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Influence of Climate on Soil Organic Carbon in Chinese Paddy Soils

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Abstract: Soil organic carbon (SOC) is a major component of the global carbon cycle and has a potentially large impact on the greenhouse effect. Paddy soils are important agricultural soils worldwide, especially in Asia. Thus, a better understanding of the relationship between SOC of paddy soils and climate variables is crucial to a robust understanding of the potential effect of climate change on the global carbon cycle. A soil profile data set (n = 1490) from the Second National Soil Survey of China conducted from 1979 to 1994 was used to explore the relationships of SOC density with mean annual temperature (MAT) and mean annual precipitation (MAP) in six soil regions and eight paddy soil subgroups. Results showed that SOC density of paddy soils was negatively correlated with MAT and positively correlated with MAP ($P < 0.01$). The relationships of SOC density with MAT and MAP were weak and varied among the six soil regions and eight paddy soil subgroups. A preliminary assessment of the response of SOC in Chinese paddy soils to climate indicated that climate could lead to a 13% SOC loss from paddy soils. Compared to other soil regions, paddy soils in Northern China will potentially more sensitive to climate change over the next several decades. Paddy soils in Middle and Lower Yangtze River Basin could be a potential carbon sink. Reducing the climate impact on paddy soil SOC will mitigate the positive feedback loop between SOC release and global climate change.

Keywords: soil organic carbon; paddy soils; mean annual temperature; mean annual precipitation; climate change

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1 Introduction

Soil is not only the foundation of agricultural productivity, but also a key carbon sink in the terrestrial ecosystem as well as a recorder of climate change. Globally, ~1500 Pg of organic carbon is stored in soils in the form of organic matter, twice as much as that present in the atmosphere and three times as much as that held in terrestrial vegetation (Eswaran *et al*., 1993; Lal *et al*., 1995; Batjes, 1996). Consequently, any slight change in the soil organic carbon (SOC) pool may greatly affect the concentrations of greenhouse gases in the atmosphere and subsequently, global climate change (Routh *et al*., 2014). Therefore, a better understanding of the relationship between SOC and climatic factors is crucial in assessing the potential effect of climate change on the global carbon cycle.

The concentration and turnover rate of SOC are profoundly affected by a range of factors such as climate (Xiong *et al*., 2014), topography (Chen *et al*., 2016a),

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biota (Toriyama *et al.*, 2015), parent material (Wagai *et al.*, 2008), time (Zheng *et al.*, 2016) and land management (Pinheiro *et al.*, 2015; Kibet *et al.*, 2016). Many of these factors are mutually interactive (Sollins *et al.*, 1996). However, it is widely held that climate, particularly temperature and precipitation is the most important factor regulating SOC, because climate dictates crop choice, production methods, and decomposition processes of plant litter (Alvarez and Lavado, 1998). The response of SOC to climate factors has become an increasingly critical research field in soil and environmental sciences (Ganuza and Almendros, 2003; Martin *et al.*, 2010; Wan *et al.*, 2011; Álvaro-Fuentes *et al.*, 2012; Sommer and Bossio, 2014; Muñoz-Rojas *et al.*, 2015). Most research indicates that SOC increases with increasing precipitation and decreasing temperature, and is sensitive to climate change (Hontoria *et al.*, 1999; Lal, 2004), there are, however, conflicting conclusions (Spain, 1990; Homann *et al.*, 1995). Therefore, a consensus has not been established on the relationship between SOC and climate change (Kirschbaum, 2006; Farina *et al.*, 2011). This is partly because these studies cover multiple scales, from single landscapes to global, which affects the correlation between climate and SOC. Wang *et al.* (2010b; 2010c) suggest that the provincial scale is optimal for such research. The sensitivity of SOC to climate change is different in different climatic zones (Ganuza and Almendros, 2003; Lal, 2004). Further reason for discrepancy exists because each study focuses on SOC with different land use types, such as forestland (Toriyama *et al.*, 2015), grassland (Olsson *et al.*, 2014), agriculture land, and multiple land use types (Dai and Huang, 2006; Wang *et al.*, 2012; Wiesmeier *et al.*, 2013). Summarily, though considerable research has explored the relationship between SOC and climate, comparatively few studies have included paddy soils, a considerable pool of SOC. To our knowledge, only Wang *et al.* (2005) examined the relationships of SOC storage with mean annual precipitation (MAP) and mean annual temperature (MAT) using 508 paddy soil profiles from the Second National Soil Survey of China.

Paddy soils are anthropogenic soils with a long history of rice cultivation under irrigated or rain-fed conditions, and a suborder of Anthrosols in Chinese soil taxonomy (Gong, 1999; Shi *et al.*, 2010a). Paddy soil represents a major cultivated soil in China, accounting for 24% of total cultivated land (FAO, 2008). They are extensively distributed in different regions throughout the country and have been divided into different subgroups. Also, paddy soils represent a large portion of global cropland, and may be more promising for sequestering C due to its unique water management requirements (Xu *et al.*, 2011). Therefore, SOC in paddy soils has the potential to change with the climate and can play a critical role in mitigating global warming.

Nonetheless, detailed studies about the effect of climatic factors on SOC in different regions as well as different subgroups of paddy soils in China are lacking, largely due to spatial data gaps or insufficient data density. Therefore, the objectives of this paper are to: 1) identify the relationships between SOC in paddy soils and climatic factors in different regions and different subgroups; and 2) establish the potential effect of climate change on SOC in paddy soils over the next several decades. Results of this research will connect paddy SOC and climate in China, and provide a theoretical basis for model calibration in order to estimate SOC storage more accurately.

2 Materials and Methods

2.1 Study area

China is vast in size, covering about 50 degrees of latitude and 60 degrees of longitude (Fig. 1). It has extensive climatic features. Temperature generally increases from north to south and fall into five climatic zones: cold temperate, mid-temperate, warm-temperate, subtropical and tropical. Similarly, precipitation generally increases from northwest to southeast and falls into four zones: arid, semi-arid, sub-humid and humid. According to the annual accumulated temperature (AAT) in China, five climatic zones are generally divided as follows: cold-temperate zone (<1600℃), mid-temperate zone (1600℃–3400℃), warm-temperate zone (3400℃–4500℃), subtropical zone (4500℃–8000℃), and tropical zone (>8000℃) (Zhang, 1991). In general, most paddy soils are distributed in southern and eastern China with humid and warm climates, where precipitation is plentiful and temperature is high year-round (dense paddy soils for short). By contrast, the others are distributed in vast north areas of China with dry and cold climates (sparse paddy soils for short) (Fig. 1). Therefore, three climatic zones are divided in this study as follows: temperate zone (<4500℃), subtropical zone (4500℃–8000℃), and tropical zone (>8000℃).

Based on the spatial distribution pattern of paddy soils and regionalization map of paddy soils in China reported by Li (1992), paddy soils in this paper are divided into six soil regions: Northern China, Middle and Lower Yangtze River Basin, Southeastern China, Southern China, Southwestern China and Central China (Fig. 1). According to the forming features, diagnostic characteristics and water regimes of paddy soils as well as ferric oxide alteration and distribution in soil profile, paddy soils are classified into eight soil subgroups referring to the World Reference Base for Soil Resources (WRB) system (IUSS Working Group WRB, 2007; Shi *et al.*, 2010b): hydromorphic (hydragric anthrosols); submergenic (hydragric anthrosols); percogenic (hydragric anthrosols); gleyed (gleyic-hydragric anthrosols); degleyed (gleyic-hydragric anthrosols); bleached (hydragric anthrosols); salinized (hydragric anthrosols) and acid sulfate (fluvic cambisols).

2.2 Data sources

Soil attribute data of paddy soil profiles (n = 1490) were obtained from the Second National Soil Survey of China conducted from 1979 to 1994. Of these profiles, 525 were from the Soil Species of China published in a series of monographs (National Soil Survey Office, 1996). The remaining profiles were from Soil Species published by various individual provinces. The soil attribute database includes profile location, terrain position, elevation, soil type, soil depth, bulk density, particle size distribution, soil organic carbon, and other physicochemical soil properties. The soil spatial database was digitized from the 1∶1 000 000 Soil Map of the People's Republic of China (Office for the Second National Soil Survey of China, 1995). Further, a more detailed 1∶1 000 000 paddy soil database of China was developed by linking the soil attribute database with the soil spatial database using a Pedological Knowledge-Based (PKB) approach (Zhao *et al.*, 2006). Presently, this is the most accurate and reliable database for paddy soils in China (Shi *et al.*, 2006a; 2006b).

Climate data in China were provided by the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences. The spatial resolution of all climatic grid maps is 1 km × 1 km. The climate database includes AAT, MAT, MAP, mean monthly temperature (MMT), and mean monthly precipitation (MMP). Also, AAT, MAT and MAP of all soil profile locations were extracted from the corresponding grid climate data layer. Here, AAT refers to the annual accumulated temperature during the growing season of thermophilic crops (e.g., the mean daily air temperature

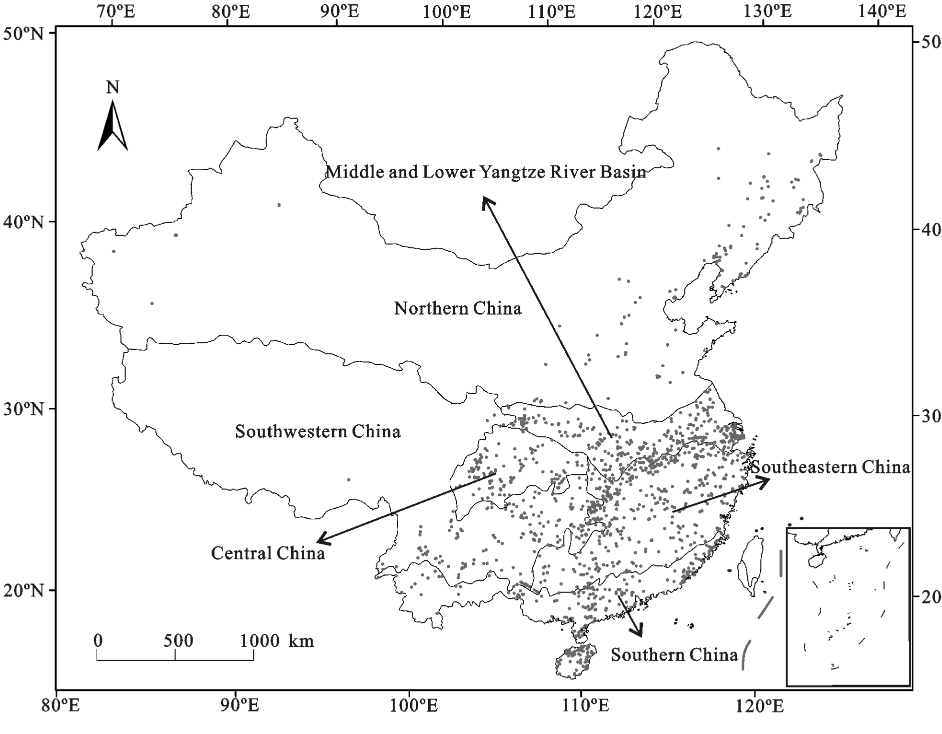

Fig. 1 Distribution of soil profile sites of paddy soils in China (Li, 1992)

≥10℃), which is a main index for determining climatic zones in China.

2.3 SOC density and SOC storage calculation

The SOC density of each profile was calculated according to Equation (1) (Liu *et al*., 2006):

$$SOCD = \sum_{i=1}^{n}(1-\theta_i)\times\rho_i\times C_i\times T_i / 10 \quad (1)$$

where *SOCD* is soil organic carbon density of a profile (t C/ha); θ_i is gravel (≥ 2 mm) content in horizon *i* (%); ρ_i is the soil bulk density of horizon *i* (g/cm^3); C_i is SOC content of horizon *i* (g C/kg); T_i is the thickness of horizon *i* (cm); and *n* is the number of horizons of the profile. SOC contents were analyzed by using the Walkley and Black method (Page *et al*., 1982). All parameter results were obtained from the soil attribute database. The SOC density in Chinese paddy soils was estimated by the mean value based on sampling at depths of 0–20 cm and 0–100 cm. SOC storage for each polygon in the map was calculated by multiplying SOC density by the surface area of the polygon. SOC storage within each region was calculated by summing the SOC storage of all polygons in the corresponding region.

2.4 Statistical analysis

SPSS software 20.0 was used for the statistical analyses (SPSS Inc. Chicago, IL, USA). Coefficient of variation (CV) was calculated as the ratio of the standard deviation to the mean to describe the dispersion of SOC density and climate factors. One-way analysis of variance (ANOVA) was performed to determine the effects of different climatic zones on SOC density. Partial correlation analysis was performed to analyze correlations of SOC density with MAT and MAP due to significant relationships between MAT and MAP (r = 0.72; P < 0.001). Multiple linear regression (stepwise) was used to find the best predictive models for SOC density across the whole country and the six individual regions of China. Since SOC density in Chinese paddy soil was not normally distributed (Table 1, those for SOC density in six soil regions and eight paddy soil subgroups are not shown), it was log-transformed when statistical analysis was applied. Thus, all values are nearly normally distributed and meet the requirement of correlation and multiple linear regression analysis.

3 Results

3.1 Variability of SOC density and climate factors

SOC density ranged from 1.70 t C/ha to 553.80 t C/ha and from 5.30 t C/ha to 4462.50 t C/ha in the topsoil (0–20 cm) and total soil profile (0–100 cm), respectively, with a mean of 39.07 t C/ha and 133.47 t C/ha (Table 1). SOC density variability was high for both topsoil and soil profile layers and the CV reached 69.30% and 136.14%, respectively. All climate factors had a relatively moderate CV of >20%.

For the topsoil data, SOC density of paddy soils in the temperate zone was the highest, followed by that in the subtropical zone (Fig. 2). SOC density in the tropical zone was the lowest. There was no significant difference in SOC density between the subtropical and tropical zones (P > 0.05). The same trend was found for the total profiles.

3.2 Relationships between SOC density and climate factors in Chinese paddy soils

In general, SOC density was negatively correlated with

Table 1 Classical statistical analysis for properties of paddy SOC density and climate factors in China

Variable	SOC density (0–20 cm) (t C/ha)	SOC density (0–100 cm) (t C/ha)	MAT (℃)	MAP (mm)	AAT (℃)
Minimum	1.70	5.30	2.61	34.58	2154.97
Maximum	553.80	4462.50	25.30	2602.50	9244.42
Mean±SD	39.07±27.08	133.47±181.07	16.59±3.72	1289.87±349.92	5693.45±1366.11

Variable	SOC density (0–20 cm) (t C/ha)	SOC density (0–100 cm) (t C/ha)	MAT (℃)	MAP (mm)	AAT (℃)
CV (%)	69.30	136.14	22.41	27.13	23.99
Skewness	9.24	13.45	–0.56	–0.29	0.61
Kurtosis	146.36	261.51	2.00	0.28	0.15

Notes: SD, standard deviation; CV, coefficient of variation; MAT, mean annual temperature; MAP, mean annual precipitation; AAT, annual accumulated temperature

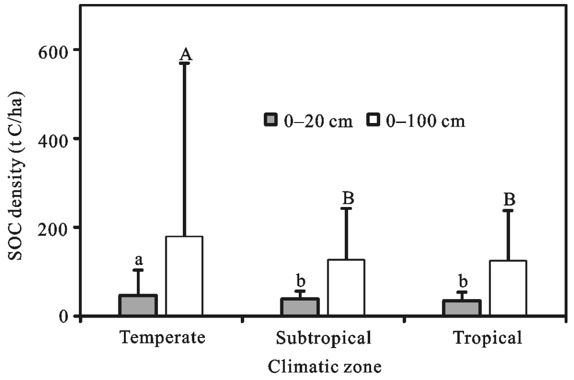

Fig. 2 SOC density of paddy soils in different climatic zones in China. Columns with the same lowercase letter are not significantly different at P = 0.05 among different climatic zones for SOC density in 0–20 cm depth, columns with the same capital letter are not significantly different at P = 0.05 among different climatic zones for SOC density in 0–100 cm depth

MAT and positively correlated with MAP across the whole country (P < 0.01) (Table 2). Also, the correlation between SOC density and MAT or MAP in the topsoil was slightly higher than that of the entire profile. Further, the relationship between SOC density and MAT or MAP varied with different climatic zones. In the subtropical zone, SOC density was negatively correlated with MAT and positively correlated with MAP at both depths (P < 0.01). In the temperate zone, SOC density was negatively correlated with MAT only in the topsoil (P < 0.01). In the tropical zone, there was no significant relationship between SOC density and MAT or MAP at both depths (P > 0.05).

3.3 Relationships between SOC density and climate factors in six soil regions

For the topsoil, SOC density of paddy soils in both Northern China and Central China was negatively correlated with MAT only (P < 0.05) (Table 3). Additionally, there were significant relationships between SOC density of paddy soils and both MAT and MAP in Southern China and Southwestern China (P < 0.05). No evidence supported the impact of climate on SOC density of paddy soils in Southeastern China. Although similar relationships between SOC density and MAT or MAP were found at a depth of 0–100 cm, two exceptions were found in Southern China and Central China: SOC density was positively correlated with MAP only in Southern China (P < 0.05) and SOC density in Central China was not affected by temperature and precipitation.

3.4 Relationship between SOC density and climate factors in eight paddy soil subgroups

The partial correlation coefficients between SOC density

Table 2 Partial correlation analysis of SOC density with MAT and MAP across all of China and in different climatic zones

Zone	Number of profiles	0–20 cm		0–100 cm	
		r_{MAT}†	r_{MAP}††	r_{MAT}†	r_{MAP}††
Whole country	1490	–0.214**	0.140**	–0.158**	0.132**
Temperate	116	–0.347**	0.020	–0.306**	0.035
Subtropical	1248	–0.141**	0.135**	–0.125**	0.108**
Tropical	126	–0.158	0.136	–0.172	0.161

Notes: † is the partial correlation coefficient between SOC density and MAT; †† is the partial correlation coefficient between SOC density and MAP;** Significant at P < 0.01

Table 3 Partial correlation analysis of SOC density with MAT and MAP in six soil regions in China

Region	Number of profiles	0–20 cm		0–100 cm	
		r_{MAT}	r_{MAP}	r_{MAT}	r_{MAP}
Southern China	269	–0.202***	0.180**	–0.092	0.122*
Southeastern China	467	–0.020	0.049	–0.034	0.025
Middle and Lower Yangtze River Basin	335	–0.038	0.174**	–0.082	0.149**
Central China	129	–0.222*	0.064	–0.161	0.002
Northern China	118	–0.352***	0.009	–0.315***	0.037
Southwestern China	172	–0.250**	0.226*	–0.229**	0.169*

Notes: *** Significant at P < 0.001; ** Significant at P < 0.01; * Significant at P < 0.05

and MAT or MAP at both depths varied greatly among eight paddy soil subgroups (Table 4). For the topsoil, SOC densities in the hydromorphic, submergenic and degleyed subgroups were negatively correlated with MAT and positively correlated with MAP ($P < 0.05$), while SOC density in the gleyed subgroup was negatively correlated with MAT, and there was a positive correlation between SOC density in the salinized subgroup and MAT ($P < 0.05$). MAT and MAP did not affect SOC density in the percogenic, bleached and acid sulfate subgroups. Similar patterns were observed at the 0–100 cm depth. Two exceptions were found in the submergenic and bleached subgroups: SOC density in these two subgroups was negatively correlated with MAT only ($P< 0.05$).

4 Discussion

4.1 Effect of climate factors on SOC density in Chinese paddy soils

SOC density in topsoil is somewhat more sensitive to climate change than the entire profile. This is the case in almost all soil profiles we analyzed. For the 0–100 cm depth, SOC density in the subtropical and tropical paddy soils was about two thirds of that in the temperate paddy soils. At the 0–20 cm depth, SOC density in both subtropical and tropical paddy soils appeared to be three quarters or more of that in the temperate paddy soils. The influence of climate factors on SOC density differed in three climatic zones. It is well known that SOC density is the result of the long-term net balance between loss and accumulation of SOC. Crop rotation systems were different in Chinese paddy soils of different climatic zones. Crop biomass varied due to the difference of temperature and precipitation within climatic zones. Thus, the recycling ratio of crop biomass and the type of crop residues had an impact on the SOC dynamics attributed to different C inputs (Haque *et al.*, 2015; Hok *et al.*, 2015; Chen *et al.*, 2016b). Besides, SOC density is intimately associated with soil respiration influenced by temperature and moisture (Kruse *et al.*, 2013; Brye *et al.*, 2016). Temperature sensitivity of soil respiration (usually measured by Q10) varies among vegetation types (Zheng *et al.*, 2009; Zeng *et al.*, 2014). The impact of temperature on SOC density in the temperate zone was a little stronger than that in the subtropical and tropical regions. This may be attributed to the increase temperature sensitivity of soil respiration in cold regions (Bradford *et al.*, 2008), which are more vulnerable to global warming. Compared to the impact of MAT on SOC density, the correlation between SOC density and MAP in different climatic zones is relatively weaker, most likely due to artificial and deliberate flooding for long period. This likely weakened the effect of MAP on SOC density of paddy soils.

The relationship between SOC density and MAT or MAP varies with soil regions. Compared to other regions, SOC density of paddy soils in Northern China (temperate zone) was the most sensitive to MAT. This is consistent with previous results (Wang *et al.*, 2005). Studies have shown that the decline in the SOC pool with projected climate change might be especially severe in boreal, tundra and polar regions compared to the mid-latitudes (Lal, 2004). Xu and Pan (2005) reported that organic carbon of paddy soils in temperature zone in China was more sensitive to global warming than other zones. Wang *et al.* (2013) concluded that with decreasing temperature, the climate effect on SOC content

Table 4 Partial correlation analysis of SOC density with MAT and MAP in eight paddy soil subgroups in China

Soil subgroup	Number of profiles	0–20 cm		0–100 cm	
		r_{MAT}	r_{MAP}	r_{MAT}	r_{MAP}
Hydromorphic	576	-0.147^{***}	0.191^{***}	-0.144^{***}	0.161^{***}
Submergenic	344	-0.374^{***}	0.170^{**}	-0.231^{***}	0.046
Percogenic	174	–0.103	0.058	–0.043	0.019
Gleyed	236	-0.263^{***}	0.084	-0.210^{***}	0.157
Degleyed	56	-0.358^{**}	0.310^{*}	-0.325^{*}	0.248^{*}
Bleached	57	–0.236	0.133	-0.356^{**}	0.193
Salinized	36	0.352^{*}	–0.334	0.218^{*}	–0.193
Acid sulfate	11	–0.034	0.024	–0.001	0.164

Notes: *** Significant at $P < 0.001$; ** Significant at $P < 0.01$; * Significant at $P < 0.05$

in dry cropland increased. The reason that SOC density has no significant correlation with climate factors in Southeastern China might be due to the low variability of MAT and MAP in this region. Therefore, due to the regional differences in the relationship between SOC density and climate factors, a region-specific model should be more accurate for predicting the changes in soil C storage in response to climate change (Wang *et al*., 2013; He *et al*., 2014).

Investigating the effect of climate factors on SOC density of paddy soils at the regional scale is more robust than that at the national scale. In this regard, our findings differed from previous studies. For example, the provincial scale was found to be optimal for studying the relationship between climate factors and SOC density in the uplands of Northeast China (Wang *et al*., 2010b; 2010c). These studies were conducted on upland soils and included more diverse soil types with 17 great groups from seven orders, while the paddy soils in our study only included one soil suborder. There were many kinds of crops in the upland soils in contrast with that in the paddy soils. Space heterogeneity in the upland soils was higher compared with that in the paddy soils at the same scale. Variability of SOC density was 20% lower at the national scale in Chinese paddy soils than that at regional scale in the upland soils of Northeast China (Wang *et al*., 2010a). Thus, the regional scale is suitable for exploring the relationship between climate and SOC density in the paddy soils considering the larger number of soil samples and less heterogeneity compared with the provincial and regional scale in the upland soils of Northeast China.

The correlations between SOC density and climate factors were also different among soil subgroups. The hydromorphic and degleyed subgroups are typically redox paddy soils with well-established diagnostic horizons. Frequent redox reaction in soils are most likely affected by MAT and MAP or their interaction driven by climate change (Pan *et al*., 2003), whereas the submergenic subgroup is located on highlands or sloped lands and thus not as easily flooded by water and more affected by temperature and precipitation. It is noteworthy that SOC density in the gleyed and salinized subgroups was affected only by MAT. The gleyed subgroup flooded by irrigation water for long periods obscured the effect of MAP on SOC density. As for the salinized subgroup, salt concentrations in soil solution is concentrated due to increased evapotranspiration induced by the increase of temperature. High salt concentrations inhibit rice growth and thus reduced the amount of organic carbon inputs to the soil.

4.2 Future response of SOC density in Chinese paddy soils to climate change

The response of the SOC pool to global climate change has been widely studied in recent years (Martin *et al*., 2010; Álvaro-Fuentes *et al*., 2012; Longbottom *et al*., 2014; Lassaletta and Aguilera, 2015; Wang *et al*., 2016). Therefore, a preliminary predictive model of SOC density at a depth of 0–20 cm vs. climate variables in Chinese paddy soils were obtained using multiple linear regression (Table 5). However, the potential effects of climate change on SOC density may be of limited value because MAT and MAP can only explain about 5.3% of the SOC density variability at a national scale. Moreover, the climate change effect on SOC density varied across the six soil regions evaluated. Adjusted R^2 in Northern China was highest (25%), followed by Southern China (9.8%), Central China (7.8%), Southwestern China (6.3%) and Middle and Lower Yangtze River Basin (3.9%).

It has been estimated that MAT would increase 3.9–6.0℃ and MAP would increase 11%–17% from 1980 to 2080 in China (http://www.ipcc.cma.gov.cn/cn/). Although uneven changes in temperature and precipitation could take place in various soil regions of China, a homogeneous climate change scenario with the same crop choice and similar management practices are assumed in order to illustrate and compare the potential magnitude of the changes in SOC storage in different regions (Table 5). If the relationship between SOC and climate factors holds, in 100 years under the aforementioned assumption, climate change could lead to a 13% loss of SOC storage from paddy soils in China. In terms of SOC storage change in six soil regions, SOC loss induced by climate change in Northern China would be the highest (39%). Therefore, paddy soils in Northern China would still be the most sensitive to climate change over the next 100 years. It has been noted that climate change could result in a 9.8 % increase in SOC storage in Middle and Lower Yangtze River Basin, indicating that paddy soils in this region could be a potential future sink. Similar results were found by Wang *et al*. (2016). In addition, SOC density in Southeastern

Table 5 Multiple regression models of Log SOCD vs. MAT and MAP and rough estimates of SOC storage change from 1980 to 2080

Region	Number of profiles	Area (10^6 ha)	Regression model	Adjusted R^2	MAT change (℃)	MAP change (%)	Total change of C storage (%)	Change of C storage (%/yr)
Whole country	1490	45.69	$\text{Log}\ SOCD = 1.638 - 1.83 \times 10^{-2}\ MAT + 1.59 \times 10^{-4}\ MAP$	0.053	+4.9(3.9–6.0)	+14(11–17)	–13.0	–0.130
Southern China	269	7.27	$\text{Log}\ SOCD = 1.933 - 3.74 \times 10^{-2}\ MAT + 2.026 \times 10^{-4}\ MAP$	0.098	+4.9(3.9–6.0)	+14(11–17)	–29.0	–0.290
Southeastern China	467	14.70	/	/	/	/	/	/
Middle and Lower Yangtze River Basin	335	12.54	$\text{Log}\ SOCD = 1.258 + 2.257 \times 10^{-4}\ MAP$	0.039	/	+14(11–17)	+9.8	+0.098
Central China	129	5.16	$\text{Log}\ SOCD = 2.047 - 3.46 \times 10^{-2}\ MAT$	0.078	+4.9(3.9–6.0)	/	–32.0	–0.320
Northern China	118	2.34	$\text{Log}\ SOCD = 1.915 - 4.41 \times 10^{-2}\ MAT$	0.250	+4.9(3.9–6.0)	/	–39.0	–0.390
Southwestern China	172	3.69	$\text{Log}\ SOCD = 2.103 - 2.94 \times 10^{-2}\ MAT$	0.063	+4.9(3.9–6.0)	/	–28.0	–0.280

China would not be affected by climate factors, which means that the decrease in SOC due to global climate change would generally be smaller for the paddy soils in that region.

4.3 Uncertainty and future studies

The correlations between SOC density and climate variables in Chinese paddy soils varied among soil regions and subgroups, but the correlations were week. Furthermore, there was no significant correlation for the southeastern region where land has been used as rice for thousands of years. These correlations may be an indicator of soil development. Paddy soils, as a unique type of anthropogenic soil, developed over a 7000-year history of rice cultivation. Therefore, climate factors had a generally low influence and were not main controlling factors of SOC density variations in Chinese paddy soils. Other factors, especially human activities, should be taken into account when explaining SOC variations. For example, Fantappiè *et al*. (2011) concluded that changes in land management and land use are the main factors affecting SOC content in Italy. Also, some studies indicated that tillage management is a more important factor in SOC changes than climate change (Thomson *et al*., 2006). So, future studies should focus on the influence of human management activities on SOC in Chinese paddy soils, such as the cropping systems, fertilizer application, irrigation, tillage, etc. Weak climate impact on SOC density in Chinese paddy soils will help to slow down the positive feedback loop between SOC release and global warming.

Influence of climate on SOC is site specific and scale dependent. In contrast, no optimal scale was detected in this study, which was conducted at only two scales (regional and national). Although the studies by Wang *et al*. (2010b; 2010c) indicated an optimal scale, Qin *et al*. (2016) conducted an intensive study on the relationship between climate factors and SOC at multiple scales and concluded that there is a minimum scale level for detecting the influence of climate factors on SOC and the minimum scale level for MAT and MAP is different. Moreover, the relationships among temperature, precipitation and soil respiration have not been consistent (Hamdi *et al*., 2011; Brye *et al*., 2016). Therefore, further study of climate factors on SOC in the paddy soils should be conducted not only at multiple macro scales but also at a micro scale.

Our findings only present a preliminary projection of the response of organic carbon in Chinese paddy soils to climate change because of multiple uncertainties. Our research was based on assumption of a homogeneous climate change scenario, the same crop choice and similar management practices. Obviously, changes in management, crop genetics, cropping systems and land use are expected to occur in the next several decades, especially if climate change predictions are realized (IPCC, 2007). However, possible management and land use changes over the next 80 years were not considered. Another possible uncertainty source could be attributable to climate scenarios (Álvaro-Fuentes *et al*., 2012). In addition, the CO_2 fertilization effect on vegetation was not considered, but this could partially compensate for SOC losses by increasing net primary productivity (Melillo *et al*., 1993). Furthermore, a simplified approach has been applied in this study. Statistical techniques alone do not explain the complex mechanisms within the soil system (Muñoz-Rojas *et al*., 2015). However, simple correlation and regression analysis in this study have identified basic trends in SOC pool responses to climate change. More effective data mining technology will further improve the research in this area.

5 Conclusions

The relationships between SOC density and climatic factors in Chinese paddy soils varied greatly across six soil regions and eight paddy soil subgroups in China. Due to long periods of artificial and deliberate flooding, the effect of MAP on SOC density was relatively weaker than that of MAT except for Middle and Lower Yangtze River Basin and Hydromorphic subgroup. The SOC density of paddy soils in Northern China (temperate zone) is more sensitive to MAT than other regions. The regional scale is suitable for studying the relationship between climate and SOC density in Chinese paddy soils. Soil organic carbon density in the hydromorphic, degleyed and submergenic subgroups were well correlated with both MAT and MAP, while for gleyed and salinized subgroups, SOC density were only correlated with MAT. Therefore, both soil regions and soil subgroups should be considered when exploring the relationships between climate factors and SOC density in Chinese paddy soils.

A preliminary look at the potential impact of climate change on SOC density in Chinese paddy soils over the next several decades was investigated in this study and empirical models were established. Climate change could lead to a 13% loss of SOC storage from paddy soils in China. Compared to other regions, paddy soils in Northern China were more sensitive to climate change. In addition, paddy soils in Middle and Lower Yangtze River Basin will be a potential sink in the future. However, weak climate impacts on SOC will help to slow down the positive feedback loop between SOC release and global climate change.

Further work should be conducted to evaluate other factors, especially agricultural management practices, and more robust data mining technology at different scales, to better understand the main controlling factors of SOC density in Chinese paddy soils.

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