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Increasing soil carbon stocks in eight typical forests 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 carbon (SOC) stock are poorly quantified, especially based on direct field measurements. In this study, we investigated the 20-year changes in the SOC stocks at eight sites from southern to northern China. The averaged SOC stocks 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 across the forest sites, with a mean increase of 127–908 kg C ha^{-1} yr^{-1}. This SOC accumulation was resulted primarily from both leaf litter and fallen logs and equivalent to 3.6–16.3% of aboveground net primary production. Our findings provide strong evidence that China's forest soils have been acting as significant carbon sinks although their strength varies with forests in different climates.

Keywords: soil organic carbon, carbon cycle, forest ecosystems, global change, permanent plot

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1 Introduction

Terrestrial ecosystems have absorbed approximately 30% of carbon dioxide (CO_2) emitted from human activities since the beginning of the industrial era (IPCC, 2013). Forests have contributed more than half of these carbon (C) fluxes (Pan et al., 2011). Since soils contain huge C stock in forest ecosystems, even a slight change in this stock will induce a considerable feedback to the atmospheric CO_2 concentration (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 response to global climate change. However, it is difficult to capture the SOC change with short-term measurements (Smith, 2004) because the soil C pool has a longer turnover time and higher spatial variability compared to vegetation biomass 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 (Van Orshoven et al., 2005; 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 lack of direct measurements representing large areas (Sitch et al., 2013). 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).

There are a few soil resampling studies that explored the SOC changes in different forests, but the results are often contrary. For instance, Schrumpf et al. (2011) found that SOC in deciduous broadleaf forests in central German increased with a change rate of 650 kg C ha^{-1} yr^{-1} from 2004 to 2009. In contrast, Prietzel et al. (2016) indicated that SOC stocks in the German Alps forests had a significant decrease with a change rate of 732 kg C ha^{-1} yr^{-1}

between 1987 and 2011. Kiser et al. (2009) found that the hardwood forest soils in central Tennessee, USA, exhibited a slight C source (-11 kg C ha^{-1} yr^{-1}) between 1976 and 2006. Chen et al. (2015) synthesized global SOC changes, and found that the relative change rates of forest SOC stocks were contradictory among long-term experiments (0.19% yr^{-1}), regional comparisons (0.34% yr^{-1}) and repeated soil samplings (-0.11% yr^{-1}). Such discrepancies can be partly attributed to the insufficient observations and inconsistent methodologies. It may also involve different effects of changing environmental factors and nitrogen inputs on soil C dynamics (Norby and Zak, 2011). In addition, to date these studies were primarily conducted in the forests of Europe and the United States, and few in China's forests.

Therefore, in this study we measured SOC density of eight permanent forest sites from tropical, subtropical, temperate, and boreal forests in China at two periods of 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. We finally assessed the changes of SOC stocks in China's forests using the site data obtained from this study.

2 Materials and methods

2.1 Study sites

From north to south, eight permanent forest plots from four forest sites (Great Xing'anLing, Mt. Dongling, Mt. Dinghu, and Jianfengling) were investigated (Fig. 1). The four sites spanned a wide range from 18.7 °N to 52.6 °N in latitude, and belonged to boreal, temperate, subtropical and tropical climate zone, respectively, with a climatic difference of approximately 26 °C in mean annual temperature and 1,200 mm in mean annual precipitation. The eight plots included a boreal larch forest (*Larix gmelinii*), two temperate deciduous broadleaf forests (*Betula platyphylla* and *Quercus wutaishanica*), a temperate pine plantation (*Pinus tabulaeformis*), a subtropical evergreen broadleaf forest, a subtropical pine plantation

(*Pinus massoniana*), a subtropical pine and broadleaf 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 at Mt. Dongling-shan, 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-year-old at the time of the first sampling, dominated by *P. tabulaeformis* (Fang et al., 2007). Three subtropical forest plots were located at Dinghu-shan Biosphere Reserve in Guangdong Province, South China (Zhou et al., 2006). The subtropical evergreen broadleaf forest was an old-growth stand more than 400 years old, co-dominated by *Castanopsis chinensis*, *Canarium pimela*, *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 broadleaf forests was approximately 110 years old at the time of the first sampling, which represent the mid-successional stages of monsoon evergreen broadleaf forest in this region. The tropical mountain rainforest plot was located at the Jianfengling National Natural Reserve, southwestern Hainan (Zhou et al., 2013); it has not been disturbed for more than 300 years and is dominated by species in families Lauraceae and Fagaceae, e.g., *Mallotus hookerianus*, *Gironniera subaequali*, *Cryptocarya chinensis*, *Cyclobalanopsis patelliformis* and *Nephel-ium topengii*. For detailed descriptions on these eight plots, see Supplementary Materials and Methods.

2.2 Soil sampling and calculation of SOC content

The first sampling was conducted between 1987 and 1998 at each of the eight forests (Table

1). We re-measured the same sample plots at each forest between 2008 and 2014 using identical sampling protocols.

At each forest plot, 2–5 soil pits were dug to collect the samples for analyzing the physical and chemical properties in the two sampling periods (most in the 1990s in the first sampling period and in the 2010s in the second sampling period). The samples were taken at a depth interval of 10 cm down to the maximum soil depth. In brief, for the boreal forest, three soil pits down to the 40-cm soil depth were established in random locations in the growing season of 1998. In August 2014, three soil pits were randomly excavated again to the same soil depth for SOC content and bulk density. For the three temperate forests, two soil profiles (100 cm depth) were dug in each plot to collect soil samples at 10 cm intervals during the summer of 1992. In the summer of 2012, three soil profiles were dug, and soils were sampled from the same respective horizons in each soil profile (Zhu et al., 2015). For the three subtropical forests, the first sampling was conducted in September of 1988 for the evergreen and the pine plots and in 1987 for the mixed plot, both at the end of the rainy season and the beginning of the dry season. Five soil pits (60 cm depth) were randomly excavated to collect samples for the calculation of 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 in 1992 and again in 2012.

Three bulk density samples were obtained for each layer with a standard container with 100 cm^3 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, removed off the fine roots by hand, and sieved (2 mm mesh). The SOC content was measured using the wet oxidation method (Nelson and Sommers, 1982). The SOC content was calculated according to Equation (1):

$$\mathrm{SOC} = \sum_{i=1}^{n} CC_i \times Bd_i \times V_i \times HF_i \tag{1}$$

where CC_i, Bd_i, and V_i are SOC content (%), bulk density (kg m^{-3}), and volume (m^3) at the *i*-th soil horizon, respectively. HF_i is calculated as $1-\frac{\text{stone volume}+\text{root volume}}{V_i}$ and is a dimensionless factor that represents the fine soil fraction within a certain soil volume.

2.3 Calculation of above-ground biomass and net primary production

Diameter at breast height (DBH, 1.3 m) and height of all living trees with DBH > 5 cm were measured at each plot in 1990s and 2010s. The above-ground biomass (AGB) of different components (stem, bark, branches, and foliage) was estimated for all tree species using the allometric equations (Table S1). A standard factor of 0.5 was used to convert biomass to C (Leith and Whittaker, 1975). The net increment of AGB ($_\Delta$Store) 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 Equation (2):

$$\mathrm{ANPP} = \mathrm{Litterfall} + \Delta\mathrm{Store} + \mathrm{Mortality} \tag{2}$$

where Litterfall and ΔStore are litter production and above-ground net biomass increment per year, respectively. Mortality defined as above-ground dead wood 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 of 2011–2014 in the temperate sites, and from May to October of 2010–2014 in the boreal sites. Litter (leaves, flowers, fruits and woody materials <2 cm diameter) was collected monthly from 10–15 litter traps (1 × 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 of 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 (that is, 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

In order to figure out C sequestration size in China's forest soils, we estimated the changes in the national forest SOC stocks, using 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 the period 1989–1993, which is close to the first sampling period in the present study (Guo et al., 2013). The changes in the national forest SOC stock were calculated as the product of SOC density, SOC density change rate and forest area for major forest types in the period of 1989–1993. In addition, to evaluate relative importance of forest soil C sequestration in 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

Soil organic carbon stocks were investigated at eight permanent forest plots from four forest sites from northern to southern China, at two periods (around 1990s and 2010s). The eight plots spanned a wide range from 18.7 °N to 52.6 °N in latitude, and included a boreal larch forest (*Larix gmelinii*) in Great Xing'anLing, two temperate deciduous broadleaf forests

(*Betula platyphylla* and *Quercus wutaishanica*) and a temperate pine plantation (*Pinus tabulaeformis*) in Mt. Dongling, a subtropical evergreen broadleaf forest, a subtropical pine plantation (*Pinus massoniana*) and a subtropical pine and broadleaf mixed forest in Mt. Dinghu, and a tropical mountain rainforest in Mt. Jianfengling (Fig. 1 and Table 1).

The changes in SOC contents, bulk density and SOC stocks in the top 20 cm soil layer between 1990s and 2010s were shown in Fig. 2 and Fig. S1. The paired *t*-test analysis indicated that SOC contents in the 0- to 20-cm depth was significantly higher in the 2010s than those in the 1990s (3.22±0.65% vs. 2.85±0.63%; $t = -5.65$, $P < 0.001$) (Table 2). The average increase rate of SOC content was 0.018±0.004% yr^{-1} in the top 20 cm depth, ranging from 0.013 to 0.039% yr^{-1} across the study sites. These increase rates of SOC content in the 0–10 cm horizon (0.031±0.020% yr^{-1}) were three times larger than those in the 10–20 cm horizon (0.010±0.009% yr^{-1}) (Table S2). At the same time, the bulk density of the top 20 cm soil layer decreased in most of the sites (6 out 8 sites), with an average decrease rate of 2.74±3.68 mg cm^{-3} yr^{-1} (Table S3). As a result, the SOC stock in the top 20 cm soil layer increased significantly in the past two decades (t=-5.85, P<0.001, Table 2), with an average accumulation rate of 332±200 kg C ha^{-1} yr^{-1} (0.72±0.40% yr^{-1}, Fig. 2, also see Table S3). The temperate pine plantation experienced the largest increase of SOC stock in the top 20 cm depth (631±111 kg C ha^{-1} yr^{-1}). In contrast, the smallest increase rate was observed in the subtropical mixed forest (117±25 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±79 kg C ha^{-1} yr^{-1}), which lead to the highest relative accumulation rate (1.40±0.22% yr^{-1}) among the study sites.

We further compared the SOC stocks of the whole soil profile, with 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, between 1990s and 2010s (Fig. 3). The SOC stocks of all sampling sites in the 2010s

https://doi.org/10.5194/bg-2019-319
Preprint. Discussion started: 12 September 2019

were higher than those in 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, $P < 0.01$, 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±274 kg C ha^{-1} yr^{-1} and a relative increase rate of 0.56±0.54% (Fig. 2). The accumulation rates of SOC 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 of the SOC stock occurred in the subtropical evergreen old growth forest (908±60 kg C ha^{-1} yr^{-1}), and the least one occurred in the temperate deciduous oak forest (127±25 kg C ha^{-1} yr^{-1}; Table S3). The relative increase rates in the subtropical evergreen old growth forest (1.33±0.09% yr^{-1}) and the subtropical mixed forest (1.49±0.16% yr^{-1}) were higher than those in the temperate forests (0.05±0.01% yr^{-1} in the oak forest, 0.14±0.03% yr^{-1} in the pine forest, and 0.19±0.02% yr^{-1} in the birch forest; Table S3).

In addition, the SOC increase rate (127–908 kg C ha^{-1} yr^{-1}) was equivalent to 3.6–16.3% of ANPP (3340–6945 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%) (Table 3; Table S4).

3.2 Relationships between SOC change rates and biotic and climatic variables

To understand the possible mechanisms for the SOC increase rates 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 = 0.237; Fig. 4a). The SOC accumulation rates were positively and significantly associated with the above-ground dead organic C production, annual litter ($R^2 = 0.66$, $P = 0.01$, Fig. 4b), and fallen log production ($R^2 = 0.69$, $P = 0.01$, Fig. 4c). The SOC accumulation rates across these forests were closely associated with the observed ANPP ($R^2 = 0.55$, $P = 0.034$, Fig. 4d), and also showed an increasing with increasing mean annual temperature and precipitation, despite insignificant (both $P > 0.1$; Fig. 4e and Fig. 4f). The multiple regression analysis indicated the relative effects of biotic factors (AGB growth rate, litter and fallen log productions) and climatic factors (MAT and MAP) on the SOC increase rates (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 the forest SOC changes comes mainly from individual experiments (Prietzel et al., 2006; Kiser et al., 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 broad-scale forest soil resampling to evaluate changes in SOC stock across eight permanent forest sites in China. Our measurements suggest that SOC stocks exhibited a significant accumulation in these forests from the 1990s to 2010s, at the accumulation rate of 127–908 kg C ha^{-1} yr^{-1}. These accumulation rates are comparable to those of the other studies that were primarily conducted in boreal and temperate forests in the other regions (-11–812 kg C ha^{-1} yr^{-1}, Fig. 5). In detail, the SOC accumulation rate of the boreal forest in the present study was estimated as 243 kg C ha^{-1} yr^{-1}, which was within the range of boreal forests in European and American forests (210–652 kg C ha^{-1} yr^{-1}) (Prietzel et al., 2006; Häkkinen et al., 2011; Chapman et al., 2013; Schrumpf et al., 2014). The SOC

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Preprint. Discussion started: 12 September 2019

accumulation rates of the three temperate forests ranged from 127 to 391 kg C ha^{-1} yr^{-1}, comparable to the regional comparisons data of 200 kg C ha^{-1} yr^{-1} in the temperate forests of China (Yang et al., 2014).

In other subtropical and tropical forest ecosystems, the direct evidence regarding SOC dynamics is relatively scarce. However, based on the estimates from regional comparisons, Pan et al. (2011) showed that tropical forest of the world was a C source of 1.38 Pg C ha^{-1} yr^{-1} from 1990 to 2007. At global scale, tropical land-use changes have caused a sharp drop in forest area, which also led to a large C releases in tropical forest soils. Similarly, Prietzel et al. (2016) reported a large loss of SOC in German Alps forests over the past three decades. These different results are probably because the high-elevation ecosystems are expected to warm more sensitive than other regions with associated changes in soil freezing and thawing events and snow cover. Moreover, they also stated that near half of the woody biomass production in these forests of the German Alps has been harvested in recent decades, which also could cause net C releases of the soils (Prietzel et al., 2016).

4.2 Links between biotic and climatic factors and SOC accumulations

The SOC accumulation rate across the eight forests was positively associated with both biotic and climatic factors. Mathematically, the relationships between biotic factors (e.g. aboveground litter and log input rates) and SOC accumulation rates were much stronger than those between climatic factors (MAT and MAP) and SOC dynamics. The positive pattern between climatic factors and SOC dynamics could be largely induced by the internal correlations between climatic and biotic factors (Fig. 4). Temperature and precipitation could exert a significant effect on the distribution of forest biomass (Yu et al., 2014) and litterfall (Jia et al., 2016) and indirect influence the SOC dynamics (Yang et al., 2014) in China's forests. Zhu et al. (2017a) revealed that the carbon pools of both standing and fallen dead

https://doi.org/10.5194/bg-2019-319
Preprint. Discussion started: 12 September 2019

wood exhibited linear increases with both MAT and MAP across forest ecosystems of China, demonstrating that larger stock of the potential SOC input existed in those forests with warm and humid climates. However, soil respiration is also considered to be positively correlated with temperature and precipitation (Raich and Schlesinger, 1992; Bond-Lamberty and Thomson, 2010). The positive trend between SOC accumulation and climatic factors indicated that the climate-driven input might outpace the output.

Compared with climatic factors, biotic factors explained the variation of SOC dynamics better. Note that in this study, we did not measure the root-derived carbon inputs to the SOC, although the below-ground production also makes a significant contribution to the SOC accumulation (Nadelhoffer and Raich, 1992; Majdi, 2001). In addition to above-ground inputs being mineralized from litter and dead wood, below-ground inputs may have more opportunity for interactions with soils (Rasse et al., 2005). Even if the effect of the climatic factors were controlled and below-ground biotic factors were not included in the analysis, the above-ground biotic factors could explain 56.4% of the variation of SOC accumulation rate. However, there was a negative but not significant correlation between vegetation growth and SOC accumulation rates in our study. This may be primarily because the biomass carbon stock of the subtropical old-growth forest decreased considerably over the past two decades (as a decrease rate of -1000 kg C ha^{-1} yr^{-1}, Table S4), but its SOC stock largely increased at a rate of 908±60 kg C ha^{-1} yr^{-1}. This result is consistent with the findings from a long-term observation by Zhou et al. (2006) and a global flux synthesis by Luyssaert et al. (2008), who stated that soils in old-growth forests served as a significant carbon sink, with an average rate of 1.3 Pg C yr^{-1} globally. Soils of the old-growth forests sequestered carbon, probably due to the large stocks of litter and dead wood in these forests (Zhu et al., 2017b).

4.3 Carbon budget of China's forests

The SOC accumulation rate (421±274 kg C ha^{-1} yr^{-1}, Fig. 2 and Table S3) is more than half of the vegetation C uptake rate in China's forests (702 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 in the past two decades rather than the positive feedback predicted by coupled carbon-climate models (Cox et al., 2000; He et al., 2016; Wang et al., 2018).

If we 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 1.14±0.53 Pg C over the past two decades (57±27 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 literatures during 2000s and national soil inventory during 1980s, Yang et al. (2014) estimated significant carbon accumulation in forest soils of China. 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 carbon sink for atmospheric CO_2 over the past two decades. According to previous estimates, the C sinks of three C sectors, i.e. forest vegetation biomass (Fang et al., 2014), dead wood and litter (Zhu et al., 2017a), over the past two decades were 71, 4, and 3 Tg C yr^{-1}, respectively. If incorporating these previous estimates into the soil C accumulation rate of 57±27 Tg C yr^{-1} in the current study, then China's forests could have sequestered a total of ~135 Tg C per year between the 1990s to 2010s, which is roughly equivalent to 14.5% of the contemporary fossil CO_2 emissions in the country (Zheng et al., 2016).

5 Conclusion

The SOC stocks within the top 20 cm depth increased by 2.4–12.6 Mg C ha^{-1} across the forests during the past two decades, with an annual accumulation rate of 332±200 kg C ha^{-1}. If all horizons of soil profiles were included, the soils sequestered 3.6–16.3% of the annual net primary production across the investigated sites, and the averaged accumulated rate (421 kg C ha^{-1} yr^{-1}) is more than half of the vegetation C uptake rate (702 kg C ha^{-1} yr^{-1}) in China's forests. These results demonstrate that these forest soils have functioned as an important C sink in recent decades, although the phenomenon may not happen everywhere in forests around the world. This study also reveals the importance of protecting and managing forest soils because they store large amounts of carbon and will release C rapidly into the atmosphere once they are disturbed.

Data availability. All relevant data are available from the corresponding author upon request.

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 programmes and performed data quality control. JZ, JF, CW, SZ, PL, JZ, ZT, CZ, RB and YP contributed to the writing of the manuscript.

Competing interests. The authors declare no competing interests.

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Table 1. Location, forest type, mean annual temperature (MAT), and mean annual precipitation (MAP) at eight forest plots in four climate zones, together with forest origin and study periods.

Site	**Forest**	**Origin**	**Latitude (°)**	**Longitude (°)**	**Elevation (m)**	**Area (m^2)**	**MAT (°C)**	**MAP (mm)**	**Study period**
Great Xing'anLing (Boreal)	Larch	Mature	52°38'42.06"N	123°46'7.80"E	466	20×30, 25×40	-4.3	477	1998–2014
Mt. Dongling (Temperate)	Birch	Secondary	39°57'05.82"N	115°25'38.93"E	1,350	30×35	4.7	519	1992–2012
	Oak	Secondary	39°57'26.66"N	115°25'29.14"E	1,150	30×40	4.6	519	1992–2012
	Pine	Plantation	39°57'33.94"N	115°25'39.40"E	1,050	20×30	5.5	506	1992–2012
Mt. Dinghu (Subtropical)	Evergreen	Old growth	23°10'11.21"N	112°32'21.97"E	275	50×50	20.9	1698	1988–2008
	Mixed	Mature	23°9'58.51"N	112°32'23.32"E	265	30×40	21.6	1680	1987–2008
	Pine	Plantation	23°10'02.75"N	112°32'30.59"E	250	30×40	21.9	1677	1988–2008
Jianfengling (Tropical)	Evergreen	Old growth	18°43'47.01"N	108°53'23.79"E	870	100×100	20.6	1628	1992–2012

Table 2. Results of the paired-samples *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.

Soil horizon	SOC content			Bulk density			SOC stock		
	t	*df*	*P*	*t*	*df*	*P*	*t*	*df*	*P*
0–10 cm	-4.22	7	**<0.01**	2.19	7	0.06	-6.50	7	**<0.001**
10–20 cm	-4.09	7	**<0.01**	3.30	7	**<0.05**	-3.26	7	**<0.05**
Top 20 cm	-5.65	7	**<0.001**	1.01	7	**0.35**	-5.85	7	**<0.001**
Whole soil profile	-	-	-	-	-	-	-4.15	7	**<0.01**

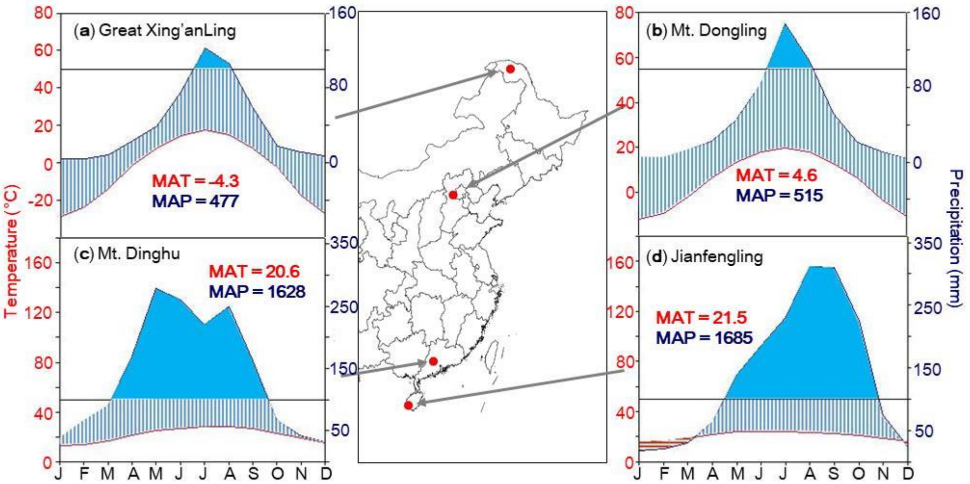
Table 3. Measured carbon stocks and fluxes of the four forest sites in China during the 1990s and the 2010s. AGB, aboveground biomass; ANPP, aboveground net primary production. For details, see supplementary information Table S1.

Parameter	Boreal	Temperate	Subtropical	Tropical
Carbon pool (Mg C ha^{-1})*				
AGB	91.1±25.0	89.6±17.4	107.0±41.7	213.6±41.4
Litter	4.4±0.0	3.9±1.3	2.1±0.7	1.8±0.2
Dead wood	1.3±0.5	4.5±1.2	7.3±6.7	5.7±0.8
Soil	69.4±6.2	231.6±14.6	67.2±19.5	102.6±19.9
Ecosystem total	166.2±31.7	329.6±34.5	183.7±68.5	323.7±62.3
Carbon flux (kg C ha^{-1} yr^{-1})				
AGB growth	899±411	1810±521	799±1572	684±145
litterfall	2424±283	1947±361	3385±1445	3970±280
Fallen log	13±4	106±75	987±967	1034±72
Standing snag	3±2	277±111	220±136	803±62
ANPP	3340±699	4139±608	5391±1655	6492±559
Soil accumulation	243±31	284±139	626±370	398±84
Ratio of soil accumulation to ANPP (%)	7.3±7.8	6.7±2.8 (3.6~9.2)	11.0±5.3 (5.7~16.3)	6.1±3.3

Note: Carbon pool of each ecosystem component at the time of the second sampling (2010s).

Figures

Figure 1. Locations and climatic conditions of the sites. (a) Great Xingan'Ling, the boreal site, (b) Mt. Dongling, the temperate site, (c) Mt. Dinghu, the subtropical site, and (d) Jianfengling, the tropical site. The blue and red lines in climatic diagrams are the monthly mean values of precipitation and temperature, respectively. The blue areas indicate the period in the year when the precipitation exceeds 100 mm per month. MAT, mean annual temperature; and MAP, mean annual precipitation.



532 **Figure 2.** Mean soil organic carbon (SOC) content (**a**), bulk density (**b**), SOC stock (**c**) and 533 their relative change rates (**d**) within 0–20 cm soil depth in the 1990s and the 2010s for the 534 four forest sites in China. For more details, see Tables S2 in supplementary information.

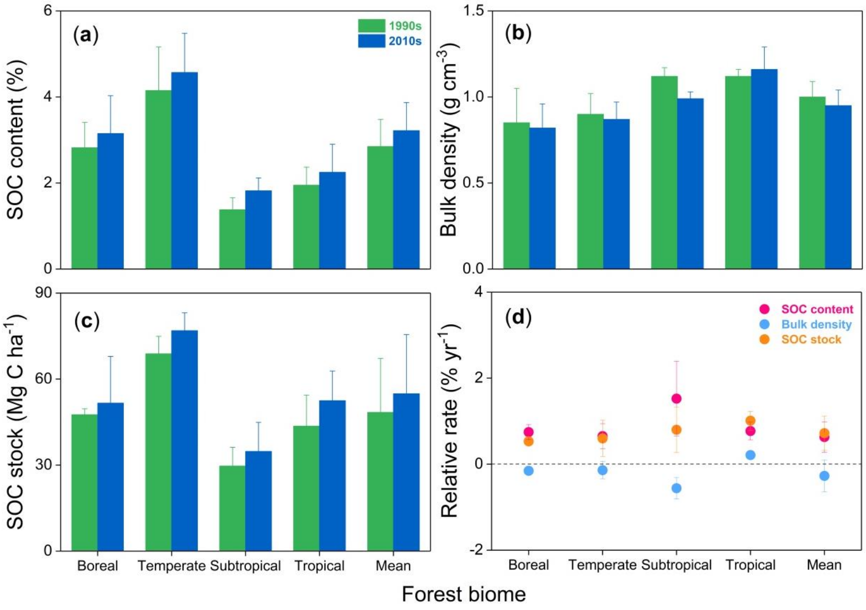


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Figure 3. Comparison of soil organic carbon stocks in eight forests of China between the 1990s and the 2010s. The soil organic carbon (SOC) stocks in all forests in the two periods are above the 1:1 line, suggesting that all these forests have increased their SOC stock during the study period. The inset graph shows the SOC sink rates by forest biomes (i.e., boreal, temperate, subtropical and tropical forests) which are categorized from the eight forests. For details of the eight forests, see Figure 1, Table 1 and Supplementary Table 1.

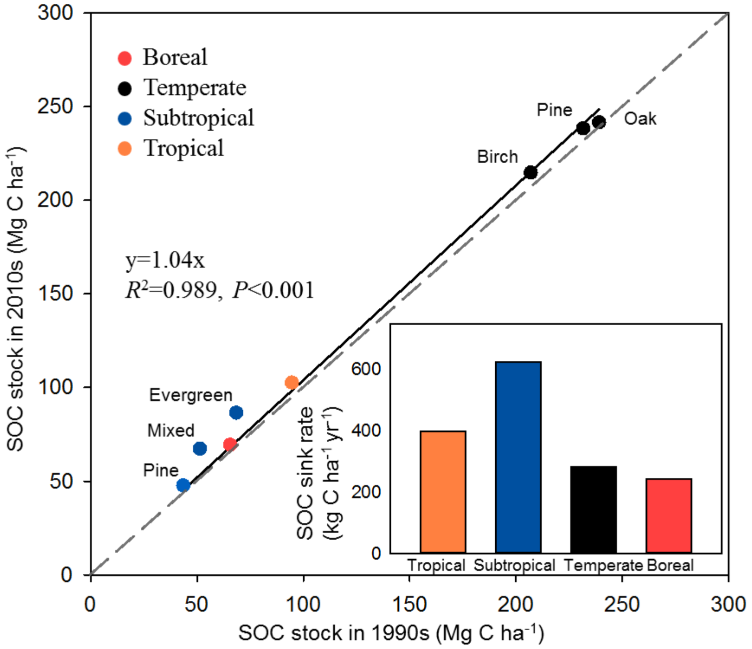

Figure 4. Relationships between soil organic carbon increase rates against biotic and climatic factors in eight forests of China. (a) Biomass increment, (b) litter production, (c) log production, (d) above-ground net primary production (ANPP), (e) mean annual temperature (MAT) and (f) mean annual precipitation (MAP); (g) the relative effects of biotic (a, b and c) and climatic (e and f) factors on soil organic carbon (SOC) increase rates (kg C ha^{-1} yr^{-1}) using partial regression analyses.

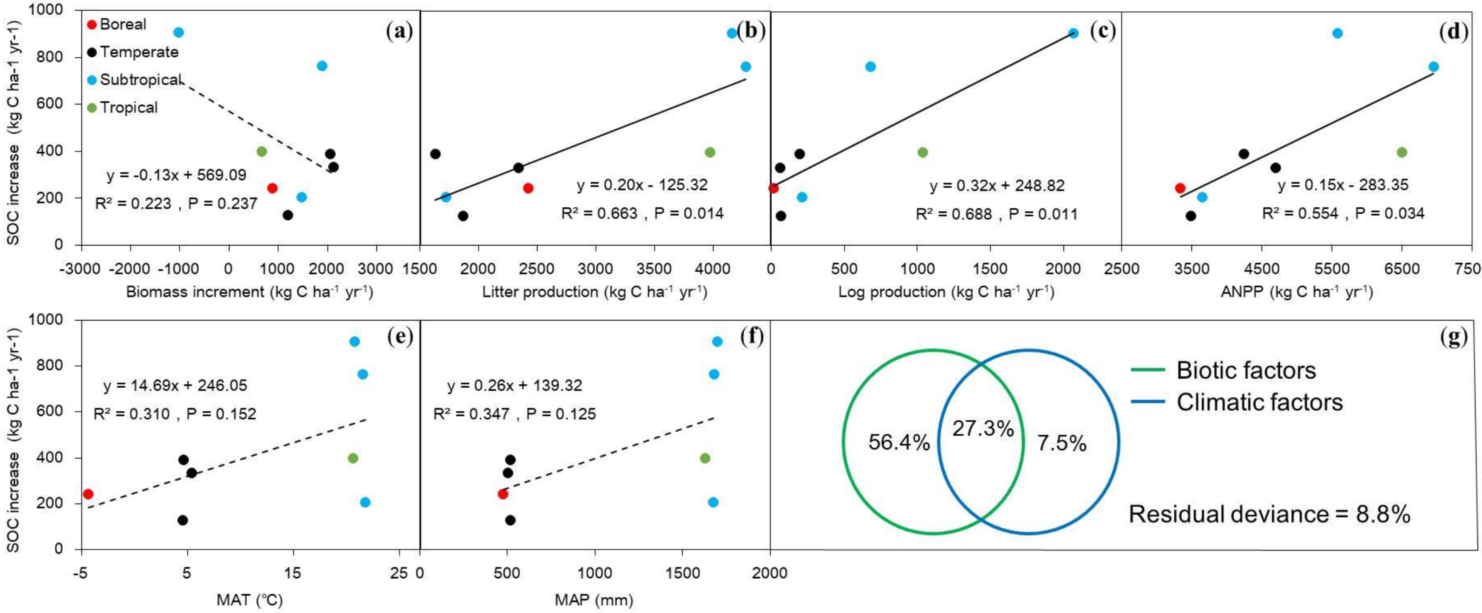

Figure 5. Comparison of the changes in forest soil organic carbon stocks according to repeated soil samplings and/or long-term observations.