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Perspective

Past and future carbon sequestration benefits of China's grain for green program

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ABSTRACT

Carbon sequestration through ecological restoration programs is an increasingly important option to reduce the rise of atmospheric carbon dioxide concentration. China's Grain for Green Program (GGP) is likely the largest centrally organized land-use change program in human history and yet its carbon sequestration benefit has yet to be systematically assessed. Here we used seven empirical/statistical equations of forest biomass carbon sequestration and five soil carbon change models to estimate the total and decadal carbon sequestration potentials of the GGP during 1999–2050, including changes in four carbon pools: aboveground biomass, roots, forest floor and soil organic carbon. The results showed that the total carbon stock in the GGP-affected areas was 682 Tg C in 2010 and the accumulative carbon sink estimates induced by the GGP would be 1697, 2635, 3438 and 4115 Tg C for 2020, 2030, 2040 and 2050, respectively. Overall, the carbon sequestration capacity of the GGP can offset about 3%–5% of China's annual carbon emissions (calculated using 2010 emissions) and about 1% of the global carbon emissions. Afforestation by the GGP contributed about 25% of biomass carbon sinks in global carbon sequestration in 2000–2010. The results suggest that large-scale ecological restoration programs such as afforestation and reforestation could help to enhance global carbon sinks, which may shed new light on the carbon sequestration benefits of such programs in China and also in other regions.

1. Introduction

Land use and cover change (LUCC) has important effects on regional ecological processes and global climate change (Ficetola et al., 2010). The conversion of natural vegetation to cropland during the past two centuries has contributed greatly to increased atmospheric carbon dioxide (CO_2) concentrations; in contrast, afforestation in cropland and wasteland may lead to carbon (C) sinks (Pan et al., 2011; Deng et al., 2014; Deng and Shangguan, 2017). Thus, afforestation and reforestation have often been proposed as effective strategies for mitigating climate change (UNFCCC, 2005; IPCC, 2007; Heimann and Reichstein, 2008).

Intentional and large-scale afforestation and reforestation projects are considered earth climate engineering works, and actual implementations are rare. China's Grain for Green Program (GGP), started in 1999 and completed in 2010, was a large-scale ecological restoration program with all-embracing purposes ranging from ameliorating regional climate to improving environmental conditions such as by reducing soil erosion (State Forestry Administration (SFA), 2000). The GGP is the largest ecological restoration program in China to date, mainly implemented through LUCC. The GGP involved the conversion of sloped ($> 15°$) and degraded cropland and barren land into forest and grassland with the intent of reducing soil erosion, enhancing biodiversity and conserving natural resources (State Forestry Administration (SFA), 2000). This program was implemented in 25 provinces, municipalities and autonomous regions located in central and western China, accounting for 82% of China's land area (State Forestry Administration (SFA), 2012). At its completion in 2010, the GGP had converted 34.4 million ha of degraded cropland and barren land into forestland or grassland. About 9.2 million ha of cropland

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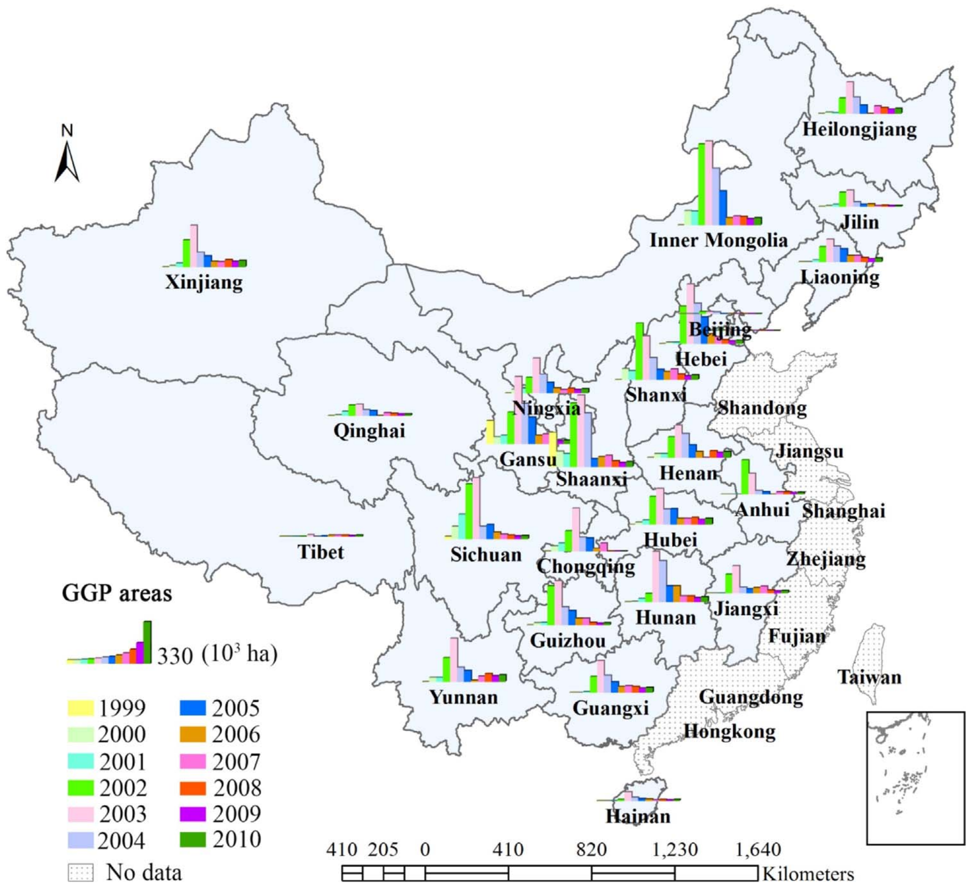

Fig. 1. Converted area (10^3 ha) under the GGP in each province per year during 1999–2010. The vertical axis in the bar graphs indicates the converted area per year, and the value (330) on the right of the bar graph in the legend represents the scale of the Y-axis in the bar graphs within the figure.

unsuitable for cropping was converted to forestland or grassland, and trees planted on 25.2 million ha of barren land deemed suitable for afforestation (State Forestry Administration (SFA), 2011; Fig. 1, Appendix Excel S1).

As China continues its rapid development, dealing with its massive and growing greenhouse gas emissions (representing 25.5% of the global total in 2011) will be vital in the context of global climate change (Dai, 2014). Consequently, the international community pays close attention to the C sequestration capacity of forests in China. The large-scale LUCC under China's GGP resulted in a large amount of new forestland, contributing to its first rank in plantation area in the world with growing forest cover (The World Bank, 2010) and its C sequestration capacity (Deng et al., 2014). Although hundreds of papers have been published reporting field observations of soil C stock change (Chang et al., 2011; Deng et al., 2014) or forest stand C stock change (Chen et al., 2009; Cheng et al., 2015; Deng et al., 2017) after afforestation or reforestation at the local scale, to our knowledge, few studies have attempted to assess the overall C sequestration benefits of China's GGP (Persson et al., 2013; Liu et al., 2014).

Given the large area affected by the GGP and lack of information on similar projects elsewhere, a comprehensive investigation of GGP effects on C sequestration would be very valuable. The results could shed light on the C sequestration benefits of large-scale ecological restoration programs, a critical knowledge gap not only for China but also for other regions. In this study, we used seven forest biomass C sequestration models and five soil C change models to estimate the trajectories of C stock change in biomass and soil in areas affected by the GGP. The study seeks to answer two fundamental questions: how much C can be sequestrated under the GGP during 1999–2050 and is the C sequestration potential significant compared to national total C emissions?

2. Materials and methods

2.1. Delimitations

Estimating the C sequestration under the GGP required several delimitations:

(i) No rotation. Because the GGP goal of preventing soil erosion on marginal lands was accomplished by increasing vegetation cover, we assumed that the trees were allowed to grow for more than 50 years without harvesting, which would yield a measurable stock of C in standing trees.

(ii) Grassland not included. The total area of land converted into grassland during 2002–2009 was 638,761 ha; in relation to the area converted into forestland this is about 3% (State Forestry Administration (SFA), 2011). Because the converted areas in 1999, 2000 and 2001 were not available and the area converted to grassland was marginal compared to conversion to forestland, grassland was not included in this study.

(iii) Survival rate. The GGP mainly afforested barren hills and croplands with a slope gradient > 15°, of which the soil was relatively poor and soil moisture was low, meaning the afforestation survival rates were unlikely to reach 100%. Thus, a correction factor of the actual afforestation survival rate was introduced. China's State Forestry Administration (SFA) survey showed that the afforestation survival rate was only 90.2% (State Forestry Administration (SFA), 2005). Thus, the actual planted areas are the cited afforestation areas multiplied by a correction factor of 0.902.

(iv) Time frame. Because the GGP came to an end in 2010, the study estimates the future potential of GGP forests as C sinks assuming that the forest areas remain unchanged and the Chinese Government does not fell the forests during the study timeframe of

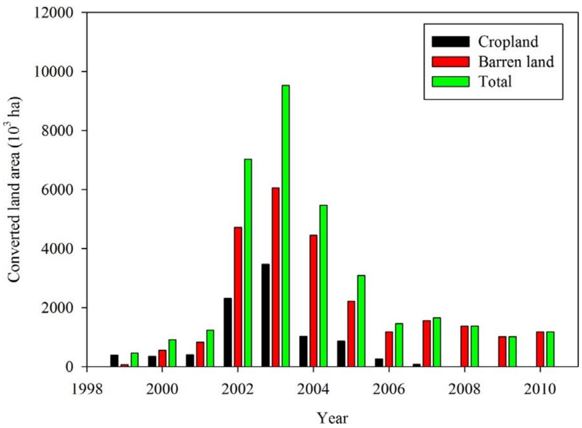

Fig. 2. Converted area under the GGP during 1999–2010 in China.

1999–2050.

(v) C sequestration baseline. The GGP was initiated with an aim to control soil erosion by restoring forest on degraded land, thus it was mainly carried out at sites with degraded soil. Due to the targeted soils' degraded character, given high erosion and unsustainable agriculture, the C sequestration was assumed to be zero (Persson et al., 2013).

2.2. Sources of the total area of GGP implementation

The area of cropland and barren land converted to forestland during 1999–2010 was collected from the China Forestry Statistical Yearbook (State Forestry Administration (SFA), 2010), in which the converted areas were presented per province and per year. In addition, the area of both cropland and barren land converted to forestland under the auspices of the GGP for 2009 and 2010 is cited in the China Forestry Development Bulletin (State Forestry Administration (SFA), 2012). These data include both the cropland and barren land converted to forestland in China (Appendix Excel S1). The annual area under the GGP during 1999–2010 is presented in Fig. 2.

2.3. C stock estimations

2.3.1. C pools in a forest ecosystem

The C in a forest ecosystem is divided into three C pools: tree biomass (aboveground and root biomass), forest floor litter and soil organic C (Niu and Duiker, 2006). The selection of three C pools is in accordance with the simulation models employed in this study.

2.3.2. Total C stocks

The total C stock for the different regions, i.e. provinces, is calculated according to Eq. (1) (State Forestry Administration (SFA), 2012):

$$C_{Total} = \sum_{j}\left[\sum_{i}(A_{ij} \times C_j \times (Y - i))\right] \tag{1}$$

where, $A_{i,j}$ is the converted area (ha) for a region j in year i; Y is the year the study was conducted, i.e. 2010, thus trees planted in year $i = 2009$ have been growing for 1 year; and C_j is the C increment per hectare and year (Mg C ha^{-1} yr^{-1}) fitted for the climate conditions of each for region j.

2.3.3. C increment

(1) Tree biomass C increment

Furthermore, a measurement of the C increment fitted to the conditions in each region was needed, i.e. Cj in Eq. (1). Four different types of Cj values were used: (i) from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Supplementary information, Word S1); (ii) net C uptake (NCU) for different forest types and climates in China compiled from scientific articles (Supplementary information, Word S2); (iii) mean annual increment (MAI) (Supplementary information, Word S3); and (iv) empirical growth curves of plantations.

Two of the NCU values were derived from China-specific studies (Ni, 2003; Fang et al., 2007) and one was the global average (Vorosmarty and Schloss, 1993). IPCC default values, i.e. in the lower accuracy level of Tier 1, were used for natural and managed forest (IPCC, 2007). MAI values are primarily derived from a national assessment (Xu et al., 2001) or, when missing, a global value of 1.6 Mg C ha^{-1} yr^{-1} (Sathaye et al., 2001) was used. The empirical growth curves of plantations were adapted from Xu et al. (2010) (Appendix Excel S2).

For the method of empirical growth curve of plantations, the C stock for various forest vegetation types was estimated by multiplying their biomasses with their corresponding C fractions (C_{Fi}) (Appendix Excel S3). The formula for the estimation of C stocks of forest biomasses follows:

$$C_{Bi} = \sum_{j}\left[\sum_{k}(A_{ijk} \times B_{ijk} \times C_{Fj})\right] \tag{2}$$

where, C_{Bi} is C stocks in living tree biomass (Mg) in year i, A_{ijk} is the area (ha) of species j planted or to be planted in year k, B_{ijk} is stand biomass per hectare (Mg ha^{-1}) of species j planted in year k in year i and C_{Fj} is the C fraction of species j.

The planting area of each tree species/forest type was estimated using the regional GGP's total area multiplied by the afforestation proportion of each tree species/forest type in every region. The data of each tree species/forest type afforestation proportion were derived from the GGP investigation report for each region, the government's forestry development announcement and related published literature (Appendix Excel S4).

(2) Forest floor litter

A modified model according to Niu and Duiker (2006) was employed to simulate the change of C in the forest floor following afforestation (Supplementary information, Word S4). The patterns of forest floor accumulation for "permanent" afforestation were extracted by digitizing graphs using the GetData Graph Digitizer (Version 2.24, Russian Federation). Then we fitted an exponential regression equation of net forest-floor C accumulation following conversion of agricultural land to "permanent" forestland. The equation follows (Supplementary information, Word S4):

$$C_{FFCi} = 24.78 \times [1 - \exp(-0.0254 \times Age_i)],\ R^2 = 0.99,\ P < 0.0001 \tag{3}$$

where, C_{FFCi} is C in the forest floor (Mg C ha^{-1}) following afforestation in year i and Age_i is the year the study was conducted.

(3) Soil C sequestration

Previous studies reported that soil organic C changes not only occurred in top soil layers (< 20 cm) but also in 0–100 cm following afforestation (Li et al., 2012; Deng et al., 2014). Thus, soil C pools in the 0–100 cm of soils were considered in this study.

Based on forest growth simulation models and a review of the literature, the rate of soil C change was estimated using five different models: (i) of Zhang et al. (2010); (ii) of Deng et al. (2014); (iii) of Zhao et al. (2013); (iv) of Niu and Duiker (2006); and (v) of Li et al. (2012) as the global average (Supplementary information, Word S5–S9).

Three of the soil C change values were derived from China-specific studies (Zhang et al., 2010; Zhao et al., 2013; Deng et al., 2014) and one used a Midwestern U.S. study (Niu and Duiker, 2006) modified by a global average value (Paul et al., 2003) which had similar marginal agricultural land to China's GGP. For the studies of Zhang et al. (2010), Zhao et al. (2013) and Niu and Duiker (2006), which only reported the results of soil C change rates in the top 20 and 30 cm of soils, we hypothesized that the SOC change examined in the upper 20 cm was equal to that for the whole upper 30 cm layer, and soil depth was the only determining factor to effect the size of soil C stock/sequestration. Based on the top 30 cm of soil C stock/sequestration we estimated the top 20 cm of soil C stock/sequestration by multiplying by a fixed coefficient of 0.67. In addition, we used the relationship between 0 and 100 and 0–20 cm soil C sequestrations (C_{se}) following cropland conversion developed by Deng et al. (2014) to estimate the 0–100 cm of soil C change rate according to the 0–20 cm of soil C change rate under the GGP. The equation was as follows:

$$C_{se\ (0\text{–}100\ \text{cm})} = 2.46 \times C_{se\ (0\text{–}20\ \text{cm})} + 0.01, R^2 = 0.95, P < 0.0001 \quad (4)$$

3. Results

3.1. Forest biomass C sequestration dynamics

Different methods generated different C sequestration trajectories and total C in forest biomass (Table 1). Of the seven methods, the highest estimate was for the IPCC method and the lowest were for the NCU method before 2030 and the empirical growth curve method after 2030. For the entire GGP area, the mean total forest biomass C stocks were estimated to be 527 ± 47 (mean ± standard error, hereafter), 1183 ± 113, 1798 ± 189, 2381 ± 274 and 2944 ± 363 Tg for 2010, 2020, 2030, 2040 and 2050, respectively (Table 1); and corresponding annual C sequestrations were 68 ± 7, 64 ± 8, 60 ± 9, 57 ± 9 and 56 ± 9 Tg (Table 1).

3.2. Soil C sequestration dynamics

Of the five methods used to estimate soil C sequestration, the Zhao method generated the highest estimate throughout the entire period and the Deng and the Li methods gave the lowest values before and after 2015, respectively. The mean soil C stocks were estimated to be 155 ± 184, 513 ± 219, 837 ± 242, 1056 ± 265 and 1171 ± 266 Tg by 2010, 2020, 2030, 2040 and 2050, respectively (Table 2); and corresponding annual soil C sequestrations were 33 ± 20, 36 ± 13, 31 ± 13, 18 ± 2 and 9 ± 3 Tg (Table 2).

3.3. Total ecosystem C sequestration dynamics

The total ecosystem C stock (i.e. the sum of total forest biomass, forest floor and soil) were estimated to be 682, 1697, 2635, 3438 and 4115 Tg in 2010, 2020, 2030, 2040 and 2050, respectively (Fig. 3A). Due to the GGP-covered regions continually expanding during 1999–2010, the GGP's C sequestrations increased significantly during this period. Our results showed that the annual C stock change of GGP-stands was a maximum at 2010. The results showed the mean annual ecosystem C sequestrations were 102, 99, 90, 75 and 64 Tg for 2010, 2020, 2030, 2040 and 2050, respectively (Fig. 3B). The proportion of soil C sequestration accounting for the total C sequestration in the forest ecosystem increased from 23% to 32% (Fig. 3), and the proportion of annual soil C sequestration to forest biomass annual C sequestration decreased from 49% to 16% during 2010–2050 (Fig. 4). Overall, the proportion of annual soil C sequestration in the total annual C sequestration decreased following the GGP development and, in contrast, the proportion of annual C sequestration of forest biomass increased over time (Fig. 4).

4. Discussion

4.1. C sink contributions of GGP

China's forestry policies and programs not only play an important role in improving the country's ecological environment, but also modify its C sequestration capacity. With the 2005 Kyoto protocol entering into force, many countries initiated research into the relationship between forest management and C sequestration (Nabuurs et al., 2000). The estimated forest ecosystem C stocks indicated that upon completion of the GGP in 2010, the mean total C sequestration was 682 Tg, equivalent to 31% of the country's total C emissions in 2010 (calculated as 2200 Tg in the Durban Conference). According to this scenario, the GGP's annual total C sequestration (102 Tg) would offset about 5% of China's total C emissions during this period (i.e. 2010). Moreover, based on the global C emission data of 10,000 Tg worldwide in 2010 (Friedkingstein et al., 2011), we estimated that the GGP's annual total C sequestrations offset

Table 1
Net forest biomass C sequestration values following afforestation under the GGP in each year of 2010–2050. Note: EGC, method of empirical growth curves (Xu et al., 2010); IPCC plantations indicates estimation used by the C increment of IPCC values for plantations, and IPCC natural forest indicates estimation used by the C increment of IPCC values for natural forest (Supplementary information, Word S1); results of Ni (2003), Fang et al. (2007) and Vorosmarty and Schloss (1993) were used in the Net Primary Productivity (NPP) method (Supplementary information, Word S2); MAI, the results of the mean annual C increment method were used (Supplementary information, Word S3); Mean indicates the mean values of the seven methods above; and SE is standard error. The data in the figure included the C sequestrations for the forest floor.

	Carbon stocks estimation methods	Year				
		2010	2020	2030	2040	2050
Carbon sequestration (Tg)	EGC (Xu et al., 2010)	575	1048	1372	1593	1756
	IPCC Plantations (IPCC, 2007)	772	1812	2827	3824	4805
	IPCC Natural forest (IPCC, 2007)	568	1320	2047	2756	3450
	Ni et al. (2003)	453	1049	1620	2172	2710
	Fang et al. (2007)	421	974	1502	2011	2505
	Vorosmarty and Schloss (1993)	470	1088	1682	2257	2817
	MAI (Xu et al., 2001)	432	997	1538	2059	2566
	Mean ± *SE*	527 ± 47	1184 ± 113	1798 ± 189	2382 ± 274	2944 ± 363
Annual carbon sequestration rate (Tg yr^{-1})	EGC (Xu et al., 2010)	57	40	27	19	15
	IPCC Plantations (IPCC, 2007)	106	103	101	99	98
	IPCC Natural forest (IPCC, 2007)	77	74	72	70	69
	Ni et al. (2003)	61	58	56	54	53
	Fang et al. (2007)	57	54	52	50	49
	Vorosmarty and Schloss (1993)	63	61	58	57	55
	MAI (Xu et al., 2001)	58	55	53	51	50
	Mean ± *SE*	68 ± 7	64 ± 8	60 ± 9	57 ± 9	56 ± 9

Table 2
Net soil C sequestration values following afforestation under the GGP in each year of 2010–2050. Note: results of Zhang et al. (2010), Deng et al. (2014), Zhao et al. (2013), Niu and Duiker (2006) and Li et al. (2012) were used for the rate of soil C change (Supplementary information, Word S5–S9); Mean indicates the mean values of the seven methods above; and SE is standard error.

	Carbon stocks estimation methods	Year				
		2010	2020	2030	2040	2050
Carbon sequestration (Tg)	Zhang et al. (2010)	90	406	694	875	1016
	Deng et al. (2014)	−294	347	1191	1619	1697
	Zhao et al. (2013)	812	1351	1551	1704	1858
	Niu and Duiker (2006)	202	409	591	772	841
	Li et al. (2012)	−33	54	160	312	444
	Mean ± SE	155 ± 184	513 ± 219	837 ± 242	1056 ± 265	1171 ± 266
Annual carbon sequestration rate (Tg yr^{-1})	Zhang et al. (2010)	28	30	28	14	14
	Deng et al. (2014)	7	85	82	26	0
	Zhao et al. (2013)	108	31	15	15	15
	Niu and Duiker (2006)	27	18	18	17	3
	Li et al. (2012)	−4	14	10	17	12
	Mean ± SE	33 ± 20	36 ± 13	31 ± 13	18 ± 2	9 ± 3

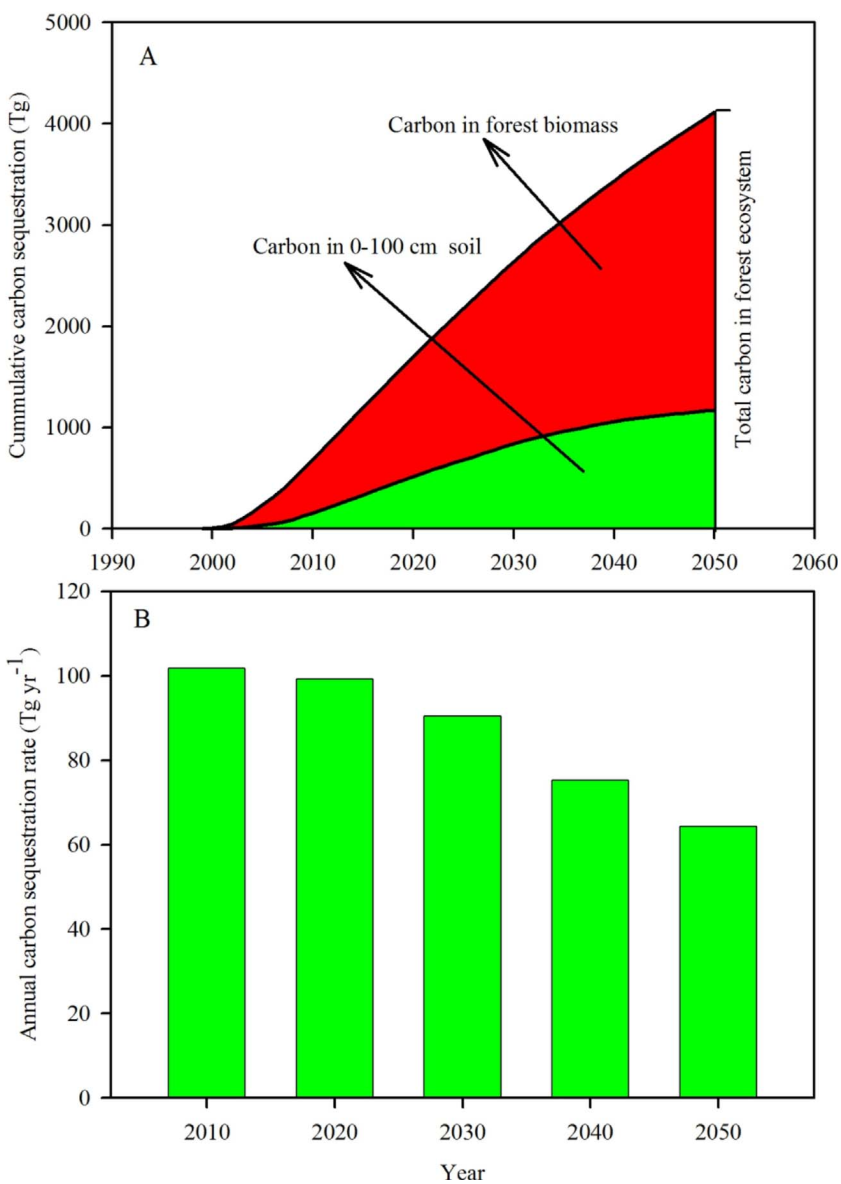

Fig. 3. Estimated net cumulative C sequestration (A) and annual total C sequestration rate (B) in the forest ecosystem (forest biomass and soil) following afforestation under the GGP for 2010–2050. Mean values were estimated using seven forest biomass estimation methods for C in forest biomass and five rates of soil C change methods. Forest biomass C includes tree biomass and forest floor C.

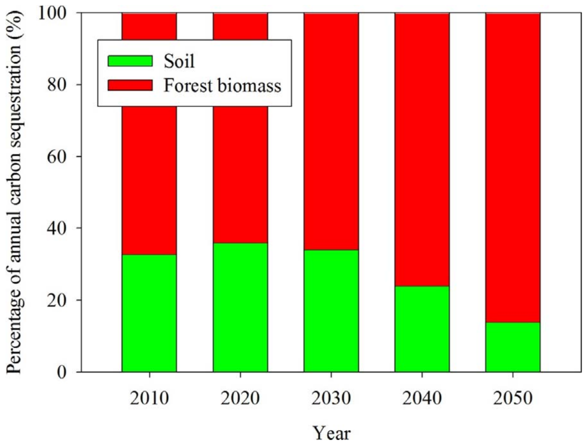

Fig. 4. The percentage of annual C sequestration rates of soil and forest biomasses accounting for the annual total C sequestration in the forest ecosystem under the GGP.

about 1% of the global C emissions. In addition, Fang et al. (2009) predicted that the China's C emissions will grow to 2400–3300 Tg in 2050, and Ding et al. (2009) predicted the value in 2050 to be 2380 Tg if atmospheric CO_2 concentrations remained below the target concentration of 470 ppm. In our study, we estimated that the accumulative C sequestration of forest biomass in China's GGP forests would reach 2944 ± 711 Tg in 2050. Thus, the fixed C in China's GGP forest biomass will approximately equal the total projected C emissions (2380–3300 Tg) (Ding et al., 2009; Fang et al., 2009) for the entire country in 2050. According to the aforementioned scenarios, the annual total C sequestration in GGP forests in 2050 (64 Tg) would offset about 2%–3% of China's annual C emissions in the same year. Fang et al. (2009) reported that the most likely trajectory of China's future C emissions, during 2006–2050, to be in the range of 102–156 Pg (1 Pg = 10^3 Tg). In this scenario, the accumulative country-wide C sequestration (4115 Tg) under the GGP forests would offset about 3%–4% of the C emissions during the same period. The results of this study show that the GGP has high C sequestration potential. Moreover, using remote-sensing data, Zomer et al. (2016) showed that in 2010, 43% of all cropland globally had at least 10% forest cover and had increased by 2% over the previous 10 years. Globally forest converted from cropland increased by 2070 Tg of biomass C during 2000–2010 (Zomer et al., 2016). In our study, we estimated that for China's forest the GGP had sequestrated 527 Tg biomass C during 2000–2010. Thus, we estimated that GGP afforestation contributed about 25% of biomass C sinks in global C sequestration in 2000–2010, indicating that China's GGP could be an effective and feasible approach for climate stabilization.

Results of the GGP's C stocks and potentials have been reported. Liu et al. (2014) used a process-based ecosystem model (i.e. IBIS, integrated biosphere simulator) to assess the magnitude of C sequestration and showed that the GGP could sequester 217.25 Tg C by 2020 and 397.95 Tg C by 2050, for forests converted from cropland. The values were significantly lower than those in our study, for which corresponding values were 1183 and 2944 Tg (Table 1). The different methods used to estimate tree biomass C sequestration may be the main reason for the large differences between these two estimates. Our inclusion of forest floor C sequestrations in forest biomass C sequestrations may also have resulted in the larger estimates in our study. Persson et al. (2013) estimated the overall C sequestration by the GGP for 1999–2008 at the national scale using official statistics and three approaches similar to the methods of estimation used in our study, based on (i) IPCC's greenhouse gas inventory guidelines, (ii) NPP and (iii) MAI (Supplementary information, Word S1–S3). However, this only included tree biomass C sequestration and not the forest floor C pool. Persson et al. (2013) found that the GGP sequestered 222–468 Tg C over its first 10 years, which was generally similar to our results for 1999–2008 (Table 1).

The soil C pool is a major C reservoir, and the GGP activities significantly changed its magnitude (Liu et al., 2014). Our results showed that soil C sequestration significantly increased following the GGP development, and mean soil C sequestration was estimated at 513 and 1171 Tg by 2020 and 2050, respectively (Table 2). However, the simulations of Liu et al. (2014) showed that net soil C accumulation did not occur for ~50 years after the GGP implementation, and decreased by 22.17 Tg in 2050, which was much lower than our results due to different methods of estimation. Generally, soil C stock decrease is temporary and in the long-term the soil C accumulates with age (Paul et al., 2002; Karhu et al., 2011). Similar to the findings of Paul et al. (2002), another study based on a field survey database also indicated that soil C accumulation commenced > 10 years after cropland conversion for the whole GGP, and tended to stabilize after cropland had been converted for 30 years (Deng et al., 2014). Thus, results from simulation models may not correspond with reality, and so using multiple methods to estimate soil C is more reliable.

4.2. Limitations and suggestions for further studies

Many factors, including the calculation methods for C sequestration, biomass growth values and SOC dynamics, introduced uncertainty into the results. The main potential sources of uncertainty are discussed in what follows.

(1) Uncertainty in biomass growth values

The IPCC (2006) considered their method valid both for natural regeneration and plantations, meaning that our results obtained using the IPCC method should be valid. The IPCC's values are widely used for estimating C inventories because their method is simple and applicable for anyone who has little data (IPCC, 2006) but does have some shortcomings. The IPCC's method assumes that aboveground biomass growth (AGBG) accumulates linearly until half of the maximum yield (Supplementary information, Word S1). Using this assumption it is possible to apply linear growth (i.e. constant AGBG) in the model, which may overestimate the C sequestration. In addition, using NCU and MAI (Supplementary information, Word S2 and S3) in China for different forest types and climates has similar problems. The growth curves of forest volume (biomass) play a crucial role in estimating C stocks in living tree biomass (Chen et al., 2009). Our study adopted allometric growth equations of stand volumes (forest biomass) suitable for local Chinese plantation tree species/forest types to estimate forest volume. No allometric growth equations have yet been developed for individual species, but some empirical curves can represent main tree species/forest types. Dependent on those available, empirical curves can be matched with only a few tree species/forest types (Table 1) and approximate alternatives are available for other tree species/forest types. To improve model prediction precision, it will be necessary to further develop forest volume growth models for various local tree species/forest types with forest age in the future.

(2) Uncertainty in soil organic C dynamics

Previous studies have found various temporal patterns for soil C stock following cropland conversion to forest under the GGP (Zhang et al., 2010; Deng et al., 2014). For example, Deng et al. (2014) reported soil C stocks initially decreased after afforestation (< 10 years), followed by an increase due to vegetation restoration, but Zhao et al. (2013) reported that soil C stocks increased after afforestation in the GGP zone. However, the derived patterns were not very clear, as different study scales were combined with large differences among soil depths used for temporal C stock changes. Generally, previous studies used only one set of soil C stock change data to estimate soil C sequestration dynamics of the GGP. For example, Chen et al. (2009)

adopted the soil C sequestration rates of Niu and Duiker (2006) to estimate soil C sequestration and potential in the GGP of Yunnan Province, China; whereas Wang et al. (2017) used the soil C sequestration rates of Deng et al. (2014) to perform the same estimates for Henan Province. The different sampling sites used to estimate soil C sequestration rates among studies (Zhang et al., 2010; Zhao et al., 2013; Deng et al., 2014), and the use of different estimation methods for soil C sequestration rate, have led to diverse estimates for soil C sequestration rates. In addition, due to the assumption that some forest management practices were adopted, such as planting groundcover crops/grass between trees and minimizing soil disturbance, Niu and Duiker (2006) reported that soil C stock increased in the first decade after afforestation. However, forest management practices have not always been implemented in the GGP zone. This implies that the use of different values of soil C stock changes to predict the mean soil C sequestration dynamics under the GGP should be reliable in our case.

(3) Uncertainty in calculations of C sequestrated

Depending on the biomass growth rate used in the model, the amount of C sequestered ranged from 421 Tg, using the NPP values of Fang et al. (2007), to 772 Tg using IPCC values for planted forests in 2010–a difference of 83% between the most conservative and the most optimistic growth rates. Additionally, due to the restrictions of a diverse climate, regional or local site conditions and their subsequent management practices, both the growth curves and the values of soil C change rates adopted in this study may result in larger estimates for poor site conditions and lower estimates for good site conditions (Chen et al., 2009). On the whole, it is feasible to forecast forest ecosystem C stock following the GGP implementation based on multiple growth curves and soil C change rates, given that specific growth curves and soil C change rates for different site conditions are unavailable. Moreover, we also considered C sequestration in the forest floor (litter) after afforestation. This is the first study to attempt to assess the overall (i.e. forest biomass, forest floor and soil) C sequestration benefits of GGP. The projected result should more closely approximate reality by using multiple methods to estimate C sequestration compared with other reports using a single method (e.g. Chen et al., 2009; Liu et al., 2014).

Making the estimates more accurate would entail collecting province-specific data regarding the tree species planted, biomass growth rate and soil C sequestration rates, because biomass growth and soil C sequestration dynamics are strongly dependent on local factors such as climate, tree species, soil quality, irrigation and fertilization (Persson et al., 2013). Another way to obtain more accurate estimates would be to improve spatial resolution of statistical datasets by dividing the GGP area into smaller areas of homogenous environmental conditions because the province-scale is very coarse. Doing so would yield better approximations of forest biomass growth and soil C sequestration rates, which are related to environmental conditions. Chen et al. (2015) have used remote-sensing image data to quantify the status of land-use conversions before and after the GGP, however, the image classification scheme did not include sparse forest, sparse shrub or sparse grass, although these data were included in governmental statistics (Chen et al., 2015). Moreover, the delay in identifying the newly forested areas using remote sensing is due to the large uncertainties characteristic of newly forested areas, particularly for forests younger than 5 years old (Chen et al., 2015). Further studies should be conducted to improve the estimates using meteorology datasets of higher resolution.

Our study did not include the impact of anthropogenic management in the estimations, which may cause some uncertainties (Liu et al., 2014), and this should be considered in future studies. Forest disturbances, such as harvesting, fires and insect outbreaks were not integrated into the estimations. On average, only 0.62% of newly planted forests are used for timber production and firewood annually (State Forestry Administration (SFA), 2012). The ratio of harvested forests to the new planted forests is very low. There are no direct observations from the GGP program concerning fire disturbances, forest diseases and insect outbreaks (Liu et al., 2014); however, the annual forest area experiencing these perturbations is about 3.36% of the national forest area (State Forestry Administration (SFA), 2012). Thus, we assumed negligible effects of harvest and disturbance (∼4%) for the current phase of the GGP.

4.3. Insights of afforestation efforts

Our estimations showed that the accumulative C sink induced by the GGP changed from 682 to 4115 Tg C during 2010–2050, indicating a considerable contribution to China's C sink over the coming decades from the GGP. In addition to the ecological benefits, the economic benefits of the GGP program are considerable, ranging from $18.93 billion to $94.65 billion for 2000–2050, based on a C price of $4.60–$23.00 per Mg C (Liu et al., 2014). This may exceed the current total investment in the program of $38.99 billion (State Forestry Administration (SFA), 2012). Moreover, afforestation could lead to substantial economic values of other ecosystem services, such as tourism, biodiversity, soil and water conservation, and pollution reduction (Liu et al., 2008). The ecological and socioeconomic effects of China's GGP on ecosystem services show that implementing such ecological restoration projects is a very feasible measure relative to other C sequestration programs.

In our calculation of the C stock, we assumed that the planted trees were not harvested under the GGP. However, it is possible that trees planted under the GGP will be harvested although they are not generally commercial species. According to the Technical Regulations for the Ecological Service Forest (Wang, 2003), these trees can be harvested until they are over-mature. A next step should be considering harvesting scenarios in estimations of long-term C sequestration potential under the GGP. Some studies have reported that the GGP may reduce cultivated land resources and food security (Feng et al., 2005; Xu et al., 2006). Thus, if there was no reasonable mechanism to ensure that farmers continue to increase their income and maintain their living standards, the GGP may introduce the risk of land reversion in rural regions (Chen et al., 2016). So, to ensure the effectiveness of the GGP policy, it appears imperative to improve the use of abandoned farmland or under-utilized land. Local governments must play a key role in crafting appropriate land-use plans and guiding farmers to develop suitable land release and rotation mechanisms at regional and local (especially county and township) levels, and in liaising with local communities and government departments to manage land use effectively and productively (Chen et al., 2016). Only in this way can long-term implementation of the GGP be guaranteed, and so further contribute to the GGP's C sequestration capacity. In addition, the calculations were made without any consideration that whatever forest C gains the Chinese program contributes to the global C account (or any afforestation program for that matter) are offset by forest C imports into China. Simply because countries increase forest area or biomass does not mean that they have reduced demand for forest-based products and deforestation could occur somewhere else. If such deforestation is considered, then the total C impact of the afforestation program is reduced in a global sense. So, to predict the C potential under the afforestation efforts on a large temporal scale, further studies are necessary concerning the balance of C pools between afforestation and deforestation, and any lack of such data may lead to underestimating of the C stock.

5. Conclusions

Afforestation establishment on degraded land has been proposed as an effective method for mitigating climate change in terrestrial ecosystems. Large-scale ecological restoration programs such as afforestation are presumed to be effective vehicles to mitigate climate change; however, few studies have focused on C sequestration of large-scale programs. China's GGP is one such program that was originally intended to be all-embracing – from ameliorating regional climate to improving environmental and socioeconomic conditions. To date, no studies have assessed the overall C sequestration benefits of the GGP. Our results showed that the total C stock in the GGP-affected areas was 682 Tg C in 2010 and the accumulative C sink estimates induced by the GGP would be 1697, 2635, 3438 and 4115 Tg C for 2020, 2030, 2040 and 2050, respectively. Overall, the C sequestration capacity of the GGP can offset about 3%–5% of China's annual C emissions (calculated using 2010 emissions) and about 1% of global C emissions. Afforestation in China's GGP contributed about 25% of the biomass C sinks in the global C sequestration during 2000–2010. The results suggest that large-scale ecological restoration programs such as afforestation and reforestation could help to enhance global C sinks, which can shed new light on their C sequestration benefits in China as well as other regions.

Author contributions

L.D., S.L. and Z.S. designed research and collected data; L.D. performed research; S.L. contributed new reagents/analytic tools; L.D., S.L., and Z.S. analyzed data; and L.D., S.L., D.K., C.P., S.S. and Z.S. wrote the paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2017.09.006.

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