

# Estimation of provincial forest carbon sink capacities in Chinese mainland

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Received October 30, 2010; accepted December 28, 2010

Estimation of the capacity of provincial forest carbon sinks in Chinese mainland using the CO2FIX model provides data support for the effective management of provincial regions. According to China's Sixth National Forest Inventory, we estimate the capacities of original and new afforestation carbon sinks under the assumption of using the country's non-forest land for afforestation and reforestation to achieve a new forested area of 57323200 ha. The carbon absorption capacity of China's forest ecosystems estimated from 2005 to 2050 reaches 8.4 GtC. The absorption capacities of original forest and new afforestation respectively are 4.9 and 3.5 GtC. The annual capacity of all forest carbon sinks has a roughly decreasing trend. Inner Mongolia Autonomous Region, Yunnan, Sichuan and Heilongjiang provinces make major contributions to the carbon sink capacity.

**climate protection, forest carbon sink, China**

**Citation:** Ma X Z, Wang Z. Estimation of provincial forest carbon sink capacities in Chinese mainland. *Chinese Sci Bull*, 2011, 56: 883–889, doi: 10.1007/s11434-011-4402-6

According to the Intergovernmental Panel on Climate Change [1], national carbon dioxide emissions refer to actual emissions considering carbon sinks. Currently, forests are the major carbon sinks for Chinese mainland. Estimating the capacities of the forest carbon sinks allows for a better understanding of China's carbon emissions. The calculation of the capacity of carbon sinks for the whole of China has already been investigated [2–6], but when we consider the national management of carbon dioxide emissions, we need to calculate the capacities of carbon sinks of provinces and autonomous regions to more effectively manage carbon emission reduction.

Employing the CO2FIX model developed by Wageningen University [7], this paper investigates the forest carbon sinks of the Chinese mainland provinces and autonomous regions. The CO2FIX model is a carbon balance model at the ecosystem level that can simulate carbon stocks and carbon fluxes in the forest biomass, the soil or-

ganic matter and the wood products in forest ecosystems with a time-step of one year. When wood products are discarded at the end of their lifespan, they can be recycled, deposited in a landfill or they can be used for bioenergy. Carbon is released to the atmosphere in these processes. So the CO2FIX model tracks the carbon sinks of the end products in wood products module. The CO2FIX model V3.2 considers the stand density of vegetation growth and competition among species, the use of forest products, soil carbon dynamics and other factors. This version includes bioenergy modules, financial module and carbon accounting module in addition.

The CO2FIX model analyzes the effects of bioenergy technology and alternative technologies on non-carbon-dioxide greenhouse gas emissions. According to the different contributions of the same amounts of greenhouse gases to global warming, the model calculates the total reduction in greenhouse gas emissions. After the parameters are set, the CO2FIX model can provide the carbon content stored in living (aboveground plus belowground) biomass, soil matter and wood products per unit forest area. Finally, it gives the

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cumulative carbon sequestration of forest ecosystems and the amount of carbon dioxide absorbed from the atmosphere per unit forest area.

## 1 Provincial carbon sinks

### 1.1 Models

Because the CO2FIX model provides data for carbon sinks per unit area, the basic model of the forest carbon sink estimation is

$$C^{(f)} = PA, \quad (1)$$

where  $C^{(f)}$  is the capacity of the forest carbon sink,  $P$  is the capacity of the forest carbon sink per unit area of the forest ecosystem, and  $A$  is the forest area. There are three main parts to the capacity of forest carbon sinks:

$$C_i^{(f)} = C_i^{(0)} + C_i^{(1)} + C_i^{(2)}, \quad (2)$$

where  $i$  is the province in Chinese mainland,  $C_i^{(f)}$  is the total capacity of all forest carbon sinks in province  $i$ , and  $C_i^{(0)}$ ,  $C_i^{(1)}$  and  $C_i^{(2)}$  respectively are the capacities of carbon sinks relating to new afforestation, non-timber forest and timber forest in province  $i$ .

China's Sixth National Forest Inventory [8] shows that each province has several different species of trees and there are large differences in the areas covered by the different species. The main species of tree used for timber is assumed as the species of afforestation in this paper. When an afforestation tree matures, it will be harvested and another tree of the same species will be planted in its place.

### 1.2 Parameters and data sources

China's Sixth National Forest Resources Inventory shows that the total area of non-forested land in China is 57323200 ha including barren hills and wasteland, felling and burned land and sandy wasteland. Therefore, the area available to new planting is 57323200 ha. Areas available to provincial afforestation are listed in Table 1. According to China's

forestry development objectives [9], forest coverage will exceed 23% until 2020 and then remain above 26% until 2050. Accordingly, this study assumes a campaign of planting trees on barren land commencing in 2005. The area of national annual afforestation is 2500000 ha, and thus, 40000000 ha would be afforested by 2020. The national non-forest plantations would be completed by 2027. The area of new planting in each province over the years can be determined in accordance with the provincial non-forest area proportion of the total area. The afforestation area of each species over the years can be obtained by allocating new planting areas to the species of afforestation on an average basis. The choice of species is in accordance with China's Sixth National Forest Resources Inventory, with the dominant species having the largest area being selected. The number of afforestation species will range from 1 to 8 according to provincial differences in the existing species.

The provincial areas of original forest of different age used to estimate the carbon sequestration capacity of original forest is derived from China's Sixth National Forest Resources Inventory. The inventory also provides areas of young forest, middle-aged forest and near-mature forest for different species. Areas are then allocated to species of different age in accordance with the growth of the trees. The original forest areas of different age and species are thus obtained. Because it is difficult to obtain the growth data of domestic plants, which are required by the model, the original forest species are selected on the basis of the proportion of the area of young and middle-aged forest relative to the total area being more than 70%, while ignoring species covering a limited area.

Estimating the capacity of the forest carbon sink per unit area requires the density of wood, annual turnover rate of foliage, branches and roots, growth rate, harvest rate, current annual increment (CAI) and the relative CAI of foliage, branches and roots (Table 2) [10–34]. It also requires the mortality and harvest scenarios for different ages and species (Table S1). The relative growth rate of foliage, branches and roots to trunks can be obtained from data of the net productivity for various parts. In the case that data for several species cannot be obtained, the species are replaced

**Table 1** Areas of non-forested land for afforestation in Chinese mainland<sup>a)</sup> (Unit: 10000 ha)

Region	Non-forest land area	Region	Non-forest land area	Region	Non-forest land area	Region	Non-forest land area
Total	5732.32	Heilongjiang	179.51	Henan	78.54	Guizhou	216.47
Beijing	30.89	Shanghai	0	Hubei	59.2	Yunnan	421.81
Tianjin	1.73	Jiangsu	12.74	Hunan	94.15	Tibet	14.56
Hebei	234.84	Zhejiang	36.9	Guangdong	91.62	Shaanxi	250.11
Shanxi	368.53	Anhui	27.81	Guangxi	195.99	Gansu	296.23
Inner Mongolia	2075.44	Fujian	82.51	Hainan	18.94	Qinghai	191.49
Liaoning	123.85	Jiangxi	70.41	Chongqing	81.16	Ningxia	68.82
Jilin	20.54	Shandong	46.56	Sichuan	247.14	Xinjiang	93.83

a) Data sources: [9]. Inner Mongolia Autonomous Region, Tibet Autonomous Region, Xinjiang Uygur Autonomous Region, Ningxia Hui Autonomous Region and Guangxi Zhuang Autonomous Region are respectively abbreviated to Inner Monogolia, Tibet, Xinjiang, Ningxia and Guangxi (the same below).

**Table 2** Parameters of the biomass module

Tree species	Wood density (MgDM m <sup>-3</sup> )	Turnover rate of branch, foliage and root	Growing season (Month)	Rotation length (a)	References of CAI <sup>a)</sup>
Fir	0.366	0.05/0.33/0.1	3–10	60	[10,24]
Spruce	0.342	0.05/0.33/0.1	3–10	70	[11,25]
Cypress	0.478	0.05/0.33/0.1	4–10	37	[12,26]
Larch	0.490	0.05/1.00/0.1	4–10	40	[13,27]
Chinese pine	0.360	0.05/0.33/0.1	3–10	40	[14,27]
Masson pine	0.431	0.05/0.33/0.1	3–11	30	[15,28]
<i>Pinus yunnanensis</i>	0.483	0.05/0.33/0.1	3–10	60	[10,24]
<i>Pinus kesiya</i>	0.454	0.05/0.33/0.1	3–10	60	[10,24]
<i>Pinus densata</i>	0.413	0.05/0.33/0.1	3–10	60	[10,24]
Chinafir	0.307	0.05/0.33/0.1	3–11	25	[16,29]
<i>Metasequoia</i>	0.270	0.05/1.00/0.1	4–11	18	[17,30]
Robur	0.676	0.05/1.00/0.1	3–10	45	[18,31]
Birch	0.541	0.05/1.00/0.1	4–10	45	[19,24]
Hardwood	0.598	0.05/0.33/0.1	3–11	35	[20,24]
<i>Eucalyptus</i>	0.578	0.05/0.33/0.1	3–12	10	[21,32]
Poplar	0.396	0.05/1.00/0.1	4–11	40	[22,33]
Softwide forest	0.443	0.05/1.00/0.1	3–11	20	[23,34]
<i>Theropencedrymion</i>	0.405	0.05/0.50/0.1	3–10	45	[20,31]
Broad-leaved mixed forest	0.482	0.05/0.50/0.1	4–11	40	[22,33]

a) Unit of CAI: m<sup>3</sup> ha<sup>-1</sup> a<sup>-1</sup>.

with alternative species with a similar rotation cycle. Because most productive forest land has been used for forestry, the productivity of the remaining land is generally low. Therefore, it is estimated that the annual growth in afforestation will be reduced by 40%. This assumption avoids overestimation of the carbon sink capacity of the new forest [35]. The carbon content of trees is set to the IPCC default value of 0.5 mg carbon per mg dry matter (MgC MgDM<sup>-1</sup>) [36]. Wood densities of each species are derived from the local average value in line with relevant literature [37]. The cycle time of forest rotation is provided by the National Forest Inventory Technical Requirements [38].

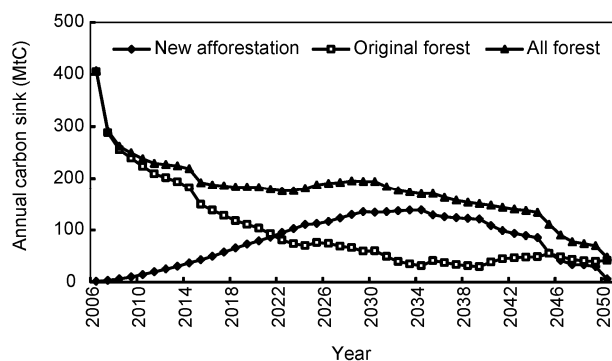
Meteorological data for the soil module including the monthly mean temperature and monthly precipitation are obtained from the World Climate website (<http://www.worldclimate.com/>). The weather data for a province are replaced by the average of meteorological data for cities in the province. The study areas are the provinces of China such as Gansu and Inner Mongolia, which have significant meteorological zonal differences. Therefore, the weighted average for cities in a province is used in estimating the value for the province. Considering that national non-forest land is mainly sandy wasteland (the proportions of other land types are small), the initial values of branches, foliage and roots in such areas are assumed to be zero in the soil module. The remaining parameters are set to its default value.

The wood product module provides two sets of default parameters on the end products allocation process, the end of life process and the life span for products in use and recycling, a set with high processing and recycling efficiency

and a set with low processing and recycling efficiency. Taking into account the actual situation in China, low processing and recycling efficiency should be chosen. This study uses default parameters in the biomass energy module. In the calculation, it is considered that the burning of coal is replaced by the burning of harvest residues and industrial waste wood using improved stove technology.

## 2 Provincial forest carbon sinks

According to the method and related parameters described in section 1.2, we simulated annual carbon sequestration by new planting and original forest in China's provinces and autonomous regions. The results are presented in Figure 1. The total annual sequestration of carbon by forest in China has a declining trend from 406 MtC in 2006 to 47 MtC in 2050. The total capacity of the country's forest carbon sinks is dominated by original forest during the period 2006 to 2022. After 2022, carbon sequestration through afforestation becomes dominant owing to the weakening carbon sink capacity of the mature original forest and the larger capacity of new areas of afforestation. After 2040, the carbon sink capacity of the original forest increases slightly as a result of reforestation after logging. The simulation shows that China's forest ecosystems can cumulatively absorb 8.4 GtC from 2005 to 2050, with the original forest absorbing 4.9 GtC and new afforestation absorbing 3.5 GtC. The carbon absorbed from the atmosphere is fixed in the biomass, soil and wood products. The cumulative carbon sequestration volumes respectively reach 3.7, 2.7 and 2 GtC, respectively

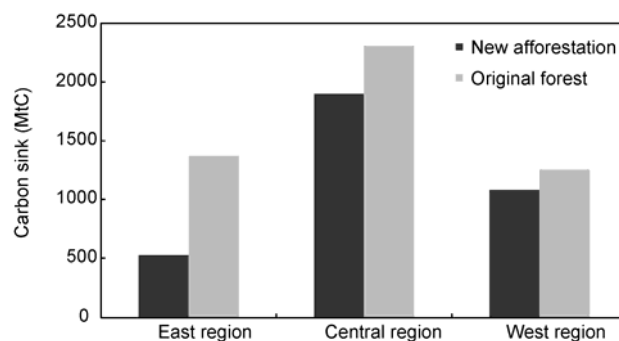


**Figure 1** China's annual forest carbon sink capacity from 2006 to 2050.

accounting for 43.3%, 32.5% and 24.4% of the total national forest carbon; i.e. the carbon sink capacity of biomass is the greatest.

Notably, the annual carbon sequestration of China's new afforestation increases with the area of new planting from 2005 and peaks at 138 MtC in the year 2043. In the following years, carbon sequestration by new afforestation slows, which is mainly due to newly planted trees gradually entering the felling stage. Therefore, there is a sharp decline in the carbon sink capacity of new afforestation.

Calculations show that among the three major regions of China [39], forest in the eastern region absorbs 1.9 GtC from atmospheric carbon dioxide from 2005 to 2050, accounting for 22% of the national total capacity of forest carbon sinks, where carbon sequestration by the original forest and new afforestation is respectively 1.4 and 0.5 GtC. Figure 2 shows that the total capacity of carbon sinks in the central region is 4.2 GtC, accounting for 50% of the total capacity of forest carbon sinks across the country, where carbon sequestration by the original forest and new affor-

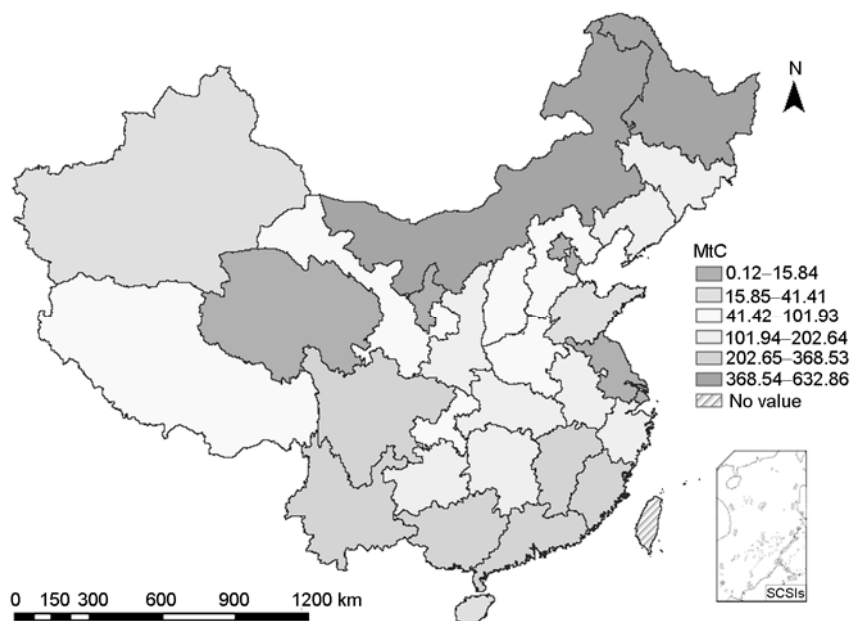


**Figure 2** Carbon sequestration potential of original forest and afforestation in the three major regions of Chinese mainland.

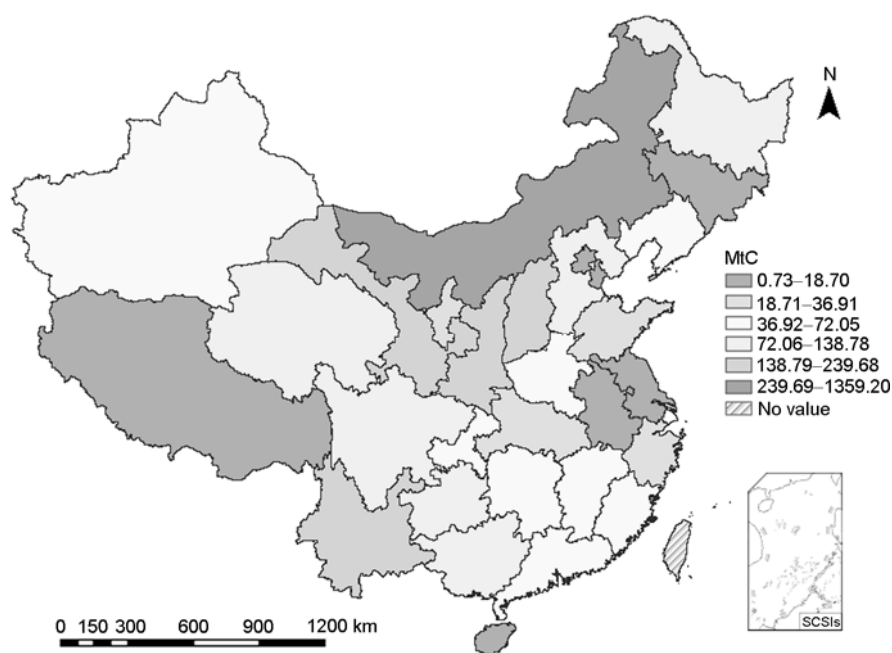
estation is respectively 2.3 and 1.9 GtC. The total capacity of carbon sinks in the western region is 2.3 GtC, where carbon sequestration by the original forest and new afforestation is respectively 1.3 and 1 GtC. Carbon capacities of three regions are closely linked to their forest area. In the three major regions of China, the central region has the largest forest area, accounting for 49% of the national total, while the eastern and western regions have 25% and 26% of the national total area respectively.

Figures 3 and 4 respectively show the provincial cumulative carbon sink capacities of original forest and new afforestation from 2005 to 2050. In Figure 3, Inner Mongolia (0.6 GtC) and Heilongjiang (0.5 GtC) have the greatest potential for carbon sequestration by original forest. Southern provinces such as Sichuan, Yunnan, Guangxi and Guangdong have good potential for carbon sequestration by original forest, whereas northwestern provinces such as Qinghai, Xinjiang and eastern provinces such as Shandong and Jiangsu have less potential.

Figure 4 shows that Inner Mongolia has the greatest non-



**Figure 3** Provincial carbon sinks of original forest from 2005 to 2050.



**Figure 4** Provincial carbon sinks of new afforestation from 2005 to 2050.

forest area, accounting for 36.21% of the country's total area of non-forested land. The cumulative amount of carbon absorbed from the atmosphere reaches 1.4 GtC by 2050, or 39% of the total of new afforestation in China. The non-forested areas of Yunnan, Shanxi, and Gansu are larger than those of other provinces, as are the carbon sink capacities of new afforestation, which are respectively 207.3, 234.7, and 239.7 MtC. In addition, Hebei, Heilongjiang, Shaanxi, Sichuan, Guizhou and Guangxi have large potential for carbon sequestration, but the lack of annual rainfall would restrict the development of forestry in these regions. The carbon sequestration potential of afforestation in some provinces is less than 18.7 MtC; e.g. in Jiangsu, Shandong, Zhejiang, Hunan, and Hubei in eastern China, Tibet in western China, Beijing, Tianjin and Jilin.

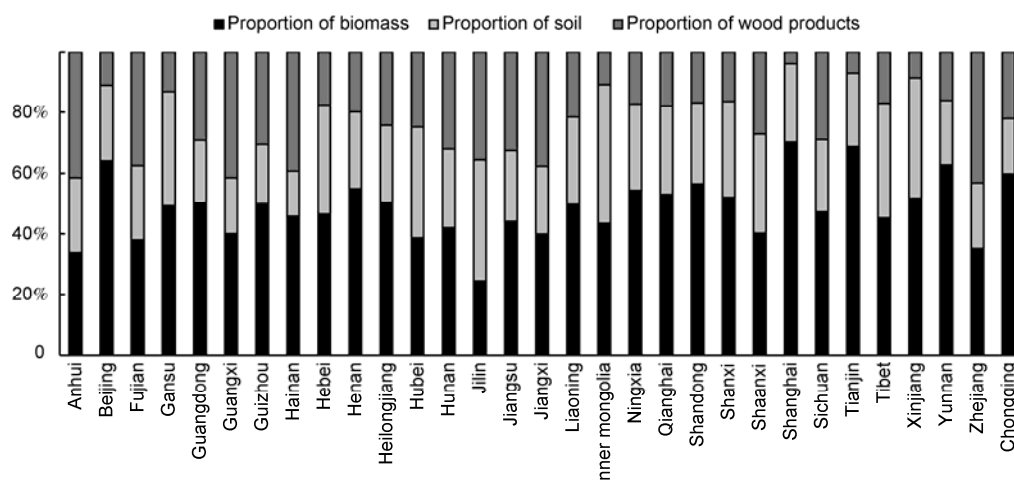
The overall results are presented in Table 3 and indicate that Inner Mongolia, Yunnan, Sichuan and Heilongjiang

will be the major carbon sink areas in the future. Shandong and Jiangsu in eastern China have smaller potential carbon sequestration both for original forest and new afforestation. Xinjiang, Qinghai and Tibet, despite being vast inland provinces, have limited potential carbon sequestration because of the restrictions of climate, soil and other natural and geographical conditions and there is no doubt that this will greatly affect their ecological environment and sustainable development.

Figure 5 illustrates the carbon sink components of provincial forest ecosystems (comprising original forest and new afforestation) in 2050 based on the CO2FIX model. The results show that the amount of carbon stored in biomass is large in most provinces but small in Jilin and Anhui. In Anhui and Jilin, new afforestation plays a leading role in forest carbon sequestration, and thus the carbon sink capacity in biomass is more easily affected by logging. In 2050,

**Table 3** Provincial cumulative carbon sequestration of all forest from 2005 to 2050 (Unit: MtC)

Region	Total carbon sinks	Region	Total carbon sinks	Region	Total carbon sinks
Anhui	149.61	Heilongjiang	666.73	Shanxi	304.14
Beijing	30.23	Hubei	170.39	Shaanxi	321.12
Fujian	337.81	Hunan	252.17	Shanghai	0.12
Gansu	319.24	Jilin	159.12	Sichuan	398.70
Guangdong	389.23	Jiangsu	18.15	Tianjin	3.31
Guangxi	357.66	Jiangxi	383.72	Tibet	108.58
Guizhou	284.68	Liaoning	212.06	Xinjiang	72.11
Hainan	56.33	Inner Mongolia	1992.06	Yunnan	575.83
Hebei	220.03	Ningxia	38.25	Zhejiang	197.34
Henan	129.09	Qinghai	103.16		
Chongqing	111.09	Shandong	75.76		



**Figure 5** Carbon sink capacity proportions of biomass, soil and wood products in forest ecosystems

most new trees in these two provinces will enter their harvesting period, which will lead to a decline in the carbon sink capacity in biomass, and thus a decline in the proportion of carbon sink capacity in biomass relative to the total capacity of carbon sinks. Figure 5 shows that in northern provinces, such as Inner Mongolia, Heilongjiang, Jilin, Ningxia, Shanxi and Liaoning, the carbon storage capacity of forest soil is higher than that of wood products, while in the southern provinces, such as Sichuan, Guangxi, Guangdong, Jiangxi, Fujian, Hunan and Hainan, soil carbon storage is equal to or slightly lower than the carbon storage of wood products. The forecast reflects that the cumulative carbon storage in soil is closely related to provincial climate conditions. In the southern provinces, the accumulated temperature is higher than zero degrees Celsius. Since rainfall has a stronger relationship than snowfall with potential evaporation, decomposition is faster in these provinces. Therefore, the carbon sink capacity of soil is less than that of biomass and that of wood products.

Notably, government policy is to plant trees on all national forest land. Such a planting area would be greater than the practical afforestation area, as government management of the afforestation would likely be inefficient. Therefore, this paper gives an upper limit to forest carbon sink capacity. This approach is similar to that employed in estimating the carbon sink capacity in the water cycle by Liu et al. [40].

### 3 Conclusions

China's carbon emissions can be reduced through establishing forest carbon sinks. China's forest ecosystems are capable of absorbing 8.4 GtC from atmospheric carbon dioxide between 2005 and 2050, with original forest accumulatively fixing 4.9 GtC and new afforestation 3.5 GtC.

Annual carbon sequestration for all forests shows a de-

clining trend, from 406 MtC in 2006 to 47 MtC in 2050. From 2006 to 2022, original forest carbon sinks will be dominant, while the carbon sinks of new afforestation will be dominant after 2022. It was also found that among the three major regions of China, 1.9 and 2.3 GtC of carbon dioxide will be fixed in eastern and western forests respectively from 2005 to 2050, while 4.2 GtC will be in the central region, accounting for 50% of the country's carbon sink capacity.

At the provincial scale, Inner Mongolia and Heilongjiang have the greatest potential for carbon sequestration in original forests; Sichuan, Yunnan, Guangxi and Guangdong also have great potential. Inner Mongolia, Yunnan, Shanxi and Gansu have large carbon sink capacities for new afforestation. Shandong and Jiangsu in the eastern region have limited sequestration potential both for original forest and afforestation.

The calculations show that the cumulative carbon storage in soil is closely related to provincial climate conditions. In the southern provinces, the accumulated temperature is higher than zero degrees Celsius. Because rainfall has a greater relationship than snowfall with potential evaporation, decomposition is faster in these provinces, and the carbon sink capacity of soil is less than that of biomass and wood products.

It is worth mentioning that there is uncertainty in selecting tree species to newly plant, and in allocating land to different species. Employing the average distribution method affects the estimation of the provincial carbon sequestration potential. These issues need further investigation.

*We would like to thank Dr Yue Qun and Lü Jinwen for their discussions. This work was supported by the National Natural Science Foundation of China (40771076) and the Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-325-7).*

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## Supporting Information

### Table S1 Natural mortality and profiles of harvesting

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