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Relation of soil organic matter concentration to climate and altitude in zonal soils of China

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Abstract

With a total of 886 data sets distributed in different regions of China, the relation of soil organic matter (SOM) concentration to climate and altitude was investigated. These data sets were obtained from the 2nd National Soil Survey of China that was completed in early 1980s. According to climate gradient and vegetation community succession, six geographical regions, including eastern, southern, northern, northeastern, northwestern and southwestern China, were divided to identify the key factors regulating surface SOM concentration in different geographical regions. Correlation analysis indicates that surface SOM concentration is in general negatively correlated with annual mean temperature (T) and positively correlated with annual mean precipitation (P) and altitude (H). A further investigation suggested that multiple regression models with different combination of T, P and H could explain 41.5%–56.2% of the variability in surface SOM concentration for different geographical regions, while the driving variables are different. Variables of T and P determined surface SOM concentration in northern, northeastern and northwestern China. In eastern and southern China, variables of P and H are key factors regulating surface SOM concentration. Surface SOM concentration in southwestern China is determined by a linear combination of T, P and H.

Keywords: Soil organic matter; Climate; Altitude; Zonal soil; Regression model; China

1. Introduction

Soil organic matter (SOM) is a major component of global carbon cycle (Schlesinger, 1997). As the largest pool of terrestrial organic carbon, the global soil organic carbon pool is estimated to be 1500~1600 Pg (Post et al., 1982; Eswaran et al., 1993; Batjes, 1996; Amundson, 2001), which is roughly equivalent to the sum of the atmospheric pool of 750 Pg and the biotic pool of 600 Pg (Schimel, 1995; Houghton, 1995). SOM can act both as a sink and a source of carbon in response to climate, land use changes, and to the rising atmospheric CO_2 levels (Jobbágy and Jackson, 2000; Kirschbaum, 2000). Small changes of SOM may influence long-term ecosystem sustainability, the global carbon budget and the atmospheric CO_2 concentration (Amundson, 2001). It is therefore crucial to ascertain the relation of regional SOM concentration to climatic variables and other native parameters in order to further assess the possible impact of climate change on the global carbon cycle (Post et al., 1996; Ringrose et al., 1998).

The concentration and turnover rate of SOM are influenced by a large number of soil-forming factors, such as climate (Alvarez and Lavado, 1998; Ganuza and Almendros, 2003), topography (Burke, 1999; Raghubanshi, 1992), vegetation (Finzi et al., 1998), parent material (Spain, 1990) and chronosequence (Schlesinger, 1990) and management (Yang and Wander, 1999). Many of these factors are mutually interactive (Sollins et al., 1996). It is generally recognized that climate, especially temperature and precipitation, is the most important factor regulating SOM (Jenny, 1980; Sims and Nielsen, 1986; Homann et al., 1995; Alvarez

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and Lavado, 1998), as it determines to a great extent the vegetation cover, the quantity and quality of the organic residues inputting the soil, the rate of SOM mineralization and litter decomposition, and hence the turnover of SOM (Schimel et al., 1994; Garten et al., 1999; Hontoria et al., 1999; Quideau et al., 2001; Heviaa et al., 2003). Dokuchaev (1899) demonstrated that soil distribution could be characterized by latitudinal and vertical zonality which was basically consistent with climate and vegetation zonality in Russian Chernozem (after Kovda, 1981). Jenny et al. (1949) related the decomposition of organic matter to climatic parameters in continental of America. Turner and Lambert (2000) found that the native SOM levels are associated with the dynamic balance of C inputs and C losses under native eco-climatic conditions. Until now, quantitative relationships between SOM and temperature and precipitation have been recognized on small scales (Callesen et al., 2003; Powers and Schlesinger, 2002). Generally, SOM increases with precipitation and decreases with temperature (Jenny, 1980; Burke et al., 1989; Grigal and Ohmann, 1992; Hontoria et al., 1999; Percival et al., 2000; Ganuza and Almendros, 2003; Lemenih and Itanna, 2004). Alvarez and Lavado (1998) also reported that SOM content in the top 0–50 cm soil layer is positively correlated with the precipitation/temperature ratio in the Pampa and Chaco soils in Argentina. However, the relationship of SOM and climatic variables at a relative large scale is weaker, which makes it difficult to predict changes in SOM as a function of projected climate change on a continental scale (Kern et al., 1998). To quantitatively evaluate the potential influence of climate change on SOM at a regional and/or global scale, it is essential to identify the key climatic factors regulating SOM, and to develop relationships between these key factors and SOM across different land scale and different regions.

Altitude is often employed to study the effects of climatic variables on SOM dynamics (Townsend et al., 1995; Trumbore et al., 1996; Garten et al., 1999, Lemenih and Itanna, 2004). Generally, temperature decreased and precipitation increased with increasing altitude. The changes in climate along altitudinal gradients influence the composition and productivity of vegetation and, consequently, affect the quantity and turnover of SOM (Garten et al., 1999; Hontoria et al., 1999; Quideau et al., 2001). Altitude also influences SOM by controlling soil water balance, soil erosion and geologic deposition processes (Tan et al., 2004). Garten et al. (1999) emphasized the advantages of altitude gradients in forest soil for testing the effects of environmental variables on SOM dynamics. The relationship between SOM and altitude has also been investigated and positive correlations were reported (Sims and Nielsen, 1986; Tate, 1992).

China is an important developing country with extensive land area, complex eco-climate zones and a long cultivated history. Total organic carbon storage in Chinese soils was estimated ranging from 50 to 200 Pg (Wang et al., 2000; Ni, 2001; Pan et al., 2003; Wu et al., 2003), accounting for 6.73% of the global soil organic carbon pool (Wang et al., 2000). In China, soil-formation factors (climate, parent material, topography, vegetation, time and human activities) are very complex and vary significantly, so that formed regionally multifarious soil types. The distribution of many soil types, so-called zonal soils, shows an obvious zonality along the climate gradient and vegetation community succession in China (State Soil Survey Service of China (SSSSC), 1998). However, few studies have been dedicated to quantifying the relationship between SOM and climate and altitude on a regional scale of China. The objectives of this paper are to identify the dominant variables regulating SOM in different geographical regions and to further quantify the relationship between SOM concentration and climate and altitude.

2. Materials and methods

2.1. Study area

China is located in the east of Eurasia, and the west coast of Pacific Ocean. It extended approximately 5500 km from south to north, and 6000 km from east to west. From Tibetan Plateau in the southwest to coast plain in the east, topography is characterized by an obvious ladderlike, higher in the west and lower in the east. It has a typical Indian monsoon climate, with dry winters and springs following rainy summers and autumns. Most of the rainfall is concomitant with warm temperature. Along the decreasing temperature from south to north, it falls into five climate zones, including tropical, subtropical, warm temperate, temperate and cold temperate. Along the decreasing precipitation from southeast to northwest, it falls into four eco-climate zones, including humid, sub-humid, semiarid and arid. In light of the Köppen–Geiger climate classification system, China covers five major climate zones including tropical–rainy, dry, warm–temperate rainy, sub-arctic (boreal) and ice–snow climate (Fig. 1) (Domrös and Peng, 1988). According to natural geographical location, climate gradient and vegetation community succession, China is divided into six geographical regions, i.e. eastern, southern, northern, northeastern, northwestern and southwestern China (Fig. 1).

2.2. Data source and selection

The soils in China are classified into 12 soil orders. The distribution of soil types has an obvious horizontal zonality coincident with eco-climate zones and vertical zonality along the mountains (State Soil Survey Service of China (SSSSC), 1998). The data used in this study are taken from the 2nd State Soil Survey of China (i.e., the last survey of Chinese soils) completed in the early 1980s. In order to better understand the relationships of SOM to climatic

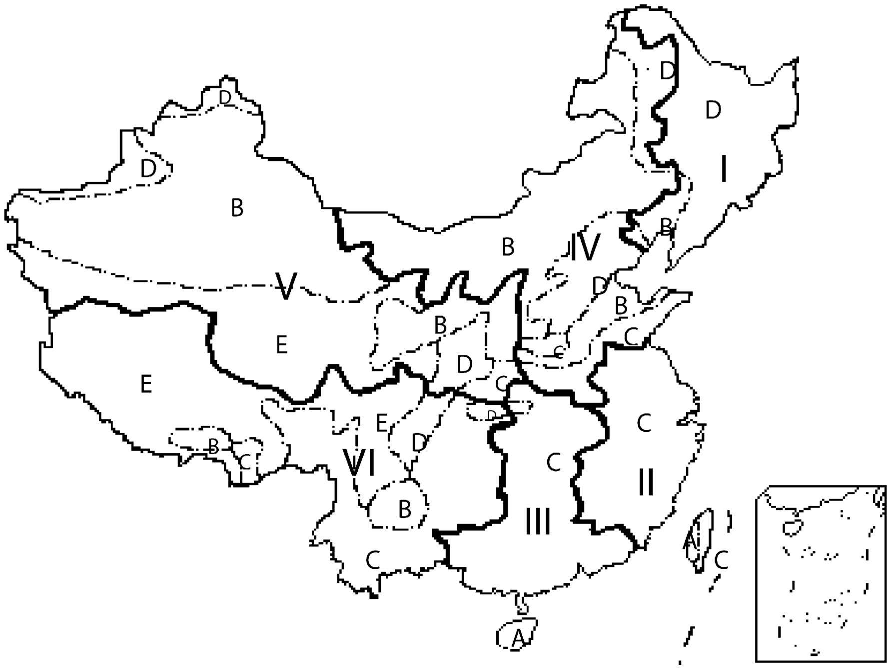

Fig. 1. The Geographical regions and the Köppen–Geiger climate zones in China. The symbol of geographical regions: I: northeastern China, II: eastern China, III: southern China, IV: northern China, V: northwestern China, VI: southwestern China. The symbol of Köppen–Geiger regions: A: tropical–rainy climate, B: dry climate, C: warm–temperate rainy climate, D: subarctic (boreal) climate, E: ice–snow climate (Domrös and Peng, 1988).

variables and altitude, 886 taxonomically recognized typical zonal soil series profiles were selected. Formation process, geographical distribution and principal properties of these soil series were mainly controlled by climate and vegetation regimes along horizontal and vertical dimension. These soils were classified into seven orders of ferro-allitic, eluvial, semi-eluvial, caliche, arid, desert and alpine soil in the 2nd State Soil Survey of China (State Soil Survey Service of China (SSSSC), 1998). Other soil orders classified by the State Soil Survey Service of China, which genetic process was mainly controlled by human's activities (such as paddy soil, organic soil, etc.) and its distribution presented an azonal phenomenon, are excluded in this study. Among the selected soil profiles, some were cultivated and some were not cultivated. Percentage of the cultivated soil profiles is showed in Table 1. The data sets of SOM concentration in surface soil (taxonomic A horizon, not including plowpan, Ap, in cultivated soils), annual mean temperature, annual mean precipitation and altitude of sites that typical soil series profile located were obtained from a series book of monographs in the China Soil Series Vols. 1–6 (SSSSC, 1993, 1994a,b, 1995a,b, 1996). At each typical zonal soil series profile, soil samples of A horizon were taken with soil sample tube from at lest five cores within taxonomic A horizon and mixed. SOM of soil samples was determined by using Walkley–Black procedure (SSSSC, 1998), and the mean SOM concentration in soils of A horizon was used in this study. Table 1 shows the statistical characteristics of all 886 soil profiles and their distribution in six geographical regions of China. Because most of SOM are accumulated in the surface soil and because the bulk density of selected soil profiles is not completely available in the books of China Soil Series, we paid our attention to the SOM concentration of surface soils instead of surface SOM pool.

Table 1
Basic characteristics of typical zonal soils in whole country and six geographical regions of China

Regions	Numbers of soil profiles	Percentage of cultivated soil profiles (%)	Depth of surface soil (A horizon) (cm)			Annual mean temperature (°C)			Annual mean precipitation (mm)			Altitude (m)		
			Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.	Min.	Median	Max.
Whole country	886	48.5	3	18	46	−5.5	8.0	25.5	33	639	3000	10	650	5000
Northeastern China	199	57.8	5	18	44	−5.5	4.7	10.2	278	555	1100	20	240	1110
Eastern China	86	37.2	4	14	35	10.0	16.5	21.3	869	1451	2500	12	160	1910
Southern China	113	31.0	6	17	40	1.0	17.4	25.5	789	1522	2670	10	240	2800
Northern China	175	56.0	3	20	46	−2.0	6.5	15.3	175	460	1250	15	850	2870
Northwestern China	216	47.7	3	18	37	−5.0	6.0	15.6	33	450	1100	360	1800	4640
Southwestern China	97	52.6	3	16	28	−5.0	13.6	22.0	493	1027	3000	192	1500	5000

2.3. Data analysis

One-way analysis of variance (ANOVA) and Fisher's Least Significant Difference (LSD) was used to test the significance of geometric means of SOM concentration at 0.05 probability level. Simple correlation analysis was used to quantify the relationship between SOM concentrations and mean annual precipitation, mean annual temperature and altitude. Partial correlation analysis was applied to identify the effects of temperature, precipitation and altitude on SOM concentration. Linear multiple regression (forward stepwise) was used to find the best predictive models for SOM in the whole country and in six geographical regions of China. All the statistical analysis was performed with the SPSS software 12.0.

3. Results and discussion

3.1. SOM concentration and the distribution in different geographical regions

The statistical parameters and variations of surface SOM concentration of 886 typical zonal soil series in whole country and of typical zonal soil series in six geographical regions are listed in Table 2. The surface SOM concentration in whole country ranges from 1.3 to 241.0 g kg^{-1}, with an arithmetic mean of 32.3 g kg^{-1}, indicating a wide variability of SOM concentration in A horizon of zonal soils. Using the logarithmically transformed data sets, the geometric mean of surface SOM concentration is 22.9 g kg^{-1} for whole country, close to the median value of 21.8 g kg^{-1}. Approximately 66% of soil samples have surface SOM concentrations ranging from 10.4 to 52.6 g kg^{-1}, while 95% of the samples have surface SOM concentrations ranging from 5.1 to 117.0 g kg^{-1}. Therefore, the geometric mean is recommended as representative mean value of SOM concentration due to its lognormal feature, while the arithmetic mean should be discarded (McGrath and Zhang, 2003).

Quantities and composition of SOM are attributed to several natural factors that control soil formation, such as climate, vegetation, topography, parent material and time (Jenny, 1980). In cultivated soil and some uncultivated soils, human activities and management also affect SOM concentration greatly. Integrated effect of these natural factors and human activities on soils makes the quantities of SOM maintain a steady dynamic balance in each giving eco-climatic zone. As shown in Table 2, surface SOM concentration of zonal soils in six geographical regions of China is quite different. The soils in northern and northwestern China have the lowest SOM concentrations with geometric mean of 18.4 and 19.5 g kg^{-1}, respectively. It might be attributed to the semiarid and arid climate as well as the severe disturbance by humans, particularly in northwestern China where annual precipitation was very low and concentrated in a short time period. The vegetation in northwestern China is relatively sparse and the cultivation is aggressive (such as steep slope cropping system) which induced severe soil erosion and degradation. As a result, SOM in the surface layer has a lower concentration (Wang et al., 2000). In comparison with the SOM in northwestern China, SOM in southwestern China has the highest concentrations with a geometric mean of 40.4 g kg^{-1}, and that in northeastern China has a relative higher concentration with a geometric mean of 25.7 g kg^{-1}, which might be attributed to the humid and cooler climate and the good vegetation coverage. Surface SOM concentrations in eastern and southern China were in middle comparing to other regions (Table 2). A possible explanation is that eastern and southern China are located in humid and warmer climate zones where vegetation grows fast with a higher net primary production, and thus higher litter volumes inputting into the soil than other regions. Nevertheless, native SOM transformation and litter decomposition by active soil microorganism in this climatic–ecological system are also faster. Consequently, SOM concentration was not very high.

3.2. Simple correlation analysis of SOM concentration against temperature, precipitation and altitude

A linear function and two non-linear functions of power and exponential were used to fit the relationships between SOM and annual mean temperature, annual mean precipitation and altitude. The two non-linear functions were logarithmically transformed to corresponding linear func-

Table 2
Statistical parameters of SOM concentration in typical zonal soils (A horizon) of China

Regions	Number	Arithmetic mean (g kg^{-1})	STD	Min. (g kg^{-1})	Median (g kg^{-1})	Max. (g kg^{-1})	Geometric mean[a] (g kg^{-1})
Whole country	886	32.3	30.8	1.3	21.8	241.0	22.9bd
Northeastern China	199	32.5	25.1	4.9	24.5	127.8	25.7cd
Eastern China	86	26.3	21.3	5.1	19.0	115.2	20.0ab
Southern China	113	29.0	20.2	3.1	23.1	144.3	23.9bc
Northern China	175	26.0	26.7	4.0	19.2	182.3	18.4a
Northwestern China	216	31.8	35.6	1.3	16.1	241.0	19.5a
Southwestern China	97	53.6	43.3	7.4	39.6	184.7	40.4e

[a] Fisher's Least Significant Difference (LSD) was used to test the significance at 0.05 probability level. Geometric means followed by the same letter do not significantly differ from each other.

Table 3
Single correlation coefficient between SOM concentration (M) and annual mean temperature (T), annual mean precipitation (P) and altitude (H)

Regions	Number	r_{MT}	r_{MP}	r_{MH}
Whole country	886	−0.263**	0.234**	0.271**
Northeastern China	199	−0.720**	0.168*	0.278**
Eastern China	86	−0.034	0.531**	0.701**
Southern China	113	−0.234*	0.335*	0.595**
Northern China	175	−0.547**	−0.016	0.332**
Northwestern China	216	−0.457**	0.507**	0.432**
Southwestern China	97	−0.574**	−0.084	0.525**

* Significant at $P<0.05$.
** Significant at $P<0.01$.

tions. Results (not shown) indicated that the exponential function is the best one among the three functions to characterize the relationship between SOM and temperature, precipitation and altitude. So we used the exponential function to do the simple and partial correlation analysis.

Because some parameters of surface SOM concentration, temperature, precipitation and altitude do not show a normal distribution, in order to get rid of the extreme values Spearman's rank coefficient was employed to find out the correlations among these parameters. Table 3 shows the results of correlation analysis, where r is the correlation coefficient and the subscript represents two parameters to be correlated. Obviously, surface SOM concentration is positively correlated with altitude in all cases, positively correlated with annual precipitation except in northern and southwestern China, and negatively correlated with annual mean temperature except in eastern China. However, the correlation coefficients between surface SOM concentration and temperature, precipitation and altitude are relatively weak except r_{MT} in northeastern China and r_{MH} in eastern China (Table 3), suggesting that the variance of surface SOM concentration of zonal soil series in China may be not well explained by a single factor.

Climate is the most important factor regulating soil organic matter (Alvarez and Lavado, 1998). The weak correlations between SOM and temperature and between SOM and precipitation (Table 3) are due to the fact that the SOM is affected by multiple factors including precipitation, temperature, altitude and some other factors that are not taken into account in this research. The correlation between SOM and any single factor may be screened by some other factors. The weak correlation may also be introduced by the site-specific combination of temperature, precipitation, and altitude.

3.3. Partial correlation analysis for separating the temperature, precipitation and altitude effects

A more rigorous statistical approach, partial correlation analysis, was used to isolate the effects of temperature, precipitation and altitude which otherwise obscured. A partial correlation coefficient measures the correlation between any pair of variables when other variables are held constant. Table 4 shows the results of partial correlation analysis, where $r_{MT,P,H}$ is the partial correlation coefficient between surface SOM concentration and temperature (T) when precipitation (P) and altitude (H) are held constant. The partial correlation coefficients of $r_{MP,T,H}$ and $r_{MH,T,P}$ have the same meaning as that of $r_{MT,P,H}$.

In comparison with simple correlation (Table 3), the partial correlation coefficient between surface SOM concentration and temperature ($r_{MT,P,H}$) and precipitation ($r_{MP,T,H}$) becomes more significant for whole country and different geographical regions. The values of $r_{MT,P,H}$ and $r_{MP,T,H}$ on the country scale increased from 0.263 to 0.643 and from 0.234 to 0.636, respectively. However, the value of $r_{MH,T,P}$ decreased from 0.271~0.701 when the effect of varying temperature and precipitation are involved to 0.013~0.515 when temperature and precipitation are held constant, which suggests that the surface SOM concentration in zonal soils of China is mainly influenced by climatic factors of temperature and precipitation. Impact of altitude on SOM might be indirectly expressed through temperature and precipitation.

Surface SOM concentration is positively correlated with precipitation and negatively correlated with temperature in all cases (Table 4), suggesting that precipitation is propitious to surface SOM while higher temperature makes against. This agreed with previous reports (Burke et al., 1989; Grigal and Ohmann, 1992; Hontoria et al., 1999; Ganuza and Almendros, 2003). The relation of SOM to altitude shows region-specific. The SOM concentration is positively correlated with altitude in the regions of eastern, southern and southwestern China, while there is no significant relationship between these two parameters in the regions of northeastern, northern and northwestern China (Table 4). It is noteworthy that the values of $r_{MT,P,H}$ and $r_{MP,T,H}$ in the regions of northeastern, northern and northwestern China is in general higher than those in other regions (Table 4), which partly explained why the correlation of SOM to altitude is not significant in these regions.

Results of Table 4 also suggest that factors regulating SOM concentration vary in different geographical regions. Dominant factors are temperature and precipitation in northern, northeastern and northwestern China, precipitation

Table 4
Partial correlation coefficients between SOM concentration (M) and annual mean temperature (T), annual mean precipitation (P) and altitude (H)

Regions	Number	$r_{MT,P,H}$	$r_{MP,T,H}$	$r_{MH,T,P}$
Whole country	886	−0.643**	0.636**	0.246**
Northeastern China	199	−0.783**	0.467**	0.074
Eastern China	86	−0.260*	0.547**	0.483**
Southern China	113	−0.347**	0.417**	0.515**
Northern China	175	−0.708**	0.537**	0.013
Northwestern China	216	−0.635**	0.663**	−0.090
Southwestern China	97	−0.603**	0.240**	0.233*

* Significant at $P<0.05$.
** Significant at $P<0.01$.

Table 5
Multivariate regression model of SOM concentration against annual mean temperature (T), annual mean precipitation (P) and altitude (H)

Regions	Number	Regression models	R^2
Whole country	886	$\mathrm{Ln(SOM)}=2.71-9.77\times10^{-2}T+1.44\times10^{-3}P+1.76\times10^{-4}H$	0.404*
Northeastern China	199	$\mathrm{Ln(SOM)}=3.47-0.199T+1.23\times10^{-3}P$	0.562*
Eastern China	86	$\mathrm{Ln(SOM)}=1.74+7.26\times10^{-4}P+7.70\times10^{-4}H$	0.458*
Southern China	113	$\mathrm{Ln(SOM)}=2.14+4.70\times10^{-4}P+7.22\times10^{-4}H$	0.415*
Northern China	175	$\mathrm{Ln(SOM)}=2.43-0.163T+3.01\times10^{-3}P$	0.550*
Northwestern China	216	$\mathrm{Ln(SOM)}=2.60-0.143T+2.84\times10^{-3}P$	0.550*
Southwestern China	97	$\mathrm{Ln(SOM)}=3.30-6.35\times10^{-2}T+7.13\times10^{-4}P+2.61\times10^{-4}H$	0.419*

* Significant at $P<0.01$.

and altitude in eastern and southern China, temperature, precipitation and altitude in southwestern China. When other factors are held constant, the single factor, temperature or precipitation, is a good predictor of surface SOM concentration in the most regions of China. The feature of partial correlation allows us to conveniently interpret the observed data sets, and makes predictive models become possible.

3.4. Predictive models for SOM concentration

In order to determine the integrative effect of temperature, precipitation and altitude on SOM concentration, we applied a forward stepwise regression method. Results of the stepwise regression are shown in Table 5.

Analysis of the stepwise regression indicated that a combination of temperature (T, in °C), annual precipitation (P, in mm) and altitude (H, in m) can explain about 40% of the variability in the surface SOM concentration on a country scale (Table 5). This result is consistent with the study by Hontoria et al. (1999). They reported that 45% of the variability in soil organic carbon in peninsular Spain could be explained by the parameters of annual precipitation, annual mean temperature and altitude. The relative low values of R^2 might be attributed to measurement error of variables, the natural variability in the sampling site and to some other factors that were not considered in this study due to insufficient records. These factors include composition of vegetation, degree of erosion, topographic position and local succession of perturbations over the past decades that are thought to affect SOM (Hontoria et al., 1999).

Regression models were also obtained for the six geographical regions of China (Table 5). A combination of temperature and annual precipitation explained 56.2%, 55.0% and 55.0% of the variability in the surface SOM concentration in the regions of northeastern, northern and northwestern China, respectively (Table 5). In the regions of eastern and southern China, the model determined by annual precipitation and altitude explained 45.8% and 41.5% of the variability in the SOM concentration, respectively. A combination of temperature, annual precipitation and altitude explained 41.9% of the variability in the SOM concentration in southwestern China. All of these results suggest that climate has greater influence on the surface SOM concentration in the north of China where temperate zone is classified, while altitude has greater influence in the south of China where subtropical and tropical zones are classified.

The relation of SOM concentration to temperature and precipitation in Table 5 opens a question of how much precipitation should be increased to compensate the loss of carbon induced by global warming. By employing the models in Table 5, we roughly calculated that given SOM concentration no change, the annual precipitation should respectively increase 35, 35, 70 and 90 mm in the regions of northern, northwestern, southwestern and northeastern China for compensating the loss of carbon when annual temperature increases by 1 °C. Clearly, the possible impact of global warming on soil carbon would be more serious in northeastern China than that in the other three regions. With respect to the relation of SOM concentration to precipitation in the regions of eastern and southern China, it seems that global warming may not have a great influence on SOM.

4. Conclusions

SOM concentration in surface soils (A horizon) varies widely for the zonal soils in China. Surface SOM concentration generally decreases with the increment of temperature, and is positively correlated with annual precipitation and altitude. Multiple regression models with different combination of temperature, precipitation and altitude could explain 41.5%–56.2% of the variability in surface SOM concentration for different geographical regions. The SOM concentration can be quantitatively described by a combination of temperature and annual precipitation for the regions of northeastern, northern and northwestern China, by a combination of precipitation and altitude for the regions of eastern and southern China, and by a combination of all these three parameters for the southwestern China, respectively.

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