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Increasing soil carbon stocks in eight permanent forest plots in China

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Supporting information

Supplementary Materials and Methods

Study sites and field measurements

The sites of this study were selected in boreal, temperate, subtropical and tropical forests spanning approximately 26° latitude in the eastern China (Fig. 1, Table 1). The detailed information about each site is described below.

Boreal forest: The boreal site was established in Tahe, Great Xing'anling, northeastern China (52°38'42"N, 123°46'08"E), in May 1998 (Wang et al., 2001). The topography is gently undulating with an average slope of 10°. The elevation is 466 m. The mean annual temperature (MAT) and precipitation (MAP) are -4.3 °C and 477 mm, respectively. The frost-free period is shorter than 100 days, and the snow pack lasts for approximately 5 months in this region. The *Larix* forest was a 100-year-old mature forest at the time of the first sampling, dominated by *Larix gmelinii* accompanied by *Betula platyphylla*, *Pinus sylvestris*, *Picea koraiensis*, and *Populus davidiana*. The understory is dominated by *Ledum palustre*. The parent material is granite bedrock, and the soil is a dark brown forest soil. The soil in the plots has depths of 30–40 cm, with a pH between 5.0 and 6.0.

Temperate forests: The temperate site on Mt. Dongling stands near the Xiaolongmen forestland (39°57'04"N–39°57'35"N, 115°25'25"E–115°25'45"E), Beijing, China. The temperate forests in this region are protected and have not experienced serious anthropogenic disturbance (Fang et al., 2007). The MAT and MAP were 4.8 °C and 612 mm, respectively (Fig. 1, Table 1). We selected three plots from the top to the foot of a mountain as the temperate plots of deciduous broadleaf birch (*Betula platyphylla*) and oak (*Quercus wutaishanica*) forests and a pine (*Pinus tabuliformis*) plantation in 1992. The soil in this region has a depth of 90–110 cm and a pH that ranges between 6.0 and 7.0.

The birch plot is located on a northwest-facing slope near the peak of the mountain, with an elevation of 1,350 m. The forest is dominated by *B. platyphylla* accompanied by *B. utilis* and *Populus alba*. The woody plants in the understory include *Sorbus pohuashanensis*, *Lonicera japonica*, *Prunus armeniaca*, *Corylus mandshurica*, *Acer mono*, *Abelia biflora*, *Leptodermis oblonga*, *Spiraea sargentiana*, and *Macrocarpium officinalis*. The oak plot is located on a southwest-facing slope on the middle of the mountain, with an elevation of 1,150 m. The forest is a secondary forest recovered from human disturbance, dominated by *Q. wutaishanica* accompanied by *B. utili*. The understory woody plants include *S. sargentiana*, *A. mono*, *Lespedeza bicolor*, *L. japonica*, *C. mandshurica*, and *Deutzia scabra*. Both the birch and the oak forests are secondary deciduous broadleaf forests (55 years at the time of the first sampling). The pine forest is on a southeast-facing slope at the foot of the mountain, with an altitude of 1,050 m. The pine forest was a 30-year-old plantation at the time of the first sampling, dominated by only one tree species, *P. tabuliformis*, with very few plants in the understory and a thick litter floor.

Subtropical forests: The subtropical site is located in the Dinghushan Biosphere Reserve (23°09'21"N–23°11'30"N, 112°30'39"E–112°33'41"E) in Guangdong Province, China. The region has a typical southern subtropical monsoon climate (warm and humid). The MAP is 1,678 mm, 80% of which falls in the wet season (April to September), and the MAT is 22.3 °C. The altitude in the reserve ranges from 10 m to 1,000 m. The bedrock is sandstone and shale, with a pH that ranges between 4.0 and 4.9.

A 50 × 50 m^2 plot, representative of the monsoon evergreen broadleaf forests in the region, was established in 1979 at an elevation of 275 m on a south-facing slope. The evergreen broadleaf forest has not been disturbed for more than 400 years (Zhou et al., 2006). The plants in the evergreen plot are typical and natives of tropics and subtropics, including *Castanopsis chinensis*, *Canarium pimela*, *Schima superba*, and *Engelhardtia roxburghiana*,

among others. The sub-canopy layer is mainly composed of *Cryptocarya concinna* and *Machilus chinensis*. Another two 30 × 40 m^2 plots had also been established in 1979. The pine (*Pinus massoniana*) plantation and the mature mixed pine and broadleaf forests are the other two most common forest communities that represent the early- and mid-successional stages of monsoon evergreen broadleaf forest, respectively, in this region. The age of the pine plantation was approximately 40 years at the time of the first sampling.

Tropical forest: The tropical site was established in the Jianfengling National Natural Reserve (18°23'N–18°50'N, 108°36'E–109°05'E) on southwestern Hainan Island, China, in 1992 (Zhou et al., 2013). The region has a typical tropical mountain rain forest with an elevation of 800–1,000 m. The MAT and MAP were 19.8 °C and 2,449 mm, respectively. The primary forest in this region 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*. The soils are lateritic yellow soil, with a pH that ranges between 4.3 and 4.7.

References

Fang, J. Y., Liu, G. H., Zhu, B., Wang, X. K., and Liu, S. B.: Carbon budgets of three temperate forest ecosystems in Dongling Mt., Beijing, China. Sci. China Earth Sci., 50, 92–101, https://doi.org/10.1007/s11430-007-2031-3, 2007.

Wang, C., Gower, S. T., Wang, Y., Zhao, H., Yan, P., and Bond-Lamberty, B. P.: The influence of fire on carbon distribution and net primary production of boreal *Larix gmelinii* forests in north-eastern China. Glob. Change Biol., 7, 719–730, https://doi.org/10.1046/j.1354-1013.2001.00441.x, 2001.

Zhou, G., Liu, S., Li, Z., Zhang, D., Tang, X., Zhou, C., Yan, J., Mo, J.: Old-growth forests can accumulate carbon in soils. Science, 314, 1417, https://doi:10.1126/science.1130168,

2006.

Zhou, Z., Jiang, L., Du, E., Hu, H., Li, Y., Chen, D., and Fang, J.: Temperature and substrate availability regulate soil respiration in the tropical mountain rainforests, Hainan Island, China. J. Plant Ecol., 6, 325–334, https://doi.org/10.1093/jpe/rtt034, 2013.

Table S1. Allometric equations of above-ground biomass by species and sites used in this study. The equations are expressed as B=a (D^2 H)^b, where B, D, and H are the biomass (kg), DBH (cm) and height (m) of each stem, respectively.

Site	Species	Component	a	b	R^2
Boreal	*Larix gmelinii*	Bole	0.01258	0.99331	0.99
		Branch	0.00136	1.02797	0.99
		Leaf and Fruit	0.01009	0.64543	0.98
	Betula platyphylla	Bole	0.02853	0.89271	0.99
		Branch	0.00278	1.02568	0.99
		Leaf and Fruit	0.01545	0.61265	0.98
Temperate	*Pinus tabulaeformis*	Stem	0.0475	0.8539	0.98
		Branch	0.0017	1.1515	0.94
		Leaf	0.0134	0.8099	0.92
		Fruit	0.0013	0.9055	0.27
	Betula platyphylla & B. dahurica	Stem	0.0319	0.9356	0.99
		Branch	0.00063	1.2781	0.91
		Leaf and Fruit	0.00016	1.1688	0.88
	Quercus wutaishanica	Stem	0.0369	0.9165	0.99
		Branch	0.00051	1.3377	0.9
		Leaf and Fruit	0.00021	1.171	0.95
	Populus davidiana	Stem	0.2286	0.6933	0.98
		Branch	0.0247	0.7378	0.96
		Leaf and Fruit	0.0108	0.8181	0.98
	Acer mono	Stem	0.03136	0.9775	0.99
		Branch	0.00588	1.103	0.98
		Leaf and Fruit	0.01141	0.8803	0.98
	Ulmus macrocarpa	Stem	0.05229	0.891	0.99
		Branch	0.01233	0.9359	0.91
		Leaf and Fruit	0.01736	0.7738	0.85
	Fraxinus rhynchophylla	Stem	0.06013	0.8906	0.99
		Branch	0.00556	1.169	0.98
		Leaf and Fruit	0.00829	0.9919	0.98
	Juglans mandshurica	Stem	0.02511	0.9271	0.99
		Branch	0.00957	0.974	0.86
		Leaf and Fruit	0.08725	0.2634	0.81
	Tilia mongolica	Stem	0.0811	0.7994	0.99
		Branch	0.05703	0.463	0.88
		Leaf and Fruit	0.001259	0.7802	0.98
Sub-tropical	All species	Stem	0.0608	2.5585	0.97
		Branch	0.0254	2.587	0.97
		Leaf and Fruit	0.0385	2.0739	0.97
Tropical	All species	Stem	0.022816	0.992674	0.98
		Branch	0.005915	0.999046	0.98
		Leaf and Fruit	0.005997	0.804661	0.98

Table S2. Mean soil organic carbon (SOC) content, bulk density, and SOC stock at the 0–10 and 10–20 cm depths in the 1990s and the 2010s at the four forest biomes.

Biome	Forest type	0-10 cm			10-20 cm		
		1990s	2010s	Change rate	1990s	2010s	Change rate
SOC content*							
Boreal	Larch	7.9±1.4	8.1±1.2	+0.02±0.00	1.8±0.4	1.9±0.8	+0.01±0.00
Temperate	Birch	8.8±4.5	8.7±1.7	-0.00±0.00	3.3±1.3	3.7±0.3	+0.02±0.01
	Oak	4.3±0.1	4.8±0.6	+0.03±0.00	3.2±0.0	3.3±0.9	+0.01±0.00
	Pine	3.1±0.4	4.3±1.5	+0.06±0.02	2.8±0.1	3.2±0.7	+0.02±0.00
	Mean	**5.4±3.0**	**6.0±2.4**	**+0.03±0.03**	**3.1±0.3**	**3.4±0.3**	**+0.02±0.01**
Subtropical	Evergreen	2.5±0.4	3.6±0.4	+0.05±0.01	1.3±0.2	1.7±0.3	+0.02±0.00
	Mixed	1.8±0.5	2.5±0.4	+0.03±0.01	1.0±0.1	1.1±0.3	+0.01±0.00
	Pine	1.1±0.3	1.7±0.2	+0.03±0.01	0.7±0.2	0.7±0.2	+0.00±0.00
	Mean	**1.8±0.7**	**2.6±1.0**	**+0.04±0.01**	**1.0±0.3**	**1.1±0.5**	**+0.01±0.01**
Tropical	Evergreen	2.5±0.5	3.2±1.0	+0.03±0.01	1.4±0.2	1.4±0.3	+0.00±0.00
Mean		**4.0±2.8**	**4.6±2.6**	**+0.03±0.02**	**1.9±1.1**	**2.1±1.2**	**+0.01±0.01**
Bulk density*							
Boreal	Larch	0.3±0.1	0.3±0.1	+2.6±0.5	1.4±0.3	1.3±0.2	-5.2±1.1
Temperate	Birch	0.5±0.4	0.6±0.1	+4.6±2.3	0.9±0.1	0.9±0.1	-3.0±0.3
	Oak	0.9±0.0	0.8±0.1	-3.6±0.3	1.0±0.1	1.0±0.1	-0.1±0.0
	Pine	1.1±0.1	0.9±0.2	-5.5±0.6	1.1±0.0	1.1±0.1	+0.1±0.0
	Mean	**0.8±0.3**	**0.8±0.2**	**-1.5±5.3**	**1.0±0.1**	**1.0±0.1**	**-1.0±1.7**
Subtropical	Evergreen	0.9±0.1	0.8±0.0	-3.0±0.2	1.0±0.1	0.9±0.0	-3.4±0.2
	Mixed	1.1±0.1	0.9±0.0	-11.3±0.5	1.1±0.1	1.1±0.0	-2.4±0.1
	Pine	1.3±0.1	1.1±0.0	-8.5±0.3	1.3±0.1	1.1±0.0	-8.9±0.3
	Mean	**1.1±0.2**	**0.9±0.1**	**-7.7±4.2**	**1.1±0.2**	**1.0±0.1**	**-4.9±3.5**
Tropical	Evergreen	1.1±0.0	1.2±0.2	+1.9±0.2	1.1±0.1	1.2±0.1	+2.9±0.2
Mean		**0.9±0.3**	**0.8±0.3**	**-3.1±5.6**	**1.1±0.2**	**1.1±0.2**	**-2.5±3.6**
SOC stock*							
Boreal	Larch	22.1±0.9	26.1±4.9	+247.1±30.3	25.5±1.1	25.6±11.4	+4.0±0.8
Temperate	Birch	44.2±1.0	51.8±2.2	+379.4±12.6	30.4±8.8	32.1±0.8	+82.7±13.2
	Oak	38.6±2.3	40.1±10.9	+72.7±12.3	30.7±2.6	31.7±7.5	+47.9±8.3
	Pine	32.5±2.5	40.7±9.7	+413.2±68.4	30.1±2.6	34.4±9.5	+217.6±40.5
	Mean	**38.4±5.9**	**44.2±6.6**	**+288.4±187.5**	**30.4±0.3**	**32.7±1.5**	**+116.1±89.5**
Subtropical	Evergreen	22.6±4.0	30.1±3.8	+375.0±55.9	13.1±2.0	15.5±3.1	+123.3±21.6
	Mixed	20.1±5.9	21.9±3.7	+85.8±18.8	10.7±1.5	11.3±2.8	+31.5±6.3
	Pine	14.1±3.9	17.9±2.6	+189.6±38.0	8.5±1.9	7.5±2.0	-51.4±12.2
	Mean	**18.9±4.3**	**23.3±6.2**	**+217.2±146.6**	**10.8±2.3**	**11.5±4.0**	**+34.5±87.4**
Tropical	Evergreen	28.5±6.9	36.5±6.7	+401.8±84.1	15.2±3.9	15.9±3.6	+39.2±9.2
Mean		**27.8±10.1**	**33.1±11.2**	**+270.6±141.5**	**20.5±9.6**	**21.8±10.5**	**+61.9±81.2**

*Shown are SOC contents (%) and their change rates (% yr^{-1}), soil bulk density (g cm^{-3}) and their change rates (mg cm^{-3} yr^{-1}) and SOC stock (Mg C ha^{-1}) and their change rates (kg C ha^{-1} yr^{-1}) between the 1990s and the 2010s.

Table S3. Mean soil organic carbon (SOC) content, bulk density, SOC stock and their change rates during the past two decades at eight forest sites, which are categorized into four forest biomes.

Biome	Forest type	SOC content (%)			Bulk density (g cm^{-3})			SOC stock (Mg C ha^{-1})			
		1990s	2010s	Change rate (% yr^{-1})	1990s	2010s	Change rate (mg cm^{-3} yr^{-1})	1990s	2010s	Change rate (kg C ha^{-1} yr^{-1})	Relative rate (% yr^{-1})
0–20 cm soil depth											
Boreal	Larch	2.8±0.6	3.2±0.9	+0.02±0.01	0.9±0.2	0.8±0.1	-1.3±0.3	47.6±2.0	51.6±16.3	251.1±46.4	+0.5±0.1
Temperate	Birch	5.3±2.4	5.8±0.9	+0.03±0.01	0.7±0.3	0.7±0.1	+0.8±0.2	74.6±9.8	83.8±3.0	462.1±37.2	+0.6±0.1
	Oak	3.7±0.0	4.0±0.7	+0.01±0.00	0.9±0.1	0.9±0.1	-1.9±0.1	69.4±4.8	71.8±18.5	120.6±19.9	+0.2±0.0
	Pine	3.0±0.3	3.7±1.1	+0.04±0.01	1.1±0.1	1.0±0.1	-2.7±0.2	62.5±5.1	75.1±19.2	630.8±111.2	+1.0±0.2
	Mean	**4.2±1.0**	**4.6±0.9**	**+0.03±0.01**	**0.9±0.1**	**0.9±0.1**	**-1.3±1.8**	**68.8±6.1**	**76.9±6.2**	**404.5±259.9**	**+0.6±0.4**
Subtropical	Evergreen	1.9±0.3	2.6±0.4	+0.04±0.01	1.0±0.1	0.9±0.0	-3.2±0.2	35.6±6.0	45.6±6.9	498.3±78.8	+1.4±0.2
	Mixed	1.4±0.3	1.7±0.3	+0.02±0.00	1.1±0.1	1.0±0.0	-6.9±0.3	30.8±7.3	33.3±6.4	117.3±25.2	+0.4±0.1
	Pine	0.9±0.2	1.2±0.2	+0.01±0.00	1.3±0.1	1.1±0.0	-8.7±0.3	22.7±5.8	25.4±4.5	138.2±29.7	+0.6±0.1
	Mean	**1.4±0.3**	**1.8±0.3**	**+0.02±0.01**	**1.1±0.1**	**1.0±0.0**	**-6.3±2.8**	**29.7±6.5**	**34.8±10.1**	**251.3±214.2**	**+0.9±0.5**
Tropical	Evergreen	2.0±0.4	2.3±0.7	+0.02±0.00	1.1±0.0	1.2±0.1	+2.4±0.2	43.6±10.8	52.5±10.3	441.0±96.6	+1.0±0.2
Mean		**2.9±0.6**	**3.2±0.7**	**+0.02±0.00**	**1.0±0.1**	**1.0±0.1**	**-2.7±3.7**	**48.4±18.8**	**54.9±20.6**	**332.4±200.2**	**+0.7±0.4**
Whole soil depth											
Boreal	Larch	1.4±0.2	1.5±0.1	+0.00±0.00	1.2±0.2	1.2±0.2	+0.8±0.1	65.6±11.0	69.4±6.2	243.4±31.1	+0.4±0.1
Temperate	Birch	2.0±0.3	2.1±0.2	+0.01±0.00	1.1±0.1	1.0±0.2	-2.8±0.4	207.0±31.7	214.8±19.5	390.8±47.4	+0.2±0.0
	Oak	2.0±0.7	2.4±0.2	+0.02±0.00	1.2±0.1	1.0±0.1	-10.3±0.9	239.1±80.4	241.7±15.2	127.2±25.3	+0.1±0.0
	Pine	1.8±0.5	1.9±0.3	+0.00±0.00	1.3±0.1	1.3±0.1	-0.1±0.0	231.7±67.0	238.4±41.4	332.8±76.7	+0.1±0.0
	Mean	**1.9±0.1**	**2.1±0.1**	**+0.01±0.01**	**1.2±0.1**	**1.1±0.2**	**-4.3±5.3**	**226.0±16.8**	**231.6±14.6**	**283.6±138.5**	**+0.1±0.1**
Subtropical	Evergreen	1.1±0.1	1.4±0.1	+0.02±0.00	1.1±0.1	1.0±0.0	-3.6±0.2	68.4±5.7	86.6±4.5	907.5±60.1	+1.3±0.1
	Mixed	0.7±0.1	1.0±0.1	+0.01±0.00	1.2±0.1	1.1±0.04	-3.8±0.2	51.4±5.5	67.4±7.2	763.3±82.4	+1.5±0.2
	Pine	0.6±0.1	0.7±0.1	+0.01±0.00	1.3±0.1	1.1±0.0	-9.0±0.3	43.5±5.7	47.7±6.5	206.6±28.3	+0.5±0.1
	Mean	**0.8±0.2**	**1.1±0.3**	**+0.02±0.01**	**1.2±0.1**	**1.1±0.1**	**-5.5±3.0**	**54.4±12.7**	**67.2±19.5**	**627.6±370.1**	**+1.1±0.5**
Tropical	Evergreen	0.7±0.2	0.8±0.2	+0.00±0.00	1.3±0.0	1.3±0.1	+0.5±0.0	94.6±21.8	102.6±19.9	397.9±84.2	+0.4±0.1
Mean		**1.3±0.3**	**1.5±0.2**	**+0.01±0.01**	**1.2±0.1**	**1.1±0.1**	**-3.5±4.2**	**125.2±85.2**	**133.6±83.1**	**421.2±274.4**	**+0.6±0.5**

Table S4. Measured carbon input rates and ratio of soil accumulation to the above-ground net primary production (ANPP) of the eight forest types.

Parameters	Boreal	Temperate			Subtropical			Tropical
	Larch	Birch	Oak	Pine	Evergreen	Mixed	Pine	Evergreen
Carbon pool (Mg C ha^{-1})								
AGB	91.1 ±25.0	99.3 ±9.0	69.6 ±4.4	100.0 ±17.4	140.0 ±5.5	120.9 ±16.3	60.1 ±3.4	213.6 ±41.4
Litter	4.4 ±0.0	5.1 ±1.1	2.5 ±0.4	4.1 ±0.8	1.4 ±0.4	2.2 ±0.3	2.8 ±0.5	1.8 ±0.2
Dead wood	1.3 ±0.5	5.6 ±0.8	3.3 ±0.1	4.5 ±0.6	13.2 ±0.2	8.7 ±5.7	0.1 ±0.1	5.7 ±0.8
Soil	69.4 ±6.2	214.8 ±19.5	241.7 ±15.2	238.4 ±41.4	86.6 ±7.2	67.4 ±6.5	47.7 ±4.5	102.6 ±19.9
Ecosystem total	166.2 ±31.7	324.9 ±30.3	317.1 ±20.2	346.9 ±60.2	241.2 ±13.3	199.2 ±28.8	110.7 ±8.5	323.7 ±62.3
Carbon flux (kg C ha^{-1} yr^{-1})								
AGB growth	899.4 ±411.0	2075.2 ±253.3	1209.0 ±240.61	2144.4 ±495.76	-1000.3 ±78.2	1911.0 ±207.58	1485.3 ±166.9	684.1 ±145.0
Litterfall	2424.2 ±283.1	1630.2 ±220.4	1869.8 ±249.7	2340.1 ±310.0	4160.2 ±449.0	4277.3 ±272.8	1718.8 ±430.0	3970.0 ±279.8
Fallen log	13.0 ±3.7	192.2 ±26.0	66.2 ±7.4	60.0 ±12.8	2070.3 ±221.2	679.5 ±43.6	210.3 ±50.8	1034.3 ±71.6
Standing snag	3.5 ±1.8	337.9 ±46.8	343.8 ±46.1	148.5 ±18.5	346.8 ±42.3	76.9 ±3.2	236.3 ±56.9	803.4 ±62.4
ANPP	3340.1 ±698.8	4235.4 ±546.1	3488.8 ±544.2	4693.0 ±837.5	5577.0 ±789.8	6944.7 ±528.4	3650.6 ±704.7	6491.6 ±559.2
Soil accumulation	243.4 ±31.1	390.8 ±47.4	127.2 ±25.3	332.8 ±76.7	907.5 ±60.1	763.3 ±82.4	206.6 ±28.3	397.9 ±84.2
Ratio of soil accumulation to ANPP (%)	7.3 ±7.8	9.2 ±3.8	3.6 ±3.4	7.1 ±5.4	16.3 ±4.2	11.0 ±3.0	5.7 ±3.5	6.1 ±3.3

Table S5. Summary for C pools and changes in each component of forests in China over the past two decades.

Component	Carbon pool (Pg C)	Carbon density (Mg ha^{-1})	National sink (Tg C yr^{-1})	Source
Biomass	6.9	41.3	70.9	Guo et al., 2013
Soil	20.0	106.1	57.1	Tang et al., 2018; This study
Litter	0.5	3.2	2.8	Zhu et al., 2017
Dead wood	0.4	2.8	3.9	Zhu et al., 2017
Ecosystem	**27.4**	**153.4**	**134.7**	

Figure S1. Changes in soil organic carbon contents (left, %) and bulk densities (right, g cm^{-3}) with soil depth for the eight forests in the 1990s and the 2010s in China. For the details on the sites, see Table 1.

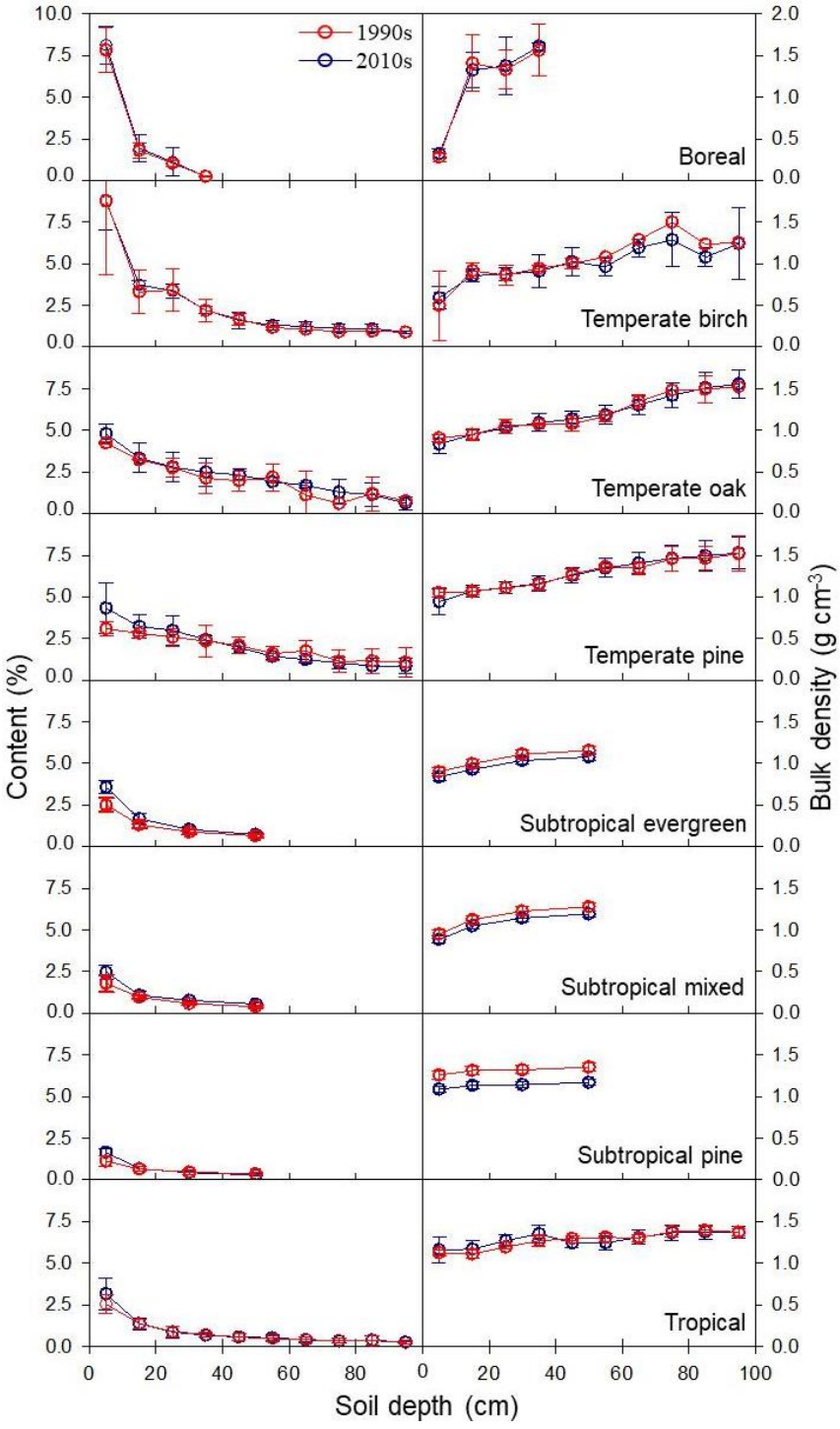

Figure S2. Comparison of soil organic carbon stocks of the surface soil depth (0-20 cm) in the eight forest plots of China between the 1990s and the 2010s. The inset graph shows the SOC change rates of the surface soil depth (0-20 cm) by forest biomes.