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Estimation of the relative contributions of forest areal expansion and growth to China's forest stand biomass carbon sequestration from 1977 to 2018

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ABSTRACT

As a prominent part of global and regional terrestrial carbon (C) pools, increases in forest biomass C sinks can be attributed to either forest areal expansion (FAE) or increased biomass C density (IBCD). Accurate estimates of the relative contributions of FAE and IBCD to forest C sequestration can improve our understanding of forest C cycling processes and will help to formulate rational afforestation policies to cope with global warming. In this study, the Continuous Biomass Expansion Factor (CBEF) model and Forest Identity concept were used to map the spatiotemporal variation of the relative contribution of FAE and IBCD to the C sequestration of forest (natural and planted forests) in China and seven regions during the past 40 years. Our results suggest that: (1) total forest biomass C density and stocks of forest increased from 35.41 Mg C ha^{-1} and 4128.50 Tg C to 43.95 Mg C ha^{-1} and 7906.23 Tg C in China from 1977 to 2018, respectively; (2) for all forests, the IBCD has been a smaller contributor to C sinks than FAE in China from 1977 to 2018 (33.27 vs. 66.73%); (3) the contribution of FAE to C sinks is greater than that of IBCD in planted forests (63.99 vs. 36.01%), while in natural forests, IBCD has a larger contribution than FAE (57.82 vs. 42.18%) from 1977 to 2018 and the relative contribution of FAE has exceeded IBCD in the last decade; and (4) these patterns varied at the regional level such that the relative contribution of FAE increased for planted forests in most regions but for natural forests, IBCD gradually reached saturation and C stocks declined in northern regions in the last decade. The results from this study suggest that total biomass C sinks will keep increasing because of the increased forest area contributed by afforestation and the relatively young trees in planted forests. This study facilitates a more comprehensive assessment of forest C budgets and improves our understanding of ecological mechanisms of forest biomass carbon stock and dynamics.

1. Introduction

As an important contributor to carbon (C) sequestration in terrestrial ecosystems, forests are considered one of the most economical and effective ways to mitigate the effects of climate change (Bonan et al., 2008; Arneth et al., 2010; Pan et al., 2011; Qin et al., 2019; Zhao et al., 2019). Statistically, China's forest area accounted for 22.96% of the land surface in 2018 and it has the largest planted forest in the world (FAO, 2010; Chinese Ministry of Forestry, 2019). During the past two decades, numerous studies have shown that Chinese forests function as

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significant C sinks notwithstanding large spatial and temporal differences (Fang et al., 2001, 2007; Piao et al., 2005, 2009; Ju et al., 2007; Wang et al., 2007; Zhang et al., 2015; Chen et al., 2019). In general, the sequestration of C by forests has been attributed to forest areal expansion (FAE) and increased biomass C density (IBCD) (Guo et al., 2013; Fang et al., 2014; Li et al., 2016).

Fang et al. (2014) proposed a method to separate the relative contributions of FAE and IBCD to the changes of forest biomass C storage that used the Forest Identity concept developed by Kauppi et al. (2006) and Waggoner (2008) to explore the influence of variables contributing to changes in C sinks in east Asia. Using the same method, Li et al. (2016) analyzed the spatial and temporal variability of the relative contributions of FAE and IBCD to China's forest C sinks from 1977 to 2008. These studies found that the contribution of FAE to C sinks is greater than that of IBCD and the relative contributions of the two factors varied across different geographical locations and forest types (natural vs. planted forests) (Fang et al., 2014; Li et al., 2016). However, the relative contributions varied through time, especially in the last decade, forests have been saturated with C density (it has declined or stopped increasing) in some regions (Nabuurs et al., 2013; Chen et al., 2019; Tong et al., 2020), so that detailed analysis of the spatial and temporal variability of the relative contributions is essential for understanding the mechanisms, dynamics, and processes of the terrestrial ecosystem C cycle (Goodale et al., 2002; Birdsey et al., 2006; Fang et al., 2010; McKinley et al., 2011; Lu et al., 2019; Ming et al., 2019; Zhao et al., 2019). In addition, the most recent spatiotemporal distribution of the relative contributions of FAE and IBCD in China has not been reported until now.

Forest C sequestration is affected by anthropogenic activities (He et al., 2015). Since the 1970s, China has pursued afforestation projects and forest C stocks increased by 40% during the first 30 years. Carbon sinks have doubled in areas where forest projects have been implemented during the past decade as well (Fang et al., 2014, 2018; Lu et al., 2018). China's forest coverage is expected to grow to 26% of the total land surface by 2050 (Xu et al., 2007, 2010, 2010; Liu et al., 2014; Hu et al., 2015). Generally, forest inventories are recognized as the most accurate method to assess forest C sinks at regional scales (Fang et al., 2001, 2007; Pan et al., 2004, 2011; Zhang et al., 2013, 2015). In addition, the method for estimating forest C stocks that uses the allometric relationships between forest biomass and timber volume developed by Fang et al. (2001) has been widely applied (e.g. Fang et al., 2007, 2014; Zhang et al., 2015). Most of the studies that have used this approach have assumed that the C fraction of forest biomass was 0.5, notwithstanding the likelihood it varies across different forests and tree species (and for that matter different climate zones). For example, the C fraction of *TILIA Tuan Szyszyl* is 0.4392 and *Cryptomeria Fortunei* is 0.5235 (Zhao et al., 2019). Therefore, by using a single C coefficient, the error associated with the estimation of forest C sinks may be as much as 20% (Fang et al., 2001, 2007, 2014; Ma et al., 2002; Ju et al., 2007; Li and Lei, 2010; Tian, 2011; Pan et al., 2011; Zhang et al., 2013, 2015). Zhao et al. (2019) collected C fraction coefficients for 46 forest types based on a literature review and used them with the data from the 7 national forest inventories to calculate forest C density and C stocks.

In this study, we update forest C stocks and C density to include the 2014–2018 forest inventory by the method in Zhao et al. (2019) and thereby include eight forest inventory datasets. Meanwhile, we quantified the spatiotemporal variation of the change rates and relative contributions of IBCD and FAE by combining the forest inventory data with the Forest Identity concept, to explore the possible mechanisms for forest biomass C dynamics from 1977 to 2018 and compared the variation of the relative contributions of IBCD and FAE in natural and planted forests during the periods of 2004–2018 and 1977–2018 in China and seven regions. Moreover, we discuss the reasons why China's future forest biomass C sinks will show an increasing trend moving forward.

2. Materials and methods

2.1. Forest inventory datasets

China has implemented national forest inventories every five years since the 1970s. This study uses inventory data from eight periods: 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, 2009–2013 and 2014–2018 (Chinese Ministry of Forestry, 1983, 1989, 1994, 2000, 2005, 2010, 2014, 2019). The National Forest Inventory relies on a forest resource survey method that uses strict technical protocols and permanent sample plots to conduct regular re-inspections by province. The permanent sample plots are systematically sampled and arranged at the intersection of the one-fifty thousandth or one-hundred thousandth kilometer network of the new national topographic map. Modern geospatial technologies (GPS, GIS) support the sampling. The shape of the permanent sample plot is generally square, and the area is generally 0.0667 ha. At 20 km*20 km intervals across the country, the system collects data for about 24,000 permanent sample plots to survey tree species and vegetation cover (Fang et al., 2001, 2007). China's forests are divided into three types: forest stands (including natural and planted forests), economic forests and bamboo forests. The inventories document forest area and timber volume by age group (young, middle-aged, premature, mature, and over-mature) and forest type at the provincial level (Li et al., 2016). In this study, we divided the country into seven regions (Fig. 1) (Northern, Northwestern, Northeastern, Southwestern, Eastern, Central and Southern) and considered the forest stands with canopy coverage ≥20%, and the DBH (Diameter at Breast Height) ≥5 cm (Zhao et al., 2019; Fang et al., 2007).

2.2. Biomass C stocks estimation of forest stands

Based on forest inventory datasets, we used the refined Continuous Biomass Expansion Factor (CBEF) model with parameters taken from Zhang et al. (2013, 2015) and refined fraction of carbon (CF) for each tree type from Zhao et al. (2019) to calculate forest stands biomass C stocks. This method uses the allometric equation connecting biomass and timber volume put forward by Fang et al. (1998, 2001) and the refined the parameters (a, b) provided by Zhang et al. (2013) from published literature as follows:

$$M = (a \cdot V + b) \cdot A \cdot CF \tag{1}$$

where M is the total forest stand aboveground C stocks (Tg C); V is the stand volume (m^3 ha^{-1}); A is forest area (ha); a and b are coefficients for specific forest types (Appendix S1); and CF is the carbon fraction (Appendix S2).

Since 1994, the canopy coverage threshold used to delineate forests in China has been changed from >30% to >20%. To study the temporal dynamics of forest biomass, we used the method proposed by Fang et al. (2007) to correct forest biomass C stocks and area at the provincial level for the three inventories before 1994.

2.3. Valuation of the relative contributions of FAE and IBCD to C stocks

Due to the complexity of forest ecosystems, there are often many species types in a region which makes it difficult to consider the sources of specific forest type carbon sinks in specific regions. We take the forest as a whole and estimate the relative contribution of forest area expansion and forest growth to C sink at the provincial level. Fang et al. (2014) used the Forest Identity concept (Kauppi et al., 2006; Waggoner, 2008) to separate the relative contributions of changes in IBCD and FAE to forest biomass C stocks for a region. Based on the equations in Fang et al. (2014) and (Li et al. (2016)), the relationship between total biomass C stocks (M, Tg C), forest area (A, ha) and biomass C density (D, Mg C ha^{-1}) in one region can be described by Eq. (2), and their respective

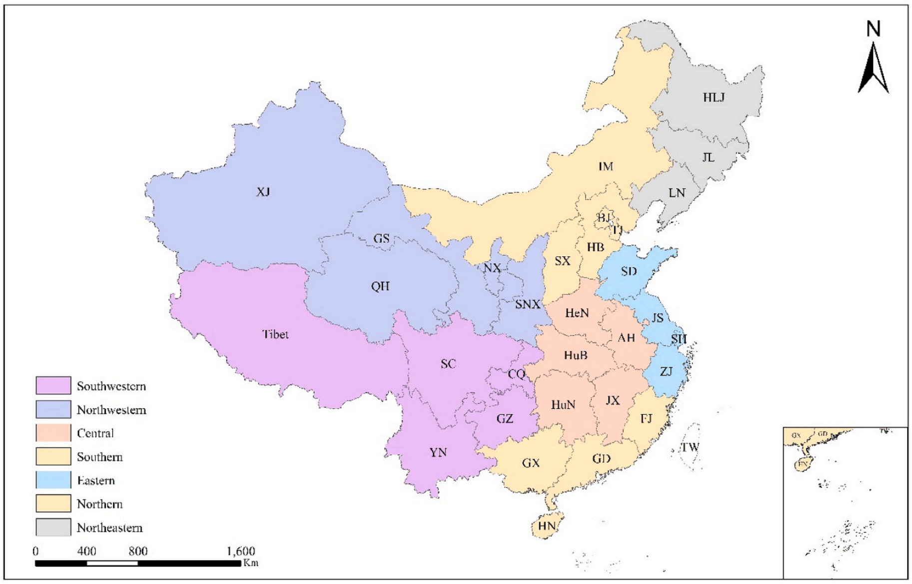

Fig. 1. Seven regions of China.

change rates (m, a, and d) over time (t) can be derived from Eqs. (3) and (4).

$$M = A \times B \tag{2}$$

Given that $\ln(M) = \ln(A) + \ln(D)$, the relative change rates (m, a, and d) of M, A, D should be:

$$\frac{d\ln(M)}{dt} = \frac{d\ln(A)}{dt} + \frac{d\ln(D)}{dt} \tag{3}$$

and therefore:

$$m \approx \frac{d\ln(M)}{dt},\ a \approx \frac{d\ln(A)}{dt}, d \approx \frac{d\ln(D)}{dt} \tag{4}$$

where $m = a + d$.,

Therefore, the relative contribution of IBCD (R_d, %) and FAE (R_a, %) to the forest C sinks can be denoted as Eq. (5) (Li et al., 2016):

$$R_a\ (\%) = \frac{a}{m} \times 100; R_d(\%) = \frac{d}{m} \times 100 \tag{5}$$

and the C sinks attributed to area expansion (M_a) and forest growth (M_d) are as follows:

$$M_a = R_a(\%) \times \delta M, M_d = R_d(\%) \times \delta M \tag{6}$$

3. Results

3.1. Relative contributions of FAE and IBCD to forest biomass C sequestration in China

During the period 1977–1981 to 2014–2018, the forest area increased by 6328.38 × 10^4 ha, growing by 1.47% per year on average (Table 1). At the same time, the size of the forest stand biomass C stocks has nearly doubled, increasing with some fluctuations from 4128.50 to 7906.23 Tg C, indicating an average rate of biomass C sequestration of 102.10 Tg C yr^{-1} (Table 1). From 1977 to 2018, the biomass C density of forest decreased slightly due to the harvest of mature forests during the first four periods but later increased, leading to an average rate of change of 0.65% per year, and an overall change in density from 35.41 to 43.95 Mg C ha^{-1} from 1977 to 1981 to 2014–2018. The results summarized in Table 1 show that the contribution of FAE to forest biomass C sinks is greater than that of IBCD (66.73 vs. 33.27%) and the increases in the forest biomass C sinks that are attributable to FAE and IBCD were 2520.75 and 1256.98 Tg C, respectively. The results also show that the change rates and relative contributions of the contributing factors varied in different time periods. For example, there is just one period in which IBCD contributes more to C sequestration than FAE, due to the reduction of deforestation from 1999 to 2003 to 2004–2008 (Fang et al., 2014, 2018, 2018; Li et al., 2016). From the period 1999–2003 onwards, the change rates and relative contribution of FAE to forest C

Table 1
Summary of forest variables in eight inventory periods.

Periods	Area (A) (10^4ha)	Carbon stock (M) (Tg C)	Density(D) (Mg C ha^{-1})	Net carbon change (Tg C yr^{-1})	a (% yr^{-1})	D (% yr^{-1})	R_a (%)	R_d (%)	M_a (Tg C)	M_d (Tg C)
1977–1981	11,660.47	4128.50	35.41	–	–	–	–	–	–	–
1984–1988	12,452.83	4161.49	33.42	4.71	0.94	−0.83	826.02	−726.02	272.50	−239.51
1989–1993	13,216.01	4510.46	34.13	69.79	1.19	0.42	73.87	26.13	257.77	91.20
1994–1998	12,919.94	4478.91	34.67	−6.31	−0.45	0.31	322.76	−222.76	−101.83	70.28
1999–2003	14,278.67	5375.01	37.64	179.22	2.00	1.65	54.83	45.17	491.31	404.79
2004–2008	15,558.99	6629.81	42.61	250.96	1.72	2.48	40.93	59.07	513.55	741.25
2009–2013	16,460.35	7375.14	44.81	149.06	1.13	1.00	52.86	47.14	393.98	351.35
2014–2018	17,988.85	7906.23	43.95	106.22	1.78	−0.39	127.70	−27.70	678.20	−147.10
1977–2018	–	–	–	102.10	1.17	0.58	66.73	33.27	2520.75	1256.98

*a: forest area change rate; d: forest C density change rate; R_a: relative contribution of FAE to C sinks; R_d: relative contribution of IBCD to C sinks; M_a: C sinks attributed to FAE; M_d: C sinks attributed to IBCD.

sinks have shown an increasing trend, which can be attributed to the initiation of the "Grain for Green" program in 1998.

3.2. Spatiotemporal variation in the relative contributions of FAE and IBCD to C sequestration

There are considerable regional differences in the rates of change and relative contributions of FAE and IBCD to the C sinks from 1977 to 1981 to 2014–2018 (Appendix S3; S4). From 1977 to 2018, the rates of change of FAE and IBCD were positive in all regions. The eastern region had the smallest forest area (713.54×10^4 ha in 2014–2018) and C sinks (4.87 Tg C yr^{-1}) of the seven regions, but the fastest growth in biomass C density with a mean rate of 2.20% per year from 1977 to 2018. The largest FAE occurred in the southwestern region (1.88% yr^{-1}, 4910.24×10^4 ha in 2014–2018) and this region had the largest C sinks (40.56 Tg C yr^{-1}) and largest forest area of the seven regions in 2018. The rate of change in IBCD was greater than FAE in the central, northeastern, and eastern regions from 1977 to 2018. The relative contribution of IBCD to the C sinks is greater than FAE in the aforementioned three regions, but for other regions, the relationships between the change of IBCD and FAE were reversed during the entire study period. The southwestern region has the largest difference in terms of the relative contribution to C sinks between FAE and IBCD from 1977 to 2018, with contributions of 85.79 and 14.21%, respectively. The northern and southern regions came next, with IBCD (63.92%) dominating in terms of its contribution to the C sinks in the northern region and FAE (62.80%) dominating in terms of its contribution to the C sinks in the southern region from 1977 to 2018.

The rates of change of FAE and IBCD or one of the two were negative in all regions in one or more periods from 1977 to 2018. Specifically, forest biomass density showed negative growth (i.e. C loss) in various regions except the northern and eastern regions from 1981 to 1988. Similarly, during the period 1993–1998, forest area dropped sharply in the northern, northeastern, northwestern and eastern regions and growth slowed in the southwestern and southern regions. From 1998 to 2003, forest area and biomass density start to increase, especially biomass density which displayed the largest increases in all but the northwestern region during the subsequent periods when the forest protection policy was implemented. In recent years, forest area and biomass C density have continued to increase, but the rate has slowed. In the last two inventories, the gap in the rate of change between forest area and biomass C density has diminished in the northwestern and southern regions. However, forest area shrunk in the central region (−1.73% yr^{-1}) and biomass C density decreased in the southwestern (−0.83% yr^{-1}), northeastern (−0.62% yr^{-1}) and northern (−5.10% yr^{-1}) regions, leading to C loss in the northeastern and northern regions from 2009 to 2013 to 2014–2018 (Appendix S3).

The relative contributions of IBCD and FAE to C sequestration varied in different regions and time periods. The central region had the largest variation in terms of the relative contributions of the FAE and IBCD to C sequestration from 2009 to 2013 to 2014–2018, with relative contributions of −71.78 Tg C and 75.44 Tg C to carbon sinks, respectively (Appendix S4). In the first half of the study period for all regions, the relative contributions of the contributing factors show larger variations and tend to be stable in the second half of the study period, except for the central, northeastern and northern regions in the last two inventories, given negative contributions of FAE to C sequestration due to the harvest of mature forests. In recent years, a series of forest restoration projects has also ensured that the increase of forest area has made larger contributions than the regrowth of forest in most regions and has shown an increasing trend in the southern and southwestern regions as well. The main reason for this was deforestation and the implementation of policies to protect forests from overexploitation during the past few years.

To reveal the mechanisms that control forest C sequestration further, we next calculated the national and regional change rates of forest area and C density and the relative contributions of FAE and IBCD to the natural and planted forest C sinks between 1977-2018 and 2004–2018, respectively.

3.3. Relative contributions of FAE and IBCD to the C sequestration of natural and planted forests

Natural forests played the role of C sinks (66.68 Tg C yr^{-1}) in China from 1977 to 2018 (Appendix S5), with IBCD and FAE at mean rates of 0.77 and 0.56% per year contributing 57.82 and 42.18% of the growth in biomass C sequestration of natural forests from 1977 to 2018, respectively (Fig. 2a). Among the seven regions, the relative contributions of IBCD is larger to C sequestration than FAE in all but the southwestern region during the period from 1977 to 2018. The largest contribution of IBCD in the other six regions occurred in the northeastern region (91.84%) where the forest area increased marginally (0.03% yr^{-1}), and the southern (91.21%), northern (78.20%), and eastern (77.90%) regions also saw large contributions of IBCD (Fig. 2a). In the southwestern region the relative contribution of FAE to C sequestration is greater than that of IBCD (68.64 vs. 31.36%), with annual rates of change of 1.32 and 0.60%, respectively (Fig. 2a).

Natural forests have functioned as larger C sequestration sinks (69.79 Tg C yr^{-1}) and displayed higher rates of change in terms of FAE which has contributed 51.87% (0.60% yr^{-1}) of the growth in biomass C sequestration at the national level from 2004 to 2018 (Appendix S5, Fig. 2b). However, C sequestration declined in the northern region (−10.71 Tg C yr^{-1}) because forest C density decreased −1.92% per year from 2004 to 2018. The IBCD was the sole contributor to the growth in C sequestration in the southern region from 2004 to 2018 due to the decrease in the forest area (−0.77% yr^{-1}). The IBCD was the larger contributor to the C sinks in the eastern and central regions during the past decade, with relative contributions of 75.30 and 82.26%, respectively. On the contrary, the contribution of FAE to C sequestration is greater than that IBCD of natural forests in the southwestern (83.23%), northeastern (66.44%) and northwestern (56.11%) regions from 2004 to 2018 (Fig. 2b).

Planted forests have also acted as a C sink (35.42 Tg C yr^{-1}) during the entire study period. The planted forests area increased from $1676.27*10^4$ ha to $5712.67*10^4$ ha, biomass density increased from 13.49 to 26.90 Mg C ha-1, and C stocks have increased linearly from 226.12 to 1536.56 Tg C from 1977 to 2018 (Appendix S6, Fig. 2c). Unlike natural forests, the area of planted forests displayed higher growth rates than biomass C density and made larger contributions to C sequestration than IBCD across China as a whole and in six of the seven regions from 1977 to 2018. Meanwhile, the IBCD contributions of planted forests may have exceeded that of the FAE (50.51 vs. 49.49%) in the eastern region during the period from 1977 to 2018. The uncertainty associated with this particular pair of change metrics reflects the small margin and the possibility that the sampling error in the original surveys may account for some or all of this difference. Overall, the results are clear and show that FAE and IBCD increased at mean rates of 3.31 and 1.87% per year and contributed 63.99 and 36.01% of the increases in the biomass C pool of planted forests during the period 1977–2018. The southwestern region displayed the highest annual change rate (6.01%) of FAE and it responsible for 76.37% of the increase in C sequestration, followed by the northern region with a 3.44% yr^{-1} rate of change with FAE and it contributing 70.56% of the increase in C sequestration (Fig. 2c).

Compared with the period 1977–2018, planted forests have grown substantially in terms of area (3.56% yr^{-1}) and the FAE has made for a larger relative contribution (75.48 vs. 63.99%) to forest biomass C sinks (57.83 Tg C yr^{-1}) nationally during the period 2004–2018 (Fig. 2d) (Appendix S6). At the regional level, FAE has grown at higher mean rates and has made larger contributions than IBCD in the southwestern (98.09%), southern (95.35%), northwestern (75.56%), northern (59.71%) and central (57.32%) regions in contrast to the northeastern (44.49%), and eastern (31.93%) regions where the rate of IBCD has exceeded that of FAE and the contributions of FAE and IBCD were

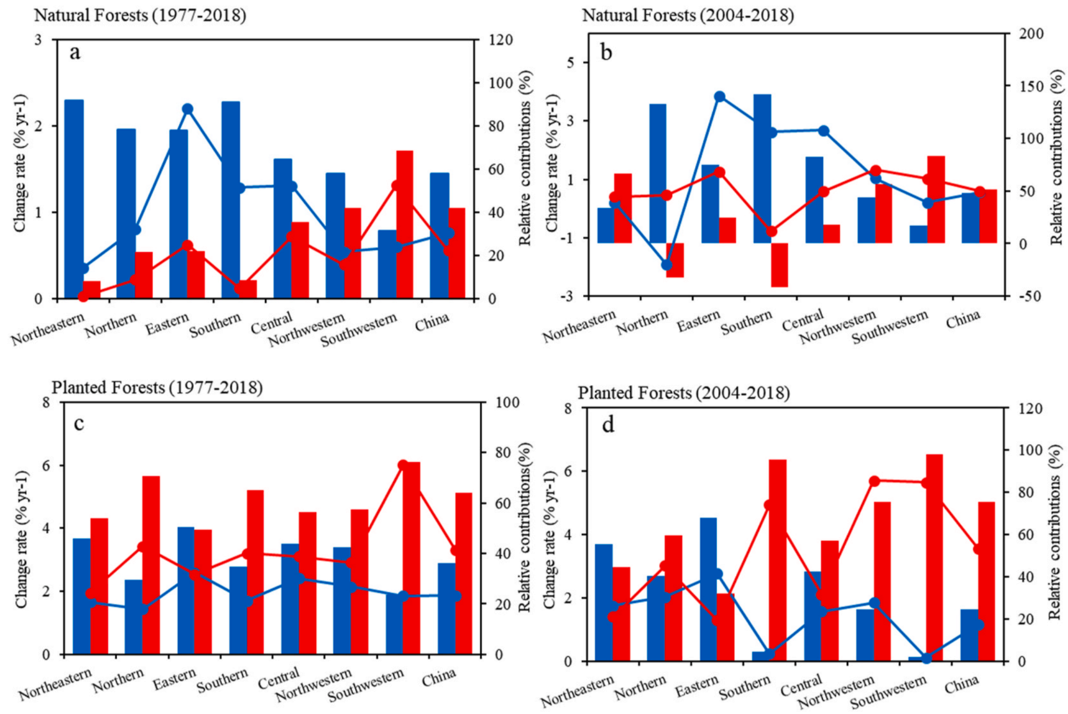

Fig. 2. The rate of change (% yr^{-1}, left y axis) and the relative contribution (%, right y axis) of FAE (in red) and IBCD (in blue) to C sinks in natural and planted forests in seven regions of China during the periods 2004–2018 and 1977–2018, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

approximately equal (Fig. 2d).

On the whole, forests sequestered 3778 Tg C in China from 1977 to 2018, with the natural forest contributions mainly attributed to the IBCD (1426.42 Tg C; 57.82%) and the planted forest contributions mostly attributed to FAE (838.50 Tg C; 63.99%).

4. Discussion

4.1. The variations of FAE and IBCD to biomass C sinks in different forests

China's forests acted as C sinks with a peak rate of 250.96 Tg C yr^{-1} from 1999 to 2003 to 2004–2008. This study updated forest biomass carbon sinks and density of China from 1977 to 2018. Compared with previous studies which also used the CBEF method and inventory data to calculate forest carbon stocks, our estimation results were lower than those of Fang et al. (2001, 2007) and Zhang et al. (2013, 2015). This gap gradually narrowed until the period 2004–2008 when our estimates surpassed those of Zhang et al. (2013, 2015) (Appendix S7). The possible explanation is that all previous studies used a single carbon fraction coefficient (0.5) for dominant tree species, while we used different carbon coefficients for 46 tree species (Appendix S2). Moreover, some forest types with higher carbon coefficients, such as hardwoods, Quercus and Larix, will produce more biomass carbon stocks as they grow (Zhao et al., 2019). Therefore, this increase in forest species diversity in the most recent two inventory stages may have also contributed to the widening gap between estimates in this study and other studies (Appendix S7). The planted and natural forests contributed 1310.44 and 2467.06 Tg C in China from 1977 to 2018, respectively. The variations in the regional patterns in the contributions of FAE and IBCD can be attributed to differences in natural factors (e.g., climate, soils, topography, wildfires and other extreme weather events) and human variables (e.g., population pressure, forest management policies) (Brown et al., 1997; Fang et al., 2004; Magnani et al., 2007; Zhang et al., 2015).

For planted forests, the C sequestration rate in the last decade has significantly increased compared with the whole study period (Appendix S6). FAE made a larger contribution than IBCD at both the national and regional levels from 1977 to 2018. However, IBCD contributed more to C sinks than FAE in the northeastern and eastern regions during the last decade (Fig. 2c and d). The implementation of afforestation projects provided increases in the forest area and made larger contributions to C sinks in the short term, but the continuous growth of the forest vegetation and the IBCD offer larger contributions to C sequestration over the long-term (Peng et al., 2011; Du et al., 2014; Fang et al., 2014). However, FAE has made larger contributions than IBCD to C sequestration in the southern, central, northwestern and southwestern regions from 2004 to 2018 compared with the whole study period owing to six major ecological restoration projects (Three-North Protection Forest System; Fast-growing Forests in Key Areas Projects) that have been implemented in these areas since 2000 (Li et al., 2016; Fang et al., 2018; Lu et al., 2018).

In contrast to planted forests, natural forest C sequestration rates have shown negative growth in the northern region during the last decade (Appendix S5), because the increase in biomass C stocks attributed to the development of young and middle-aged forests was more than offset by the harvest of mature forests (Zhao et al., 2019). IBCD was a larger contributor to C sinks in natural forests at the national level (57.82 vs. 42.18% for biomass density vs. FAE) and in all regions except for the southwestern region from 1977 to 2018; however, FAE has exceeded IBCD during the last decade in all but the central and southern regions. Natural forests have functioned as persistent C sinks owing to their larger base, but have recorded small increases. With the implementation of the nationwide Natural Forest Conservation Project in the late 2000s, natural forest C density has gradually reached saturation and these forests have faced greater logging pressure in recent decades (Li, 2004; Lei, 2005). Natural forest C sequestration may be more susceptible to disturbances, including positive (global warming, C dioxide fertilization, nitrogen deposition) and negative effects (natural disasters, forest fires, extreme climate) compared to planted forests (Lei, 2005; Guo et al., 2013; Zhang and Liang, 2014; Yu et al., 2019).

4.2. Effects of forest aging on forest carbon sink

From 1977 to 2018, the biomass of carbon stocks of forest stands in all age groups increased, and the total carbon stocks of premature, mature and over-mature forests (hereafter, mature forests) in each inventory period accounted for more than half of the total forest stands (Fig. 3). The area and volume of mature forest stands also increased during the study period. Besides, the biomass of carbon stocks of mature forest stands increased steadily from 1.77 in 1977–1981 to 3.89 Pg C in 2009–2013, and increased slowly to 3.98 Pg C during the period 2014–2018. However, the carbon density of mature forest stands decreased, especially the carbon density of over-mature forest stands dropped from 85.71 in 2004–2008 to 76.38 Mg C ha^{-1} in 2014–2018. Meanwhile, the relative contribution of the change in forest carbon density to the carbon sink of over-mature forests became negative from 2004 to 2008 to 2014–2018 (Appendix S8). In addition to the death of forests caused by natural disasters, the biggest reason for this situation may be China's implementation of deforestation measures. According to the "*Forest Law of the People's Republic of China*", mature forests are subject to reforestation through regular selective cutting, clear-cutting, and gradual cutting.

Some studies in the United States of America (Wear et al., 1999; Coulston et al., 2015), Europe (Nabuurs et al., 2013), and Canada (Harel et al., 2021) suggest that forest carbon stocks may no longer accumulate carbon and thus accumulation may slow down. On the other hand, in addition to CO_2 fertilization, some studies have shown that warming can change autumn phenology (Chen et al., 2020). Rising temperature postpones leaf senescence in autumn, and thus the carbon uptake period of vegetation is lengthened, which means that the vegetation can continue to sequester carbon sinks (Zhang et al., 2020). In contrast, a previous study by Zhu et al. (2018), which was based on North American forest inventory data and biomass growth models, showed that the potential of carbon sequestration in North America was close to saturation under climate change. A recent study has shown that carbon loss from forest degradation exceeds that from forest deforestation in the Brazilian Amazon (Qin et al., 2021). Another study by Nabuurs et al. (2013) highlighted that better forest management practices will help accelerate the aging of Europe's forests, and thus it is recommended to selectively deforest and plant more trees.

4.3. China's future forest biomass C sinks

The forest stands were divided into 5 age groups in China's forest inventories (Xiao, 2005). In general, the young age structure of some forests contributes to lower biomass C densities and smaller C pool contributions when compared with mature forests (Pan et al., 2004; Fang et al., 2007, 2014; Hu et al., 2015). For China's forests during the period 2014–2018, the area of young, middle-aged, premature, mature, and over-mature aged forests was 32.67, 31.27, 15.91, 13.72, and 6.43% of the total forest area, respectively (Fig. 4). In comparison, the respective percentages for C stocks were 19.80, 29.78, 19.41, 19.81, and 11.17%, respectively (China State Administration of Forestry, 2019).

Since the 1970s, China has implemented a series of forest restoration and afforestation programs to reduce soil erosion and protect fragile ecological environments (Wang et al., 2007; Li et al., 2016; Chen et al., 2019). The area of planted forest has increased rapidly by 3.31% yr^{-1} from 1676.27 $\times$ 10^4 ha in 1977–1981 to 5712.67 $\times$ 10^4 ha in 2014–2018 due to these government programs. At the same time, the contribution of planted forests growth to C sinks has also increased, the average biomass C density of planted forest doubled from 13.49 to 26.90 Mg C ha^{-1} during the period 1977–2018, which indicates that planted forest will contribute to forest biomass C sequestration through future growth (Guo et al., 2010; Xu et al., 2010; Liu et al., 2014; Hu et al., 2015; He et al., 2017). The area of natural forest also shows a slight increase (22.96% increment) and this coupled with its size (more than twice the total area of planted forest) means that natural forest had 4 times the forest C storage of planted forests in the 2014–2018 inventory (C stocks of natural forests and planted forests are 6369.43 and 1310.44 Tg C, respectively) (Appendices S2; S3). On the other hand, the areas of young and middle-aged trees in natural forests account for 60.94% of the total natural forest area, and 70.42% of the total planted forest area during the period 2014–2018 (Fig. 4).

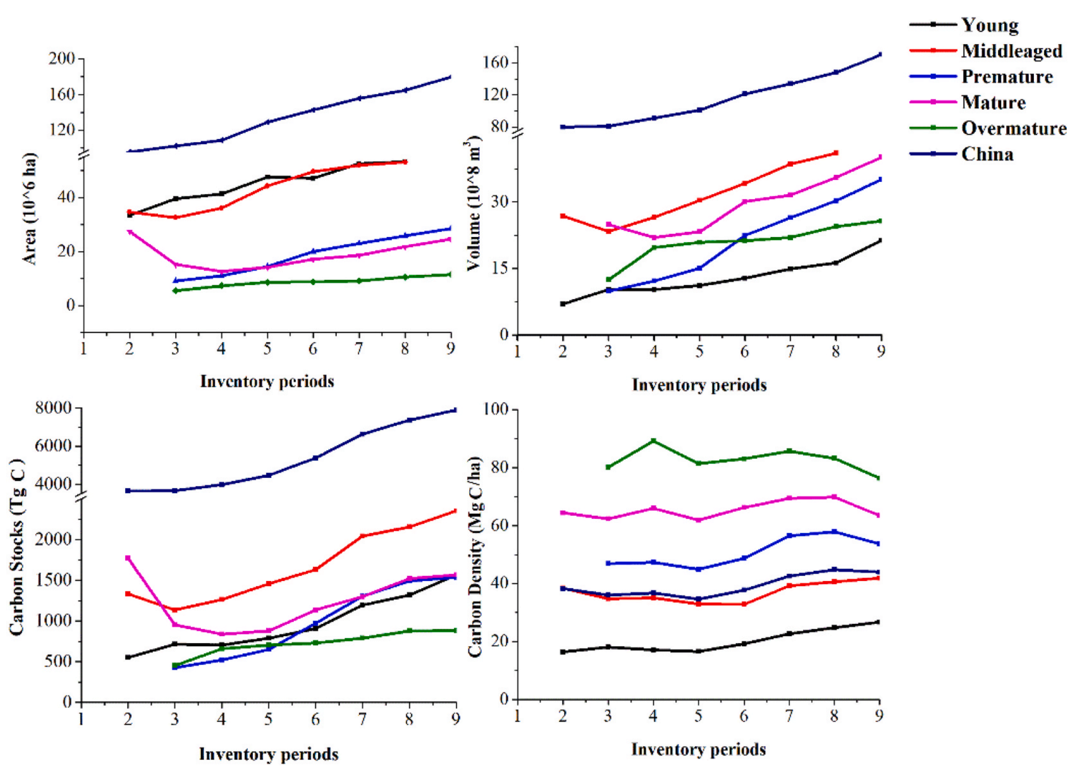

Fig. 3. The change of area, volume, carbon stocks, and carbon density of different forests age groups in eight inventory periods.

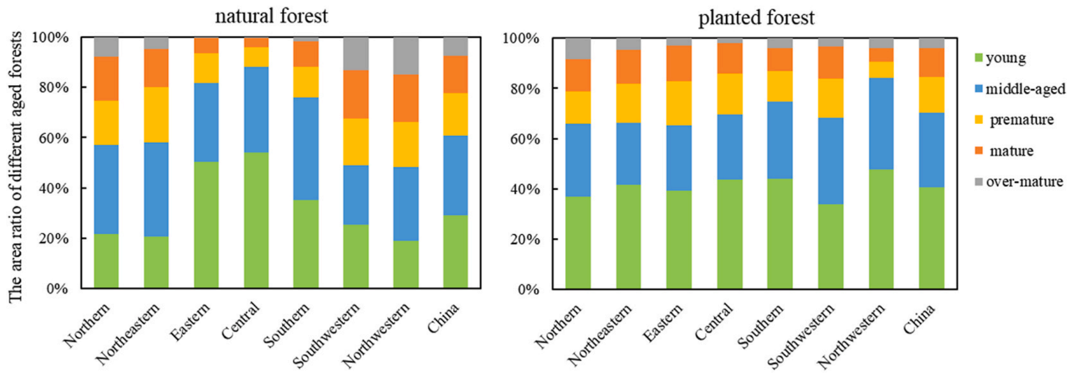

Fig. 4. The age structures of natural and planted forest area during the period 2014–2018.

The northern, eastern and central regions that are greatly affected by human activities were the first areas in China to carry out afforestation in the 1970s (Fang et al., 2014; Li et al., 2016). Due to the growth and development of forests, the relative contribution of the IBCD to forest biomass C sequestration has exceeded that of FAE in the aforementioned regions since 2000 (Appendix S4), but their forest biomass C density is still the lowest among the seven regions in the latest inventory (Appendix S3). Meanwhile, the contribution of FAE to forest biomass C sequestration exceeds that of the IBCD in the southwestern, northwestern and southern regions because of the intensification of afforestation activities since 2000 (Appendix S4) (Guo et al., 2010; Li et al., 2016; He et al., 2017). This suggests that China's forest biomass C stocks have huge growth potential in future years.

4.4. Uncertainties of these estimates

Traditionally, estimation of forest biomass C stocks using forest area and volume from national forest inventory datasets has been considered to be one of the most accurate methods (Brown et al., 1997; Smith et al., 2002). However, there are several sources of uncertainty in forest biomass C sink estimation, such as the variation of inventory methods, the errors and ensuing need to take into account the confidence intervals that accompany sparse sample data, and forest C stocks conversion at the provincial scale before 1994, because of the change in the canopy cover threshold used in China from 0.3 to 0.2 (Pan et al., 2004; Fang et al., 2007). The CBEF method that relies on the correlation between forest volume and biomass adds to this uncertainty because the R^2 values range from 0.7 to 0.9 (Zhang et al., 2013).

The increases in the forest biomass C sinks are not only affected by the FAE and IBCD, but also some complicated factors such as CO_2 and nitrogen deposition, which has increased soil organic C storage by reducing soil organic matter decomposition rates (Pregitzer et al., 2008; Janssens et al., 2010), silviculture and forest management, which may alter C allocation patterns in trees (Delucia et al., 1999; McGuire et al., 1995; Piao et al., 2012), and thinning and harvesting (Liu et al., 2012; Chen et al., 2019). However, these factors are highly heterogeneous at the national scale and specific data are not available, such that these factors cannot be used to improve forest carbon sink estimates based on forest area expansion and increased biomass C density. Notwithstanding these uncertainties, the results from this study offer relatively high precision and a comprehensive assessment of the forest C budget.

5. Conclusions

China's forest biomass C stocks have increased from 4128.50 Tg C in 1977–1981 to 7906.23 Tg C in 2014–2018 by adding 102.10 Tg C yr^{-1} on average over the past four decades. This study used the 8 inventory datasets from 1977 to 2018 and the C fraction coefficients for 46 tree species in the CBEF model to estimate the relative contributions of FAE and IBCD to China's forest C pool from 1977 to 2018. The FAE with mean rates of 1.17 and 3.31% per year has been a larger contributor to C sequestration for all forests (66.73%) and planted forests (63.99%), respectively due to the afforestation and reforestation campaigns launched in the 1970s. However, the IBCD has increased at a mean rate of 0.77% per year and was the major contributor to forest biomass C sinks (57.82%) in natural forests during the period 1977–2018.

Regional disparities are also evident. For forest C sinks in the top three areas, FAE was the major contributor in the southwestern (85.79%), southern (62.80%) and northern (63.92%) regions from 1977 to 2018. The C sequestration of natural forests came from IBCD and for planted forests it came from FAE during the period 1997 to 2018. However, the relative contribution of FAE has increased for all forests since 2000 due to the implementation of forest protection projects that increased the planted forest area. This state-of-affairs means that China's forest biomass C sinks will increase for many years.

Credit author statement

Dr. Miaomiao Zhao designed the research, analyzed the data and wrote the manuscript. Jilin Yang, Na Zhao, Xiangming Xiao, and Tianxiang Yue assisted with the analysis, Jilin Yang and John Wilson also provided valuable comments and suggestions on the methods and interpretation of the results and helped with the writing of various part of this manuscript.

Declaration of 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113757.

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