# Updated estimation of forest biomass carbon pools in China, 1977–2018

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**Abstract**. China is one of the major forest countries in the world and the accurate estimation of its forest biomass carbon (C) pool is critical for evaluating the country's C budget and ecosystem services of forests. Although several studies have estimated China's forest biomass using national forest inventory data, most of them were limited to the period of 2004–2008. In this study, we extended our estimation to the most recent period of 2014–2018. Using datasets of eight inventory periods from 1977 to 2018 and the continuous biomass expansion factor method, we estimated that the total biomass C pool and average biomass C density in Chinese forests increased from 4717 Tg C (1 Tg = $10^{12}$ g) in the period of 1977–1981 to 7975 Tg C in the period of 2014–2018 and 38.2 Mg C ha$^{-1}$ to 45.8 Mg C ha$^{-1}$ (1 Mg = $10^{6}$ g), respectively, with a net increase of 3258 Tg C and an annual sink of 88.0 Tg C yr$^{-1}$. Over the recent 10 years (2009–2018), the average national forest biomass C density and C sink were 44.6 Mg C ha$^{-1}$ and 154.8 Tg C yr$^{-1}$, respectively, much larger than those of 39.6 Mg C ha$^{-1}$ and 63.3 Tg C yr$^{-1}$ in the period 1977–2008. These pronounced increases were largely attributed to afforestation practices, forest growth, and environmental changes. Our results have documented the importance of ecological restoration practices, provided an essential basis for assessing ecosystem services, and helped to achieve China's C neutrality target.

***Keywords:*** Forest biomass; C sink; C density; China; Ecological restoration projects

## 1 Introduction

Terrestrial ecosystems carbon (C) sinks, which absorb approximately 30% of annual anthropogenic carbon dioxide ($CO_2$) emissions, are mostly contributed by forests (Pan et al., 2011; Terrer et al., 2021). Globally, forests cover ~30% of the land area (Fahey et al., 2010; Guo et al., 2013), and sequester large amounts of C in woody biomass and soils (Pugh et al., 2019). Even small changes in the forest C pool could induce profound feedback on the climate system of the planet (He, 2012). Thus, forests play fundamental roles in regulating the global C balance and mitigating climate change (Pan et al., 2011; Harris et al., 2021).

China has a forest area of ~0.2 billion hectares, accounting for 5.51% of the global total forest and ranking fifth among countries (FAO, 2021). The forests in China are distributed over a wide range of climatic conditions and are diverse in forest types, which makes them unique for forest C cycle research (Fang et al., 2010). Meanwhile, China's forests especially planted forests are generally young with low biomass C density, implying a great C sequestration potential in the future (Xu et al., 2010; Zhao et al., 2019). In 2020, the Chinese government announced a goal to achieving C neutrality by 2060, for which sequestering more C through forest C sinks have been regarded as an essential part of China's action plans (Yu et al., 2021). Therefore, accurate estimates of the forest biomass C pool and sink capacity are crucial for China's aim of reducing net greenhouse gas emissions (Xu et al., 2010) and in reaching national C neutrality.

However, there are several limitations in the previous studies. On the one hand, most of the estimates of China's forest biomass C pool (and the corresponding C sink) were based on the national forest inventory data no later than the 7th National Forest Inventory (2004–2008) (e.g., Fang et al., 1996, 2001, 2007; Fang & Chen, 2001; Xu et al., 2010; Guo et al., 2013; Zhang et al., 2013; Li et al., 2015; Zhang et al., 2015). Nevertheless, China's large-area planted forests formed by extensive afforestation since the 1980s have just grown into the rapid-growing middle-aged stage in the most recent decade (2009–2018) (Lu et al., 2018), thus clarifying how China's forest C pool has changed since the 2010s is of vital importance to accurately evaluate the C sink formed by large-scale afforestation. Meanwhile, a four-decade long estimate of the forest C pool can also provide necessary information for exploring the driving mechanism of China's forest C sink and validating the conclusions from various models. On the other hand, the estimated C pool and/or sinks of China's forest differed considerably among their dedicated periods. For example, the estimate of the forest C sink during 1994–1998, ranged from -2.9 to 108 Tg C $yr^{-1}$ (Fang et al., 2007; Zhang et al., 2013; Li et al., 2015; Zhao et al., 2019). This large discrepancy could be due to limitations in sample size and data representativeness, diversity of data sources, inconsistent biomass-volume fit relationships (Li et al., 2015; Tang et al., 2018), or particularly divergences in the methodologies. Therefore, it is necessary to adopt a unified and well-validated method to update the estimations of the forest biomass C pool at the national scale over the past four decades, especially the most recent decade (2009–2018), to fill gaps in our knowledge regarding China’s forest C pool and its changes.

In this study, we used eight national forest inventories compiled during the period 1977–2018, and conducted a well-validated biomass expansion factor (BEF) method to update the estimate of China’s forest biomass C pool. Three major aims of the study are to (1) objectively describe the long-term changes in China’s forest biomass C pool and C sink at the national scale, especially focusing on the changes in the most recent decade (2009–2018), (2) clarify the contributions of different forest zonal types, age-groups and forest stand origins to China’s forest biomass C pool and its changes, and (3) qualitatively evaluate the potential influencing factors of China’s forest C sink by comparing the changes in biomass C stocks in the most recent decade with those in the earlier 30 years (1977–2008).

## 2 Methods

### 2.1 Methods for estimation

Mean biomass density (MBD), remote sensing, and BEF are three common methods for estimating large spatial-scale forest biomass C stocks (Guo et al., 2010; Zhang et al., 2013). The MBD method, defined as multiplying the mean biomass density value of each forest type by its area, is widely used to estimate the biomass C stocks at different spatial scales. However, because of investigators’ intentional tendencies to choose better-growing stands during forest censuses, the MBD method usually overestimates the C pool (Fang et al., 2006; Guo et al., 2010). The remote sensing method can provide the large-scale information of vegetation, while there are several inherent methodological issues that must be addressed, such as atmospheric and background noises, similar spectral characteristics of different vegetation, and saturation of signals in dense vegetation (Zhang et al., 2013). Different from the above two methods, the BEF method is based on the internal relationship between the biomass and timber volume of forests (Fang et al., 2002). By establishing proper regression models between biomass and timber volume, the BEF method can incorporate the effects of forest age, forest stand density, and forest site quality on biomass density, thus achieving appropriate estimates of the forest biomass C pool (Fang et al., 2002; Guo et al., 2010). Thus, the BEF method has obvious advantages in estimating forest biomass at regional and national scales (Fang et al., 1998; Fang & Wang, 2001; Guo et al., 2010; Teobaldelli et al., 2009).

Here, we used the continuous BEF method suggested by Fang et al. (2001) to estimate China’s forest biomass C stocks during 1977–2018, which is a well-validated approach that enables upscaling estimates from field plots to a regional level. In this approach, the BEF is calculated by the first-order derivative formula [Eq. (1)] using the ground survey data of forest volume, and then BEF is used to calculate biomass [Eq. (2)]:

$$\mathrm{BEF}=a+b/x \quad (1)$$

$$y=\mathrm{BEF}\cdot V \quad (2)$$

where $x$, and $V$ are the stock volume density and stock volume of a forest type at a certain age in each province, and $a$ and $b$ are BEF function coefficients. BEF is the biomass expansion factor, and $y$ is the biomass of a forest type at a certain age. The coefficients in Eq. (1) were retrieved from previous studies (Fang et al., 1998, 2002; Fang & Wang, 2001) (Table S1). A constant C conversion factor of 0.5 was used to convert biomass into C (Fang et al., 2001).

## 2.2 Data sources

Eight national forest inventory datasets compiled by the Chinese Ministry of Forestry Administration from 1977 to 2018 were used in this study. Forests’ dominant tree species, area, timber volume, forest age, and stand origins were reported for all provinces. According to Fang (2000), five zonal forest types including cold-temperate coniferous, temperate coniferous, temperate deciduous broad-leaved, temperate/subtropical mixed, and evergreen broad-leaved are dominant tree species. To quantify age-related tree growth, forests were further divided into five subgroups: young, middle-aged, premature, mature, and overmature. Forest area and C stocks were calculated for each province. Chongqing Municipality, which was separated from Sichuan Province in 1997, was merged into Sichuan here. The detailed data of Taiwan, Hong Kong, and Macau are missing from the inventory datasets; thus, the calculations did not account for these three regions.

## 2.3 Data correction

Since 1994, the canopy coverage criterion of forests in the national forest inventory has been changed from >0.3 to >0.2. We unified the criterion by adopting the power functions [Eqs. (3) and (4)] provided by Guo et al. (2013):

$$AREA_{0.2}=1.290\times AREA_{0.3}^{\;0.995} \quad (R^2=0.996) \quad (3)$$

$$CARBON_{0.2}=1.147\times CARBON_{0.3}^{0.996}\quad (R^2=0.996) \qquad (4)$$

where $AREA_{0.2}$ and $AREA_{0.3}$ are the forest areas ($10^4$ ha) with canopy coverages of 0.2 and 0.3, respectively, and $CARBON_{0.2}$ and $CARBON_{0.3}$ are the biomass C pools (Tg C) with crown densities of 0.2 and 0.3, respectively.

## 3 Results

### 3.1 Forest biomass C pool and its changes

The total forest biomass C stock, average biomass C density, and biomass C sink during 1977–2008 were 5447 Tg C, 39.6 Mg C ha$^{-1}$, and 63.3 Tg C yr$^{-1}$, respectively (Table 1). The corresponding values were 7525 Tg C, 44.6 Mg C ha$^{-1}$, and 154.8 Tg C yr$^{-1}$, respectively, during 2009–2018, making an increasing C sink of 91.5 Tg C yr$^{-1}$ (Table 1; Table S3). Compared with the forest biomass C pool during 1977–1981, it increased by 3258 Tg C (69.1%) during the four decades up to 2014–2018. The C density of forest biomass increased by 7.61 Mg C ha$^{-1}$ (19.9%) during 1977–2018 (Table 1, Figure 1). Meanwhile, the forest area increased by 41.0% from $1.24\times10^8$ ha during 1977–1981 to $1.74\times10^8$ ha during 2014–2018 (Table 1). All these changes had led to a large C sink of 180.2 Tg C yr$^{-1}$ in 2014–2018 (Table 1, Figure 1). In addition, the forest biomass C pool varied considerably across the different periods. It was found to have decreased by 2.9 Tg C yr$^{-1}$ over 1994–1998, which was thought to have been due to the decrease in the area of natural forest from 1994–1998 (Table 1 and 2, Figure 1).

The biomass C pools of planted forests and natural forests increased significantly during the study periods (Table 2). The biomass C pool of the planted forest increased from 250 Tg C in 1977–1981 to 1470 Tg C in 2014–2018. This indicated that biomass C sinks had an average increase of 33.0 Tg C yr$^{-1}$. The biomass C density of planted forests increased from 15.6 Mg C ha$^{-1}$ during 1977–1981 to 28.3 Mg C ha$^{-1}$ during 2014–2018. Compared with the previous three decades (1977–2008), the average biomass C density and C sink in the recent decade (2014–2018) increased by 4.6 Mg C ha$^{-1}$ and 10.0 Tg C yr$^{-1}$, respectively. For natural forests, the biomass C pool increased in most timesteps during the study periods. Especially in the recent 10 years, the biomass C sink of natural forests has grown rapidly, indicating 100.8 Tg C yr$^{-1}$ during 2009–2013 and 128.1 Tg C yr$^{-1}$ during 2014–2018 (Table 2). Compared with the previous three decades (1977–2008), the average biomass C density and C sink in the recent decade (2014–2018) increased by 7.8 Mg C ha$^{-1}$ and 81.5 Tg C yr$^{-1}$, respectively. From 1977 to 2018, the increase in the biomass C pool of natural forests was 2037 Tg C, indicating C sinks of 55.1 Tg C yr$^{-1}$ on average.

**Table 1** Forest area, biomass C pool, C density, and C sinks from 1977 to 2018

| Period | Forest parameter | | | |
|---|---|---|---|---|
| | Area $10^4$ ha | C pool Tg C | C density Mg C ha$^{-1}$ | C sink Tg C yr$^{-1}$ |
| 1977–1981 | 12350 | 4717 | 38.2 | |
| 1984–1988 | 13169 | 4885 | 37.1 | 23.9 |
| 1989–1993 | 13971 | 5402 | 38.7 | 103.5 |
| 1994–1998 | 13241 | 5388 | 40.7 | -2.9 |
| 1999–2003 | 14279 | 5862 | 41.1 | 94.9 |
| 2004–2008 | 15559 | 6427 | 41.3 | 112.9 |
| **Average** | | | | |
| **1977–2008** | **13762** | **5447** | **39.6** | **63.3** |
| 2009–2013 | 16349 | 7074 | 43.3 | 129.4 |
| 2014–2018 | 17409 | 7975 | 45.8 | 180.2 |
| **Average** | | | | |
| **2009–2018** | **16879** | **7525** | **44.6** | **154.8** |
| **Overall change** | | | | |
| **1977–2018** | **5059** | **3258** | **7.61** | **88.0** |

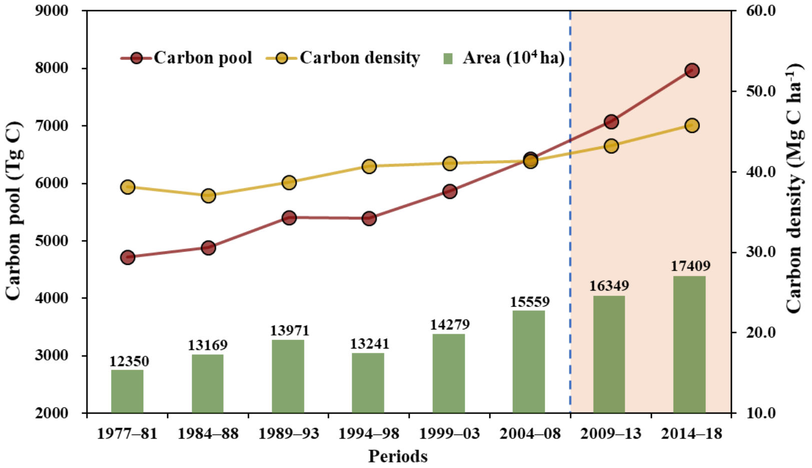

**Figure 1** Changes in the area, biomass C pool, and C density of forests from 1977 to 2018. The pink box highlights the results of the recent decade.

**Table 2** Area, biomass C pool, C density, and C sink of planted and natural forests

| Period | Planted forest | | | | Natural forest | | | |
|---|---|---|---|---|---|---|---|---|
| | Area | C pool | C density | C sink | Area | C pool | C density | C sink |
| | $10^4$ ha | Tg C | Mg C ha$^{-1}$ | Tg C yr$^{-1}$ | $10^4$ ha | Tg C | Mg C ha$^{-1}$ | Tg C yr$^{-1}$ |
| 1977–1981 | 1595 | 250 | 15.6 | | 10755 | 4468 | 41.5 | |
| 1984–1988 | 2347 | 418 | 17.8 | 24.1 | 10822 | 4467 | 41.3 | -0.1 |
| 1989–1993 | 2675 | 526 | 19.7 | 21.6 | 11296 | 4876 | 43.2 | 81.9 |
| 1994–1998 | 2914 | 642 | 22.0 | 23.3 | 10326 | 4746 | 46.0 | -26.2 |
| 1999–2003 | 3229 | 836 | 25.9 | 38.7 | 11049 | 5026 | 45.5 | 56.2 |
| 2004–2008 | 4000 | 1067 | 26.7 | 46.2 | 11559 | 5360 | 46.4 | 66.7 |
| **Average 1977–2008** | **2794** | **623** | **22.3** | **30.3** | **10968** | **4824** | **44.0** | **33.0** |
| 2009–2013 | 4665 | 1183 | 25.4 | 23.3 | 11685 | 5864 | 50.2 | 100.8 |
| 2014–2018 | 5193 | 1470 | 28.3 | 57.3 | 12212 | 6505 | 53.3 | 128.1 |
| **Average 2009–2018** | **4931** | **1327** | **26.9** | **40.3** | **11948** | **6185** | **51.8** | **114.5** |
| **Overall change 1977–2018** | | | | **33.0** | | | | **55.1** |

## 3.2 Changes in biomass C pools in different zonal forest types

Compared with 1977–2008, temperate coniferous forest, temperate deciduous broad-leaved forest and evergreen broad-leaved forest all presented larger area during 2009–2018. With the exception of the temperate deciduous broad-leaved forest, the C sinks of four of the five forest types increased in the recent 10 years (2009–2018) in comparison to 1977–2008 (Table 3). In particular, the biomass C sink of evergreen broad-leaved forests during 2009–2018 was 84.6 Tg C yr$^{-1}$, which is much higher than the average C sink for the previous 30 years (22.8 Tg C yr$^{-1}$, 1977–2008). The C pool of the evergreen broad-leaved forest reached 2747 Tg C during 2014–2018 (Table 3, Table S2). Overall changes in the biomass C pools from 1977 to 2018 indicated that, with the exception of cold-temperate coniferous forests, the biomass C pools of four out of the five forest types all increased. The largest increase took place in the evergreen broad-leaved forest (1463 Tg C), which had an average annual C sink of 39.5 Tg C yr$^{-1}$ (Table S2). For more details about the area, C pool, C density and C sinks between 1977 and 2018, please refer to Table S2.

**Table 3** Area, biomass C pool, C density, and average C sink of different zonal forest types in the recent decade compared to the previous 30 years*

| Zonal forest types | Periods | Area<br>$10^4$ ha | C pool<br>Tg C | C density<br>Mg C $ha^{-1}$ | C sink<br>Tg C $yr^{-1}$ |
|---|---|---|---|---|---|
| Cold-temperate coniferous forest | 1977–2008 | 2080 | 1461 | 70.2 | -8.2 |
| | 2009–2018 | 1844 | 1321 | 71.6 | 11.3 |
| Temperate coniferous forest | 1977–2008 | 1125 | 381 | 33.9 | 9.9 |
| | 2009–2018 | 1740 | 652 | 37.5 | 13.7 |
| Temperate deciduous broad-leaved forest | 1977–2008 | 3614 | 1430 | 39.6 | 26.2 |
| | 2009–2018 | 3714 | 1730 | 46.6 | 19.5 |
| Temperate/subtropical mixed forest | 1977–2008 | 3989 | 975 | 24.4 | 12.6 |
| | 2009–2018 | 3834 | 1308 | 34.1 | 25.7 |
| Evergreen broad-leaved forest | 1977–2008 | 2953 | 1200 | 40.7 | 22.8 |
| | 2009–2018 | 5748 | 2515 | 43.7 | 84.6 |

* The average C sink for the previous 30 years was calculated by dividing the difference between the 2004–2008 and 1977–1981 C pools by 27. The average C sink over the recent decade was calculated by dividing the difference between the 2014–2018 and 2004–2008 C pools by 10.

### 3.3 Biomass C sequestration in different forest age groups

In the original national forest inventory, only three age groups were recognised, namely young forests, middle-aged forests, and old-aged forests. In the subsequent inventories (after 1984), forests were categorized into five different age groups as we mentioned above (Table S6). To facilitate the comparison of different periods, we grouped the premature forest, mature forest, and overmature forest into one forest age group—old-aged forest. The young and middle-aged forests remained unchanged. The 3 classes are aggregated from the 5 classes.

The growth rate by area and C pool of all forest age groups over the recent 10 years (2009–2018) were higher than those for the previous 30 years (1977–2008). In addition, the forest area and C pool for each age group reached the highest level recorded during 2014–2018. The area and C pool of old-aged forests were both the largest, at $6.33\times10^7$ ha and 4387 Tg C, respectively (Figure 2). The area of young, middle-aged, and old-aged forests increased from 1977 to 2018 by $1.47\times10^7$ ha, $1.08\times10^7$ ha, and $2.51\times10^7$ ha, respectively (Figure 2,

Table S5). Meanwhile, the C pools increased by 657 Tg C, 791 Tg C, and 1810 Tg C, respectively (Figure 2, Table S5). The biomass C densities of young, middle-aged, and old-aged forests increased by 7.9, 7.5, and 1.9 Mg C ha$^{-1}$, respectively (Figure 2, Table S5).

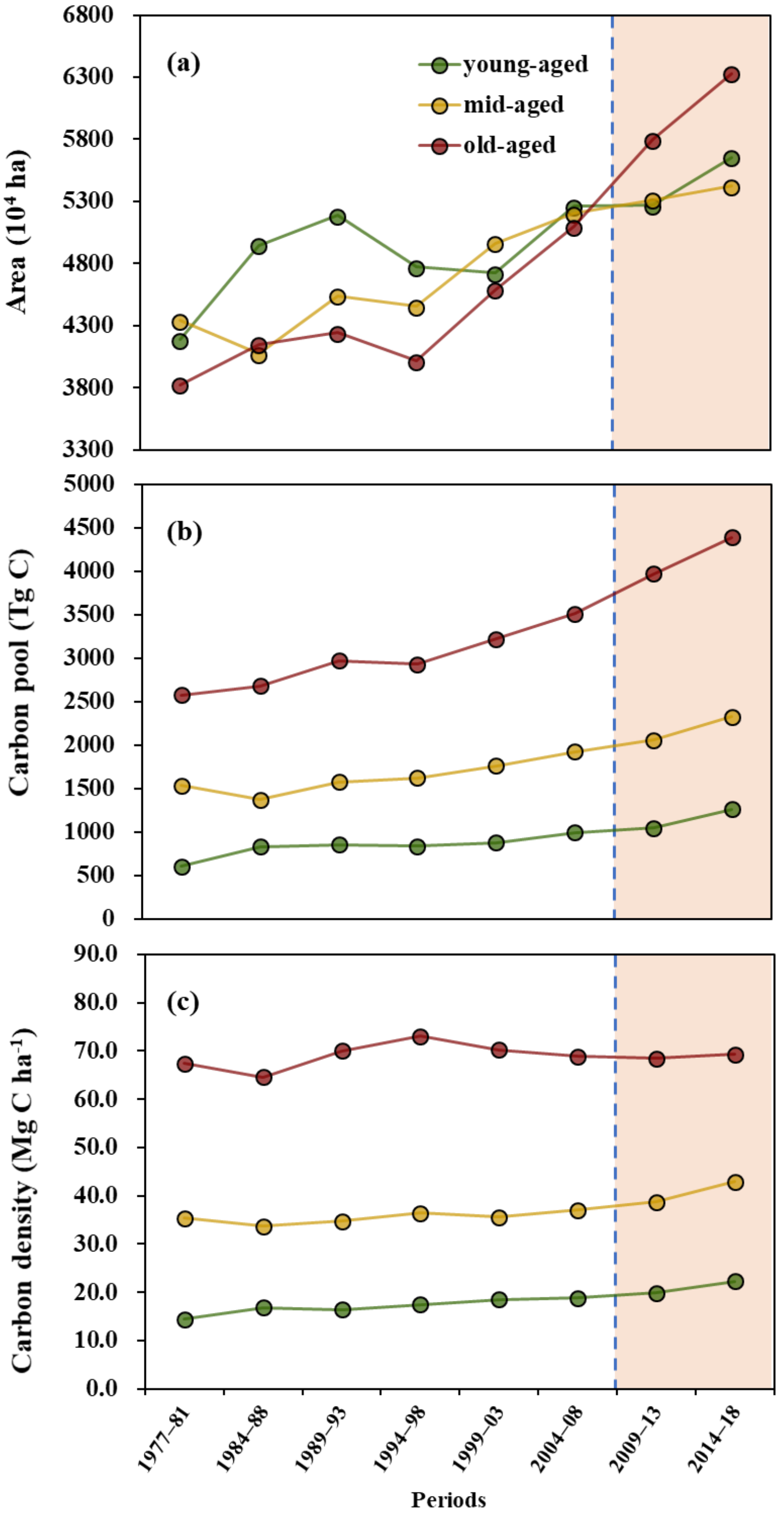

**Figure 2** Changes in area (a), C pool (b) and C density (c) of forest for each age group from 1977 to 2018. The pink box highlights the latest results from the recent ten years.

## 4 Discussion

### 4.1 China's forest C sink size

National forest inventories provide the most comprehensive statistical and temporal datasets for investigating forest change. Using data from eight forest inventories including the most recent forest inventory period of 2014–2018, this study provided an updated estimate of China's forest biomass C pool, and obtained how it has varied over the last 40 years (1977–2018). Our results showed that the latest forest biomass C pool (7975 Tg C, 2014–2018) was much larger than 4717 Tg C from 1977–1981, with an increase of 3258 Tg C (69.1%), and accordingly, the C sink averaged 88.0 Tg C yr$^{-1}$. In particular, the biomass C pool increased by 154.8 Tg C per year during the period of 2009–2018, which was significantly higher than the average C sequestration rate of 63.3 Tg C yr$^{-1}$ in the earlier three decades (1977–2008). In summary, China's forests acted as a significant C sink in biomass during 1977–2018, while the C sink was further enhanced in the most recent decade.

In terms of the order of magnitude, our estimates of biomass C stocks are comparable with those from previous studies (e.g., Fang et al., 2007; Zhang et al., 2013; Li et al., 2015; Zhang et al., 2021; Zhao et al., 2019, 2021), while there are some discrepancies between the size of the C pool in this study and those reported by others. In particular, most studies provided smaller estimates than ours in the periods prior to 1994 (Table S7). This may be due to methodological differences in the conversion of canopy coverage criteria. Some studies did not consider the shift from the old criterion (>0.3 canopy coverage) to the new criterion (>0.2 canopy coverage), which led to shrinking forest areas and thus significant underestimation of the C pool in the earlier periods (e.g., Li et al., 2015; Zhang et al., 2021). Others used a linear model proposed by Fang et al. (2007) to correct the inventory data (e.g., Zhang et al., 2013; Zhao et al., 2019, 2021), while the linear conversion equations would underestimate forest areas and biomass C stocks in the provinces with large amounts of forests (Figure S1). Obviously, these underestimates would inevitably induce previous studies to report higher C sinks than those of this study. Moreover, the divergences in BEF model parameters, root to shoot ratio, and C conversion factor would also contribute to the discrepancies among the estimates of C stocks, thus inducing the different C sequestration rates (e.g., Zhao et al., 2019, 2021).

Despite the differences in the estimates of biomass C stocks and their changes, most previous studies, and this work all agreed that the average biomass C sink of China's forests since the 1980s is approximately 100 Tg C yr$^{-1}$. In addition, several studies based on field investigations pointed out that both the dead organic matter and soils in China's forest also functioned as C sinks over the past four decades, with average values of 6.7 and 57.3 Tg C yr$^{-1}$, respectively (Zhu et al., 2017; Yang et al., 2014; Fang et al., 2018). Together with the biomass C sink estimated in this study, it suggested that China's forest ecosystems would sequester approximately 100–200 Tg C yr$^{-1}$ in total over the last four decades. Recently, some studies based on "top-down" atmospheric inversions reported that the net land C sink of China could reach 0.8–1.1 Pg C yr$^{-1}$ during the 2010s, and suggested that this large sink was mainly attributed to forest ecosystems (Wang et al., 2020, 2022). However, according to the size of the forest C sink we mentioned above, that large C sink could not be supported by this and other studies based on field investigations including national forest inventories.

### 4.2 Potential influencing factors of biomass C sinks

As we mentioned above, China's forests presented an enhanced biomass C sink in most provinces during the recent decade (Table S3). Further analyses of this study showed that the enhancement of the biomass C sink widely occurred in China's forests during 2009–2018 (Table S3), although the enhancing extent would be different between forest stand origins or among forest zonal types/age-groups (Table 2, 3, S7). It has been demonstrated that forest area expansion and increased forest growth jointly contributed to the enhancement of China's forest C sink, in which area expansion contributed more to planted forests while forest growth was a great contributor to natural forests (Fang et al., 2014a; Li et al., 2016). This conclusion could also explain the enhanced C sink during the period of 2009–2018 observed in this study. Our results showed that between the 7th Forest Inventory (2004–2008) and the 9th Forest Inventory (2014–2018), the area of planted forest increased by 30% (from $0.40\times10^8$ to $0.52\times10^8$ ha), while the C sink increased by only 24% (from 46.2 to 57.3 Tg C yr$^{-1}$) during the same period, indicating that area expansion is the main factor driving the enhanced C sink of planted forests (Table 2). In contrast, the area of natural forest increased by only approximately 6% (from $1.15\times10^8$ to $1.22\times10^8$ ha), but the corresponding C sink nearly doubled (from 66.7 to 128.1 Tg C yr$^{-1}$) (Table 2), suggesting that the enhanced C sink of natural forests is mainly contributed by forest growth rather than area expansion.

The area expansion of China's forest could be largely due to national ecological projects. Since the late 1970s, China has launched six key national ecological projects to restore degraded ecosystems, and to protect the country's environment (Lu et al., 2018). Within the framework of these projects, large-scale afforestation and reforestation have been conducted, which contributed 71.2% of the total forest area expansion in China during 1977–2018 (Table 2), resulting China having the largest planted forest area in the world (Guo et al., 2013; Lu et al., 2018). Obviously, such area expansion, which was mainly led by ecological projects, would promote the increase in the biomass C sink in China's forests, especially in planted forests.

The increased growth in China's forest could be due to several reasons. On the one hand, environmental changes (e.g., elevated $CO_2$, climatic change, nitrogen deposition, etc.) may be an important reason for the increase in China's forest growth over the recent decade (Piao et al., 2009a, b; Tian et al., 2011; Pan et al., 2011, 2013; Fang et al., 2014b; Liu et al., 2021). We noticed that differing from what happened in the old-aged forest, in which the C density remained roughly steady, the C densities in the young- and middle-aged forests showed a significant increase from 1977 to 2018, especially during 2009–2018 (Figure 2). A previous study pointed out that such an increase in the C density of the forest at an age-stage often means accelerated tree growth induced by environmental changes (Fang et al., 2014b). Meanwhile, after excluding the potential impacts from tree species and forest age, our regression analysis showed that the average C density presented significantly positive relationships with atmospheric $CO_2$ concentration, mean annual temperature (MAT), and nitrogen deposition (Figure S2), which could also reflect the promoting effect of elevated $CO_2$, rising temperature and increased nitrogen deposition on forest growth. Over the past four decades, China's forests have experienced significant increases in $CO_2$ concentration (Global Monitoring Laboratory, https://www.gml.noaa.gov/), MAT (China Meteorological Data Service Center, https://data.cma.cn/data/index.html) and nitrogen deposition (Eyring et al., 2013), which have increased from 342 ppm, 10.5 °C and 0.8 g N $m^{-2}$ during the first five years of the 1980s to 404 ppm, 11.6 °C and 1.4 g N $m^{-2}$ during 2014–2018, respectively. In particular, the annual mean growth rates of $CO_2$ and MAT in the most recent decade (2.29 ppm $yr^{-1}$ and 0.07 °C $yr^{-1}$, respectively) were greater than those in the previous three decades (1.68 ppm $yr^{-1}$ and 0.04 °C $yr^{-1}$, respectively). All these changes would accelerate the growth of forests in China, and thus lead to the enhanced biomass C sink in the past 40 years, especially in the most recent decade.

On the other hand, the implementation of ecological projects could be another important reason for the increased forest growth in China. These projects implemented a series of forest management practices, such as forest enclosure, tending, and reduction of timber harvesting, to promote the growth of forests and achieved remarkable effects (Xu et al., 2017; Fang et al., 2018; Lu et al., 2018). For example, due to the illegal occupation of forestland and vast excessive logging, China's natural forest experienced a sharp decline in the area during the period of 1994–1998 (Table 2) (National Forestry Administration, 2000). Although the stock volume density and C density continued to rise, the severely shrinking area induced reductions in forest stock volumes and C stocks (Table 2). Thus, the government launched the Natural Forest Protection project in 1998 (National Forestry Administration, 2000). As a result, the area and biomass C pool of natural forests increased greatly from 1.03 $\times 10^8$ ha and 4746 Tg C during 1994–1998 to 1.22 $\times 10^8$ ha and 6505 Tg C during 2014–2018, respectively (Table 2). Meanwhile, in the recent decade, extensive young forests planted by these projects have gradually entered the middle-aged or premature stages, in which forests usually have rapid growth rates (Guo et al., 2013). Our results showed that during 1977–2018, the areas of middle- and old-aged forests expanded from $4.3\times 10^7$ and $3.8\times 10^7$ ha to $5.4\times 10^7$ and $6.3\times 10^7$ ha, respectively (Figure 2, Table S5), suggesting that a large area of young forests entered a rapid growth stage with high C sequestration ability. The large C sinks brought by these forests could be an important source of power for China's forest C sinks after 2010 (Cai et al., 2021; Yu et al., 2021).

## 4.3 Effects of human intervention on forest C sink management

In current forest C sink management, human intervention exists in many aspects, among which the most important is the cultivation of planted forest. Planted forests play a critical role in enhancing ecosystem services, absorbing atmospheric $CO_2$, and mitigating climate change (Fang et al., 2001; Li et al., 2018, 2019; Lu et al., 2018; Tang et al., 2018). In this study, we found that China's planted forest is an important C sink, acting as the main source of the forest C sink in nearly half of China's provinces (Table S4), and currently contributing more than 30% of the total forest biomass C sink across the whole country (Table 2). This result proved that afforestation indeed promoted the growth of China's forest C sink.

However, it could be easy to fall into the misunderstanding of using this result to prove the success of China's afforestation and further overemphasize its importance in forest C sink management. The national forest inventory only records the forest stands that are successfully established and last retained, thus the area of planted forest would be much less than the actual afforestation area. From 1977 to 2018, the cumulative afforestation area in China was approximately $1.9\times 10^8$ ha, nearly four times the current planted forest (National Forestry and Grasslands Administration, 2019a). This implied that most of the trees cultivated in afforestation projects have failed to survive to the current moment. This situation is particularly widespread in the vast arid and semi-arid regions of China. Compared with natural forests, planted forests are more sensitive and vulnerable to drought stress because of their high transpiration rate, high plant density and low biodiversity (Isbell et al., 2015; Martin-Benito et al.,2010; Zhong et al., 2021). Therefore, planted forests in arid and semi-arid regions such as Northwest China generally present low survival rates due to frequent drought events (Cao et al., 2008, 2011; Wang et al., 2020; Zhang et al., 2022). Although people try to improve the survival rate of trees by selecting an appropriate afforestation method, choosing proper tree species, and cooperating with a series of management measures, such as the application of fertilizer and irrigation, tending operations, etc. (Liu et al., 2016; Zhou et al., 2013), it is still a significant challenge to achieve successful afforestation in the arid and semi-arid regions of China (Wang et al., 2014; Yu et al., 2019; Zhong et al., 2021; Zhou et al., 2013). Currently, most of the land available for afforestation in China is distributed in arid and semi-arid regions or other regions with poor site conditions (Zhang et al., 2018a), which would be bound to greatly decrease in the success rate of afforestation. Thus, the realizability of enhancing forest C sinks through large-scale afforestation must be carefully evaluated in the future.

Compared with the implementation of large-scale afforestation, our results suggested that enhancing the regeneration of old-growth forests, especially those in natural forests, would be of greater significance for the future management of forest C sinks. We noticed that from 1977 to 2018, the biomass C density of old-aged forests generally remained stable (Table 2). This result suggested that the observed C sink of old-aged forests would mainly derive from their area expansion, i.e., the transformation from young- and middle-aged forests to old-aged forests, rather than forest growth. Due to the high mortality rate of old-growth trees, old-aged forests, especially overmature forests would even present a decline in C density, thus leading to a negative contribution to the C sink (Zhao et al., 2021). Therefore, for old-aged forests, it is necessary to properly adopt practices such as thinning, selective cutting, sanitary cutting, and reforestation (Zhao et al., 2021) to maintain a healthy state, avoid C release caused by the large-scale death of trees, and promote their regeneration to function as a significant C sink. This would be critical for the maintenance and management of forest C sinks. Of course, such artificial regeneration practices would inevitably remove biomass C from forests, but it does not mean an equivalent amount of C release because C in harvesting timbers is often turned into deposited C in wood products, e.g., furniture, house building, instruments, etc., which could exist for tens or even hundreds of years (Skog, 2008; van Deusen, 2010; Zhang et al., 2018b), providing sufficient growth time for young trees after regeneration. However, it should be noted that several studies have found that ageing forests could still maintain rising

C densities, although their biomass C accumulation rates gradually decreased (Cao et al., 2012; Luyssaert et al., 2008; Yue et al., 2018; Zhao et al., 2014). Thus, the adoption of artificial regeneration practices in old-aged forests also needs to be carefully evaluated to avoid unnecessary C release.

## 4.4 Uncertainty of estimations

The estimation involved in the study is presented with some uncertainties. In general, the national forest inventory data were assumed to have small errors of less than 5% (Fang et al., 2001). The survey accuracy of the forest area and timber volume was over 90% (National Forestry and Grasslands Administration, 2019b). The method used to calculate biomass from surveyed stand volume data, and the $R^2$ of the BEF function [Eq. (1) and (2)] of the dominant tree species was higher than 0.80 (Table S1), suggesting that our estimates of forest biomass were statistically reliable. Previous studies have shown that the estimated error of forest biomass at the national scale using the BEF function is unlikely to exceed 3% (Fang & Chen, 2001; Fang et al., 1996, 2002). A constant C conversion factor of 0.5 may introduce a systematic error of -5.9%–2.5% (Ma et al., 2020). Despite these uncertainties, the results of this study provide relatively high accuracy and a comprehensive assessment of the forest C budget.

## 5 Conclusions

In this study, we estimated forest biomass C storage and its changes in China over the past 40 years (1977–2018) and updated their estimates in the most recent decade (2009–2018) using the biomass expansion factor method and eight national forest inventories conducted every five years. We concluded that the Chinese forest biomass C pool increased by 3258 Tg C with an annual C sink of 88.0 Tg C $yr^{-1}$ from 1977 to 2018. The biomass C pool and C sink in the recent 10 years (7525 Tg C and 154.8 Tg C $yr^{-1}$, 2009–2018) were much higher than those of the previous 30 years (5447 Tg C and 63.3 Tg C $yr^{-1}$, 1977–2008), although the C sink strength displayed large variations in different periods. Afforestation practices, forest growth, and environmental changes were proposed as the main drivers of this significant C increase especially in the recent decade. Our study updates the previous estimates of China’s forest C storage and its changes and provides an essential basis for policy-making for ecosystem services and the carbon neutrality target in China.

## Author contribution

JY Fang and C Yang designed the study, C Yang and Y Shi analysed the data, ZD Guo provided part of datasets, WJ Sun, Y Shi, JL Zhu, CJ J, YH Feng, SH Ma, and JY Fang wrote the manuscript and gave final approval for publication.

## Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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