China was 93 Pg C in the 1960s and 92 Pg C in the 1980s (Wang et al. 2003). The soil carbon sink after afforestation depends on tree species, planting time, soil texture and climate conditions, and the spatial heterogeneity is difficult to estimate and exhibits more significant regional variations in the forest and grassland sectors (Le Maire et al. 2005; Ni 2013). There is generally a continuous increase of soil carbon for about 40 years after afforestation after a net decrease (8.2–15.0 Tg C/ha) (Paul et al. 2003). Soil carbon after afforestation is much lower compared with plant biomass. Therefore, following the first 15 years after implementation, the role of afforestation engineering in carbon fixation is mainly reflected in the increase in plant biomass, particularly aboveground biomass. Therefore, the actual carbon sequestration from China afforestation projects should be larger than reported here, since the soil carbon benefit, time lag and the other type of trees have not been added in this study.

Conclusions

The afforestation projects were not initially designed as a means of mitigating climate change, and indeed have had more important and immediate local and regional environmental benefits. However, afforestation has been proposed as a feasible way of geoengineering against anthropogenic climate change, especially increasing global temperatures in the twenty-first century (Moore et al. 2010). This study was aimed to get a credible value for the carbon sequestration from globally most significant afforestation projects currently underway—China's large-scale ecological projects. This study shows that the carbon contribution amounts to 0.78–1.14 Pg C (average value is 1.02 Pg C) until 2008. Results from these projects are relatively small on a global scale, but are significant on a regional basis. The main carbon sinks from these projects are located in the south and northeast regions, where most forest is located. The total carbon sink amounts to 2 % of the industrial emission from 1981 to 2008 in China. China has put continuous emphasis on ecological project plans in its 12th five-year plan (2011–2015) and long-term development strategy from 2006 to 2020. The economic value of afforestation project carbon storage depends critically on carbon market mechanisms and a realistic market price for carbon. This can be addressed both domestically via consumption taxes such as Scandinavian gasoline taxes, or through international cooperation such as re-launching of the EU ETS scheme. In future, afforestation projects may play a more important role in mitigating climate change both in China and internationally, though it is conceivable that competition for land between agriculture and forest will limit this. Even geoengineered scenarios of increased terrestrial biomass cannot reverse the atmospheric concentrations to the preindustrial levels until 2100 (Lenton and Vaughan 2009). This fundamental limit on the available surface area suggests that CO_2 mitigation must come overwhelmingly from reduced emissions from fossil fuels.

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