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Regional Variation in Carbon Sequestration Potential of Forest Ecosystems in China

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Abstract: Enhancing forest carbon (C) storage is recognized as one of the most economic and green approaches to offsetting anthropogenic CO_2 emissions. However, experimental evidence for C sequestration potential (C_{sp}) in China's forest ecosystems and its spatial patterns remain unclear, although a deep understanding is essential for policy-makers making decisions on reforestation. Here, we surveyed the literature from 2004 to 2014 to obtain C density data on forest ecosystems in China and used mature forests as a reference to explore C_{sp}. The results showed that the C densities of vegetation and soil (0–100 cm) in China's forest ecosystems were about 69.23 Mg C/ha and 116.52 Mg C/ha, respectively. In mature forests, the C_{sp} of vegetation and soil are expected to increase to 129.26 Mg C/ha (87.1%) and 154.39 Mg C/ha (32.4%) in the coming decades, respectively. Moreover, the potential increase of C storage in vegetation (10.81 Pg C) is estimated at approximately twice that of soil (5.01 Pg C). Higher C_{sp} may occur in the subtropical humid regions and policy-makers should pay particular attention to the development of new reforestation strategies for these areas. In addition to soil nutrients and environment, climate was an important factor influencing the spatial patterns of C density in forest ecosystems in China. Interestingly, climate influenced the spatial patterns of vegetation and soil C density via different routes, having a positive effect on vegetation C density and a negative effect on soil C density. This estimation of the potential for increasing forest C storage provided new insights into the vital roles of China's forest ecosystems in future C sequestration. More importantly, our findings emphasize that climate constraints on forest C sequestration should be considered in reforestation strategies in China because the effects of climate were the opposite for spatial patterns of C density in vegetation and soil.

Keywords: carbon density; forest; reforestation; storage; sequestration potential

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1 Introduction

Forests, as the principal component of terrestrial ecosystems, play an important role in the maintenance of regional ecology and make a huge contribution to carbon (C) sequestration (Liu *et al.*, 2000; Ma *et al.*, 2015). Forest ecosystems store around 45% of the organic C in terrestrial ecosystems (Bonan, 2008), and their annual C sequestration is approximately two-thirds that of terrestrial ecosystems (Liu *et al.*, 2000). Due to the considerable C sequestration potential (C_{sp}) of forest ecosystems, enhancing their C storage is considered an effective and economic approach for sequestration of anthropogenic CO_2 emissions (Gower, 2003; Houghton, 2005; Fang *et al.*, 2007; Bonan, 2008). Thus, forest ecosystems have irreplaceable roles in regulating the global C cycle, in

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mitigating the rise in atmospheric CO_2, and, consequently, in stabilizing global climate (Liu *et al.*, 2000).

China's forests cover approximately 2.08 × 10^6 ha (Liu and Buheaosier, 2000) and have considerable C sequestration potential. Over the past two decades, some researchers have used the Forest Resource Inventory of China (FRIC) database to estimate C storage in vegetation (Wang *et al.*, 2000; Fang *et al.*, 2001; Zhao and Zhou, 2005). Soil C storage has been estimated using different sources, such as the Soil Resource Inventory database (Xie *et al.*, 2004), the Carbon Exchange between Vegetation, Soil, and Atmosphere (CEVSA) model (Li *et al.*, 2004), and the literature (Zhou *et al.*, 2000). Integrated investigation of forest C storage (aboveground biomass, belowground biomass, and soil) is essential because the outcome can not only provide guidance for C assessment in China's forest ecosystems, but could also reveal feedback from forest ecosystems to global climate change (McKinley *et al.*, 2011; Pan *et al.*, 2011; Fang *et al.*, 2014). Unfortunately, the amount of C storage in China's forest ecosystems is still unclear.

The potential magnitude of forest C sequestration in China is of concern to both the public and government. To date, there have been few quantitative studies on the C sequestration potential in China's forest ecosystems, although this information is essential for policy-makers dealing with reforestation. In practice, quantifying the relationships between forest age and vegetation and soil C densities is a major challenge for accurately assessing forest C_{sp} at a regional or global scale. However, some studies have demonstrated that ecosystem C storage could theoretically reach saturation (i.e., an upper limit) with forest succession (Keith *et al.*, 2009), and that forest C stored in both vegetation and soil are closely correlated with forest age (Zak *et al.*, 1990; Jimenez *et al.*, 2008; Xu *et al.*, 2010; Yang *et al.*, 2011). Therefore, forest age is considered a critical factor in the determination of forest biomass (Pan *et al.*, 2004).

This study used the forest succession theory (Horn, 1975; Shugart and West, 1980) to obtain a forest age standard for mature forests using a logistic growth curve relating forest age with vegetation C density (Xu *et al.*, 2010) and soil C density (Zak *et al.*, 1990; Yang *et al.*, 2011). The estimated C_{sp} for China's forest ecosystems was determined using data from 1764 vegetation plots and 752 soil plots (0–100 cm layer) drawn from literature published from 2004 to 2014. The purposes of this study were to: 1) estimate the C_{sp} of China's forest ecosystems and 2) explore the spatial patterns of C_{sp} as well as the main influencing factors. Accurate assessment of forest C_{sp} may help us understand the response mechanisms of forest ecosystems to natural and human disturbance (He *et al.*, 2008; Keith *et al.*, 2009). Furthermore, the findings could provide new insights for policy-makers to develop future reforestation strategies to increase the C sequestration capacity.

2 Materials and Methods

2.1 Study area

Forests account for 16.6% of the land area of China, and most forests are located in the northeast and the southwest regions (Fig. 1). Mean annual temperature (MAT) and mean annual precipitation (MAP) across China forests range from –4.3℃ to 25.1℃ and 158.9 to 2142.2 mm, respectively (Yang *et al.*, 2014). forests in China were divided into eight climatic regions (Fu *et al.*, 2001): forests in cold humid regions (I, forest area 1.08 × 10^7 ha); temperate humid and semi-humid regions (II, forest area 3.21 × 10^7 ha); temperate arid and semi-arid regions (III, forest area 5.39 × 10^6 ha); warm temperate humid and sub-humid regions (IV, forest area 7.98 × 10^6 ha); subtropical humid regions (V, forest area 7.62 × 10^7 ha); tropical humid regions (VI, forest area 3.23 × 10^7 ha);

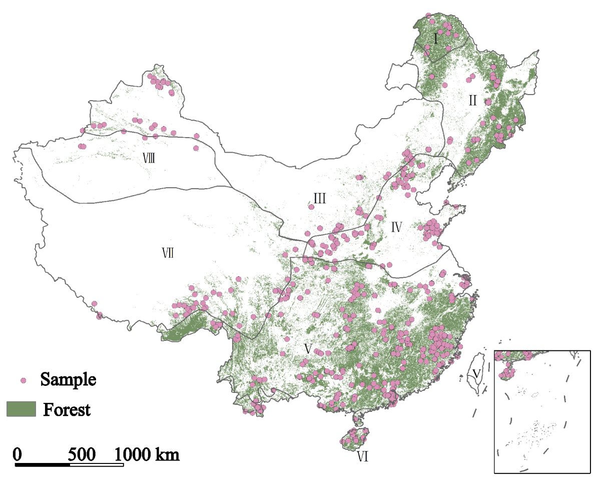

Fig. 1 Distribution of carbon density in vegetation and soil from 2004 to 2014 in China's forest ecosystems. (I) Forest in cold humid regions; (II) forest in temperate humid and semi-humid regions; (III) forest in temperate arid and semi-arid regions; (IV) forest in warm temperate humid and sub-humid regions; (V) forest in subtropical humid regions; (VI) forest in tropical humid regions; (VII) forest in Qinghai-Tibet Plateau; and (VIII) forest in warm temperate arid regions

Qinghai-Tibet Plateau (VII, forest area 1.04×10^7 ha); and warm temperate arid regions (VIII, forest area 0.76×10^6 ha).

2.2 Data collection and compilation

Literatures on vegetation and soil C densities in China's forest ecosystems published between 2004 and 2014 in the China National Knowledge Infrastructure (CNKI) (http://www.cnki.net) and Institute for Scientific Information (ISI) (http://apps.webofknowledge.com) were used for collecting data. We extracted information on C storage in vegetation and soil, including aboveground biomass, belowground biomass, soil C content in different soil layers, C storage in vegetation and soils, forest types, topography, altitude, and climate. In total, we collected data at 1764 vegetation plots and 752 soil (0–100 cm layer) plots (Fig. 1) those could be used to calculate C densities (Mg C/ha) in vegetation and soil. A coefficient of 0.5 was used to convert vegetation biomass to C density for those plots that provide biomass data only (Keith *et al*., 2009; Cook *et al.*, 2014).

Soil organic C (SOC) density (Mg C/ha) was calculated using Equation (1) (Wen and He, 2016), unless the data had already been reported in the literature. In practice, measured soil bulk was used to estimate SOC storage. For plots without records of bulk density, the mean value (1.3 g/cm^3) of the Second Soil Survey in China was used as a substitute (Wang *et al.*, 2000). When soils were sampled at depths less than 100 cm, empirical relationships were used to relate SOC density to a 100 cm soil layer (Chai *et al.*, 2015), unless the sampled soil depth was down to rock. Such relationships have been developed for 74 typical terrestrial ecosystems in China, using the long-term monitoring data of the China's Ecosystem Research Network. The accuracy of these estimates was validated using 200 random plots from the Second Soil Survey in China (Xu *et al.*, 2015). The results of that study showed that the predicted values for SOC density (*SOCD*) were closely correlated with, and almost equal to the measured values ($y = 1.08x - 0.19$, $R^2 = 0.95$).

$$SOCD = \sum_{j=1}^{n}(c_j \times b_j \times h_j) \quad (1)$$

where c, b, h, and s are SOC content (%), soil bulk density (g/cm^3), and soil thickness (cm) of plot j, respectively.

Additionally, MAT (℃) and MAP (mm) were obtained for 1961–2010, by interpolating the long-term monitoring data from 722 meteorological stations in China (Gao *et al.*, 2013). Data on soil texture (soil clay, silt, and sand percentages) were derived from the Second Soil Resource Inventory in China. Forest area data for different regions were extracted from the 2008 report on China's land cover (Liu and Buheaosier, 2000). Soil nitrogen (N, g/kg) and phosphorus (P, ‰) contents, and land cover data were obtained from the China National Science and Technology Platform, the Earth system science data sharing platform 'http://www.geodata.cn'. Altitude was extracted from the Digital Elevation Model (DEM) issued by National Remote Sensing Center of China. The Normalized Difference Vegetation Index (NDVI) data sets from 2006 to 2010 were derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) NDVI composite, at a spatial resolution of 1-km and monthly frequency, and were downloaded from China's Geospatial Data Cloud 'http://www.giscloud.cn'. The maximum monthly NDVI was used as the annual NDVI; these data were averaged into 5 year NDVIs.

2.3 Methods of estimating increments of Carbon storage

Carbon density in vegetation and soil has been shown to increase with forest age and reach a relatively stable state in mature forests (Johnson *et al.*, 1995; Six *et al.*, 2002; Stewart *et al.*, 2007; West and Six, 2007; Keith *et al.*, 2009). In light of previous studies and classic succession theory, C storage in vegetation and soil may ultimately reach a level of saturation (or upper limit) with succession (Fig. 2a). However, the accumulation process for soil C storage generally lags behind that of vegetation. Therefore, a logical framework was constructed to calculate C_{sp} and the potential increments of C in China's forests in scenarios for mature forests (Fig. 2b).

It was assumed that C accumulation rates in forests were very low in the later stage of forest succession (Fig. 2b). In this study, a mature forest was defined as that in which C density in vegetation and soil had reached 95% of the maximum of C density (Fig. 2). In practice, the age of mature forests was identified using a logistic growth curve relating C density in vegetation (or soil) and forest age (Equation (2)).

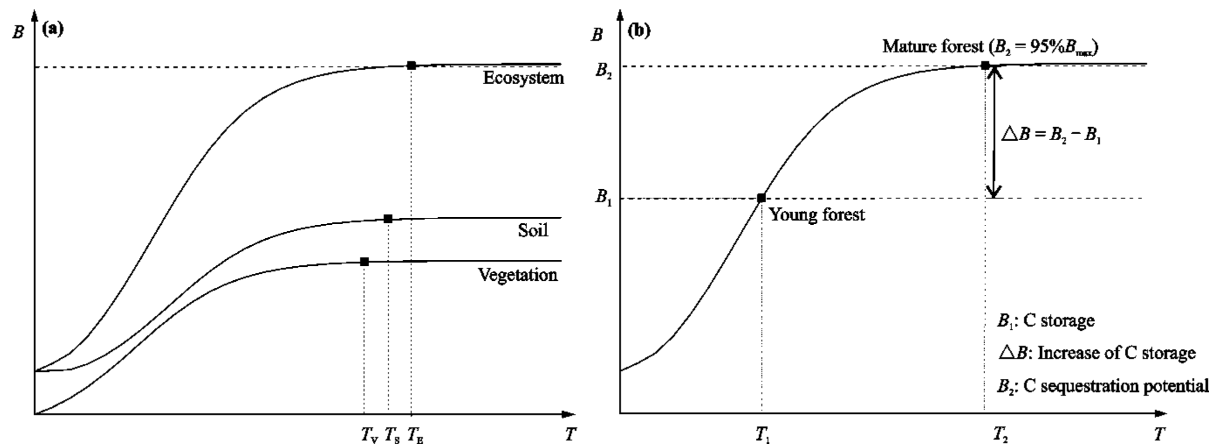

Fig. 2 Changes in carbon storage with secondary succession of forests. T_V, T_S, and T_E are the forest ages when the carbon density of vegetation, soil, and ecosystem reach saturation. B_1 and T_1 are the current carbon density and the corresponding forest age. B_{max} is the maximum carbon density for a specific forest. B_2 and T_2 are 95% of the B_{max} and the corresponding forest age

$$B=\frac{w}{1+k\times\exp(-a\times T)} \quad (2)$$

where B is C density in vegetation or soil, T is forest age, and w, k, and a are parameters.

For vegetation, the logistic growth curve was used to fit vegetation C density and forest age using 36 dominant tree species. The ages of mature forests were then calculated using the system established by Xu *et al.* (2010). The system calculates w, k, and a parameters for the 36 plant species using Equation (2) and enables 95% of the maximum C density to be fitted well (Table 1). The results showed that the average age of the forests in China that were defined as mature was approximately 75 years (Table 1). For soil, the data from worldwide forest research (Zak *et al.*, 1990; Yang *et al.*, 2011) was used to establish a new logistic growth curve between soil C density and forest age. We found that this curve provided an excellent fit for the data from Equation (2) (R^2 = 0.93, P = 0.003). Forest age for newly defined mature forests was about 76 years when soil C density reached 95% of the maximum C density. By combining soil and vegetation criteria, we selected a forest age of 76 years to define mature forests in China (Table 1). There are differences in the published literature on the age at which forests are classified as mature. For example, some studies considered 154–200 or 400 years as the threshold of maturity for boreal and temperate forests (Jarvis, 1989; Zhou *et al.*, 2006; Luyssaert *et al.*, 2008; Hudiburg *et al.*, 2009), whereas other defined mature forests as those that had attained an age of 80–100 years (Jarvis, 1989; Keith *et al.*, 2009; Liu *et al.*, 2012).

Two approaches can be used to estimate the current forest C density. In the first approach (statistical analysis approach), C density and storage in vegetation and soil in forests are calculated at regional and national scales. Initially, the mean C density is calculated in each climate region. Then C storage is calculated based on distinct forest areas in specific climate regions (Fig. 1). Finally, the accumulation of C storage is summed using the data from different regions (Equation (3)).

$$C_S=\sum_{i=1}^{n}(\overline{C}_i\times S_i) \quad (3)$$

where C_S, $\overline{C}_i$ and S_i are total C storage (Pg C), mean C density (Mg C/ha), and forest area (ha) in different climatic regions.

In the second approach, we predicted forest C density for the period 2006–2010 using an artificial neural network (ANN) analysis (Foody *et al.*, 2003; Yang *et al.*, 2014). ANN analysis usually comprises an input layer, hidden layer, and output layer. The input variables (latitude, altitude, MAT, MAP, and NDVI) and output variable (C density in vegetation at 144 plots or soil at 107 plots during 2006–2010) were normalized on a scale between –1 and 1. Yang *et al.* (2014) used a similar ANN net for the prediction of soil C density in China's forest ecosystems. It has been reported previously that climatic factors such as MAT and MAP are the key factors controlling the large-scale spatial patterns of forest C density (Davidson *et al.*, 2000; Liu *et al.*, 2012). The normalized data set was then used to train the neural

Table 1 Accumulation equation of forest biomass and the derivation process of forest age for mature forests in China

No.	Forest type	w	k	a	R^2	B_{max}	T_{max}	B_2	T_2
1	*Pinus koraiensis*	218.56	7.95	0.04	0.95	216.84	191.88	205.99	135.29
2	*Abies*	357.50	4.35	0.02	0.92	355.95	327.38	338.16	205.22
3	*Picea*	274.47	5.74	0.03	0.98	272.90	234.16	259.26	155.35
4	*Tsuga*	203.06	4.80	0.02	0.96	202.09	343.67	191.98	220.01
5	*Cupressus*	155.72	10.57	0.04	0.91	154.09	155.93	146.39	115.36
6	*Larix*	130.20	2.66	0.07	0.98	129.85	99.25	123.36	55.61
7	*Pinus sylvestris* var. *mongolica*	201.71	10.88	0.11	0.93	199.54	65.23	189.56	48.48
8	*Pinus densiflora*	49.14	2.34	0.10	0.67	49.03	70.13	46.57	38.07
9	*Pinus thunbergii*	60.00	3.36	0.08	0.66	59.80	83.93	56.81	49.71
10	*Pinus tabuliformis*	87.98	12.24	0.11	0.98	86.92	60.38	82.57	45.72
11	*Pinus armandii*	91.06	3.28	0.07	0.87	90.76	101.88	86.22	60.02
12	*Keteleeria*	67.22	0.65	0.02	0.77	67.18	290.24	63.82	104.88
13	*Pinus massoniana*	81.67	2.17	0.05	1.00	81.49	132.33	77.42	70.46
14	*Pinus yunnanensis*	147.88	5.33	0.07	0.73	147.10	93.86	139.74	61.38
15	*Pinus kesiya* var. *langbianensis*	95.71	2.07	0.09	0.83	95.51	78.68	90.74	41.35
16	*Pinus densata*	162.21	3.63	0.06	0.97	161.62	119.51	153.54	72.02
17	*Cunninghamia*	69.61	2.44	0.10	0.96	69.44	71.73	65.97	39.33
18	*Cryptomeria*	111.63	2.51	0.11	0.94	111.35	62.06	105.78	34.29
19	*Metasequoia*	140.00	12.32	0.20	0.58	138.30	33.76	131.38	25.59
20	*Fraxinus mandschurica*, *Juglans mandshurica*, *Phellodendron*	212.83	8.07	0.06	0.99	211.13	113.80	200.57	80.44
21	*Cinnamomum*	120.00	5.40	0.06	0.39	119.36	122.05	113.39	80.00
22	*Phoebe*	206.99	9.19	0.06	0.90	205.11	112.32	194.85	81.19
23	*Quercus*	197.09	8.49	0.04	0.99	195.43	163.69	185.66	116.74
24	*Betula*	163.34	7.48	0.05	0.99	162.13	133.87	154.02	93.36
25	Other hard broadleaved	160.99	10.31	0.05	0.99	159.35	140.40	151.38	103.46
26	*Tilia*	266.71	7.82	0.06	0.96	264.64	117.88	251.41	82.87
27	*Sassafras*	210.00	24.99	0.17	0.88	204.88	40.44	194.64	33.71
28	*Eucalyptus*	89.87	7.15	0.14	0.90	89.23	48.24	84.77	33.36
29	*Casuarina*	156.02	6.44	0.07	0.80	155.02	98.96	147.27	67.14
30	*Populus*	70.76	1.49	0.14	0.93	70.65	48.17	67.12	23.12
31	*Paulownia*	110.42	4.09	0.05	0.88	109.97	136.79	104.47	84.66
32	Other soft broadleaved	132.24	5.28	0.13	0.96	131.55	53.05	124.97	34.62
33	Nonmerchantable woods	199.15	20.73	0.35	0.98	195.11	19.55	185.35	15.93
34	Mixed conifer	158.94	20.80	0.10	0.95	155.70	67.92	147.92	55.38
35	Mixed conifer and deciduous	290.96	8.58	0.06	0.99	288.49	123.35	274.06	88.13
36	Mixed broadleaved	237.57	12.27	0.17	0.98	234.69	41.19	222.96	31.20
	Average					157.89	116.48	150.00	74.60

Notes: B_{max} and T_{max} are the maximum of biomass density and corresponding forest age for specific forest. B_2 and T_2 are 95% B_{max} and corresponding forest age

network, in order to build the relationship between them. The successfully trained network was then used to simulate vegetation or soil C density of pixels with a resolution of 25 km, based on the area of forests in China. Finally, we used the same statistical method as the first approach to calculate the regional and national vegetation and soil C densities and storage (Equation (3)).

The C density data for mature forests was used to estimate the C_{sp} of China's forest ecosystems. The potential increment of C storage in forest ecosystems under mature forest scenarios was calculated using the following formula:

$$\Delta C = C_{sp} - C_s \quad (4)$$

where ΔC, C_{sp}, and C_s are the increments of C storage (Pg C), C sequestration potential (Pg C), and the current C storage (Pg C), respectively.

2.4 Statistical analysis

One-way analysis of variance (ANOVA) was used to test differences of C density among different climatic regions. A general linear model was used to explore the relationships between vegetation or soil C density, longitude, latitude, MAT, and MAP for all forests or only for mature forests. Furthermore, the mechanisms controlling the spatial patterns in forest C density in vegetation and soil were explored at a large scale using the structural equation model (SEM) in Amos software (version 17.0, Chicago, IL, USA). For vegetation, factors affecting C density include climate (MAT and MAP), soil nutrients (soil N and soil P), and soil environment (clay, soil organic matter (SOM)). For soil C storage, the relevant factors include SOM inputs (vegetation biomass) and climate (MAT and MAP), which influence SOM decomposition and soil properties (sand and silt) indirectly affect SOM decomposition. SEM was used to identify the relative contribution of each factor to forest C density in vegetation or soil; the maximum likelihood method in the Amos software was used to assess the direct and indirect associations of C density and climate, soil nutrient, and soil environment. The results are shown as standardized regression coefficients (Barto *et al.*, 2010; Cheng *et al.*, 2014), which can identify the main driving factors for the spatial pattern of forest C storage.

ANN analysis was performed using MATLAB software (The MathWorks, Natick, MA, USA). All statistical analyses and graphs were completed using SPSS software (version 17.0, Chicago, IL, USA) and Origin software (version 6.0, Northampton, MA, USA). Significant differences were set at $P < 0.05$ level.

3 Results

3.1 Carbon storage in China's forest ecosystems

Linear relationships were fitted between the predicted and measured carbon density for vegetation and soil of China's forest ecosystems, with a coefficient of determination (R^2) of 0.44 and 0.68, and a root mean square error (RMSE) of 38.70 and 41.70 Mg C/ha, respectively (Fig. 3). The results illustrate that the ANN approach can generate reliable predictions of C density in both vegetation and soil.

Forest C density and storage (vegetation plus soil) were estimated as 185.75 Mg C/ha and 35.55 Pg C, respectively in China's forest ecosystems during the period 2004–2014 (2010s), respectively. The statistical and ANN analyses gave slight differences between regional and national C densities and storage (Table 2). The average C densities of vegetation and soil were 69.23 and 116.52 Mg C/ha by the statistical analysis, and 71.76 and 144.60 Mg C/ha in ANN analysis. The estimates of C storage for forest vegetation and soil in China were 12.05 and 23.5 Pg C for the statistical analysis, and 12.73 and 26.74 Pg C for the ANN analysis.

3.2 Carbon sequestration potential in China's forest ecosystems

Under mature forest scenarios, C_{sp} was extremely high

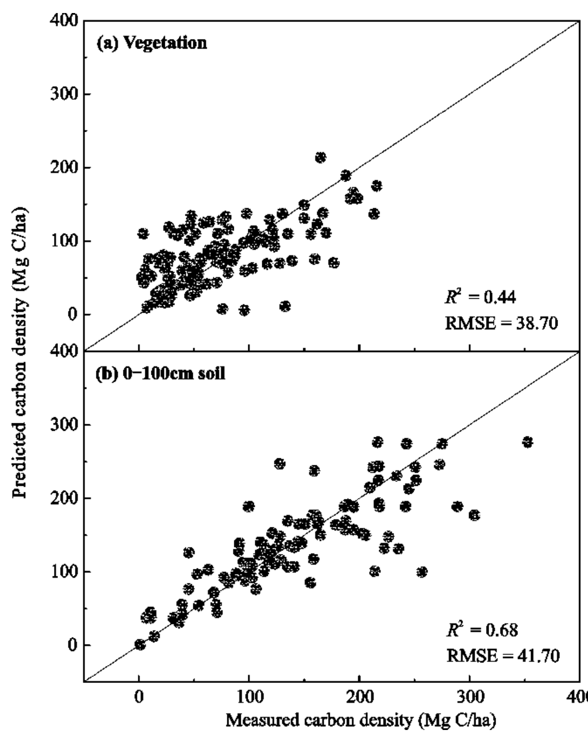

Fig. 3 Comparison between predicted and measured carbon density in vegetation and soil using the artificial neural network (ANN) approach. The line shows that estimated carbon density is equal to the measured value. RMSE and R^2 represent root mean square error and the coefficient of determination, respectively

Table 2 Results of different studies on carbon storage in China's forests

Data source	Method	Year	Vegetation C density (Mg C/ha)	Soil depth (cm)	Soil C density (Mg C/ha)	References
The Fourth Forest Resource Inventory	Volume-biomass method	1989–1993	38.70			(Liu *et al*., 2000)
Documents collected	Documents collected	1989–1993	57.07	Unknown	193.55	(Zhou *et al*., 2000)
The Third Forest Resource Inventory	Volume-biomass method	1984–1988	6.47–118.14			(Wang *et al*., 2001)
The Fifth Forest Resource Inventory	Volume-biomass method	1994–1998	44.91			(Fang *et al*., 2001)
Climate data	Modeling	1981–1998	70.30	0–100	>120.00	(Li *et al*., 2004)
The Fourth Forest Resource Inventory	Volume-biomass method	1989–1993	41.32			(Zhao and Zhou, 2006)
The Second Soil Resource Inventory	The equation estimation	1979–1990		0–100	115.90	(Xie *et al*., 2004)
The Fourth Forest Resource Inventory	Volume-biomass method	1999–2003	38.56			(Xu *et al*., 2007)
The Sixth Forest Resource Inventory	Volume-biomass method	1999–2003	41.00			(Fang *et al*., 2007b)
The Seventh Forest Resource Inventory	Volume-biomass method	2004–2008	42.82			(Li *et al*., 2011)
The Seventh Forest Resource Inventory	Volume-biomass method	2004–2008				(Guo *et al*., 2013)
Documents collected	Statistics	2004–2014	69.23	0–100	116.52	This study
Remote sensing data	Artificial neural network	2006–2010	71.76	0–100	144.60	This study
Data source	**Method**	**Year**	**Forest area (10^6 ha)**	**Vegetation C storage (Pg C)**	**Soil C storage (Pg C)**	**References**
The Fourth Forest Resource Inventory	Volume-biomass method	1989–1993	108.64	4.20		(Liu *et al*., 2000)
Documents collected	Documents collected	1989–1993	108.62	6.20	21.02	(Zhou *et al*., 2000)
The Third Forest Resource Inventory	Volume-biomass method	1984–1988	124.65	3.26–3.73		(Wang *et al*., 2001)
The Fifth Forest Resource Inventory	Volume-biomass method	1994–1998	105.82	4.75		(Fang *et al*., 2001)
Climate data	Modeling	1981–1998	121.63	8.72	23.20	(Li *et al*., 2004)
The Fourth Forest Resource Inventory	Volume-biomass method	1989–1993	108.64	3.78		(Zhao and Zhou, 2006)
The Second Soil Resource Inventory	The equation estimation	1979–1990	150.33		17.39	(Xie *et al*., 2004)
The Fourth Forest Resource Inventory	Volume-biomass method	1999–2003	151.43	5.51		(Xu *et al*., 2007)
The Sixth Forest Resource Inventory	Volume-biomass method	1999–2003	142.80	5.85		(Fang *et al*., 2007b)
The Seventh Forest Resource Inventory	Volume-biomass method	2004–2008	181.38	7.81		(Li *et al*., 2011)
The Seventh Forest Resource Inventory	Volume-biomass method	2004–2008	181.38	6.90		(Guo *et al*., 2013)
Documents collected	Statistics	2004–2014	175.99	12.05	23.50	This study
Remote sensing data	Artificial neural network	2006–2010	175.99	12.73	26.74	This study

Note: Vegetation C includes aboveground and belowground vegetation, underbrushes, and grasslands

in China's forest ecosystems. Future forest C density and C storage were estimated as 283.65 Mg C/ha and 51.37 Pg C, respectively. The potential increment in C densities of vegetation and soil for mature forests was predicted as 129.26 and 154.39 Mg C/ha (Fig. 4a), respectively, and the corresponding increases in the ratios of C density were 44.5% for vegetation and 55.5% for soil (Fig. 4b). Although the largest saturated C density was observed in temperate humid and semi-humid regions, subtropical humid regions had the highest saturated C storage with the value of 12.25 Pg C (Fig. 4b), followed by the subtropical (10.69 Pg C) and tropical humid regions (4.9 Pg C). These could be attributed to their larger forest areas.

3.3 Potential increment of carbon storage in China's forest ecosystems

Mature forest scenarios indicated a potential increment of C density and storage of 97.9 Mg C/ha (52.7%) and 15.82 Pg C (45.5%), respectively. In detail, the ratios of potential increment for vegetation and soil could be as great as 61.6% and 38.4%, respectively (Fig. 5a).

The potential increment of C storage in vegetation was estimated to be twice that of soil (10.81 *vs*. 5.01 Pg C; Fig. 5b). Furthermore, the highest increment in C density in vegetation and soil was found to be 94.04 and 121.14 Mg C/ha in temperate arid and semi-arid regions, respectively (Fig. 6a). However, the smallest increase was observed in cold humid regions (19.64 and 9.57 Mg C/ha, respectively; Fig. 6).

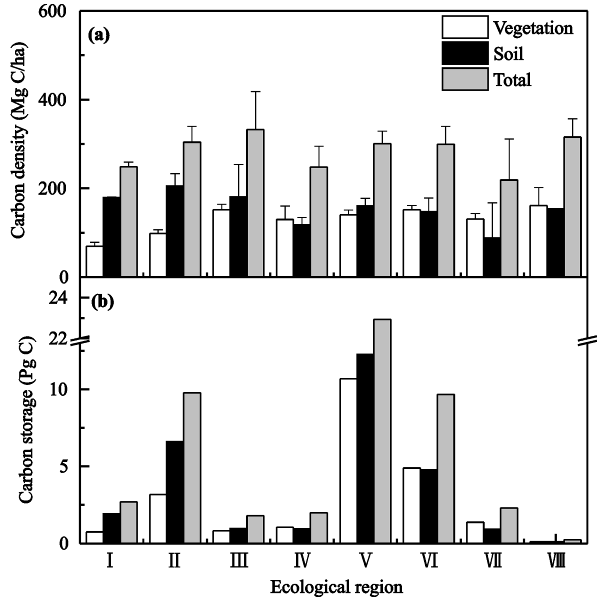

Fig. 4 Carbon sequestration potential of China's forest ecosystems under mature forest scenarios. The error bars indicate standard errors (mean ± SE). See the explanation of the codes for the different regions in Fig. 1

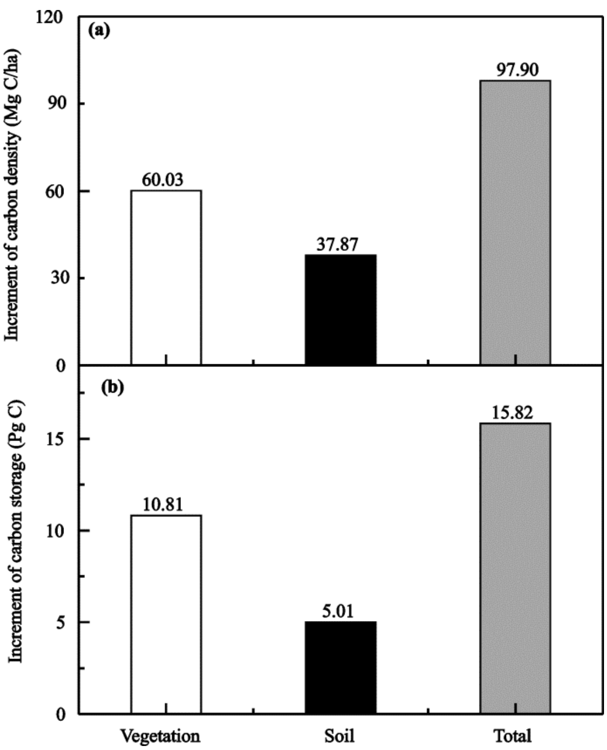

Fig. 5 Potential increment in carbon density and storage in Chinese forest under mature forest scenarios

3.4 Spatial patterns of vegetation and soil carbon density in China's mature forest ecosystems

The spatial patterns of forest C density showed that vegetation C in South China was higher than that of North China. However, the spatial patterns of soil C storage were reversed (Fig. 7). The spatial pattern of C density in the vegetation and soil of mature forests was related to latitude and longitude. Vegetation C density decreased with increasing latitude across forest types, whereas soil C density increased. High vegetation C density appeared in southwest regions of China, while high soil C density appeared in northeast regions of China.

3.5 Factors influencing spatial patterns of carbon density in China's mature forest ecosystems

Analysis using the SEM model showed that climate, soil nutrients, and soil environment might explain 48% of the spatial variations for vegetation C density, with climate contributing a strong positive effect (70%, Fig. 8a). Climate, soil environment, and SOM inputs explained 78% of the spatial patterns in the 0–100 cm soil C storage. Although climate was the most important factor for soil C density (61%), it had a negative effect (Fig. 8b).

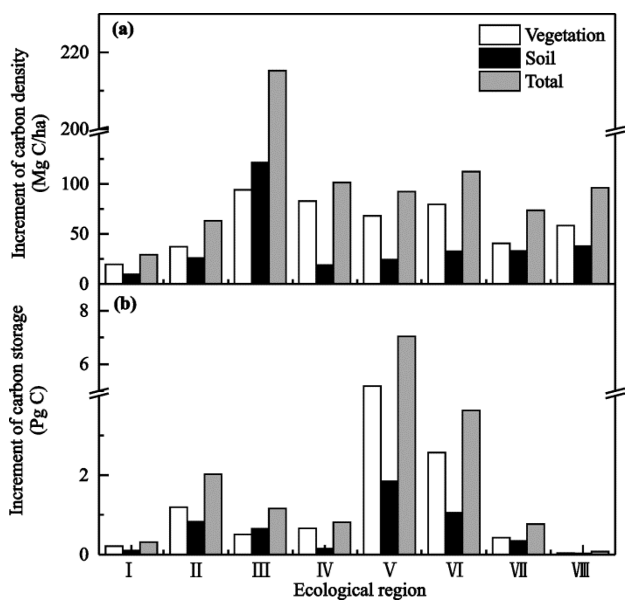

Fig. 6 Potential increment of carbon density and storage in China's forest ecosystems for different regions. See the explanation of the codes for the different regions in Fig. 1

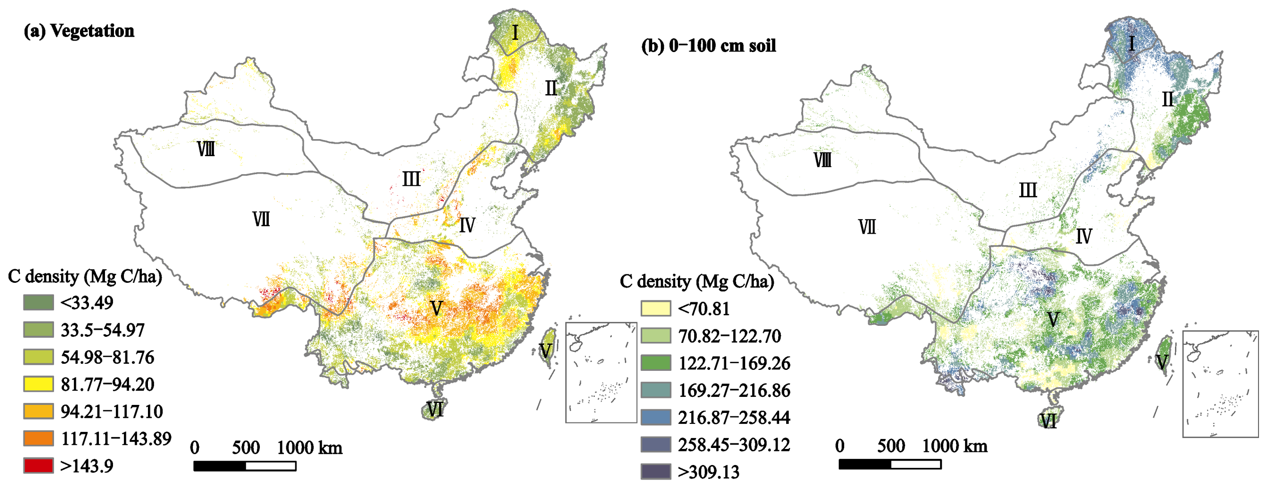

Fig. 7 Spatial pattern of vegetation and soil carbon density in China's forest ecosystems

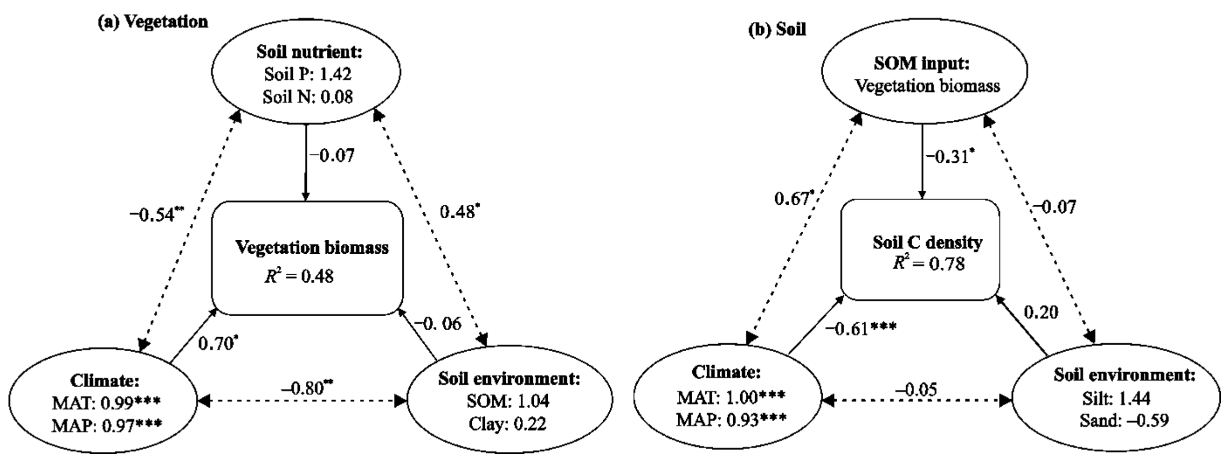

Fig. 8 Controlling mechanisms of vegetation carbon density (Mg C/ha) and soil carbon density (Mg C/ha): * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Minus sign represents a negative effect. The dotted lines represent correlation coefficients and the data on the solid arrows represent the regression coefficients.

4 Discussion

4.1 Comparison of various estimates of carbon storage in China's forest ecosystems

The analyses showed that the average vegetation C density was about 69.23 Mg C/ha in China's forest ecosystems in the 2010s. A survey of data in the literature yielded estimates of vegetation C density (not including shrubs and grasses) as 57.07 Mg C/ha (Zhou *et al.*, 2000). Using the data from FRIC, estimates of approximately 44.91 Mg C/ha (Fang *et al.*, 2001) or 42.82 Mg C/ha (Li *et al.*, 2011) were obtained. Moreover, a modeling approach gave an estimate of 70.3 Mg C/ha (Li *et al.*, 2004). These obvious differences among the various estimates of vegetation C density are mainly attributable to variation in data sources and integration methods (Table 2). In this study, soil C density was estimated to be about 116.52 Mg C/ha for China's forest ecosystems in the 2010s. In previous studies, Xie *et al.* (2004) estimated soil C densities of 115.9 Mg C/ha using Soil Resource Inventory data, Li *et al.* (2004) estimated soil C densities of 120 Mg C/ha by the CEVSA model, and Zhou *et al.* (2000) calculated soil C densities of 193.55 Mg C/ha using data collected from the literature. Some of the above-mentioned differences might be explained by: 1) differences in sampling location and estimation methods; 2) field investigations being conducted at different seasons or years; and 3) apparent deficiency in soil C density, especially for deeper soil layers. In this study, vegetation and soil C storage in the 2010s were 12.05 and 23.50 Pg C, respectively, using the statistical approach. Li *et al.* (2004) reported C storage values of

8.72 Pg C in vegetation and 23.20 Pg C in soil for China's forest ecosystems, using the CEVSA model. C storage values of 6.20 and 21.02 Pg C in vegetation and soil, respectively, have been reported (Zhou *et al.*, 2000). In addition, C storage values of vegetation were estimated as 7.81 Pg C (Li *et al.*, 2011) and 6.90 Pg C (Guo *et al.*, 2013), using the FRIC data. Differences in vegetation and soil data source might be the main factors explaining variation in the C density of China's forest ecosystems (Table 2). Most previous studies used FRIC data to estimate vegetation C storage (Zhou *et al.*, 2000; Fang *et al.*, 2001; Zhao and Zhou, 2005), and used the Soil Resource Inventory database to calculate SOC storage (Xie *et al.*, 2004; Xu *et al.*, 2015). In contrast, we collected a substantial amount of field-measured data for forest vegetation and soil C density. Additionally, differences in the methods used to estimate C storage might partly contribute to the greater uncertainty at large scales (Wang *et al.*, 2003; Yang *et al.*, 2007). Furthermore, different key parameters selected for calculation (e.g., plant C content, soil bulk density, soil depth, and areas) might also cause large uncertainties in forest C storage estimates (Jobbágy and Jackson, 2000; Wang *et al.*, 2003). To some extent, different sampling times might lead to uncertainties in estimation accuracy as well. As shown in Table 2, the range of estimates of vegetation was large, and may require the identification of further factors to explain its origin. It should be noted that vegetation C density in the reported studies included aboveground and belowground vegetation, shrubs, and grasses. Our finding supports the view that other approaches combined with sufficient data will also provide robust estimates of forest C storage values.

4.2 Spatial patterns of carbon sequestration potential in China's forest ecosystems

Mature forest scenarios predicted the upper threshold of C density and C storage in China's forest ecosystems would be 283.65 Mg C/ha and 51.37 Pg C. Therefore, potential increments of C density and storage are expected to be 97.9 Mg C/ha (52.7%) and 15.82 Pg C (45.5%), respectively, where vegetation and soil contribute 61.6% and 38.4%, respectively (Fig. 5). These estimates are based on the assumption that the existing forests in China continue to grow well and that the forest areas will be conserved in the future. In reality, the afforested area in China has increased by about 33 million ha, with a dramatic 20.36% increase from 2004 to 2008 and 21.63% increase between 2009 and 2013, according to the 7th and 8th FRIC. Moreover, with the development of the economy and public awareness, many effective approaches have been employed to protect the current forests and to encourage reforestation. Therefore, the thresholds reported here are reasonable, and may even underestimate the C_{sp} of China's forests in the future.

The C_{sp} of China's forests vary among different regions, with the subtropical humid regions having greatest C sequestration potential. Comparison of similar forest areas in different regions indicates that the highest increment of C storage is expected in subtropical humid regions (around 7.04 Pg C), while the greatest increment of C density is observed in the temperate arid and semi-arid regions. Forests in the subtropical humid regions will play important roles as C sinks in the future because these regions have the highest productivity and highest atmospheric N deposition (Lewis *et al.*, 2009; Jia *et al.*, 2014; Zhu *et al.*, 2015). Atmospheric deposition supplies a large amount of N to China's subtropical forests, where SOC and N are generally poor, because of heavy leaching and fast mineralization. As a result, the N inputs stimulate tree growth before the levels of soil N reach saturation (LeBauer and Treseder, 2008; Thomas *et al.*, 2010). Similar findings have been reported in a recent study (Yu *et al.*, 2014), which showed that large and expanding areas of young, recently planted, and natural forests in subtropical China, combined with high and increasing N deposition, may bring about continuous absorption of substantial C by these forests in future. Therefore, the role of subtropical forests in global C cycle must be emphasized. Of course, this estimate of the potential for C sequestration in the vegetation and soil of China's forest ecosystems must be verified by further work. In addition, forest C sequestration potential was probably overestimated in this study because of the unaccounted impact of human activity on the C sink in ecosystems. This impact may be as much as 42%, based on a study of ingestion by herbivores, and the effects of fire, water erosion, and forestry utilization (Wang *et al.*, 2015).

4.3 Influences of climate on spatial patterns of vegetation and soil carbon density

Vegetation C density in mature forests decreased with increasing latitude, but soil C density increased. Lal (2005) reported a similar pattern of soil C density. The differences in latitudinal patterns between forest vegetation and soil may result from different C accumulation processes, and from climate control mechanisms, such as MAT and MAP (Davidson *et al.*, 2000; Liu *et al.*, 2012). More specifically, the long-term accumulation of SOM in forests depends on the balance between the input and decomposition of organic material. SOM input comes mainly from leaf litter and root secretions, which are positively related to primary production in forests (interactively controlled by MAT and MAP). In contrast, SOM decomposition is primarily controlled by temperature, and is elevated with increasing temperature; soil moisture does not appear to seriously limit SOM decomposition (Zhang *et al.*, 2008). As a general rule, higher MAT and larger MAP appeared at low latitudes. Temperature not only influences productivity and SOM input, but also controls the accumulation of SOM by regulating decomposition (Davidson *et al.*, 2000; Liu *et al.*, 2012; Wang *et al.*, 2016). High temperature and precipitation are common at low latitudes in China and promotes SOM input to some extent, but also strongly accelerate SOM decomposition. These effects are a consequence of the exponential increase in SOM decomposition rates with increasing temperature, without serious limitation of soil moisture (Post *et al.*, 1982; Davidson *et al.*, 2000). In contrast, in high-latitude regions, low temperatures appear to depress decomposition rates resulting in SOM accumulation. However, the input of new SOM is also decreased to some extent due to the reduction in primary productivity at low temperatures.

The climate exerts important effects on the spatial patterns of C density in vegetation and soil in China's forest ecosystems, but the controlling mechanisms are apparently different between vegetation and soil (Fig. 8). Vegetation C density increased with increasing MAT and MAP, mainly due to their positive effects on productivity (Liu *et al.*, 2012; Wen and He, 2016). On the other hand, soil C density depended on the balance between SOM input and decomposition, and thus displayed a more complex response to changes in MAT and MAP (Davidson *et al.*, 2000). Surprisingly, vegetation and soil C densities exhibited weak trends with MAT and MAP for all 1764 forest plots. Although, higher MAT and MAP facilitate primary productivity and SOM input, the negative effects of increasing MAT on SOM decomposition were far stronger (Orchard and Cook, 1983; Cox *et al.*, 2000; Davidson *et al.*, 2000). These findings highlight the fact that divergent effects of climate on vegetation C density and soil C density need to be considered in future studies (Fig. 8). Furthermore, it is imperative for policy-makers in China to consider the key influences of climate factors on vegetation and soil C when they designate locations and select tree species for reforestation. Areas with high vegetation or soil C density should be protected and maintained, while areas in which vegetation or soil C density are likely to increase should be selected for reforestation.

5 Conclusions

This study used mature forest scenarios to demonstrate the spatial patterns and principal influencing factors of C_{sp} in China's forest ecosystems, their spatial patterns, and the main influencing factors. The results showed that C_{sp} in China's forest ecosystems is expected to be 10.81 Pg C in vegetation and 5.01 Pg C in soil with increasing forest age. The values of C_{sp} varied among different regions, and the subtropical humid regions having highest C sequestration potential, following by tropical humid regions, while the warm temperate arid region having lowest C sequestration potential. Hence, forests in the subtropical humid regions and tropical humid regions will play vital roles as C sinks in the future. This finding should be taken into consideration in future reforestation and forest management strategies. Meanwhile, we found that climate had important effects on the spatial patterns of C density in vegetation and soil in China's forest ecosystems, but the influencing routes were different. Climate had a positive effect on vegetation C density and a negative effect on soil C density. These findings indicate that policy-makers must carefully consider the distribution of reforestation in China in relation to climate, in order to better utilize the potential capacity of China's forest ecosystems to offset anthropogenic CO_2 emissions in the future.

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