Increasing soil carbon stocks in eight permanent forest plots in China

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Abstract. Forest soils represent a major stock of organic carbon (C) in the terrestrial biosphere, but the dynamics of soil organic C (SOC) stock are poorly quantified, largely due to lack of direct field measurements. In this study, we investigated the 20-year changes in SOC stocks in eight permanent forest plots, which represent boreal (1998–2014), temperate (1992–2012), subtropical (1987–2008), and tropical forest biomes (1992–2012) across China. SOC contents increased significantly from the 1990s to the 2010s, mostly in the upper 0–20 cm soil depth, and soil bulk densities do not change significantly during the same period. As a result, the averaged SOC stocks increased significantly from 125.2 ± 85.2 Mg C ha⁻¹ in the 1990s to 133.6 ± 83.1 Mg C ha⁻¹ in the 2010s across the forest plots, with a mean increase of 127.2–907.5 kg C ha⁻¹ yr⁻¹. This SOC accumulation resulted primarily from increasing leaf litter and fallen logs, which accounted for 3.6%–16.3% of above-ground net primary production. Our findings provided direct evidence that China’s forest soils have been acting as significant C sinks, although their strength varies in forests with different climates.

1 Introduction

Terrestrial ecosystems have absorbed approximately 30% of the carbon dioxide (CO₂) emitted from human activity since the beginning of the industrial era (IPCC, 2013). Forests have contributed more than half of these carbon (C) fluxes of terrestrial ecosystems (Pan et al., 2011). Since soils contain a huge C stock in forest ecosystems, even a slight change in this stock will induce a considerable feedback to atmospheric CO₂ concentrations (Lal, 2004; Luo et al., 2011). Thus, accurate assessment of the changes in soil organic carbon (SOC) is critical to understanding how forest soils will respond to global climate change. However, it is difficult to capture the SOC change with short-term measurements (Smith, 2004) because the soil C pool typically has a longer turnover time and higher spatial variability compared to the vegetation C pool (Schrumpf et al., 2011; Canadell and Schulze, 2014).

Previous efforts have estimated the changes in regional SOC stocks with indirect approaches, such as regional assessments (Yang et al., 2014) and model simulations (Todd-
Brown et al., 2013). These estimates often involve large uncertainties due to the inherently high spatial variability of soils and a lack of direct measurements representing large areas (Sitch et al., 2015). One reliable approach to reducing the uncertainties is to conduct long-term monitoring of forest SOC stocks at sites that represent broader landscapes (Prietzel et al., 2016). Unfortunately, such repeated, accurate field-based measurements of SOC stocks from which to generate change estimates are generally lacking and inadequate worldwide (Zhao et al., 2019).

A few soil resampling studies have explored SOC changes in different forests, but the results are often contradictory. For instance, Schrumpf et al. (2014) found that SOC in deciduous broadleaved forests in central Germany increased, with a change rate of 650.0 kg C ha\(^{-1}\) yr\(^{-1}\) from 2004–2009. In contrast, Prietzel et al. (2016) indicated that SOC stocks in German forests decreased significantly, with average change rates of 988.2 kg C ha\(^{-1}\) yr\(^{-1}\) in forests in the Alps between 1986 and 2011, and 441.1 kg C ha\(^{-1}\) yr\(^{-1}\) in the Berchtesgaden region between 1976 and 2011. Kiser et al. (2009) found that the hardwood forest soils in central Tennessee, USA, exhibited a slight C source and that the relative change rate ranged from −0.4 % yr\(^{-1}\) to 0.3 % yr\(^{-1}\) between 1976 and 2006. Chen et al. (2015) synthesized global SOC changes and found that the relative rates of change in forest SOC stocks were contradictory among long-term experiments (0.2 % yr\(^{-1}\)), regional comparisons (0.3 % yr\(^{-1}\)), and repeated soil samplings (−0.1 % yr\(^{-1}\)). Such discrepancies can be partly attributed to insufficient observations and inconsistent methodologies. The different effects of changing environmental factors and nitrogen inputs on soil C dynamics may also be involved (Norby and Zak, 2011). In addition, to date these studies have primarily been conducted in the forests of Europe and the USA, but few have been carried out in China’s forests.

Forests in China cover an area of 156 Mha (Guo et al., 2013) and range from boreal coniferous forests and deciduous broadleaved forests in the northeast to tropical rain forests and evergreen broadleaved forests in the south and southwest. They include almost all major forest biomes of the Northern Hemisphere (Fang et al., 2012). Such variations in climate and forest types have provided ideal opportunities to examine the spatial patterns of SOC in relation to meteorological and biological factors. At the national scale, the mean annual air temperature of China increased by more than 1 °C between 1982 and 2011, which is considerably higher than the global average (Fang et al., 2018). Since the 1980s, the Chinese Government has implemented several large-scale national forest protection projects. These climatic changes and conservation practices in China have significantly stimulated C uptake into forest ecosystems (Fang et al., 2014, 2018; Feng et al., 2019). Several studies have assessed the temporal dynamics of SOC stock across China’s forests using model simulations (Piao et al., 2009) or regional assessments (Pan et al., 2011; Tang et al., 2018). However, these estimates revealed contrasting trends in SOC dynamics and also lacked direct measurements of SOC change.

Therefore, in this study we measured SOC density (C amount per unit area) of eight permanent forest plots from tropical, subtropical, temperate, and boreal forests in China during two periods in the 1990s and 2010s to quantify their SOC changes. We then analyzed the potential biotic and climatic drivers in the SOC dynamics across these forests. Finally, we assessed the changes in SOC stocks in China’s forests using the site data obtained from this study.

## 2 Materials and methods

### 2.1 Study sites

We investigated eight permanent forest plots in four forest sites (from north to south: Great Xing‘anling, Mt. Dongling, Mt. Dinghu, and Jianfengling) (Fig. 1). The four sites spanned a wide range from 18.7 to 52.6°N in latitude, and belonged to boreal, temperate, subtropical, and tropical climate zones, respectively, with a climatic difference of approximately 26 °C in mean annual temperature and 1200 mm in mean annual precipitation. The eight plots are comprised of a boreal larch forest (Larix gmeliiii), two temperate deciduous broadleaved forests (Betula platyphylla and Quercus wutaishanica), a temperate pine plantation (Pinus tabuliformis), a subtropical evergreen broadleaved forest, a subtropical pine plantation (P. massoniana), a subtropical pine and broadleaved mixed forest, and a tropical mountain rainforest (for details, see Table 1).

Stand characteristics of all eight plots are summarized in Table 1. The boreal larch forest was a 100-year-old mature stand at the time of the first sampling (Wang et al., 2001). Three temperate forest plots (birch, oak, and pine forests) were located along an elevation gradient on Mt. Dongling, Beijing. Both birch and oak forest plots were 55-year-old secondary forests at the time of the first sampling, dominated by B. platyphylla and Q. wutaishanica, respectively. The temperate pine plantation was 30 years old at the time of the first sampling and was dominated by P. tabuliformis (Fang et al., 2007). Three subtropical forest plots were located in Dinghu Biosphere Reserve in Guangdong Province, southern China (Zhou et al., 2006). The subtropical evergreen broadleaved forest is an old-growth stand that is more than 400 years old, co-dominated by Castanopsis chinensis, Canarium pinela, Schima superba, and Engelhardtia roxburghiana. The subtropical pine (P. massoniana) plantation was approximately 40 years old at the time of the first sampling. The mature mixed pine and broadleaved forest was approximately 110 years old at the time of the first sampling and represented the mid-successional stages of monsoon evergreen broadleaved forest in this region. The tropical mountain rainforest plot was located at the Jianfengling National Natural Reserve, southwestern Hainan (Zhou et al.,...
2013). It had not been disturbed for more than 300 years and was dominated by species in the families Lauraceae and Fagaceae, such as *Mallotus hookerianus*, *Gironniera subaequalis*, *Cryptocarya chinensis*, *Cyclobalanopsis patelliformis*, and *Nephelium topengii*. For detailed descriptions of these eight plots, see the Supplement.

### 2.2 Soil sampling and calculation of SOC content

The first sampling was conducted between 1987 and 1998 in each of the eight forests (Table 1). We remeasured the same sample plots in each forest between 2008 and 2014 using identical sampling protocols.

In each forest plot, two to five pits were dug to collect soil samples for analyzing the physical and chemical properties during the two sampling periods (mostly in the 1990s during the first sampling period and in the 2010s during the second sampling period). The samples were taken at depth intervals of 10 cm down to the maximum soil depth. In brief, for the boreal forest, three soil pits were established down to the 40 cm soil depth in random locations in the growing season in 1998. In August 2014, three soil pits were again randomly excavated to the same soil depth to allow sampling for SOC content and bulk density. In September 2008, the soil sampling was repeated. For the tropical forest, five soil profiles (100 cm depth) were established at 10 cm intervals during summer 1992 and again in summer 2012.

We used consistent sampling and analysis approaches to determine the bulk density and SOC content between the two sampling times. Three bulk density samples were obtained for each layer using a standard container that was 100 cm³ in volume. The soil moisture was determined by weighing to the nearest 0.1 g after 48 h oven-drying at 105 °C. The bulk density was calculated as the ratio of the oven-dried mass to the container volume. Another three paired samples for C analysis were air-dried. Following this, fine roots were removed by hand and sieved (2 mm mesh). The SOC content was measured using the wet oxidation method (Nelson and Sommers, 1982) and was calculated according to Eq. (1):

\[
SOC = \sum_{i=1}^{n} CC_i \times Bd_i \times V_i \times HF_i, \tag{1}
\]

where \( CC_i \), \( Bd_i \), and \( V_i \) are SOC content (%), bulk density (kg m⁻³), and volume (m³) at the \( i \)th soil horizon, respectively. HF is calculated as 1 - stone volume root volume and is a dimensionless factor that represents the fine soil fraction within a certain soil volume.
2.3 Calculation of above-ground biomass (AGB) and net primary production

Diameter at breast height (DBH, 1.3 m) and height of all living trees with DBH > 5 cm were both measured in each plot in the 1990s and 2010s. The AGB of different components (stem, bark, branches, and foliage) was estimated for all tree species using allometric equations (Table S1 in the Supplement). A standard factor of 0.5 was used to convert biomass to C (Leith and Whittaker, 1975). The net increment of AGB (ΔStore) was calculated for each plot as the difference between the biomass in the 1990s and the 2010s. The above-ground net primary production (ANPP, kg C ha\(^{-1}\) yr\(^{-1}\)) was calculated from Eq. (2):

\[
ANPP = \text{Litterfall} + \Delta \text{Store} + \text{Mortality},
\]

where Litterfall and ΔStore are litter production and above-ground net biomass increment per year, respectively. Mortality (defined as above-ground deadwood production) was estimated as the summed production of fallen logs and standing snags per year.

2.4 Litter and fallen log production

Annual litterfall was collected from June 2010 to June 2013 in the tropical sites, from June 1990 to June 2008 in the subtropical sites, from April to November 2011–2014 in the temperate sites, and from May to October 2010–2014 in the boreal sites. Litter (leaves, flowers, fruits, and woody material < 2 cm diameter) was collected monthly from 10 to 15 L traps (1 x 1 m\(^2\), 1 m above ground) in each plot to calculate annual litter production. After collection, the samples were taken to the laboratory, oven-dried at 65°C to a constant mass and weighed. The 10–15 replicates from each plot were averaged as the monthly mean value. Annual litter production (kg C ha\(^{-1}\) yr\(^{-1}\)) was estimated as the sum of the monthly production in the year of collection.

Log production represents the mortality (i.e., death of entire trees) per year. Annual log production was determined from 2010 to 2013 in tropical sites, from 1989 to 1996 in subtropical sites, from 2011 to 2014 in temperate sites, and from 2010 to 2014 in boreal sites. Stocks of fallen logs were harvested and weighed during each investigated year.

2.5 Forest area and fossil fuel emission data

To calculate the amount of C sequestration in China’s forest soils, we estimated the changes in the national forest SOC stocks. We used the mean SOC accumulation rates obtained from this study and the data of forest area for each forest type documented in the national forest inventory in 1989–1993, which approximates the first sampling period in the present study (Guo et al., 2013). The changes in national forest SOC stock were calculated as the product of SOC density, SOC density change rate, and forest area for major forest types.
during the period 1989–1993. In addition, to evaluate the relative importance of forest soil C sequestration in the national C budget, we obtained the data of fossil fuel emissions during 1991–2010 from the Carbon Dioxide Information Analysis Center (Zheng et al., 2016).

3 Results

3.1 Changes in SOC

SOC stocks were investigated in eight permanent forest plots in four forest sites from northern to southern China over two periods: the 1990s and 2010s. The changes in SOC contents, bulk density, and SOC stocks in the top 20 cm soil layer between the 1990s and the 2010s are shown in Fig. 2 and Figs. S1 and S2 in the Supplement. The paired t-test analysis indicated that SOC content in the 0–20 cm depth was significantly higher in the 2010s than in the 1990s (3.2 ± 0.7 % vs. 2.9 ± 0.6 %; \( t = -5.65; P < 0.001 \)) (Table 2). The average rate of increase in SOC content was 0.02 % yr\(^{-1}\) in the top 20 cm depth, ranging from 0.01 % yr\(^{-1}\) to 0.04 % yr\(^{-1}\) across the study sites. These rates of increase in SOC content in the 0–10 cm horizon (0.03±0.02 % yr\(^{-1}\)) were 3 times larger than those in the 10–20 cm horizon (0.01±0.01 % yr\(^{-1}\)) (Table S2). At the same time, the bulk density of the top 20 cm soil layer decreased in most sites (6 of 8 sites), with an average rate of decrease of 2.7±3.7 mg cm\(^{-3}\) yr\(^{-1}\) (Table S3). As a result, the SOC stock in the top 20 cm soil layer was found to have increased significantly in the past 2 decades \((t = -5.85, P < 0.001, \text{Table 2})\), with an average accumulation rate of 332.4±200.2 kg C ha\(^{-1}\) yr\(^{-1}\) (0.7±0.4 % yr\(^{-1}\); Fig. 2; see Table S1). The temperate pine plantation experienced the largest increase in SOC stock in the top 20 cm depth (630.8±111.2 kg C ha\(^{-1}\) yr\(^{-1}\)). In contrast, the smallest rate of increase was observed in the subtropical mixed forest (117.3±25.2 kg C ha\(^{-1}\) yr\(^{-1}\)). It should be noted that SOC stock in the top 20 cm depth in the subtropical evergreen old-growth forest increased from 35.6±6.0 Mg C ha\(^{-1}\) in 1988 to 45.6±6.9 Mg C ha\(^{-1}\) in 2008 (increased by 498.3±78.8 kg C ha\(^{-1}\) yr\(^{-1}\)), which led to the highest relative accumulation rate (1.4±0.2 % yr\(^{-1}\)) among the study sites.

We further compared SOC stocks of the whole soil profile between 1990s and 2010s at a depth of 0–40 cm in the boreal site, 0–60 cm in the subtropical site, and 0–100 cm in the temperate and tropical sites (Fig. 3). The SOC stocks of all sampling sites in the 2010s were higher than those in the 1990s. The paired t-test analysis revealed a significant increase in SOC stocks for the whole soil profile during the sampling period \((t = -4.15, P < 0.01, \text{Table 2})\). The mean SOC stocks of the whole soil profile in the eight forests increased from 125.2±85.2 Mg C ha\(^{-1}\) in the 1990s to 133.6±83.1 Mg C ha\(^{-1}\) in the 2010s, with an accumulation rate of 421.2±274.4 kg C ha\(^{-1}\) yr\(^{-1}\) and a relative increase rate of 0.6±0.5 % (Fig. 2). The SOC accumulation rates displayed large variability among different climate zones and forest types. For different climate zones, the SOC accumulation rates in the subtropical and tropical sites were relatively higher than those in the boreal and temperate sites (Fig. 3). The greatest increase in SOC stock occurred in the subtropical evergreen old-growth forest (907.5±60.1 kg C ha\(^{-1}\) yr\(^{-1}\)), and the least in the temperate deciduous oak forest (127.2±25.3 kg C ha\(^{-1}\) yr\(^{-1}\); Table S3). The relative rates of increase in the subtropical evergreen old-growth forest (1.3±0.1 % yr\(^{-1}\)) and the subtropical mixed forest (1.5±0.2 % yr\(^{-1}\)) were higher than those in the temperate forests (0.1±0.0 % yr\(^{-1}\) in the oak forest, 0.1±0.0 % yr\(^{-1}\) in the pine forest, and 0.2±0.0 % yr\(^{-1}\) in the birch forest; Table S3).

In addition, the rates of SOC increase (127.2–907.5 kg C ha\(^{-1}\) yr\(^{-1}\) ) was equivalent to 3.6 %–16.3 % of ANPP (3340.1–6944.7 kg C ha\(^{-1}\) yr\(^{-1}\) ), with the highest rate in the subtropical evergreen forest (16.3±4.2 %) and the lowest in the temperate oak forest (3.6±3.4 %) (Tables 3 and S4).

3.2 Relationships between SOC change rates and biotic and climatic variables

To understand the possible mechanisms for the rates of SOC increase as described above, we analyzed the driving forces for this significantly increased SOC stock using measurements of AGB growth rate, above-ground litter and fallen log production, and ANPP (Table 3). The linear regression analysis showed that there was no significant correlation between SOC change rates and AGB growth rate \((P > 0.05, \text{Fig. 4a})\). The SOC accumulation rates were positively and significantly associated with annual litter \((R^2 = 0.66; P = 0.01, \text{Fig. 4b})\) and fallen log production \((R^2 = 0.69; P = 0.01, \text{Fig. 4c})\). The SOC accumulation rates across these forests were closely associated with the observed ANPP \((R^2 = 0.55; P = 0.03, \text{Fig. 4d})\) and also showed an increasing trend with increasing mean annual temperature and precipitation, despite being insignificant \((P > 0.1, \text{Fig. 4e and f})\). The multiple regression analysis indicated the relative effects of biotic factors (AGB growth rate, litter, and fallen log production) and climatic factors (mean annual temperature and precipitation) on the rates of SOC increase (Fig. 4g). When the effects of climatic factors were under control, the biotic factors independently explained 56.4 % of the variations. By comparison, when the effects of biotic factors were under control, only 7.5 % of the variations were explained by the climatic factors.

4 Discussion

4.1 SOC accumulation

Previous evidence of forest SOC changes comes mainly from individual experiments (Prietzel et al., 2006; Kiser et al.,
Figure 2. Mean soil organic carbon (SOC) content (a), bulk density (b), SOC stock (c), and their relative change rates (d) within 0–20 cm soil depth in the 1990s and the 2010s for the four forest sites in China. For more details, see Table S2 in the Supplement.

Table 2. Results of the paired-sample t tests for soil organic carbon (SOC) content, bulk density, and SOC stock at different soil depths in the eight forest plots between the 1990s and the 2010s.

<table>
<thead>
<tr>
<th>Soil horizon</th>
<th>SOC content</th>
<th></th>
<th>Bulk density</th>
<th></th>
<th>SOC stock</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t df P</td>
<td></td>
<td>t df P</td>
<td></td>
<td>t df P</td>
<td></td>
</tr>
<tr>
<td>0–10 cm</td>
<td>-4.22 7 &lt; 0.01</td>
<td></td>
<td>2.19 7 0.06</td>
<td></td>
<td>-6.50 7 &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>10–20 cm</td>
<td>-4.09 7 &lt; 0.01</td>
<td></td>
<td>3.30 7 &lt; 0.05</td>
<td></td>
<td>-3.26 7 &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Top 20 cm</td>
<td>-5.65 7 &lt; 0.001</td>
<td></td>
<td>1.01 7 0.35</td>
<td></td>
<td>-5.85 7 &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Whole soil profile</td>
<td>- - - -</td>
<td></td>
<td>- - - -</td>
<td></td>
<td>-4.15 7 &lt; 0.01</td>
<td></td>
</tr>
</tbody>
</table>

2009; Häkkinen et al., 2011) or regional comparisons (Lettens et al., 2005; Pan et al., 2011; Ortiz et al., 2013) in European and American forests. In this study, we performed a broadscale forest soil resampling to evaluate changes in SOC stock across eight permanent forest plots in China. Our measurements suggest that SOC stocks exhibited a significant accumulation in these forests from the 1990s to the 2010s, at the accumulation rate of 127.2–907.5 kg C ha\(^{-1}\) yr\(^{-1}\). These accumulation rates are comparable to those of other studies that were primarily conducted in boreal and temperate forests in other regions (−11.0–812.0 kg C ha\(^{-1}\) yr\(^{-1}\), Fig. 5). In detail, the rate of SOC accumulation of the boreal forest in the present study was estimated as 243.4 kg C ha\(^{-1}\) yr\(^{-1}\), which was within the range of boreal forests in European and American forests (115.6–740.0 kg C ha\(^{-1}\) yr\(^{-1}\)) (Prietzel et al., 2006; Dölle and Schmidt, 2009; Häkkinen et al., 2011; Wang et al., 2011; Rantakari et al., 2012; Chapman et al., 2013; Schrumpf et al., 2014). The rates of SOC accumulation in the three temperate forests ranged from 127.2 to 390.8 kg C ha\(^{-1}\) yr\(^{-1}\), comparable to the regional comparison data of 200.0 kg C ha\(^{-1}\) yr\(^{-1}\) in the temperate forests of China (Yang et al., 2014). Evidence from soil inventory-based studies of SOC dynamics also demonstrated that soil of boreal and temperate forests in European countries is likely to accumulate C (Berg et al., 2009; Nielsen et al., 2012; Tefs and Gleixner, 2012; Grüneberg et al., 2014). The mean rate of SOC accumulation in the humus layers of boreal forests in Sweden was estimated to be 251.0 kg C ha\(^{-1}\) yr\(^{-1}\) during the period 1961–2002 (Berg et al., 2009). Nielsen et al. (2012) assessed the rates of SOC change in Denmark’s broadleaved deciduous and coniferous forests using two soil inventories conducted during 1990 and 2005. The estimated rates
deforestation, soils in subtropical and tropical forests have
of C from tropical forest soils. Without land-use change and
ventories provided data for analysis of the mineral soils
2013). However, based on the estimates from regional com-
evidence of SOC dynamics is relatively scarce (Tang and Li,
2) (5
1 SD. For details, see Table S1 in the Supplement.
of SOC change in the broadleaved and coniferous forests
90.0 and 310.0 kg C ha\(^{-1}\) yr\(^{-1}\), respectively. Two soil
inventories were found to have sequestered 410.0 kg C ha\(^{-1}\)
(1987–2008 (Grüneberg et al., 2014). Therefore, evidence from long-term
suggests that soils of boreal and temperate forests in the Northern
Hemisphere have functioned as C sinks during past decades.
In other subtropical and tropical forest ecosystems, direct
evidence of SOC dynamics is relatively scarce (Tang and Li,
2013). However, based on the estimates from regional compari-
Pan et al. (2011) showed that global tropical forests
were a source of 1.4 Pg C ha\(^{-1}\) yr\(^{-1}\) from 1990 to 2007. At
the global scale, tropical land-use changes have caused a
sharp drop in forest area, which also led to a large release of
C from tropical forest soils. Without land-use change and
deforestation, soils in subtropical and tropical forests have
functioned as a considerable C sink during the past 2 decades
in this study (627.6 ± 370.1 and 397.9 ± 84.2 kg C ha\(^{-1}\) yr\(^{-1}\),
respectively; Table 3). Limited forest management (e.g., litter
and deadwood harvest), as well as catastrophic land-use changes,
can result in the loss of C from forest soil. Prietzel et al. (2016)
reported a large loss of SOC in forests in the German Alps, where half of the woody biomass and
deadwood had been harvested over recent decades. On the one
hand, harvesting the forest floor can decrease litter and dead-
wood inputs into soils and subsequently lead to the loss of
soil C (Davidson and Janssens, 2006). On the other hand, a
decrease in the amount of the forest floor may lead to an

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Boreal</th>
<th>Temperate</th>
<th>Subtropical</th>
<th>Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGB (Mg C ha(^{-1}))</td>
<td>91.1 ± 25.0</td>
<td>89.6 ± 17.4</td>
<td>107.0 ± 41.7</td>
<td>213.6 ± 41.4</td>
</tr>
<tr>
<td>Litter</td>
<td>4.4 ± 0.0</td>
<td>3.9 ± 1.3</td>
<td>2.1 ± 0.7</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Deadwood</td>
<td>1.3 ± 0.5</td>
<td>4.5 ± 1.2</td>
<td>7.3 ± 6.7</td>
<td>5.7 ± 0.8</td>
</tr>
<tr>
<td>Soil</td>
<td>69.4 ± 6.2</td>
<td>231.6 ± 14.6</td>
<td>67.2 ± 19.5</td>
<td>102.6 ± 19.9</td>
</tr>
<tr>
<td>Ecosystem total</td>
<td>166.2 ± 31.7</td>
<td>329.6 ± 34.5</td>
<td>183.7 ± 68.5</td>
<td>323.7 ± 62.3</td>
</tr>
<tr>
<td>Carbon flux (kg C ha(^{-1}) yr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGB growth</td>
<td>899.4 ± 411.0</td>
<td>1809.5 ± 521.2</td>
<td>798.7 ± 1572.4</td>
<td>684.1 ± 145.0</td>
</tr>
<tr>
<td>litterfall</td>
<td>2424.2 ± 283.1</td>
<td>1946.7 ± 361.2</td>
<td>3385.4 ± 1444.6</td>
<td>3970.0 ± 279.8</td>
</tr>
<tr>
<td>Fallen log</td>
<td>13.0 ± 3.7</td>
<td>106.1 ± 74.5</td>
<td>986.7 ± 967.3</td>
<td>1034.2 ± 71.6</td>
</tr>
<tr>
<td>Standing snag</td>
<td>3.5 ± 1.8</td>
<td>276.7 ± 111.1</td>
<td>220.0 ± 135.7</td>
<td>803.4 ± 62.4</td>
</tr>
<tr>
<td>ANPP</td>
<td>3340.1 ± 698.8</td>
<td>4139.0 ± 607.7</td>
<td>5390.8 ± 1655.3</td>
<td>6491.6 ± 559.2</td>
</tr>
<tr>
<td>Soil accumulation</td>
<td>243.4 ± 31.1</td>
<td>283.6 ± 138.5</td>
<td>627.6 ± 370.1</td>
<td>397.9 ± 84.2</td>
</tr>
<tr>
<td>Ratio of soil accumulation to ANPP (%)</td>
<td>7.3 ± 7.8</td>
<td>6.7 ± 2.8</td>
<td>11.0 ± 5.3</td>
<td>6.1 ± 3.3</td>
</tr>
</tbody>
</table>

Table 3. Measured C stocks and fluxes of the four forest sites in China during the 1990s and the 2010s.

Figure 3. Comparison of soil organic carbon (SOC) stocks in eight forest plots in China between the 1990s and the 2010s. The SOC stocks in all forests during the two periods are above the 1 : 1 line, suggesting that all these forests have increased their SOC stock during the study period. The inset graph shows the SOC sink rates by forest biome (i.e., boreal, temperate, subtropical, and tropical forests), which are categorized from the eight forest plots. SOC stocks and change rates are presented as means ±1 SD. For details, see Fig. 1 and Tables 1 and S1.
Figure 4. Relationships between rates of increase in soil organic carbon (SOC) against biotic and climatic factors in eight forests in China. (a) Biomass increment, (b) litter production, (c) log production, (d) above-ground net primary production (ANPP), (e) mean annual temperature (MAT), (f) mean annual precipitation (MAP), and (g) the relative effects of biotic (a, b, c) and climatic (e, f) factors on SOC increase rates (kg C ha\(^{-1}\) yr\(^{-1}\)) using partial regression analyses. Solid lines indicate significant relationships \((P < 0.05)\), and dashed lines represent insignificant trends \((P > 0.05)\) between SOC increase rates and biotic and climatic factors.

crease in soil erosion, especially in mountain forests (Evans et al., 2013). Additionally, high-elevation ecosystems are expected to be more sensitive to warming than other regions, with associated changes in soil freezing and thawing events and in snow cover, which may be another reason for the SOC losses in forests in the German Alps.

4.2 Links between biotic and climatic factors and in SOC accumulation

The forest biomass of China has functioned as a significant C sink over recent decades (Pan et al., 2011; Fang et al., 2014, 2018). The increase in C accumulation by vegetation supplied more C inputs into soils, including inputs of litter, woody debris, and root exudates, and resulted in SOC accumulation (Zhu et al., 2017). However, the rate of SOC change did not increase with the rate of biomass change in this study (Table S4). We found that soil in the subtropical old-growth forest increased at the highest sink rate of 907.5 ± 60.1 kg C ha\(^{-1}\) yr\(^{-1}\) but that vegetation functioned as a significant C source (−1000.3 ± 78.2 kg C ha\(^{-1}\) yr\(^{-1}\)). This was because the relatively higher annual litterfall and fallen log production occurred in the old-growth forest, which subsequently resulted in soil C accumulation (Fig. 4). The positive (but not significant) trend between climatic factors and SOC dynamics may largely be induced by the internal correlations between climatic and biotic factors (Fig. 4).

The heterotrophic respiration of global forest soil has increased significantly over past decades (Bond-Lamberty et al., 2018), suggesting that the increment in the rate of soil C input outweighs that of the rate of soil C output. The increasing heterotrophic respiration of forest soil is mainly due to ongoing climate change, and especially to increasing temperature. The increment in forest growth rate is due to increasing temperature, together with increasing CO\(_2\) and nitrogen fertilization (Norby et al., 2010; Feng et al., 2019). Thus, the sensitivity of forest net primary production to ongoing climate change should outweigh that of respiration. We also found that SOC stock increased from 68.4 to 86.6 Mg C ha\(^{-1}\), albeit the biomass C stock decreased significantly from 1988 to 2008 in the subtropical old-growth plot. The greatest amount of litter and deadwood production and standing crop occurred in the old-growth plot, which resulted in relatively higher soil C sequestration in the old-growth plot compared to other plots (Fig. 4, Table S4). Biotic factors explained the variation in SOC dynamics better than climatic factors. In this study, we did not, however, measure root-derived C inputs to SOC, although below-ground production also makes a significant contribution to SOC accumulation (Nadelhoff and Raich, 1992; Majdi, 2001; Pausch and Kuzyakov, 2018). Above-ground inputs are mineralized from litter and deadwood, and below-ground inputs may benefit from interactions with soils (Rasse et al., 2005). Even if the effect of climatic factors were controlled and below-ground biotic factors were not included in the analysis, the above-ground biotic factors would explain 56.4 % of the variation in the rate of SOC accumulation.

4.3 Regional carbon budget

The rate of SOC accumulation (421.2 ± 274.4 kg C ha\(^{-1}\) yr\(^{-1}\), Fig. 2 and Table S3) is more
Figure 5. Comparison of the changes in forest soil organic carbon (SOC) stocks according to repeated soil samplings and/or long-term observation. Different colors, shapes, and sizes represent different forest biomes, ages, and soil depths, respectively. The numbers in parentheses indicate the sampling times and intervals between the two soil samplings.

than one-half of the vegetation C uptake rate in China’s forests (702.0 kg C ha$^{-1}$ yr$^{-1}$) (Guo et al., 2013; Fang et al., 2018). This result suggests that China’s forest soils have contributed to a negative feedback to climate warming during the past 2 decades, rather than the positive feedback predicted by coupled C–climate models (Cox et al., 2000; He et al., 2016; Wang et al., 2018).

If we roughly use the inventory-based forest area of 138.8 Mha in China (Guo et al., 2013) and extend the current SOC sink rates obtained in this study to all the forests in the country, China’s forest soils have sequestered approximately 1.1 ± 0.5 Pg C during the past 2 decades (57.1 ± 26.5 Tg C yr$^{-1}$). This C accumulation would be equivalent to 2.4%–6.8% of the country’s fossil CO$_2$ emissions during the contemporary period (1991–2010) (Zheng et al., 2016). By comparing forest SOC data obtained from published literature during the 2000s and a national soil inventory during the 1980s, Yang et al. (2014) estimated significant C accumulation in the forest soils of China. Although they did not estimate the national C budget of these forest soils, we can calculate the national C sequestration rate of forest soil as 67.2 Tg C yr$^{-1}$, based on the C sequestration rates and forest areas of the different forest types in their study. Our results further confirm the assessment, based on repeated measurements at eight permanent forest plots, that soils in China’s forests have functioned as a C sink for atmospheric CO$_2$ during the past 2 decades.

According to previous estimates, the C sinks of three C sectors: forest vegetation biomass (Fang et al., 2014), deadwood, and litter (Zhu et al., 2017) during the past 2 decades were 70.9, 3.9, and 2.8 Tg C yr$^{-1}$, respectively (Table S5). If these previous estimates are incorporated into the soil C accumulation rate of 57.1 ± 26.5 Tg C yr$^{-1}$ in the current study, then China’s forests may have sequestered a total of 134.7 Tg C per year between the 1990s and the 2010s. This is equivalent to 14.5% of the contemporary fossil CO$_2$ emissions in the country (Zheng et al., 2016). According to the estimate of Pan et al. (2011), the C sink rate of forests in the temperate regions of the Northern Hemisphere was 647.1 Tg C yr$^{-1}$. The C sequestration of China’s forests represents 20.8% of the total temperate regions. The sequestration rate of China’s forests is slightly higher than the mean value of the total temperate regions, relative to the forest area of China (i.e., 18.9% of the forest areas in the temperate regions). This result indicates that the role of forest soils in the regional C cycle cannot be ignored, although a large uncertainty about the national C budget of forest soils remains in our estimates.

4.4 Uncertainty analysis

We investigated the SOC stocks in eight permanent plots across four forest biomes in China. These plots spanned a long-term timescale (approximately 20 years) and a broad
spatial scale (approximately 34° of latitude). We also measured several C fluxes (i.e., biomass change rate, production of litterfall and deadwood) that were relevant to the rate of SOC change. Even so, the following three factors may introduce uncertainties related to the estimation of SOC dynamics.

First, the sampling times and intervals between SOC investigations were different across the sites. The first sampling was performed from 1987 to 1998 and the second was carried out from 2008 to 2014. As a result, the sampling interval ranged from 16 years in the boreal forest plot to 21 years in the subtropical mixed forest plot (Table 1). Nonuniform sampling times and intervals may lead to uncertainties in relation to SOC stocks across the forest plots.

Second, the depth of soil varied substantially, ranging from 40 cm in the boreal site to 100 cm in the temperate and tropical sites. In addition, different numbers (2–5) of soil profiles were dug in different plots during the first sampling period. To ensure consistency between the two sampling times, the same number of soil profiles were dug in similar locations to perform SOC stock investigations during the second sampling period. We performed continuous observation of litterfall and deadwood production, but the observation times and durations varied across the plots. Variability in these items may reduce the comparability of SOC dynamics among plots.

Finally, the rates of SOC change in our study and in inventory-based forest areas and forest types were used to estimate the C budget of forest soil in China. However, only eight permanent forest plots were observed in this study, and this will inevitably lead to uncertainty with respect to national estimations.

5 Conclusions

The SOC stocks within the top 20 cm increased by 2.4–12.6 Mg C ha$^{-1}$ across the forests during the past 2 decades, with an annual accumulation rate of 332.4±200.2 kg C ha$^{-1}$ yr$^{-1}$. If all soil horizon profiles were included, the soils may have been found to have sequestered 3.6%–16.3% of the annual net primary production across the investigated sites, and the averaged accumulated rate (421.2 kg C ha$^{-1}$ yr$^{-1}$) may have been more than one-half of the vegetation C uptake rate (702.0 kg C ha$^{-1}$ yr$^{-1}$) in China’s forests. These results demonstrate that these forest soils have functioned as an important C sink over recent decades, although the phenomenon may not occur uniformly in forests worldwide. Forest soils store large amounts of C and accumulate it steadily (and often slowly) but will release it rapidly to the atmosphere once they are disturbed.

Data availability. Allometric equations of above-ground biomass and the data for soil bulk density, SOC content, stock, and their change rates of the eight permanent plots are listed as in the Supplement. The remaining data that support the findings of this study are available from the corresponding author upon request.

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/bg-17-715-2020-supplement.

Author contributions. JF designed the research. JZ and JF designed the data analysis. JZ, JF, ZZ, LJ, XH, HY, GL, CW, and GZ performed SOC measurements. JF, YL, CJ, and GL designed sampling and analytical programs and performed data quality control. JZ, JF, CW, SZ, PL, JZ, ZT, CZ, RAB, and YP contributed to the writing of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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