Effects of land use, climate, topography and soil properties on regional soil organic carbon and total nitrogen in the Upstream Watershed of Miyun Reservoir, North China

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Abstract

Soil organic carbon (SOC) and total nitrogen (TN) contents as well as their relationships with site characteristics are of profound importance in assessing current regional, continental and global soil C and N stocks and potentials for C sequestration and N conservation to offset anthropogenic emissions of greenhouse gases. This study investigated contents and distribution of SOC and TN under different land uses, and the quantitative relationships between SOC or TN and site characteristics in the Upstream Watershed of Miyun Reservoir, North China. Overall, both SOC and TN contents in natural secondary forests and grasslands were much higher than in plantations and croplands. Land use alone explained 37.2% and 38.4% of variations in SOC and TN contents, respectively. The optimal models for SOC and TN, achieved by multiple regression analysis combined with principal component analysis (PCA) to remove the multicollinearity among site variables, showed that elevation, slope, soil clay and water contents were the most significant factors controlling SOC and TN contents, jointly explaining 70.3% of SOC and 67.1% of TN contents variability. Only does additional 1.9% and 3% increase in the interpretations of SOC and TN contents variability respectively when land use was added to regressions, probably due to environment factors determine land use. Therefore, environmental variables were more important for SOC and TN variability than land use in the study area, and should be taken into consideration in properly evaluating effects of future land use changes on SOC and TN on a regional scale.

Key words: soil organic carbon; soil total nitrogen; principal component analysis; multiple regression analysis

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Introduction

Soil comprises a major pool and plays an important role in the global C and N cycles (Batjes, 1996). C and N losses via the emissions of greenhouse gases (CO_2 and N_2O) from soil to the atmosphere by natural or anthropogenic causes could contribute to global warming. Consequently, sequestration of soil organic carbon (SOC) and conservation of total nitrogen (TN) are of increasingly keen scientific and political interests worldwide as a more direct measure to mitigate such emissions. SOC and TN, often tightly coupled, are controlled by a number of natural and anthropogenic factors, including climate, vegetation, topography, parent material, intrinsic soil properties, land use and management practices, etc. (Homann et al., 1995; Paustian et al., 1997). A better understanding of SOC and TN contents and their relationships with these controlling factors is critical to evaluate current regional, continental and global soil C and N pools as well as potentials for C sequestration and N conservation to offset anthropogenic greenhouse gas emissions.

Climate, topography and soil properties are considered as main environmental controls of SOC and TN (Hontoria et al., 1999). Climate is known as the primary driver for vegetation type, plant growth and litter decomposition (Perry, 1994), and thereby for soil organic matter (SOM) cycle and balance (Rustad and Fernandez, 1998). In general, SOC and TN increase with decreasing temperature and increasing precipitation (Burke et al., 1989; Miller et al., 2004), but there have been some notable exceptions. For example, SOC decreased with decreasing temperature in a mountainous forested region of Western Oregon (Homann et al., 1995) and with increasing precipitation in Australian tropical rainforests (Spain, 1990). Topographical factors, such as elevation, slope and aspect, influence SOM levels by controlling soil water balance and thus plant litter production and decomposition, as well as soil erosion and geologic deposition processes (Birkeland, 1984). Generally, SOC increases with increasing elevation (Garten et al., 1999; Griffiths et al., 2009). A positive correlation between SOC and slope was found by Hontoria et al. (1999) in Peninsular Spain, possibly due to the slope influence on land use. Among soil properties, soil

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water regime, which integrates soil and climate properties (e.g., evapotranspiration) as well as topographical features, may be a critical factor determining SOC content (Grigal and Ohmann, 1992). Soil pH influences SOC and TN by regulating microbial activities, and higher pH value has a negative effect probably because of accelerated decomposition of SOM (Motavalli et al., 1995). Soil texture has impacts not only on SOM inputs indirectly by influencing vegetation productivity via water availability and soil fertility (Schimel and Parton, 1986), but also on SOM outputs through the role of clay in the protection of SOM from decomposition (Anderson et al., 1981). It is well known that higher SOC and TN are contained in finer soils and clay content has been recognized as a key factor controlling soil C and N dynamics (Anderson et al., 1981; Homann et al., 2007).

Land use may be the dominant factor of SOC and TN in an area with same parent material and climate. Overall, distinct plant covers and soil management practices under different land uses result in great differences in SOC and TN between various land uses. Human modifications in land use usually produce considerable alterations of SOM. It is well known that soils generally lose C and N with conversions from forest or grassland to agricultural land (Murty et al., 2002; Guo and Gifford, 2002).

Besides individual effect on SOC and TN, the combined effects of environmental and anthropogenic factors have been also widely evaluated in many publications. Spain (1990) pointed out that a combination of site temperature and clay content interpreted 55.7% of C and 69.2% of N variations in Australian tropical rainforest soils. Hon-toria et al. (1999) reported that 45% of SOC variation in peninsular Spain could be explained by mean annual precipitation, mean annual temperature and land use. When added to the model, soil moisture regime, texture, elevation and slope only explained an additional 2% of the SOC variability. Dai and Huang (2006) noted that a combination of temperature and precipitation accounted for 55% of SOM variability in northern China. Because of complex interaction of environmental variables (e.g., climate, topography and soil properties) and anthropogenic factors (e.g., land use), regional SOC and TN variability should be assessed by new methodologies. In recent years, multivariate statistical analysis techniques have been applied to explain the interactive effects of multiple factors (Camdevyren et al., 2005; Kadono et al., 2008; Jagadamma et al., 2008). Although multiple regression analysis could be used to model the relationships between SOC or TN and site characteristics, the problem of multicollinearity among site characteristics has not been avoided (Bowerman and O'Connell, 1990). The principal component analysis (PCA), one of multivariate statistical analysis techniques, can effectively summarize the original variables into a few independent ones that interpret most of the variance (Kaiser, 1960). Herein, a combination of PCA and multiple regression analysis will be used to establish relationships of SOC or TN contents with site characteristics and the results will be compared with those of normal multiple regression analysis using the original measured variables

directly.

The objectives of this study were to: (1) investigate contents and distribution of SOC and TN under different land uses, (2) identify dominant factors controlling SOC and TN status, and (3) develop quantitative relations of SOC and TN contents with site characteristics (including land use, climatic, topographic and soil properties) in the Upstream Watershed of Miyun Reservoir, North China.

1 Materials and methods

1.1 Study area

Miyun Reservoir, located 100 km northeast of Beijing City, is the largest reservoir in North China and also the most important drinking water source of Beijing. Two main rivers, Chao River and Bai River, flow into Miyun Reservoir. The Upstream Watershed of Miyun Reservoir, namely the Chaobai River Watershed above Miyun reservoir, is located between latitude 40°19'N–41°31'N and longitude 115°25'E–117°33'E, covering an area of 15,788 km², i.e., about 88% of the total area of the Chaobai River Watershed, of which 49% are used for forests, 27% for grasslands, 21% for croplands and the rest are occupied by water bodies and other land uses. According to administrative division of China, about one third of the study area are located in Beijing Municipality, comprising parts of Huairou District, Miyun County and Yanqing County, and two thirds in Hebei Province, covering parts of Guyuan County, Chicheng County, Luanping County and Fengning Manchu Autonomous County. The area is located on the eastern Inner Mongolia Axis and Yanshan Platform Fold Belt and its topography comprises moderate and high mountains in the northwest and lower mountains, hills, valleys and plains in the southeast. The soil layer of the area is superficial and the soil taxa mainly include mountain meadow soil, brown soil, cinnamon soil and calcareous soil according to Chinese Soil Taxonomy (Research Group on Soil Taxonomy, 1995). The north of the area is located in semi-arid forest steppe climate zone, while the south is in semi-humid mountain climate zone. The long-term meteorological records show that mean annual precipitation is 488.9 mm, spatially ranging from 261.4 to 750.0 mm and decreasing from southeast to northwest. Mean annual temperature is 7.2°C, geographically varying from 1.4 to 13.3°C.

1.2 Soil sampling and processing

Soil sampling was performed from August to September 2009 based on different land uses and natural conditions. A total of 442 soil samples were collected from 154 sampling sites, covering seven kinds of typical land uses, i.e. grassland ($N = 10$), cropland ($N = 65$), plantations of Prince Rupprecht's larch (*Larix principis-rupprechtii* Mayr.) ($N = 15$) and Chinese pine (*Pinus tabulaeformis* Carr.) ($N = 27$), natural secondary forests of Liaodong oak (*Quercus wutaishanica* Blume) ($N = 7$) and Chinese aspen (*Populus davidiana* Dode)-Japanese birch (*Betula platyphylla* Suk.) mixed ($N = 20$), as well as shrub land ($N = 10$). At the

cropland sites, the vegetation included maize (*Zea mays* L.) ($N = 20$), wheat (*Triticum aestivum* L.) ($N = 10$), peanut (*Arachis hypogaea* L.) ($N = 5$), sorghum (*Sorghum vulgare* Pers.) ($N = 10$), soybean (*Glycine max* (L.) Merr.) ($N = 7$), potato (*Solanum tuberosum* L.) ($N = 8$) and leaf vegetables ($N = 5$). Each soil sample was collected as a composite of three randomly distributed replicates. At each site, composite samples were collected at two depths (0–10 and 10–20 cm) in shrub lands or three depths (0–10, 10–20 and 20–40 cm) under the other six land uses. In total, 149 samples were obtained at 0–10 cm, 149 samples at 10–20 cm and 144 samples at 20–40 cm. Three replicated 100-cm³ soil cores were taken by a foil sampler for each soil layer at each site for determination of soil bulk density. Meanwhile, site elevation was measured by a hand-held GPS equipment, and slope by a gradiometer.

The samples were transported to the laboratory and air-dried at room temperature, then ground with a mortar and pestle and sieved through a 2-mm sieve to remove gravel, roots and litter. A part of soil passing through the 2-mm sieve was used for analysis of soil pH and particle size, the other was further ground and sieved through a 0.147-mm sieve for determinations of SOC and TN.

1.3 Laboratory analysis

After a 12-hr drying in an oven at 105°C, soil bulk density was determined as the dry weight per unit volume of soil core, and soil water content was determined gravimetrically by weighing. Soil pH was measured in distilled water mixed 2.5:1 (by volume) with dry soil by a Delta 320 pH meter (Mettler-Toledo Instruments (Shanghai) Ltd., China). Soil particle size analysis was carried out using a Mastersizer 2000 particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK). The percentages of clay (< 0.002 mm), silt (0.002–0.05 mm) and sand (0.05–2 mm) were calculated according to the US Soil Taxonomy (Soil Survey Staff, 2010). SOC content was determined by wet oxidation using potassium dichromate in acid medium followed by redox titration (Nelson and Sommers, 1996). TN content was determined by dry combustion using a Vario EL III elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany).

1.4 Data analysis

Based on the meteorological data collected from China Meteorological Data Sharing Service System of 10 meteorological stations around and within the study area, mean annual temperature and mean annual precipitation of each sampling site were calculated using ArcGIS 9.2 software with the Kriging spatial interpolation method. Statistical comparisons of SOC and TN contents among land uses and soil layers were conducted with analysis of variance (ANOVA) followed by least-significant difference (LSD) tests at $\alpha = 0.05$ probability level.

Correlation analysis was performed to identify correlations of SOC and TN contents with environmental variables (e.g., climatic, topographic and soil properties) and correlations among these variables. The measured variables included mean annual temperature, mean annual

precipitation, elevation, slope, soil bulk density, pH, water, clay and sand contents.

Principal component analysis (PCA) of the climatic, topographic and soil properties was conducted with varimax rotation to remove the multicollinearity between these variables. Principal components derived from PCA were considered mutually orthogonal, uncorrelated, and consequently could explain the maximum residual variation (Kaiser, 1960). Each component was a linear combination of all the measured variables. Components with eigenvalues > 1 and those that explained more than 5% of the total variance were retained (Kaiser, 1960). Representative variables from each component were selected based on the correlation coefficients or factor loadings between the tested variables and each component (Sharma, 1996), and those with factor loadings > 0.5 were selected (Jagadamma et al., 2008). If the loading coefficient of a variable was > 0.5 in more than one component, it was selected from the component holding the highest coefficient for that variable. When more than one variable were available within a component, their correlations were considered. Among the significantly correlated variables, that with the highest factor loading was selected. If the heavily weighted variables within a component were not correlated, each of them was considered significant and was selected for further consideration (Jagadamma et al., 2008). The relationships of SOC or TN contents with climatic, topographic and soil properties were then obtained by multiple regression analysis using the PCA-derived representative variables as independent variables and SOC or TN contents as dependent variables. And the combined relationships of SOC or TN contents with site characteristics were then achieved by adding land uses to regression analysis. The categorical variable land use was divided into seven classes (i.e., the seven land uses) and was included in the regression using the classical approach of dummy variable (namely seven dummy variables were coded 0 for absence and 1 for presence) (Hontoria et al., 1999).

Normal multiple regression analysis was conducted using the original measured variables directly and the results were compared with those of the combination of PCA and multiple regression analysis to select the optimal regression models for SOC and TN. Additionally, path coefficients were estimated in multiple regression analysis and were used to evaluate relative contribution from each independent variable within the models.

All the statistical analyses were conducted using the SPSS 16.0 software.

2 Results

2.1 Variations of SOC and TN contents with land use and soil depth

Both SOC and TN contents in the upper 40-cm soil profile varied widely with land use (Table 1). Land use alone explained 37.2% and 38.4% of the total variations of SOC and TN contents, respectively. For all pedons, significant differences in mean SOC content were observed among all

land uses except for that among grassland, Chinese aspen-Japanese birch mixed forest (or aspen-birch mixed forest for short), Liaodong oak forest (or oak forest for short) and shrub land and that among cropland, Prince Rupprecht's larch forest (or larch forest for short) and Chinese pine forest (or pine forest for short). Similarly, mean TN content in the top 40 cm were not significantly different among grassland, aspen-birch mixed forest, oak forest and shrub land, among cropland, larch forest and pine forest, and between larch forest and oak forest. Throughout the soil profile (0–40 cm depth), aspen-birch mixed forest had the highest SOC and TN contents, followed by grassland, whereas the lowest SOC and TN contents were separately observed in cropland and pine forest, occupying only 27% and 31% of that in aspen-birch mixed forest respectively. Grouping data by soil layer category, there was a similar pattern of variations in SOC content among land uses within each soil layer, as well as for TN content.

The vertical distribution of both SOC and TN contents throughout the upper 40 cm soil profile were clearly stratified with soil depth (Table 1). There was a great decrease in SOC content with the increase of soil depth and the largest SOC content was contained in the top 10 cm soil layer within any land use except for grassland, which showed a slight increase in SOC content by 3% between 0 and 20 cm in depth and a small drop of 6.35% below 20 cm, and consequently had the highest SOC content in the second 10–20 cm soil layer. Likewise, the highest TN content was held in the upper 10 cm soil layer and a significant decrease in TN content with the increasing soil depth was found within each land use except for pine forest, which showed a considerable rise of 24% in the 20–40 cm soil layer over the previous soil layer. Significant differences in both SOC and TN contents among the three soil layers were only found in cropland and pine forest. In aspen-birch mixed forest, significant differences in both

SOC and TN contents were merely observed between the 0–10 and 20–40 cm soil layers. By contrast, no statistical significances among soil layers were associated with the other four land uses for both SOC and TN contents.

2.2 Correlations of SOC and TN contents to climatic, topographic and soil properties

There were highly significant correlations of SOC and TN contents with all the selected climatic, topographic and soil properties, as well as between these properties (Table 2). Both SOC and TN contents were positively correlated to elevation, slope, soil water and clay contents, but negatively correlated to mean annual temperature, mean annual precipitation, soil bulk density, pH and sand content at the 0.001 level. Among these properties, 32 significant correlations were found, accounting for 89% of the all correlations. Strongly and significantly positive correlations were observed between mean annual temperature and mean annual precipitation ($r = 0.68$, $P < 0.001$), soil bulk density and pH ($r = 0.46$, $P < 0.001$), and soil bulk density and sand content ($r = 0.48$, $P < 0.001$). Among the negative correlations, those that were highly significant ($r > 0.60$, $P < 0.001$) were observed between elevation and mean annual temperature, elevation and mean annual precipitation, slope and soil pH, soil bulk density and water content, and soil clay and sand contents. These significant correlations indicated multicollinearity among climatic, topographic and soil properties, which would make the interpretations of multiple regression equations for SOC and TN contents determined by these variables unreliable (Bowerman and O'Connell, 1990).

2.3 PCA of climatic, topographic and soil properties

In order to group the interrelated climatic, topographic and soil properties to the smallest possible subsets representing most of the original data set variation, PCA was performed

Table 1 Variations and significant differences of SOC and TN contents in different land uses and soil depths

Land use	SOC content (g/kg)			
	0–10 cm depth	10–20 cm depth	20–40 cm depth	0–40 cm depth ³
Grassland	30.38±8.24 bcA	31.28±11.90 aA	29.29±10.89 aA	30.32±5.83 a
Cropland	11.29±0.63 eA	9.41±0.48 bB	7.31±0.48 bC	9.33±0.31 b
Larch forest ¹	15.45±2.07 cdA	12.71±2.10 bA	10.27±2.04 bA	12.81±1.21 b
Chinese pine forest	14.87±1.13 dA	9.80±0.78 bB	7.30±0.74 bC	10.66±0.62 b
Aspen-birch mixed forest ²	45.71±4.98 aA	33.48±4.04 aAB	23.96±2.93 aB	34.38±2.59 a
Liaodong oak forest	34.09±7.15 abA	26.61±6.33 aA	20.39±4.96 aA	27.03±3.63 a
Shrub land	26.91±3.90 abA	24.50±1.75 aA	–	25.70±2.05 a
Land use	TN content (g/kg)			
	0–10 cm depth	10–20 cm depth	20–40 cm depth	0–40 cm depth ³
Grassland	3.16±0.75 abA	2.81±0.81 abA	2.60±0.69 abA	2.86±0.42 a
Cropland	1.13±0.05 bA	0.98±0.04 bB	0.77±0.04 bC	0.96±0.03 c
Larch forest ¹	1.50±0.18 bA	1.25±0.19 bA	1.03±0.19 bA	1.26±0.19 bc
Chinese pine forest	1.11±0.08 bA	0.75±0.06 bB	0.93±0.13 bC	0.93±0.06 c
Aspen-birch mixed forest ²	3.94±0.46 aA	2.84±0.36 aAB	2.20±0.28 aB	2.99±0.23 a
Liaodong oak forest	2.58±0.63 abA	2.04±0.53 abA	1.64±0.36 abA	2.09±0.30 ab
Shrub land	2.51±0.30 abA	2.31±0.16 aA	–	2.41±0.17 a

¹ Prince Rupprecht's larch forest; ² Chinese aspen-Japanese birch mixed forest; ³ mean of contents in all sampling layers.

Data are expressed by mean ± standard error. Different capital letters in the same row indicate significant differences among soil layers, and different lowercase letters in the same column represent significant differences among land uses, according to least-significant difference (LSD) test at $\alpha = 0.05$ level of probability.

Table 2 Correlation coefficients of SOC and TN contents with climatic, topographic and soil properties

	SOC	TN	MAT	MAP	Elv	Slp	ρ_b	SWC	pH	Clay	Sand
SOC	1.00										
TN	0.95***	1.00									
MAT	-0.25***	-0.27***	1.00								
MAP	-0.28***	-0.28***	0.68***	1.00							
Elv	0.47***	0.48***	-0.89***	-0.74***	1.00						
Slp	0.26***	0.22***	0.28***	0.31***	-0.03	1.00					
ρ_b	-0.75***	-0.71***	0.06	0.24***	-0.36***	-0.42***	1.00				
SWC	0.73***	0.71***	-0.15**	-0.22***	0.28***	-0.04	-0.61***	1.00			
pH	-0.42***	-0.39***	-0.22***	-0.28***	-0.08	-0.73***	0.46***	-0.14**	1.00		
Clay	0.40***	0.40***	-0.10*	-0.19***	0.24***	0.18***	-0.37***	0.28***	-0.18***	1.00	
Sand	-0.43***	-0.44***	0.13**	0.19***	-0.29***	-0.14**	0.48***	-0.36***	0.22***	-0.65***	1.00

SOC: soil organic carbon content; TN: soil total nitrogen content; MAT: mean annual temperature; MAP: mean annual precipitation; Elv: elevation; Slp: slope; ρ_b : soil bulk density; SWC: soil water content; Clay: soil clay content; Sand: soil sand content.

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

and then these variables were summarized into four principal components with eigenvalue > 1 , interpreting 86.6% of the total variance (Table 3). The first and the most important component (PC1), explaining 28.4% of the variation, showed high factor loadings (> 0.50) for elevation, mean annual temperature and mean annual precipitation. The second component (PC2) loaded heavily on slope and soil pH and explained 22.2% of the total variance. The third component (PC3) had high loadings for soil clay and sand contents. The highly weighted variables in the fourth component (PC4) were soil water content and bulk density.

Correlations among elevation, mean annual temperature and mean annual precipitation from PC1 were highly significant and strong (Table 2), therefore elevation with the highest factor loading was selected as a representative variable from PC1. Under PC2, slope and soil pH were also significantly correlated and then slope with the highest factor loading was selected. Similarly, soil clay content and water content were selected as representatives from PC3 and PC4, respectively.

2.4 Regression models for SOC and TN by multiple regression analysis combined with PCA

Relationships of SOC (g/kg) or TN (g/kg) with climatic, topographic and soil properties were obtained by multiple regression analysis with the stepwise method using the PCA-derived subset of original variables, namely elevation (Elv, m), slope (Slp, °), soil clay (Clay, g/kg) and water

contents (SWC, g/kg), and shown as follows:

$$\text{SOC} = -16.067 + 0.093\text{Clay} + 0.267\text{Slp} + 0.085\text{SWC} + 0.010\text{Elv} \quad (R^2 = 0.703, P < 0.001) \quad (1)$$

$$\text{TN} = -1.139 + 0.008\text{Clay} + 0.019\text{Slp} + 0.007\text{SWC} + 0.001\text{Elv} \quad (R^2 = 0.671, P < 0.001) \quad (2)$$

The two regression equations were highly significant and retained all the selected representative variables, which jointly explained 70.3% and 67.1% of SOC and TN contents variability, respectively.

Adding the seven land uses as dummy variables to regressions, relationships of SOC or TN with land use, climatic, topographic and soil properties were achieved as follows:

$$\text{SOC} = -7.346 + 0.066\text{Clay} + 0.235\text{Slp} + 0.079\text{SWC} + 0.009\text{Elv} - 5.146\text{Cropland} - 7.182\text{Larchforest} - 6.487\text{Pineforest} \quad (R^2 = 0.722, P < 0.001) \quad (3)$$

$$\text{TN} = -0.121 + 0.006\text{Clay} + 0.015\text{Slp} + 0.006\text{SWC} + 0.001\text{Elv} - 0.636\text{Cropland} - 0.679\text{Larchforest} - 0.783\text{Pineforest} - 0.428\text{Oakforest} \quad (R^2 = 0.701, P < 0.001) \quad (4)$$

Equation (3) retains elevation, slope, soil clay and water contents, and three land uses, which together explained 72.2% of the SOC content variability. Therefore, the introduction of the categorical variable land use contributed to additional 1.9% of the variation of SOC content. Likewise, the presence of land use explained additional 3% of variation in TN content.

2.5 Regression models for SOC and TN by normal multiple regression analysis

Using all climatic, topographic and soil properties as independent variables directly, the following regression

Table 3 PCA results based on climatic, topographic and soil properties

Principal component	PC1	PC2	PC3	PC4
Eigenvalue	2.56	1.99	1.71	1.54
Percentage of total variance (%)	28.4	22.2	19.0	17.1
Cumulative percentage (%)	28.4	50.6	69.6	86.7
Factor loading				
MAT	0.94	0.15	0.02	-0.01
MAP	0.82	0.25	0.13	0.17
Elv	-0.95	0.13	-0.13	-0.15
Slp	0.15	0.92	-0.10	0.02
ρ_b	0.18	-0.47	0.28	0.72
SWC	-0.11	-0.05	-0.17	-0.93
pH	-0.09	-0.90	0.09	0.16
Clay	-0.09	0.10	-0.91	-0.09
Sand	0.12	-0.11	0.85	0.25

Eqs. (5) and (6) for SOC and TN contents were obtained by stepwise multiple regression analysis and identified a new subset including elevation, soil bulk density (g/cm^3), water contents and pH, which together explained 67.6% and 63.0% of SOC and TN contents variability, respectively.

$$\text{SOC} = 51.285 - 21.027\rho_b + 0.061\text{SWC} + 0.008\text{Elv} - 3.389\text{pH} \quad (R^2 = 0.676, P < 0.001) \quad (5)$$

$$\text{TN} = 3.856 - 1.443\rho_b + 0.005\text{SWC} + 0.001\text{Elv} - 0.271\text{pH} \quad (R^2 = 0.630, P < 0.001) \quad (6)$$

Relationships of SOC and TN contents with site characteristics were then determined by introducing land uses as dummy variables to regression analysis and shown as follows:

$$\text{SOC} = 52.700 - 24.202\rho_b + 0.056\text{SWC} + 0.008\text{Elv} - 2.922\text{pH} + 14.391\text{Shrubland} + 5.428\text{Grassland} \quad (R^2 = 0.699, P < 0.001) \quad (7)$$

$$\text{TN} = 4.737 - 1.892\rho_b + 0.004\text{SWC} + 0.001\text{Elv} - 0.317\text{pH} + 1.516\text{Shrubland} + 0.935\text{Grassland} + 0.372\text{Cropland} + 0.318\text{Aspen-birch mixed forest} \quad (R^2 = 0.673, P < 0.001) \quad (8)$$

Introduction of land use contributed to additional 2.3% and 4.3% of variations in SOC and TN contents, respectively.

3 Discussion

3.1 SOC and TN contents affected by land use and soil depth

In this study, both SOC and TN contents in the upper 40-cm soil profile varied greatly with land use which alone explained 37.2% and 38.4% of SOC and TN contents variability respectively. Similar results were obtained by Hontoria et al. (1999), who noted that land use alone explained 33% of the SOC variability in Peninsular Spain. Under different land uses, both SOC and TN contents in natural secondary forests (e.g., aspen-birch mixed forest, oak forest and shrub land) and grasslands were much higher than in plantations (e.g., larch forest and pine forest) and croplands (Table 1). The results are consistent with the observations of previous research (Mikhailova et al., 2000; Puget and Lal, 2005) in which croplands generally held the lowest SOC and TN amounts in comparison with forests and grasslands. Moreover, the results suggest that the extent of land use made an important impact on the distribution of SOC and TN contents in different land uses in the area, that is, both SOC and TN contents decreased with the increasing intensity of land use and management practices on the whole, which supports the findings of Paustian et al. (1997) and Zeidler et al. (2002). They found that SOC amount or soil nutrients decreased with increasing soil physical disturbance or land intensification.

Agriculture in the study area is characterized by small-scale subsistence farming. Due to long farming history, intensive cultivation, reduced manure amendment and removal of crop residue, cropland soils in the area have relatively low C level, however, may have a great potential for C sequestration through improved land management practices, such as reduced- or no-tillage, increasing manure amendment and preferential crop residues management (Buyanovsky and Wagner, 1998; Lal, 2004).

Across the upper 40-cm soil profile, there existed clearly stratified distribution and downward trends of both SOC and TN contents with increasing soil depth as a whole, due to the effects of plant allocation over- and under-ground (Jobbágy and Jackson, 2000). However, grassland soil contained the highest SOC content in the second 10–20 cm soil layer reflecting the larger grass root density found in this layer, which supports the theory of Lemaire et al. (2005) that significant amounts of SOC can be stored at greater depths in grassland soils.

3.2 Effects of climatic, topographic and soil properties on SOC and TN contents

There were highly significant correlations of SOC and TN contents with all climatic, topographic and soil properties. In agreement with the results of previous studies, SOC and TN contents increased with increasing elevation, soil water and clay contents, and decreasing mean annual temperature, soil bulk density, pH and sand content. However, there were some contrasting results in our study.

Contrary to what was found in abundant studies within China (Wang et al., 2005, 2010) and elsewhere worldwide (Burke et al., 1989; Hontoria et al., 1999; Homann et al., 2007), SOC and TN contents were significantly and negatively correlated to mean annual precipitation. The contrasting result may occur on account of the region-specific climate regime and land use pattern of the study area, which are characterized by semi-arid forest steppe climate with less precipitation and most natural secondary forests and grasslands with higher SOC and TN contents in the north, while semi-humid mountain climate with more precipitation and most plantations and croplands with lower SOC and TN contents in the south. Nonexclusively, similar negative relationships between SOC or TN and precipitation have been observed in northern and southwestern China by Dai and Huang (2006) and in Australian tropical rainforest by Spain (1990).

Both SOC and TN contents showed significantly positive correlations with slope. A similar finding was made by Hontoria et al. (1999) in Peninsular Spain. Nonetheless, such a result was surprising, since a negative correlation would be generally expected from larger translocation and movement of SOM by greater runoff and potential erosion on steeper slopes (Hall, 1983). This contrasting correlation may be explained by the influence of slope on land use, namely, steeper slopes are mainly used for natural secondary forests, plantations and natural grasslands that usually hold higher SOC and TN contents, whereas gentler slopes for pastures and croplands that usually have relatively lower SOC and TN contents.

Elevation has an impact on temperature and precipitation. A highly significant and strongly negative correlation was found between elevation and temperature ($r = -0.89$, $P < 0.001$), likewise between elevation and precipitation ($r = -0.74$, $P < 0.001$). The occurrence of lower precipitation at higher elevation in the target region may be attributed to its geographic position, topography and climate. That is, the southeast of the region which comprises lower mountains, hills, valleys and plains and has a semi-humid mountain climate is closer to the sea than the northwest which comprises moderate and high mountains and has a semi-arid forest steppe climate, so precipitation decreases from southeast at lower elevation to northwest at higher elevation. The presence of highly significant correlations of elevation with temperature, precipitation, SOC and TN suggests that elevation may be a more significant controlling factor than temperature and precipitation and thereby may serve as a climate proxy and a strong predictor of SOC and TN status.

Soil water content showed highly significant and heavily positive correlations with SOC ($r = 0.73$, $P < 0.001$) and TN ($r = 0.71$, $P < 0.001$), implying a negative effect of soil drainage on SOC and TN stocks. Region-specifically, this result is of highly practical importance for the protection of poorly drained soils to enhance SOC and TN accumulations in the Upstream Watershed of Miyun Reservoir, where many projects and interventions, such as the more recent policies of converting paddy rice to dryland, forest or pasture, have been implemented to reduce agricultural water supply and irrigated area and thus to ensure downstream municipal water uses in Beijing, because of diminishing water flows and deteriorating water quality in the reservoir. Therefore presumably, soil water regime is considered as a key determinant, or more exactly constraint on SOC and TN levels.

3.3 Combined effects of land use, climatic, topographic and soil properties on SOC and TN contents

Without consideration of interrelations with other variables, each of site characteristics can alone explain a certain portion of the SOC and TN contents variations to some extent. However, an integrated interpretation by the combination of site variables can be more favorable than individual explanations of each variable, since there have usually been intercorrelations between these variables.

In this study, the higher coefficients of determination (R^2) for both SOC and TN were obtained by the equations with a combination of PCA and multiple regression analysis, rather than with normal multiple regression analysis. Therefore, the better regression models for SOC and TN contents were achieved with the former method, which removed the multicollinearity among site variables by PCA, than with the latter. That is, Eqs. (1)–(4) were selected as the final regression models for SOC and TN, which showed that a combination of elevation, slope, soil clay and water contents, identified as representatives of the original environmental variables by PCA, explained 70.3% and 67.1% of the SOC and TN contents variability, respectively. Consequently, elevation (partly as a surrogate

for temperature and precipitation), slope, soil clay and water contents, can be considered as the most important determinants of regional SOC and TN contents in the study area. However, their relative importance for the determination of SOC or TN was different according to the path coefficients estimated in multiple regression analysis. The relative contribution from each independent variable to SOC content was ranked in order of soil water content (0.586) > slope (0.245) > elevation (0.229) > soil clay content (0.074), while the rank was soil water content (0.554) > elevation (0.204) > slope (0.194) > soil clay content (0.081) for TN content.

In spite of the presence of some important factors in the models, other potentially important but poorly documented variables (e.g., greater within-site variability, microclimate, aspect, erosion, vegetation, management practices and land use history) which may be responsible for the remaining variability (Hontoria et al., 1999), are not taken into consideration. Introducing such variables to the regression models could bring about increases in R^2 values. In this study, adding land use to the regressions, R^2 values for SOC and TN contents increased to 0.722 and 0.701 respectively. That is, combined with environmental variables, land use just contributed to additional 1.9% and 3% increase in interpretations to the SOC and TN contents variability, which indicated that environmental variables were more important for SOC and TN variability than land use in the study area. However, land use alone explained 37.2% and 38.4% of the SOC and TN contents variations without consideration of other variables. The large difference between the two results may be explained by the influence of environmental factors on land use. Generally, land use is mainly determined by environmental conditions, such as climate, topography and soil properties. The effects of land use on SOC and TN therefore would overlap with those of environmental variables to a great extent and may be counteracted when environmental variables were taken into consideration. Only recently do conversions of land uses and applications of better management practices (e.g., decreasing tillage and incorporating crop residues) occur quite frequently, and in the future, an increasing SOC or TN variability would be expected as a result of such changes (Hontoria et al., 1999). More research works are needed to take environmental variables into considerations and further investigate the combined effects of environmental variables and land use and management practices to more accurately evaluate effects of future land use changes on SOC and TN on a regional scale.

4 Conclusions

In the Upstream Watershed of Miyun Reservoir, much higher SOC and TN contents were observed under natural secondary forest (e.g., aspen-birch mixed forest, oak forest and shrub land) and grassland, compared to plantation (e.g., larch forest and pine forest) and cropland. This suggests that forest and grassland are more effective in SOM accumulation, and both SOC and TN contents decreased with increasing intensity of land use and management

practices. Land use alone explained 37.2% and 38.4% of the SOC and TN contents variations, respectively. Across the upper 40-cm soil profile, there existed clearly stratified distribution and downward trends of both SOC and TN contents with the increase of soil depth as a whole.

There were highly significant correlations of SOC and TN contents with all the selected environmental variables. In detail, both SOC and TN contents increased with higher elevation, slope, soil water and clay contents, and lower mean annual temperature, mean annual precipitation, soil bulk density, pH and sand content. The better regression models for SOC and TN were obtained by multiple regression analysis combined with PCA to remove the multicollinearity among site variables than by normal multiple regression analysis, and then were selected as the final models which showed that elevation, slope, soil clay and water contents were the most significant determinants of SOC and TN contents in the study area. The four variables together explained 70.3% and 67.1% of the SOC and TN contents variability, respectively. When added to the models, land use merely explained additional 1.9% and 3% of the SOC and TN contents variability, respectively, due to environment factors determine land use. Therefore, environmental variables were more important for SOC and TN variability than land use in the study area, and should be taken into consideration in properly evaluating effects of future land use changes on SOC and TN on a regional scale.

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