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ORIGINAL PAPER

Variations of forest soil organic carbon and its influencing factors in east China

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Abstract
• ***Key message*** **Forest and soil types are the main factors that influence the distribution pattern of soil organic carbon (SOC) in forests across east China. In general, SOC density was largest in north-eastern China, followed by south-eastern China, and lowest in middle-eastern China, due to regional climate and the dominant forest type (young plantations in middle-eastern China)**.
• ***Context*** Forest SOC plays an important role in the carbon cycle in China, but large spatial heterogeneity and insufficient field observations lead to large uncertainties in the estimation of SOC.
• ***Aims*** The objectives of this study were to evaluate forest SOC density in different geographic regions, forest types, and soil types and to investigate the spatial variation of SOC in forests across east China.
• ***Methods*** The estimation of forest SOC was based on 348 soil profiles, which were collected from 116 forest sites in east China during 2008–2011.
• ***Results*** The average SOC content was 17.5 g C kg^{-1}, which leads to an average SOC density of 12.4 kg C m^{-2}. The average SOC density in the organic horizon and mineral horizon was 5.47 and 6.91 kg C m^{-2}, respectively, with 44.2 % SOC density dominating in the organic horizon. The average forest SOC density in north-eastern, middle-eastern, and south-eastern China was 13.5, 9.95, and 13.3 kg C m^{-2}, respectively.
• ***Conclusion*** SOC distribution varied among regions, forest types, and soil types in east China. The importance of influencing factors switched with depth, precipitation, and temperature dominating in the organic horizon and soil texture dominating in the mineral horizon.

Keywords East China · Forest · Soil · Soil organic carbon

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Contribution of the co-authors Yan Liu: collaboratively designing the work, measuring the samples, running data analysis, and editing the manuscript
Suyan Li: collaboratively designing and supervising the work
Xiangyang Sun: collaboratively designing the work and discussing the manuscript
Xin Yu: collecting the samples and reviewing the manuscript

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1 Introduction

Soil organic carbon (SOC) stored in forest soils comprises about 73 % of global soil carbon storage (Sedjo 1993). In temperate forest ecosystems, the carbon pool in forest soil is approximately twice as large as the pool in forest vegetation (Malhi et al. 1999). SOC is an important component in forest soils and ecosystems. SOC accumulation and decomposition rates have direct effects on terrestrial ecosystem carbon storage and the global carbon balance. SOC is also essential for improving soil quality and hence sustains forest production. Thus, understanding SOC distribution in forest ecosystems is critical.

As of 2014, forest coverage (208 million ha) is approximately 22 % in China. Additionally, plantation forests in China cover more land than those in any other countries of the world (Winjum and Schroeder 1997). China's forests are mainly distributed in the humid and sub-humid eastern regions. Forest resources in east China account for 71 % of national forest area, and growing stock accounts for 67 % of the country (The State Forest Bureau 2014). During the past several decades, large amounts of research programs on forest soil carbon cycling have been conducted at different scales in mountainous or other regions (Huang et al. 2013; Li et al. 2013; Liu et al. 2012; Zhang et al. 2011). However, these studies have usually examined carbon stocks and their dynamics for specific forest types or for single ecosystem components. In addition, previous estimates have been mainly based on China's first and second soil survey data, which limits our understanding of the current carbon stock and its distribution in forest soil. Consequently, regional- or national-scale assessments of the forest carbon balance are still lacking, and estimating carbon cycling is difficult because of the extremely complex topography, vegetations, stand age, and climate as well as natural soil variability (Bohn 1982; Batjes 1996; Eswaran et al. 1993; Kern 1994; Post et al. 1985, 1990; Pregitzer and Euskirchen 2004), and a lack of extensive soil data collection from the field. Therefore, estimation of forest soil carbon stock and allocation play an important role in predicting future climate change and forest management.

East China is one of China's major areas of forests. The forest ecosystems in east China vary from cold-temperate coniferous forests in the north-eastern provinces to temperate needle broad-leaved mixed forests, then warm temperate deciduous broad-leaved forests to subtropical evergreen broad-leaved forests to tropical monsoon forests in the south according to the climatic zones (Hou 1983). This study, based on geographical regionalization and forest district, defines east China in a very broad sense while north-eastern, middle-eastern, and south-eastern China are defined more narrowly. Field data were collected from 116 sites to estimate the forest SOC density and to analyze how various factors affected the distribution of forest SOC in east China. The objectives of this study are (1) to explore the distribution pattern of forest SOC and evaluate the density of SOC in different geographic regions, forest types, and soil types in east China and (2) to analyze the relationship between SOC density and climate-related factors (mean annual temperature (MAT), mean annual precipitation (MAP), soil-related factors (soil nitrogen, bulk density, soil texture, and pH), and position-related factors (longitude, latitude, and elevation)) in forests across east China.

2 Materials and methods

2.1 Study area

The study area is located in the eastern monsoon region of China, one of China's major forest regions. Three geographic regions were selected representing the main forest types and soil types in a very broad sense, specifically, north-eastern China, middle-eastern China, and south-eastern China (Table 1).

Three hundred forty-eight soil profiles were from 116 sites (three soil profiles at each site) in forests of east China during 2008–2011 (Fig. 1). Detailed information of these study sites is shown in Appendix 1. In this study, based on the investigation and data collection from China's second national soil survey (Chinese National Investigation Office 1993–1996; Chinese Soil Taxonomy Research Group, Institute of Soil Science, Chinese Academy of Sciences, Cooperative Research Group on Chinese Soil Taxonomy 2001), Chinese forest inventory (Chinese Ministry of Forestry 2009; Zhang 1986), and published literature, the study sites was selected mainly based on the distribution of soil and forest types and terrain. A total of 116 sites were surveyed in the three main forest regions: 40 sites in north-eastern China, 34 sites in middle-eastern China, and 42 sites in south-eastern China. The study sites covered all major climate zones, forest types, and soil types across east China.

2.2 Sampling method

Each soil profile was divided pedogenetically into three major horizons, A, B, and C horizons (National Soil Survey Office 1998). For each soil pit, soil samples were collected from each horizon. Soil profile data included extensive information on soil type (using Genetic Soil Classification of China, Chinese Soil

Table 1 Site characteristics for east China on a broad scale, including north-eastern China, middle-eastern China, and south-eastern China

Geographic region	Climatic zone	Vegetation zone	Main soil type (Genetic Soil Classification of China)	MAT (°C)	MAP (mm)
North-eastern China	Cold-temperate zone Temperate zone	Cold-temperate coniferous forests Temperate needle broad-leaved mixed forests	Brown coniferous forest soils Dark-brown earths	−6 to 7	500 to 800
Middle-eastern China	Warm temperate zone	Warm temperate deciduous broad-leaved forests	Brown earths; cinnamon soils	8 to 14	400 to 800
South-eastern China	Subtropical zone	Subtropical evergreen broad-leaved forests	Yellow-brown soil; red earths; yellow earths; lateritic red earths	16 to 28	800 to 2600
	Tropical zone	Tropical monsoon forests	Latosols		

MAT mean annual temperature, *MAP* mean annual precipitation

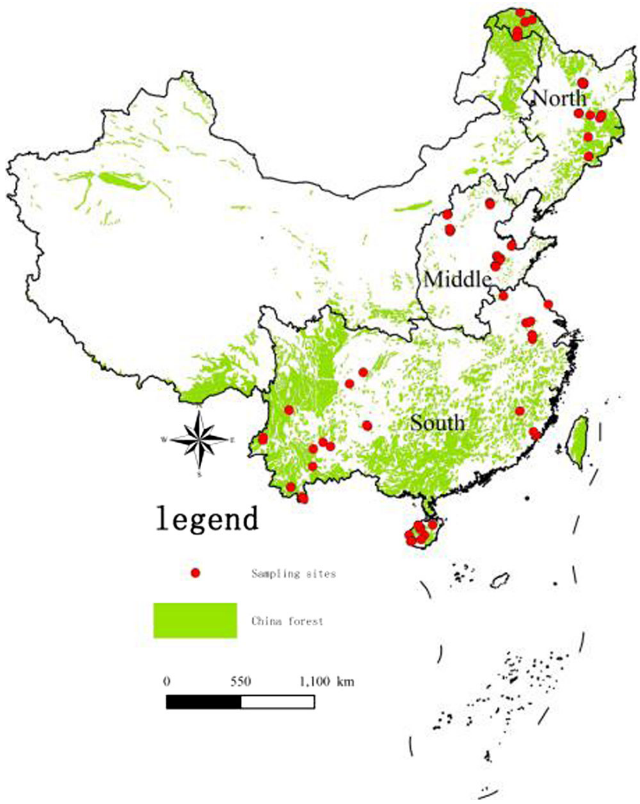

Fig. 1 Map showing the distribution of forest soil sites used in this study of east China. *North* north-eastern China, *Middle* middle-eastern China, and *South* south-eastern China

General Survey Office 1993), profile location, elevation, vegetation, bulk density, horizon depth, and organic carbon, along with other physicochemical properties. Major physicochemical properties of the 348 soil profiles are shown in Table 2. Soil bulk density samples were collected from each horizon using a cutting ring (volume of 100 cm^3). All samples were collected between June 2008 and October 2011. All the soil samples were air dried in the laboratory and passed through a 2-mm sieve to remove coarse roots and easily detectable plant litter prior to laboratory analysis. SOC content was analyzed using the dichromate oxidation (external heat applied) method (Nelson and Sommers 1975). Bulk density was determined by drying the core samples at 105 °C until constant weight. Particle-size distribution was analyzed by pipette method (ISRIC 1995). Soil pH was determined by pH meter using a ratio of soil to distilled water of 1:2.5. Soil total nitrogen (TN) was measured according to the Kjeldahl method (Parkinson and Allen 1975).

2.3 Climate data

Mean annual temperature and precipitation data were obtained from China Meteorological Data Sharing Service System (China Meteorological Administration).

2.4 Calculation of SOC density

SOC density (kg C m^{-2}) refers to the organic carbon storage per unit area (1 m^2) at a certain depth; it is the main basis for estimating SOC storage (Jin et al. 2001; Yang et al. 2011; Dai et al. 2014). In this study, for better comparison among data sets, soil profiles were divided into organic (A) horizon and mineral (B and C) horizon, with carbon content and density calculated separately. Carbon content and density in the entire soil profile were then calculated as follows.

SOC content was calculated according to Eq. 1:

$$\text{SOC content} = \frac{\sum_{i=1}^{n} T_i \times C_i \times (1-G_i)}{\sum_{i=1}^{n} T_i} \quad (1)$$

SOC density was calculated according to Eq. 2:

$$\text{SOC}_{\text{density}} = \sum_{i=1}^{n} T_i \times p_i \times C_i \times (1-G_i)/100 \quad (2)$$

where $\text{SOC}_{\text{content}}$ is the SOC content of the target depth of the soil (g C kg^{-1}), n is the number of soil horizons of the profile, T_i (cm) is the thickness of horizon i, C_i (g C kg^{-1}) is the organic carbon concentration of horizon i, and G_i (dimensionless) is the mass percentage of rock fragment content (>2 mm) of horizon i. $\text{SOC}_{\text{density}}$ is the SOC density of the target depth of the soil (kg C m^{-2}) and p_i (g cm^{-3}) is the soil bulk density of horizon i.

Table 2 Effective soil depth, SOC content, total N, C/N ratio, bulk density, pH, clay content, silt content, and sand content of each study area in east China

Geographic region	Effective soil depth (cm)	SOC content (g C kg^{-1})	Total N (g kg^{-1})	C/N ratio	Bulk density (g cm^{-3})	pH	Clay content (g kg^{-1})	Silt content (g kg^{-1})	Sand content (g kg^{-1})
North-eastern China	78 ± 23	20.9 ± 38.3	1.99 ± 3.66	13.3 ± 14.8	1.29 ± 0.31	5.4 ± 0.6	528 ± 167	268 ± 64	204 ± 119
Middle-eastern China	82 ± 26	12.2 ± 11.7	0.82 ± 0.98	17.9 ± 8.45	1.32 ± 0.19	7.5 ± 0.8	513 ± 157	304 ± 100	183 ± 111
South-eastern China	84 ± 30	19.3 ± 26.8	0.97 ± 1.63	20.2 ± 7.98	1.28 ± 0.19	6.2 ± 0.7	444 ± 95	254 ± 123	302 ± 95
Total region	82 ± 27	17.5 ± 25.5	1.28 ± 2.04	16.4 ± 8.73	1.26 ± 0.24	6.3 ± 1.2	493 ± 165	274 ± 89	233 ± 129

Mean ± standard deviation

2.5 Statistical analysis

One-way ANOVA and *t* test were conducted to evaluate whether the vertical distribution of SOC differed significantly among various study regions and soil horizons. Means of the main effects were compared by Duncan test. Pearson correlation analysis was conducted to determine the relationships between SOC density and climate-related factors (MAP, MAT), soil-related factors (nitrogen, pH, bulk density, and soil texture), and position-related factors (longitude, latitude, and elevation). Statistical analyses were performed by SPSS 16.0 program.

3 Results

3.1 The vertical and spatial distribution of SOC

In all forest soils, the bulk density of soil increased with increasing soil depth (Fig. 2). In east China, the average forest soil bulk density and SOC content in the entire soil profile were 1.28 g cm^{-3} and 17.5 g C kg^{-1} (Table 3). Soil bulk density in the mineral horizon was higher than that in the organic horizon among all the sites. Approximately 51.7 % of the study sites had SOC content in the range of 0–10.00 g C kg^{-1}, while only about 9.48 % of the study sites had SOC content more than 40 g C kg^{-1}.

This study spanned across 18° N–53° N; the forest SOC density in study sites varied considerably in east China (Fig. 3). The SOC density in the entire soil profile ranged from 0.80 to 51.4 kg C m^{-2}; the average density was 12.4 kg C m^{-2}. The SOC density in the organic horizon ranged from 0.16 to 33.9 kg C m^{-2}, and the average content was 5.47 kg C m^{-2}. The SOC density in the mineral horizon range varied from 0.50 to 34.8 kg C m^{-2}; the average density was 6.91 kg C m^{-2} (Fig. 4). The average SOC density in the organic horizon was approximately 44.2 % of the total organic carbon density in the soil profile.

3.2 SOC among different geographic regions

The soil bulk density in the north-eastern, middle-eastern, and south-eastern China ranged from 0.06 to 1.93, 0.75 to 1.91, and 0.60 to 1.75 g cm^{-3}, respectively (Table 3). The average soil bulk density was 1.29, 1.24, and 1.32 g cm^{-3}, respectively, and the average soil depth was 78, 82, and 84 cm, respectively, in the entire soil profile for the three study regions (north-eastern, middle-eastern, and south-eastern China).

SOC content decreased with increasing soil depths in all regions. SOC content ranged from 0.638 to 214, 0.292 to 91.4, and 0.266 to 89.4 g C kg^{-1}, in north-eastern, middle-eastern, and south-eastern China regions, respectively. The average SOC content in the entire soil profile for the three study

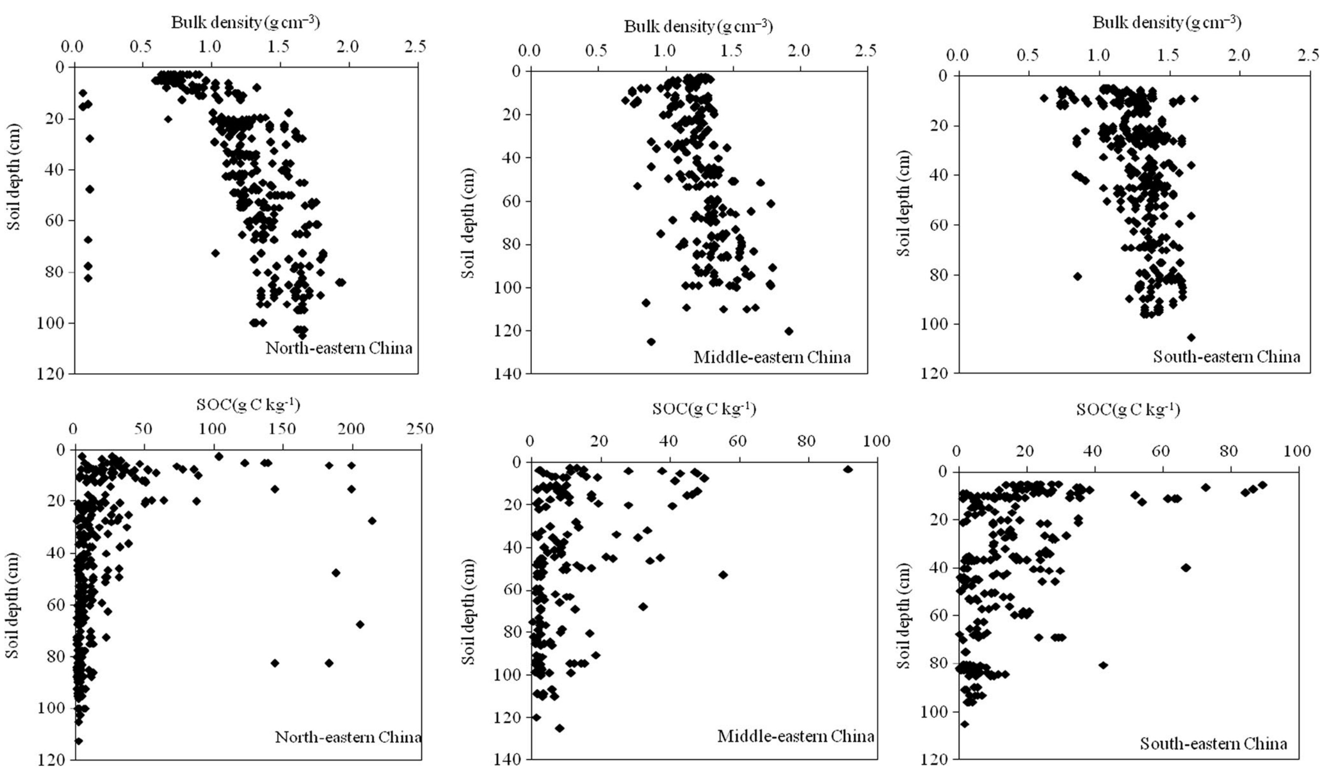

Fig. 2 Distribution of bulk density and organic carbon in forest soil profiles

Table 3 The comparison of SOC content and bulk density in east China on a broad scale, including north-eastern China, middle-eastern China, and south-eastern China

Geographic region	Soil layer	Thickness (cm)	D_b (g cm^{-3})	SOC (g C kg^{-1})
North-eastern China	Organic horizon	25 ± 15	0.88 ± 0.25Ab	50.6 ± 54.4Aa
	Mineral horizon	53 ± 25	1.40 ± 0.33Aa	15.5 ± 40.3Ba
	Profile	78 ± 23	1.29 ± 0.31a	20.9 ± 38.3a
Middle-eastern China	Organic horizon	28 ± 21	1.12 ± 0.16Aa	20.4 ± 20.8Ab
	Mineral horizon	57 ± 28	1.31 ± 0.42Aa	7.44 ± 9.43Bb
	Profile	82 ± 26	1.24 ± 0.19a	12.2 ± 11.7b
South-eastern China	Organic horizon	20 ± 7	1.16 ± 0.22Aa	27.7 ± 26.5Ab
	Mineral horizon	65 ± 28	1.32 ± 0.20Aa	16.2 ± 31.8Aa
	Profile	84 ± 30	1.28 ± 0.19a	19.3 ± 26.8a
Total region	Organic horizon	23 ± 15	1.06 ± 0.25A	33.5 ± 23.5A
	Mineral horizon	58 ± 27	1.35 ± 0.32A	13.5 ± 25.7B
	Profile	82 ± 27	1.26 ± 0.24	17.5 ± 25.5

Mean ± standard deviation. Different lowercase letters within columns indicate significant differences among different regions for each soil horizon. Different uppercase letters within columns indicate significant differences among the different soil horizons in each region

D_b bulk density

regions was 20.9, 12.2, and 19.3 g C kg^{-1}, respectively. The forest SOC content was highest in north-eastern China, intermediate in south-eastern China, and lowest in middle-eastern China.

The SOC density in the organic horizon, mineral horizon, and entire soil profile throughout three study regions ranged from 0.49 to 23.8, 0.94 to 34.7, and 1.43 to 51.4 kg C m^{-2} (north-eastern China); 0.16 to 33.9, 0.67 to 29.1, and 2.09 to 35.7 kg C m^{-2} (middle-eastern China); and 0.30 to 18.0, 0.50 to 33.6, and 0.80 to 44.3 kg C m^{-2} (south-eastern China), respectively. The average SOC density in the entire soil profile for north-eastern, middle-eastern, and south-eastern China was 13.5, 9.95, and 13.3 kg C m^{-2}, respectively (Fig. 4). The SOC density in the organic horizon was highest in north-eastern China, followed by south-eastern China, and lowest in middle-eastern China. The SOC density in the organic horizon accounted for 46.1, 52.7, and 37.1 % of the total SOC density in north-eastern, middle-eastern, and south-eastern China, respectively. The SOC density for the entire soil profile was highest in north-eastern China, intermediate in south-eastern China, and lowest in middle-eastern China.

3.3 SOC among different forest types

The average content of SOC ranged from 12.2 to 33.3 g C kg^{-1}, and there was a significant difference among the five forest types with the highest in the cold-temperate coniferous forests, followed by subtropical

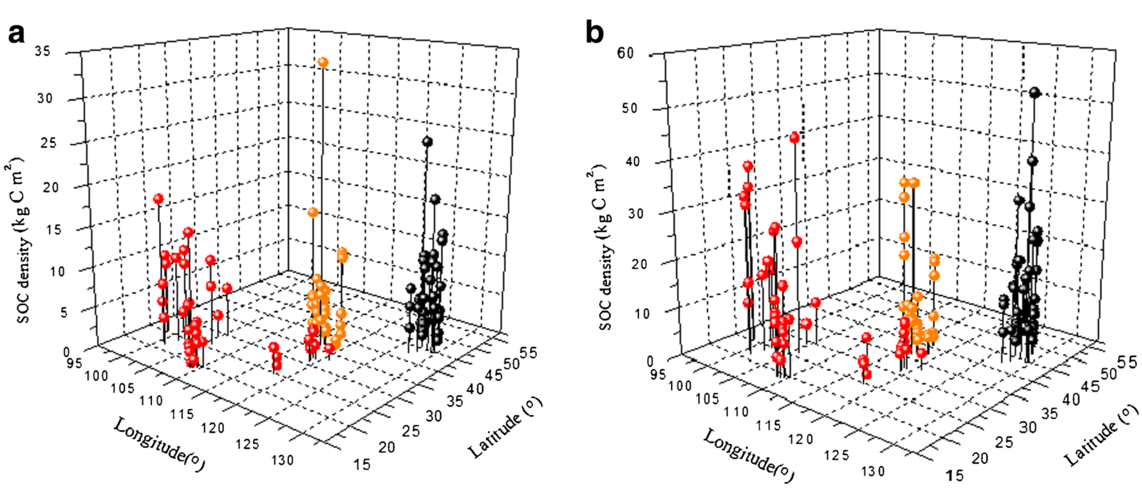

Fig. 3 Forest soil site data for organic horizons (A horizon) SOC density (kg C m^{-2}) (**a**) and the soil profiles' SOC density (kg C m^{-2}) (**b**), in relation to longitude and latitude for the site. Site data are shown in relation to their distribution among north-eastern China (*black*), middle-eastern China (*orange*), and south-eastern China (*red*)

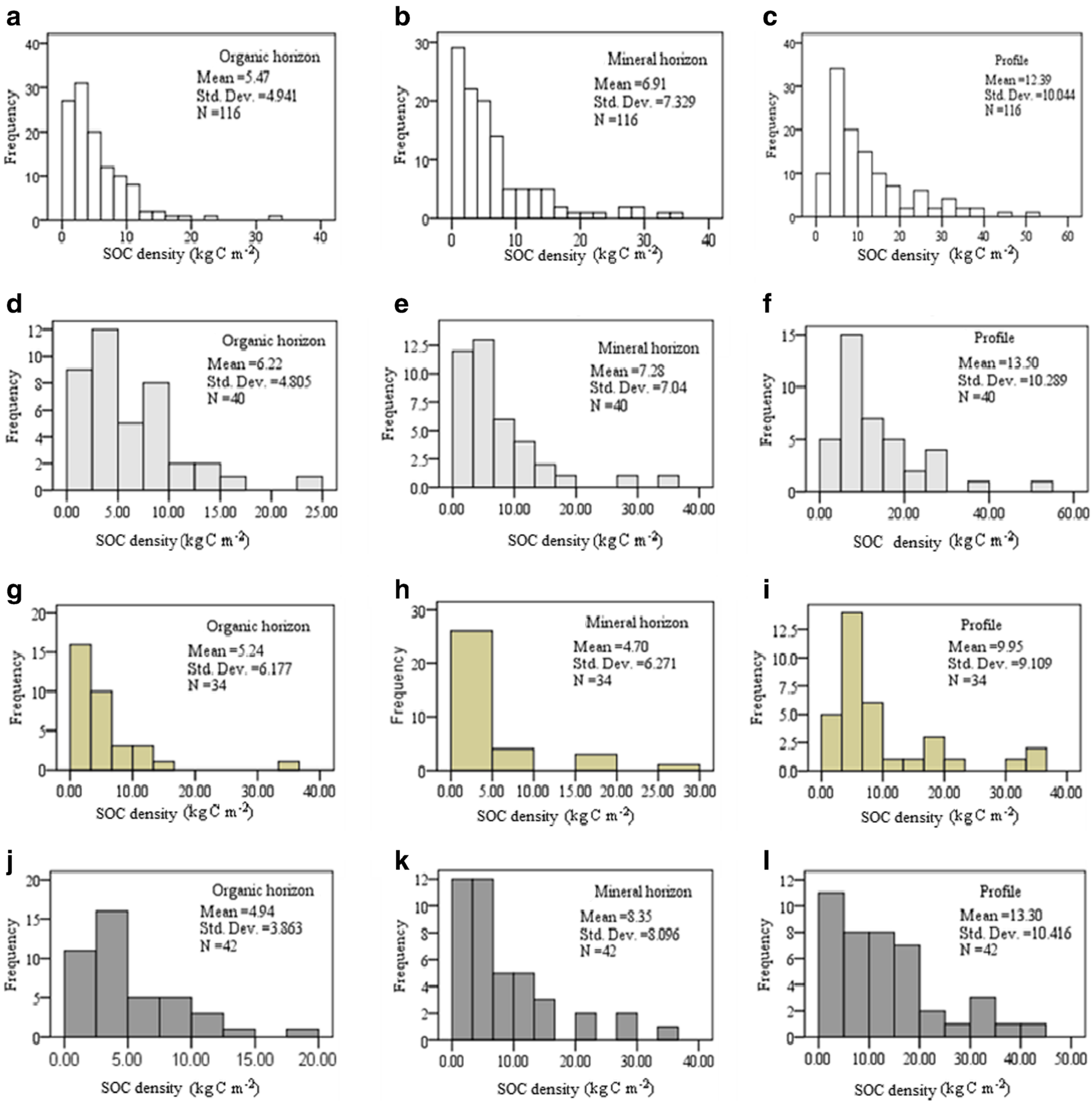

Fig. 4 Frequency distribution of SOC density in forest soils in east China at different layers (organic horizons, mineral horizons, and soil profiles). **a**–**c** Total region; **d**–**f** north-eastern China; **g**–**i** middle-eastern China; **j**–**l** south-eastern China

evergreen broad-leaved forests, temperate needle broad-leaved mixed forests, tropical monsoon forests, and the lowest in the warm temperate deciduous broad-leaved forests (Table 4). The average SOC density ranged from 9.95 to 19.8 kg C m^{-2} among five forest types. SOC density was highest in the cold-temperate coniferous forests than the other four forest types, and the lowest was observed in the warm temperate deciduous broad-leaved forests.

3.4 SOC content and density among different soil types

Organic carbon content and density showed a significant difference among 22 Genetic Soil Classification of China soil groups in east China due to the high spatial variability (Table 5). SOC density ranged from 1.43 to 35.0 kg C m^{-2} in the entire soil profiles, 0.49 to 13.7 kg C m^{-2} in the organic horizon, and 0.94 to

Table 4 SOC content and density in the different forest types in east China

Forest type	Number of profiles	SOC content (g C kg^{-1})			SOC density (kg C m^{-2})		
		Organic horizon	Mineral horizon	Profile	Organic horizon	Mineral horizon	Profile
Cold-temperate coniferous forests	36	104 ± 61.8A	22.3 ± 46.0A	33.3 ± 47.0A	8.19 ± 6.67A	11.6 ± 10.4A	19.8 ± 14.2A
Temperate needle broad-leaved mixed forests	84	20.5 ± 29.6B	12.7 ± 38.1A	15.6 ± 33.4B	5.37 ± 3.57AB	5.43 ± 3.99B	10.8 ± 6.75B
Warm temperate deciduous broad-leaved forests	102	20.4 ± 20.8B	7.44 ± 9.43A	12.2 ± 11.7B	5.24 ± 6.18AB	4.70 ± 6.27B	9.95 ± 9.11B
Subtropical evergreen broad-leaved forests	72	31.2 ± 30.8B	17.1 ± 17.6A	21.1 ± 21.5AB	5.21 ± 4.0AB	8.27 ± 8.8AB	13.5 ± 11.7B
Tropical monsoon forests	54	23.1 ± 12.2B	14.9 ± 7.54A	16.9 ± 8.32AB	4.59 ± 3.91B	8.47 ± 5.92AB	13.1 ± 7.78B

25.6 kg C m^{-2} in the mineral horizon. The floodplain forest soils' carbon density was lowest, and the highest was observed in the volcanic soils.

3.5 Relationship between SOC density and environmental factors

There were positive correlations between SOC density and latitude, elevation, MAP, nitrogen, silt content and clay content and negative correlations between SOC density and longitude, MAT, pH, bulk density, and sand content. Significant correlations were observed between SOC density and nitrogen, and bulk density and soil texture (Table 6). Strong relationships were found between the SOC density and MAT and MAP in the organic horizon. The correlation coefficients between the SOC density of the organic horizon and the climate-related factors were higher than those of the mineral horizon.

Table 5 SOC content and density for the 22 Genetic Soil Classification of China soil groups in east China

Soil groups in Genetic Soil Classification of China	Soil groups in Chinese soil taxonomy	Number of profiles	SOC content (g C kg^{-1})			SOC density (kg C m^{-2})		
			Organic horizon	Mineral horizon	Profile	Organic horizon	Mineral horizon	Profile
Brown coniferous forest soils	Umb-Cryic Cambisols	24	106 ± 56.4	10.8 ± 9.11	27.2 ± 14.0	8.01 ± 4.78	13.8 ± 11.5	21.8 ± 15.3
Bleach Spodosol	Umb-Cryic Cambisols	6	95.7 ± 8.89	5.49 ± 0.22	24.3 ± 15.5	13.7 ± 11.1	6.43 ± 0.84	20.1 ± 10.3
Floodplain forest soils	Dark-Aquic Cambosols	3	3.40 ± 1.13	0.71 ± 0.23	1.17 ± 0.47	0.49 ± 0.16	0.94 ± 0.37	1.43 ± 0.53
Peat soils	Fibri-Permagelic Histosols	6	171 ± 31.1	186 ± 21.6	180 ± 4.07	4.10 ± 0.55	12.8 ± 0.59	16.9 ± 1.14
Dark-brown earths	Dark-Aquic Cambosols/Bori-Udic Cambosols/Mollic Boric Luvisols	87	26.5 ± 18.9	8.55 ± 8.13	13.1 ± 9.56	6.31 ± 3.83	6.63 ± 5.87	12.9 ± 8.26
Albic soil	Albic-Boric Luvisols	12	30.9 ± 25.9	2.24 ± 1.33	6.85 ± 4.16	4.70 ± 2.58	2.49 ± 1.61	7.19 ± 3.89
Cinnamon soils	Hapli-Ustic Luvisols/Hapli-Ustic Cambosols	36	10.3 ± 9.21	5.48 ± 3.46	6.80 ± 4.19	2.56 ± 1.65	3.52 ± 4.57	6.08 ± 4.46
Moisture soils	Ochri-Aquic Cambosols	12	8.23 ± 6.07	6.88 ± 6.14	4.98 ± 2.68	2.69 ± 2.67	3.71 ± 1.16	6.51 ± 3.41
Brown earths	Hapli-Udic Luvisols	27	40.9 ± 25.1	6.86 ± 7.38	23.7 ± 13.6	10.4 ± 8.89	4.67 ± 5.32	15.0 ± 9.36
Coastal solonchaks	Aqui-Orthic Halosols	6	8.46 ± 5.06	5.36 ± 3.82	2.70 ± 0.26	1.18 ± 0.38	2.54 ± 0.65	3.71 ± 0.26
Chestnut soils	Calci-Ustic Lsohumosols	3	3.35 ± 0.98	11.6 ± 3.40	1.62 ± 0.48	0.96 ± 0.28	1.56 ± 0.74	2.53 ± 0.46
Skeletal soil	Lit-Ust-Alluvic Entisols	3	1.89 ± 0.31	1.57 ± 0.51	1.76 ± 0.57	1.92 ± 0.62	1.27 ± 0.41	3.19 ± 1.03
Lime concretion black soils	Shajiang Calci-Aquic Vertosols	6	6.92 ± 1.69	3.04 ± 1.56	5.08 ± 0.59	3.07 ± 0.91	2.98 ± 0.43	6.05 ± 0.47
Yellow-cinnamon soils	Hap-Ustic Luvisols	3	5.88 ± 1.45	4.59 ± 1.61	4.89 ± 1.29	1.87 ± 0.49	5.43 ± 0.93	7.30 ± 1.62
Red earths	Rhodi-Udic Ferralsols/Ferri-Udic Cambosols/Ali-Perudic Cambosols	39	13.5 ± 9.13	5.49 ± 5.05	7.15 ± 5.13	2.91 ± 1.43	5.91 ± 5.86	8.82 ± 6.65
Yellow earths	Hapli-Udic Ferralsols/Hap-Udic Luvisols	9	36.4 ± 26.8	8.91 ± 7.44	13.4 ± 15.4	4.01 ± 2.67	6.82 ± 6.97	10.8 ± 9.44
Yellow-brown soil	Hap-Udic Luvisols	6	9.10 ± 4.82	3.83 ± 1.77	5.00 ± 2.25	2.53 ± 0.93	4.18 ± 2.06	6.71 ± 2.99
Lateritic red earths	Ferric-Udic Cambisols	30	29.8 ± 18.8	13.2 ± 9.69	17.9 ± 14.7	6.21 ± 4.71	10.3 ± 6.74	16.5 ± 8.40
Latosols	Rhodi-Udic Ferralsols/Hap-Udic Ferrisols	12	22.1 ± 15.9	15.5 ± 10.2	17.7 ± 12.6	3.86 ± 3.02	6.41 ± 3.35	10.3 ± 4.15
Limestone soils	Black-Lithomorphic Isohumosols/Calci-Udic Ferrisols	6	72.9 ± 12.4	34.3 ± 3.85	49.0 ± 10.1	12.8 ± 2.87	20.3 ± 3.88	33.1 ± 6.76
Volcanic soils	Hapli-Udic Andosols	6	75.0 ± 12.7	50.4 ± 18.0	55.7 ± 16.9	9.42 ± 0.62	25.6 ± 2.87	35.0 ± 2.26
Purplish soils	Purpli-Udic Cambosols	6	16.4 ± 6.25	6.38 ± 1.15	11.2 ± 2.78	4.47 ± 1.96	2.42 ± 0.61	6.89 ± 2.57

Table 6 Relationships between SOC density and environmental factors in east China

Soil layer	Longitude	Latitude	Elevation	MAT	MAP	Nitrogen	pH	Bulk density	Sand content	Silt content	Clay content
Organic horizon	−0.065	0.285**	0.122	−0.32**	0.207*	0.443**	−0.05	−0.331**	−0.072	0.071	0.041
Mineral horizon	−0.263*	0.003	0.153	−0.049	0.003	0.392**	−0.005	−0.264**	−0.167**	0.078	0.165**
Profile	−0.223*	0.051	0.172	−0.104	0.038	0.426**	−0.015	−0.299**	−0.101*	0.075	0.075

*$P<0.05$; **$P<0.01$

4 Discussion

4.1 Distribution of SOC

Organic matter input, output, spatial location, and related soil properties and processes all help to determine the spatial variability of the SOC content (Jenny 1941; Schlesinger 1977; Liu et al. 2011). This study showed that SOC content decreased with increasing soil depth and the sharp decrease occurred from the surface to depths of 20–30 cm. Organic inputs into the soil occur mainly in the surface horizons and decrease sharply with depth. However, little variation occurred at depths below 60 cm (Fig. 2), possibly because the SOC content is primarily determined by the distribution of the root system in deep soil (Zhou et al. 2013; Jobba'gy and Jackson 2000). Moreover, decomposition weakens with increasing soil depth, which means that decomposition proceeds more slowly in plant debris located deep in the soil. Other studies have reported similar findings (Han et al. 2010; Li et al. 2013).

China's forests are mainly distributed in mountainous areas and hilly regions. Forest SOC density was characterized by high spatial variability in east China, due to the differences in climate, vegetation, and topography in mountains (Zhu et al. 2010; Yoo et al. 2006). We found that the forest SOC density for the entire soil profile was comparatively higher in north-eastern China and south-eastern China, and lower in middle-eastern China. In north-eastern China, lower temperatures could slow down the decomposition of SOC and soil respiration, allowing SOC to accumulate (Rozhkov et al. 1996; Xie et al. 2008). In addition, SOC density under natural forest was significantly higher than that in the plantation (Yang et al. 2009; Wang et al. 2014). Natural forest is mainly distributed in north-eastern and south-eastern China, with the forest area coverage of natural forest above 77.0, 32.1, and 51.3 %, respectively, in north-eastern, middle-eastern, and south-eastern China (The State Forest Bureau 2014). The lowest SOC density could be attributed to the large proportion of plantation and human activities in middle-eastern China (Xie 2004).

In order to further understand the distribution patterns of SOC density in east China, we investigated the relationships between SOC density and forest types. The results showed that the distribution pattern of forest SOC density based on forest types is similar to geographical regions. Li (2008) indicated a close relationship between the geographical distribution of vegetation and climate zone distribution and concluded that the spatial distribution characteristic of SOC density is characterized by an obvious zonality. SOC density was highest in the cold-temperate coniferous forest, mainly because of low decomposition rates of soil organic matter in the cold-temperate climate (Xie et al. 2008). In the warm temperate deciduous broad-leaved forest, SOC density was lowest because of high rates of decomposition (Li et al. 2004), especially the large area of plantation (The State Forest Bureau 2014).

We also studied soil types, especially the main zonal soils (brown coniferous forest soils, dark-brown earths, brown earths, yellow-cinnamon soils, yellow-brown earths, yellow earths, red earths, latosolic red earths, and latosols), to understand the distribution patterns of SOC density in east China. The results showed that generally SOC density decreased from north to south in east China, consistent with other reports (Wang et al. 2001; Wu et al. 2003; Zhou et al. 2003). The SOC in the main soil types was characterized by high spatial variability. Soil types changed from dark-brown earths to brown earths, to yellow-cinnamon soils, to yellow-brown earths, to yellow earths, to red earths, to latosolic red earths, and to latosols, respectively, along with temperature change from north to south (Wang et al. 2001). Therefore, the spatial distribution of the soil types responded to these climatic zones, large terrain features, and major biodiversity patterns, showing a general increasing trend of SOC density with increasing latitude in east China.

4.2 Influencing factors on SOC

Our data indicated that SOC density increased as the precipitation increased and decreased as the temperature increased. The findings were consistent with those of other studies (Wang et al. 2002, 2004; Yang et al. 2007). SOC accumulation was controlled by the rates of biomass accumulation and decomposition (Lal et al. 1995). Climate affects microbial decomposition and transformation of organic matter by influencing soil temperature, moisture, ventilation, etc. On the other hand, climate also affects vegetation growth and the subsequent litter inputs of carbon to the soil. Therefore, soil carbon stocks are highest in cool and moist biomes and lowest in hot and dry biomes (Davidson et al. 2000). Our study found that the SOC density of the organic horizon was significantly affected by temperature and precipitation, due to the litter decomposition occurring in soil surface.

The general trend of the temperature decreased from south to north and precipitation decreased from east to west in east China. SOC density increased as the latitude increased, particularly in the organic horizon. The temperature decreases with increases in latitude, and the slower activity of soil microbes leads to the decrease of the mineralization rate of soil organic matter (Zhu et al. 2010). The density of SOC showed a significant negative correlation with the longitude and a positive correlation with the elevation, mainly because the natural coniferous forest is extensively distributed in low longitude and high elevation area. In addition, human disturbance would be limited by the lower population density in the mountains. However, sometimes, the change of SOC density was not necessarily responding to longitude and latitude because climate also affected by altitude and topography (Li 2008). Longitude, latitude, and elevation are fixed parameters that are not affected by other factors. Position-related factors can only reflect the status of heat and water but not the actual situation (Lv et al. 2010).

We found significant relationships between SOC density and nitrogen, bulk density, and soil texture (Table 6), which was consistent with other findings (Fu et al. 2010; Lei et al. 2013; Yang et al. 2008). In this study, we found SOC density was significantly correlated with soil texture in the mineral horizon. These results are similar to those reported by Jobba'gy and Jackson (2000). Some research studies (Zhou et al. 2013; Zhou 2013) suggested that carbon characteristics and stability mechanisms may be different between topsoil and deep soil, and their carbon dynamic process and the response of the external environment change could be different too. The SOC in the soil surface were mainly affected and predicted by precipitation and temperature, while in deeper layers, clay content was the best predictor (Jobba'gy and Jackson 2000).

4.3 Comparisons with earlier estimates

We compared the estimates of China's forest SOC density with other estimates of SOC density and found it varied widely from one study to another for several reasons (Table 7). For example, each study acquired data from a variety of data sources and used different calculation methods in different areas and studies. In addition, a complete set of inventory data does not exist and measurements of SOC contain inherent spatial variability. Most of these reports used China's first and/or second soil survey data. For example, using the second national soil survey data, Wang et al. (2004) demonstrated that the average SOC density in China's forest could be estimated to be 13.2 kg C m^{-2}; Xie (2004) estimated the average SOC density of forests of 11.6 kg C m^{-2}. Using the same data from the second national soil survey combined with field observations in China, Yang et al. (2007) estimated the average SOC density of forests to be 10.5 kg C m^{-2}. Our estimates of SOC density was close to the results of Li (2008) because the forest profile data used in their calculation of nationwide forest SOC density were also mostly from the east of China, with very few from the northwest and west of China. However, using the data from existing literature and monographs, Zhou et al. (2000) estimated the average forest SOC density was 19.36 kg C m^{-2} higher than Li (2008), mainly because different vegetation and soil classification systems, various data sources, and different calculation methods were used in their studies. Based on the field measurements, Li et al. (2004) found that forest SOC density was relatively higher (19.1 kg C m^{-2}) using the Carbon Exchange in the Vegetation-Soil-Atmosphere (CEVSA) model.

The sampling methods, location and season of sampling, the land-cover classification system, and land-use change are the main sources of uncertainty in SOC density estimates. Soil carbon content is not likely to be uniform for a given region. In this study, the measured soil depth was used to calculate the SOC density. However, the international calculation method of measuring SOC reservoirs is typically based on organic content in the top 1 m of soil (Sombroek et al. 1993; Wang

Table 7 Comparisons of estimated forest SOC density with other studies

Reference	Data source	SOC density valuation	Soil depth (m)	SOC density (kg C m^{-2})
Wang et al. 2004	China's second national soil survey	Weighted mean value by area	1.0	13.2
Xie 2004	China's second national soil survey	Weighted mean value by area	1.0	11.6
Yang et al. 2007	China's second national soil survey and field measurement	Weighted mean value by area	1.0	10.0
Li 2008	Literature and monographs	Weighted mean value by area	0.6	12.3
Zhou et al. 2000	Literature and monographs	Weighted mean value by area	Actual depth	19.4
Li et al. 2004	Meteorological data and atmospheric CO_2	CEVSA model	1.0	19.1
This study	Field measurement	Calculated profile values	Actual depth	12.4

et al. 2004; Yang et al. 2007). This variation in methods could result in different findings. We expect our estimates to provide a large amount of detailed and reliable experimental data in carbon content and density in Chinese forest soils, although large uncertainties in estimates of forest SOC still exist obviously. More accurate carbon estimates could be improved by use of a large number of sampled forests, as well as by accounting for variations in soil type, soil depth, soil horizon, and their corresponding SOC content.

5 Conclusions

In east China, the forest SOC content and density were 17.5 g C kg^{-1} and 12.4 kg C m^{-2}, respectively. The average SOC densities in the organic horizon and mineral horizon were 5.47 and 6.91 kg C m^{-2}, respectively. The average SOC density in the organic horizon accounted for 44.2 % of the total organic carbon density. The average forest SOC density in north-eastern China and south-eastern China was higher than that of middle-eastern China. SOC density was characterized by high spatial variability in different soil types ranged from 1.43 to 35.0 kg C m^{-2}. The responses of SOC density to environmental factor variables differed among different soil horizons. The importance of influencing controls switched with depth, precipitation, and temperature dominating in the organic horizon and soil texture dominating in the mineral horizon.

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Compliance with ethical standards

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