Carbon sequestration potential of the stands under the Grain for Green Program in Yunnan Province, China

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ABSTRACT

The carbon sequestration potential in living biomass and soil organic matter under the Grain for Green Program (GGP) in Yunnan Province, one of the most important target provinces of the GGP in China, was estimated in this paper using empirical curves and factors. The area of tree species planted during 2000–2007 was collected, and four scenarios for the annual area of GGP-stands to be planted during 2008–2010 and harvest options were schemed. Empirical growth curves for different tree species were developed based on data about the growth of existing plantation in Yunnan Province from National Forestry Inventory, and were used for the estimation of the carbon stocks in the tree biomass pools by incorporating with basic wood density, biomass expansion factors and carbon fraction. Empirical factors were introduced to estimate the stock change in soil organic carbon (SOC) under the GGP. The results show that the carbon stock in the GGP-stands in Yunnan Province will increase by 12.474–12.608 TgC, 33.016–35.161 TgC, 38.119–47.100 TgC, 43.057–53.626 TgC and 49.918–56.621 by the year 2010, 2020, 2030, 2040 and 2050, respectively. The annual carbon stock change in the GGP-stands will peak at 2.342–2.536 TgC per year in 2013, followed by a gradual decrease. The estimated potential carbon sequestration by GGP-stands amounts to 10.82–12.27% of the carbon stocks of forest ecosystems in Yunnan province in the 1990s.

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1. Introduction

With an increasing concern for global climate changes resulting from more and more anthropogenic greenhouse gas, protecting carbon stocks in the existing forests and getting the new carbon stocks through afforestation and reforestation have become the important measures to enhance the carbon sequestration capacity in the terrestrial ecosystems and mitigate the increasing carbon dioxide concentration in the atmosphere. The Grain for Green Program (GGP) was initiated in China in 1999, with an aim to control soil erosion and combat desertification by restoring forest vegetation on degraded/decertified barren land and cropland with slope

gradient over 25°. 32 million hectares (Mha) of lands, including 14.67 Mha of croplands and 17.33 Mha of barren lands, were planned to be planted under the GGP during the period of 1999–2010. 24,243,468 ha of lands, involving 9,264,135 ha of croplands and 14,979,333 ha of barren lands, had been planted by the end of the year 2007 (Fig. 1) (refer to the Annual Reports on the Development of Chinese Forestry (1999–2007) edited by State Forestry Administration, PR China). It is expected that 7,756,532 ha of lands involving 5,402,532 ha of eligible croplands and 2,354,000 ha of barren lands will be planted by the year 2010 (RGCFSDS, 2002). Located in the southwest corner of China, Yunnan Province is one of the most important provinces under the GGP. After a pilot phase (2000–2001), the GGP has been implemented almost throughout Yunnan Province involving 126 counties. By the end of the year 2007, 943,125 ha of lands has been planted under GGP including 355,556 ha of eligible croplands and 587,569 ha of barren lands (Table 1 and Fig. 2) (refer to the Annual Provincial Verification

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Fig. 1. Planted area under the Grain for Green Program in China.

Fig. 2. Planted area under the Grain for Green Program in Yunnan Province.

Reports on Grain for Green Program in Yunnan (2000–2007) edited by Yunnan Provincial Forestry Department, PR China). It accounts for 3.89% of the national GGP-lands (3.84% of eligible croplands and 3.92% of barren lands under the GGP respectively) (Chen, 2002; Li, 2004).

The large scale of afforestation under the GGP will establish a large amount of new forest vegetation to enhance carbon sequestration capacity in terrestrial ecosystems in China. So far a lot of studies have touched upon the carbon stocks as well as their changes in one or more parts of the forest ecosystems in the world or some countries or regions (Grigal and Ohmann, 1992; Birdsey and Plantinga, 1993; Dixon et al., 1994; Zhou et al., 2000; Fang et al., 2001; Wang et al., 2001; Like et al., 2000; Zhao and Zhou, 2004; Liu and Lei, 2005), including some Chinese provinces or regions (Zhang et al., 2002; Cao et al., 2002; Jiao and Hu, 2005). Yet few research on the carbon sequestration potential of such a large-scale program of tree planting as Chinese GGP. A paper published in the year 2006 was the precursor of this kind and it dealt with estimating the carbon sequestration potential after afforestation on marginal croplands in U.S. (Niu and Duiker, 2006). The objective of this study is to estimate the carbon sequestration potential under GGP in Yunnan Province by means of calculating the carbon stock changes of GGP-stands, and to provide a method for further estimating the potential of national GGP-stands in the long run.

2. Materials and methods

2.1. Area of tree species of the GGP-stands in Yunnan Province

The planted area for each tree species under the GGP in Yunnan Province from 2000 to 2007 are collected from Yearly Provincial Verification Reports on the Grain for Green Project in Yunnan (2000–2007) edited by Yunnan Provincial Forestry Department, PR China (Table 1). Based on the national target of the GGP-stands up to the year 2010 (RGCFSDS, 2002) and the area proportion of the provincial GGP-stands to the national GGP-stands in the years from 2000 to 2007, it is predicted that 301,746 ha of lands will be planted under the GGP in Yunnan Province in the years from 2008 to 2010, including 113,758 ha of eligible croplands and 187,986 ha of barren lands. The annual planting area of GGP-stands varied significantly in the past and peaked in the year 2003 (346,894 ha). After a pilot phase, farmers' enthusiasm for planting GGP-stands increased rapidly during 2002–2003 due to an encouraging policy. From 2004 to 2007, government gradually cut down the subsidized area of GGP-stands in order to enhance the quality of grown and growing GGP-stands, and the annual area of GGP lands range from 52,468 to 85,400 ha during 2005–2007. Based on the governmental planned goal and the actual situation in last 3 years, the annual area to be planted from 2008 to 2010 is schemed as following two scenarios:

Table 1

Area planted and to be planted for each tree species/species group under the Grain for Green Program in Yunnan Province (ha)

Species/species group	Planted area 2000–2007 (total area)	Scenario A 2008–2010 (annual area)	Scenario B 2008–2010 (annual area)
<i>Pinus armandi</i>	77,369.8	8,051.9	5,319.6
<i>P. yunnanensis</i>	65,193.2	6,784.6	4,482.4
<i>Larix gmelini</i>	1,558.6	162.2	107.2
<i>Pinus kesiya</i> var. <i>langbianensis</i>	32,873.5	3,421.1	2,260.2
<i>Cunninghamia lanceolata</i>	26,257.7	2,732.6	1,805.4
<i>Picea asperata</i>	1,710.2	178.0	117.6
<i>Cryptomeria fortunei</i>	8,131.5	846.2	559.1
<i>Abies</i> spp.	3,543.1	368.7	243.6
<i>Keteleeria</i> spp.	61.0	6.3	4.2
<i>Platycladus orientalis</i>	25,467.2	2,650.4	1,751.0
Other conifer	10,019.9	1,042.8	688.9
<i>Cinnamomum camphora</i>	272.6	28.4	18.7
<i>Quercus</i> spp.	2,287.9	238.1	157.3
Hardwood	62,645.7	6,519.5	4,307.2
<i>Eucalyptus</i> spp.	74,116.1	7,713.3	5,095.9
<i>Sassafras tzumu</i>	1,910.6	198.8	131.4
<i>Populus deltoides</i>	2,722.5	283.3	187.2
<i>Aluierites fordii</i>	3,346.6	348.3	230.1
<i>Betula</i> spp.	32,828.4	3,416.5	2,257.1
Softwood	267,076.2	27,794.6	18,363.0
Unidentified species	69,541.9	7,237.2	4,781.4
Total	943,122.7	98,150.8	64,844.9

- (1) *Scenario A*: Evenly allocating the annual area to be planted in the following 3 years corresponding to the planed goal (Table 1);
- (2) *Scenario B*: Equally allocating the annual area to be planted in the following 3 years corresponding to the average annual area in the past 3 years (2005–2007) (Table 1).

The planting area for each species in next 3 years is predicated based on the planted area proportion of each species to all the species under the GGP in Yunnan Province (Table 1).

2.2. Methods for estimating carbon stock changes

The carbon sequestration potential of GGP is expressed as the carbon stock changes in the tree biomass and soil organic matter of GGP-stands. Although carbon stock in dead organic matter (litter and dead wood) is subjected to increase after afforestation or reforestation on cropland or barren land, its changes were not estimated in this paper due to unavailable data and lower change rate relative to living tree biomass.

2.3. Carbon stocks in living tree biomass

The carbon stocks change method was adopted for estimating carbon stocks in living tree biomass of GGP-stands, using formula (1):

$$CST_i = \sum_j \sum_k S_{jk} V_{ijk} WD_j BEF_j CF_j \quad (1)$$

where CST_i corresponds to carbon stocks (MgC) in living tree biomass in target year i , S_{ji} represents the area (ha) of species j planted or to be planted in year k , V_{ijk} indicates stand volume per hectare ($m^3 ha^{-1}$) in target year i for species j planted in year k , WD_j is the basic wood density ($Mg m^{-3}$) of species j , BEF_j is a biomass expansion factor (dimensionless) for conversion of stem biomass to stand biomass (including stems, branches, foliages and roots) for species j , CF_j is carbon fraction ($MgC Mg^{-1}$) of species j .

The stand volume of established plantations varies with tree species, site conditions, age class and forest management. Due to lack of available data, it is difficult to estimate the volume growth in terms of site conditions and forest management practices. However, the National Forestry Inventory (NFI) conducted once every 5 years since 1970s provides stand volumes corresponding to five age classes of some tree species/species group of plantations in Yunnan Province (CSIMFR and YFPD, 1993,1998,2003). The NFI data can represent an average growth value of the stand volume for different site conditions and forest management practices. The stand volume of different tree species of plantations was fitted against age class using SPSS:

$$V_{ijk} = a(1 - \exp(-bA))^c \quad (2)$$

where A represents stand age, $A = i - k$; a , b and c are parameters to be fitted. The fitted growth curves (Fig. 3) were used to estimate the stand volume of different species/species group of the GGP-stands in the target year i . Except for tree species with specific growth curve, the curves corresponding to conifer, broadleaves and mixed conifer and broadleaves were respectively used for other coniferous species, broadleaf trees and mixed tree species. Shrub, rattan and grass planted under GGP are not included in the estimation due to negligible biomass.

The biomass expansion factor (BEF) and basic wood density (WD) used in the estimation are from the China initial national communication (Table 2) (IFEEP, 2004). Carbon fractions (CF) are derived from literature reviews (Table 2) (SFAPRC, 2001).

Table 2

Values of wood density (WD), biomass expansion factor (BEF), carbon fraction (CF) and minimum rotation (MR) for different tree species

Species/species groups	WD ($Mg m^{-3}$)	BEF (whole tree)	CF	MR (years)
<i>L. gmelini</i>	0.49	1.74	0.51	61
<i>P. armandi</i>	0.396	2.29	0.50 ^a	51
<i>P. yunnanensis</i>	0.483	2.04	0.54	51
<i>P. kesiya</i> var. <i>langbianensis</i>	0.454	1.83	0.50 ^a	51
<i>Abies</i> spp.	0.366	2.12	0.49	61
<i>P. asperata</i>	0.342	2.12	0.51	101
<i>Keteleeria</i> spp. ^b	0.448	2.23	0.50 ^a	51
<i>C. fortunei</i>	0.294	1.91	0.50 ^a	36
<i>C. laceolata</i>	0.307	1.92	0.49	36
<i>P. orientalis</i>	0.478	2.11	0.5	101
Mixed conifer stand	0.405	2	0.52	–
<i>C. camphora</i>	0.46	1.89	0.49	71
<i>Quercus</i> spp.	0.676	2.09	0.5	71
Hardwood	0.598	2.34	0.50 ^a	71
<i>Betula</i> spp.	0.541	1.62	0.5	51
<i>S. tsumu</i>	0.477	2.49	0.50 ^a	26
<i>Eucalyptus</i> spp.	0.578	1.65	0.50 ^a	26
<i>P. deltoids</i>	0.378	2.16	0.51	26
<i>A. fordii</i>	0.239	3.69	0.50 ^a	26
Softwood	0.443	2.5	0.50 ^a	26
Mixed broadleaf trees	0.482	1.95	0.44	51

^a Generally used value.

^b Substituted by the value of similar species.

Over 95% of forests established under the GGP in Yunnan Province belongs to the so-called Ecological Service Forests (non-commercial plantations) (refer to the Annual Provincial Verification Reports on Grain for Green Program in Yunnan (2000–2007) edited by Yunnan Provincial Forestry Department, PR China) (Chen, 2002). According to Technical Regulations for Ecological Service Forest (SFAPRC, 2001; SCPRC, 2002), these forests are not allowed to harvest until over mature. The minimum rotation for major species of ecological service forest are listed in Table 3. However, it is possible that the forests planted or to be planted under GGP will never be harvested because the target lands are usually located at the mountainous areas. Therefore we further develop Scenario A and Scenario B as follows:

Scenario A-1: Scenario A without harvest;

Scenario A-2: Scenario A with harvest at the minimum harvest age;

Table 3

Carbon stock changes of the stands under the Grain for Green Program in Yunnan Province in the next 50 years (TgC)

	Year				
	2010	2020	2030	2040	2050
Scenario A-1					
Living biomass	8.798	25.595	32.892	34.776	35.307
Soil organic carbon	3.810	9.566	14.208	18.849	21.314
Total	12.608	35.161	47.100	53.626	56.621
Scenario A-2					
Living biomass	8.798	25.595	27.405	27.541	32.814
Soil organic carbon	3.810	9.566	14.208	18.849	21.314
Total	12.608	35.161	41.613	46.391	54.128
Scenario B-1					
Living biomass	8.721	24.057	30.380	32.007	32.468
Soil organic carbon	3.753	8.959	13.225	17.492	19.614
Total	12.474	33.016	43.606	49.499	52.083
Scenario B-2					
Living biomass	8.721	24.057	24.894	25.565	30.304
Soil organic carbon	3.753	8.959	13.225	17.492	19.614
Total	12.474	33.016	38.119	43.057	49.918

Fig. 3. Fitted growth curve for different species/species-groups of plantations in Yunnan Province.

Scenario B-1: Scenario B without harvest;

Scenario B-2: Scenario B with harvest at the minimum harvest age.

For scenarios with harvest, it is assumed that all harvested biomass will decompose immediately and all harvested lands will be regenerated immediately after harvest and the aboveground part of all cut trees will be cleared out.

2.3.1. Carbon stock changes in soil organic matter

Soil is likely to be a potential sink of carbon following afforestation in the long term, however, stock changes of soil organic carbon (SOC) following afforestation vary significantly with land use/cover types before planting and other bio-physical conditions (Post and Kwon, 2000; Paul et al., 2002), and the

changes are usually non-linear over time (Bateman and Lovett, 2000; Post and Kwon, 2000; Paul et al., 2002; Paul et al., 2003).

The GGP-lands, similar to the marginal agricultural land in U.S. (Niu and Duiker, 2006), are largely degraded croplands/barrenlands that generally have a low initial SOC stock. Intensive site and soil preparation that usually results in significant soil erosions is not allowed and original vegetation is requested to be maintained as much as possible by the GGP (refer to the Annual Provincial Verification Reports on Grain for Green Program in Yunnan (2000–2007) edited by Yunnan Provincial Forestry Department, PR China). Therefore, SOC does not likely decrease after the planting of the GGP lands although Paul et al. (2002) summarized an initial SOC loss after afforestation on croplands. Given this, factors for SOC stock changes from Niu and Duiker (2006) were used for our estimation. The SOC stock changes were then estimated by the

Fig. 4. Factors in changes of soil organic carbon (SOC) over time (Niu and Duiker, 2006); r represents the SOC change rate.

formula:

$$SOCC_i = \sum_j \sum_k r(i-k) S_{jk} \quad (3)$$

where $SOCC_i$ corresponds to the SOC stock change (MgC) in SOC pool in target year i , S_{jk} represents the area (ha) of species j planted or to be planted in year k , γ represents the factor of SOC stock change (MgC ha⁻¹ year⁻¹) (Fig. 4).

3. Results

3.1. Carbon sequestration potential of GGP-stands

Under the four scenarios, the carbon stock change of the GGP-stands in Yunnan Province is expected to be 12.474–12.608 TgC, 33.016–35.161 TgC, 38.119–47.100 TgC, 43.057–53.626 TgC and 49.918–56.621 TgC by the year 2010, 2020, 2030, 2040 and 2050,

respectively. Among them, the carbon sequestration in living tree biomass are 8.721–8.798 TgC, 24.057–25.595 TgC, 24.894–32.892 TgC, 25.565–34.776 TgC and 30.304–35.307 TgC, and the SOC stock changes are 3.753–3.810 TgC, 8.959–9.566 TgC, 13.225–14.208 TgC, 17.492–18.894 TgC and 19.614–21.314 TgC, correspondingly (Table 3). The SOC stock change accounts for 27.14–40.63% of the carbon stock change of the GGP-stands. The carbon stock change of the GGP-stands for Scenario B is less than that for Scenario A. After harvesting the carbon stock change of the GGP-stands for Scenario A-2 and Scenario B-2 are smaller than that for Scenario A-1 & Scenario B-1, correspondingly (Fig. 5). In 2012, the annual carbon stock change of GGP-stands will peak at 2.536 TgC year⁻¹ for Scenario A-1 and A-2 and 2.342 TgC year⁻¹ for Scenario B-1 and B-2, followed by a gradual decrease (Fig. 6). Particularly, there are 2.601 TgC year⁻¹ and 2.691 TgC year⁻¹ of the maximum net emission in 2030 for Scenario A-2 and Scenario B-2 due to harvesting. The carbon sequestration potential of the GGP-stands on croplands amounts to 39.84–40.24% of the total potential of GGP-stands in 2010, 36.58–38.65% in 2020, 34.13–38.31% in 2030, 35.62–38.34% in 2040 and 35.40–38.19% in 2050, respectively. Most of the carbon sequestration occurs in the period 2005–2025 (Fig. 6).

3.2. CSP of GGP-stands for the major species

The area planted with seven major tree species (e.g., *Pinus armandi*, *Pinus yunnanensis*, *Pinus kesiya* var. *langbianensis*, *Platycladus orientalis*, *Cunninghamia lanceolata*, *Eucalyptus* spp. and *Betula* spp.) accounted for 43.5% of the total area of established GGP-stands in Yunnan Province (Table 1) (refer to the Annual Provincial Verification Reports on Grain for Green Program in Yunnan (2000–2007) edited by Yunnan Provincial Forestry Department, PR China) (Chen, 2002; Li, 2004). The carbon sequestration potential of the GGP-stands of these seven major tree species in Yunnan Province is expected to account for 43.27–50.56% of the total GGP-stands for during 2020–2050. In particular,

Fig. 5. Carbon sequestration potential of the Grain for Green Program in Yunnan Province.

Fig. 6. Annual carbon sequestration potential of the Grain for Green Program in Yunnan Province.

P. armandi, *P. yunnanensis* and *Eucalyptus* spp. are the most popular tree species under GGP. By 2010, 2020, 2030, 2040 and 2050, the carbon sequestration potential of *P. armandi* stands will be 0.436–0.442, 3.505–3.624, 5.399–5.829, 5.965–6.468 and 6.175–6.715 TgC, respectively; for *P. yunnanensis* stands it will be 1.111–1.121, 2.977–3.166, 4.151–4.472, 4.879–5.279 and 5.205–5.655 TgC, respectively; and for *Eucalyptus* spp. stands it will be 1.172–1.187, 2.822–3.024, 3.612–3.905 (2.615–2.907), 4.127–4.472 (2.950–3.133) and 4.374–4.755 (4.030–4.361) TgC, respectively (the data in the brackets is the result when any harvesting happens) (Fig. 7).

4. Discussion

4.1. Applicability of growth curves

The growth curves applied play a crucial role in the estimation of the carbon stocks in the living tree biomass. In this paper the growth curves, fitted by the standing volume of plantations established in various places with relatively poorer site conditions as the lands with good site conditions were almost reclaimed to farmlands in Yunnan Province in the past, represent the mean growth under the diverse climate, site conditions as

Fig. 7. Carbon sequestration potential for seven major tree species under the Grain for Green Program in Yunnan Province.

well as management practices. Since the GGP-stands are also the plantations with the different climate and site conditions, using these growth mean curves may lead to overestimation of some areas with worse site conditions or underestimation of other areas with better site conditions. Therefore, as a whole, it is feasible to use these growth curves to estimate the growth of GGP-stands given that the growth curves for different site conditions are unavailable.

4.2. Role of the carbon sequestration of GGP-stands

In Yunnan Province, the area of GGP-lands accounts for 2.45% of the total lands, and is equal to 6.24% of the forested lands and 37.29% of plantations. The carbon stock change of the GGP-stands by the year 2050 will be up to 10.82–12.27% of the carbon stocks of the forest vegetation in Yunnan Province in the 1990s (461.43 TgC) (Zhao and Zhou, 2004), varying with different scenarios.

4.3. Harvest wood product

The harvest biomass was assumed to decompose immediately in our estimation. However, a majority of logged trees will be transformed to wood products which have certain lifetime. Within their lifetime, it is reasonable to count the carbon in the harvest wood products. Skog and Nicholson (2000) reported that the carbon stocks of these harvest wood products accounts for 14.1% of that of the total trees logged, yet Niu and Duiker (2006) argued that the proportion should be up to 32%. The carbon in the harvest wood products is not included in our estimation due to lack of data on harvest wood product.

4.4. Issue of carbon baseline

The carbon sequestration of afforestation and reforestation often involves the issues of carbon baseline and carbon leakage (IPCC, 2000; Willems, 2000; Lazams et al., 2001; UNFCCC, 2001, 2003). The baseline refers to the change of the carbon stocks within the project boundary in the absence of the project (Willems, 2000). The Chinese GGP aims to restore forest vegetation on some croplands and barren mountainous lands. The croplands for GGP are restricted to desertified lands or lands with slope gradient over 25°. In the absence of the GGP, these lands would continue to degrade or at least in a steady state. So the carbon baseline of the GGP-stands can be conservatively assumed to be zero.

4.5. Issue of carbon leakage

The carbon leakage means a countable carbon emission resulting from a project and occurring outside a project boundary (UNFCCC, 2003). The croplands and barren lands used for GGP usually have a very low productivity. These lands are often situated in the remote mountainous areas where there are usually less populated and people have enough croplands for food. Meanwhile, Chinese government provides food and/or cash subsidies for farmers who have planted trees on their croplands eligible for GGP, which can compensate these farmers for the loss of food due to the GGP. Moreover, government also provides farmers with seedlings for tree planting and transfers the ownership of the wood and non-wood forest products to these farmers (SCPRC, 2002). Besides, the major work of the GGP in Yunnan Province is carried out manually instead of mechanically. Therefore, the leakage of the GGP is unlikely to occur and is nil.

5. Conclusion

The GGP will contribute significantly to the carbon sequestration in Yunnan Province in the next 50 years. Scenario A is more optimistic, under which the governmental goal is expected to be fulfilled, and the planting area (including the area for growing grass) of the GGP will be up to 1.238 Mha and the carbon sequestration of GGP-stands will be up to 54.128–56.621 TgC by the year 2050. Scenario B are more likely under which the planting area of the GGP will be up to 1.139 Mha and the carbon sequestration of GGP-stands will be up to 49.918–52.083 TgC by the year 2050. The carbon sequestration of the seven major tree species of GGP-stands accounts for 43.27–50.56% of that of the total tree species of GGP-stands. The total carbon sequestration of GGP-stands by 2050 amount to 10.82–12.27% of the carbon stocks of the forest vegetation in Yunnan Province in the 1990s.

To get more accurate data about carbon sequestration of GGP-lands, following components need to be improved: (1) the carbon stocks in living biomass of the shrub, rattan and grass planted on GGP-lands; (2) the carbon stocks in dead organic matter (including litter and dead wood); (3) the carbon stock in the harvest wood products; and (4) factors for the changes in soil organic carbon.

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