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Storage and Density of Soil Organic Carbon in Urban Topsoil of Hilly Cities: A Case Study of Chongqing Municipality of China

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Abstract: Rapid urbanization results in the conversion of natural soil to urban soil, and consequently, the storage and density of the soil carbon pools change. Taking Chongqing Municipality of China as a study case, this investigation attempts to better understand soil carbon pools in hilly cities. First, the vegetated areas in the study area were derived from QuickBird images. Then, topsoil data from 220 soil samples (0–20 cm) in the vegetated areas were collected and their soil organic carbon (SOC) densities were analyzed. Using the Kriging interpolation method, the spatial pattern of SOC was estimated. The results show that the SOC density exhibited high spatial variability in the urban topsoil of Chongqing. First, the SOC density in topsoil decreased according to slope in the order 2°–6° < 25°–90° < 0°–2° < 6°–15° < 15°–25°. Second, the newly developed areas during 2001–2010 had a lower SOC density than the areas built before 1988. Third, urban parks and gardens had a higher SOC density in topsoil, residential green land followed, and scattered street green land ranked last. For hilly cities, the variability of terrain affects the distribution of SOC. The Kriging results indicate that Kriging method combining slope with SOC density produced a high level of accuracy. The Kriging results show that the SOC density to the north of the Jialing River was higher than the south. The vegetated areas were estimated to amount to 73.5 km^2 across the study area with an SOC storage of 0.192 Tg and an average density of 2.61 kg/m^2.

Keywords: soil organic carbon (SOC); topsoil; hilly city; Kriging interpolation

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1 Introduction

On a global scale, the soil organic carbon (SOC) pool is about 3.3 times the amount of the atmospheric carbon pool and 4.5 times the amount of the biotic carbon pool (Lal, 2004). The amount of carbon that can be stored in soils in the form of organic matter is approximately 1400–1600 Pg (1 Pg = 10^{15} g) (Post *et al.*, 1982; Eswaran *et al.*, 1993). The SOC pools of agricultural, forest and grass ecosystems have been widely studied (Wang *et al.*, 2000; Fang *et al.*, 2001; Golubiewski, 2006; Pan *et al.*, 2008; Zhang, 2010), but that of urban ecosystems has received relatively little attention (Churkina, 2008). Since urban ecosystems have undergone vast changes with rapid urbanization, it is necessary to investigate the storage, distribution and evolution of the SOC pool in urban ecosystem (Pataki *et al.*, 2006; Pouyat *et al.*, 2006).

The distribution of SOC exhibits a high spatial variability in urban ecosystems, compared with natural

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ecosystems. On the one hand, a large amount of vegetation cover has been converted to urban impervious surfaces such as buildings, roads, parking lots and roofs, which leads to loss of soil carbon through decreasing infiltration over soils (Cannell *et al*., 1999). On the other hand, physical disturbance, such as the burial or coverage of soil, transfer soil carbon from one place to another, which is different from natural or cultivated soil (Beyer *et al*., 1995; Zhou *et al*., 2003). Existing studies have found that the SOC density exhibited a high variation over different land use zones in urban areas such as residential, industrial, commercial, and recreational zones (Pouyat *et al*., 2002; 2006; Sun *et al*., 2009). For example, the SOC density in urban parks was higher than that in residential areas or roadside green land (Liu, 2009). Furthermore, owing to site-specific management practices and organic material input from human activities, the phenomenon of the accumulation of organic carbon in urban soil has been reported (Bian and Wang, 2003; He and Zhang, 2006; Zhang and Zhou, 2006).

However, for urban ecosystems, poor data availability of soil survey and measurements makes it problematic to assess the soil carbon pools across different places. Researchers need to collect a large amount of data through soil surveys for specified areas (Zhang *et al.*, 2007; Rawlins *et al.*, 2008; Sun *et al.*, 2009), but this is time-consuming and of high cost. Thus a few researchers have attempted to investigate the spatial variability based on limited soil samples using geostatistical methods, such as the commonly used Kriging method (Jiang *et al.*, 2005; Fan *et al.*, 2011). Most studies have concentrated on cities on the plains (Pouyat *et al*., 1995; Xu *et al*., 2011), and attention has rarely been paid to hilly cities (Tong and Dong, 2007; Zhang *et al*., 2007). In hilly cities, the spatial distribution of green land is more uneven, and the urban soil in the green land is highly spatially variable considering the impacts of the elevation, slope, microclimate or soil parent materials (Zhang *et al*., 2007). For the purpose of saving cost, it is feasible to use the Kriging method to estimate the distribution of SOC pools across the entire city, based on site-specific soil samples and available spatial variables.

This paper aims to quantify the SOC pool across hilly cities, taking Chongqing Municipality in the southwest of China as a study case. The main objectives were to investigate the co-variables of slope, urbanized periods and types of green land in mapping the spatial pattern of SOC density, using Kriging method and accuracy assessment. The interpolated results of SOC density are necessary for better estimations of soil carbon pools for hilly cities.

2 Materials and Methods

2.1 Study area and data sources

Chongqing′s urban core with an area of 238 km^2 (29°28'47"–29°38'25"N, 106°26'01"–106°36'04"E) was chosen as study area (Fig. 1). It is located between the two parallel north-south trending ranges of Zhongliang Mountain and Tongluo Mountain. The elevation of the study area ranges from 160 m to 560 m, and the terrain includes flat areas, hilly areas and low mountains. The flat areas with a slope of less than 6° amount to 42% of the total study area, the hilly areas with a slope of 6°–25° amount to 49%, and the low mountains with a slope of >25° amount to 9%. The study area includes both the old downtown and the newly developed urban areas, accounting for about half of the urban areas of Chongqing. Chongqing has a unique mountain city landscape in Southwest China, being influenced by terrain constraints and river separation. Since economic reforms, Chongqing has accelerated its urban expansion and evolved toward a ′polycentric′ and ′multi-nuclei′ urban pattern. As a hilly city, Chongqing has many forested small hills, remnant forests in higher mountainous ranges, and planted greenbelt along roads and rivers, which inhibit the continuous urban development between main center and multiple sub-centers. Consequently, urban green space offers a heterogeneous habitat for urban soil. Moreover, accompanying this rapid urbanization is the conversion of suburban open space to urban areas, and that of natural or cultivated soil to urban soil. The vegetation cutting or planting makes the development of urban soil and accumulation of SOC become diverse within the city.

The data from the soil samples were collected from October 2010 to June 2011. Other datasets include digital elevation model (DEM) data, roads network data, and Landsat Thematic Mapper (TM) images. DEM data with a spatial resolution of 5 m were obtained from topographic mapping at the 1∶10 000 scale, provided by Chongqing Institute of Surveying and Mapping, which could reflect the micro-sitting in the complex terrain of a hilly city. Roads network data were sourced from the vector map of land use, provided by the Chongqing Planning and Design Institute. Chongqing′s Landsat TM images (path: 128; rows: 39 and 40) in the years 1988, 2001 and 2010 were downloaded from the database of United States Geological Survey. Based on ENVI 4.6 software, urban patches were delineated from those images, using supervised classification. The land survey data collected in 1996 and 2009 were employed to correct classification errors in interpreted maps. Accuracy assessment based on 61 randomly selected samples discovered that the overall classification accuracy was as high as 91.8%, and the Kappa coefficient was 0.76.

2.2 Collection and analysis of soil samples

To avoid sampling bias, the vegetation cover of Chongqing was obtained prior to soil sample collection. Cloud-free QuickBird images with a spatial resolution of 0.6 m were chosen for vegetation classification. Based on a vegetation system including tree, bush and lawn, the vegetation map was extracted by using supervised classification with the help of ENVI 4.6 software. Two hundred and eight points were then randomly chosen to evaluate the accuracy of image classification, and it was found that the Kappa coefficient was 87.5%, indicating a high accuracy. Vegetation densities in each cell of 100 m × 100 m were calculated and shown in Fig. 2.

Second, soil sampling sites were designed in the vegetation map based on the grid point sampling technique with a size of 1 km (Fig. 2). Two hundred eighty-nine 0–20-cm samples were collected from October 2010 to June 2011, and bulk density was measured in 63 of them. Finally, only 220 valid topsoil samples were chosen for analysis. With the help of a Global Positioning System, soil sampling sites were located and terrain, vegetation cover, soil type, and soil environment were documented. The soil samples were air-dried, homogenized by hand, and passed through a 1-mm sieve. Big intrusive materials, such as part of a tree branch, wood chips and insects were separated manually from soil. Following that, approximately 5 g of soil samples were ground in an agate mortar and sieved using a 100-μm nylon sieve, for SOC analysis by the potassium dichro-

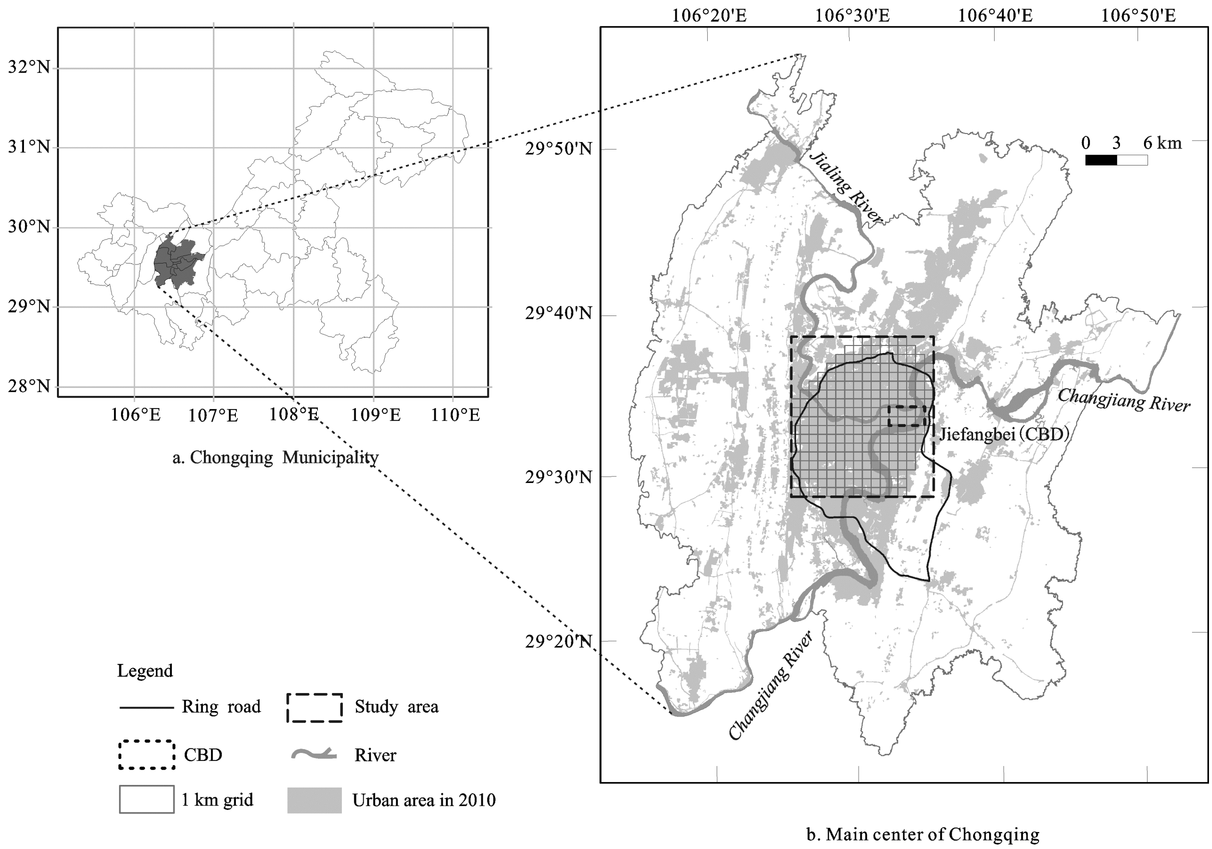

Fig. 1 Location of study area in Chingqing Municipality

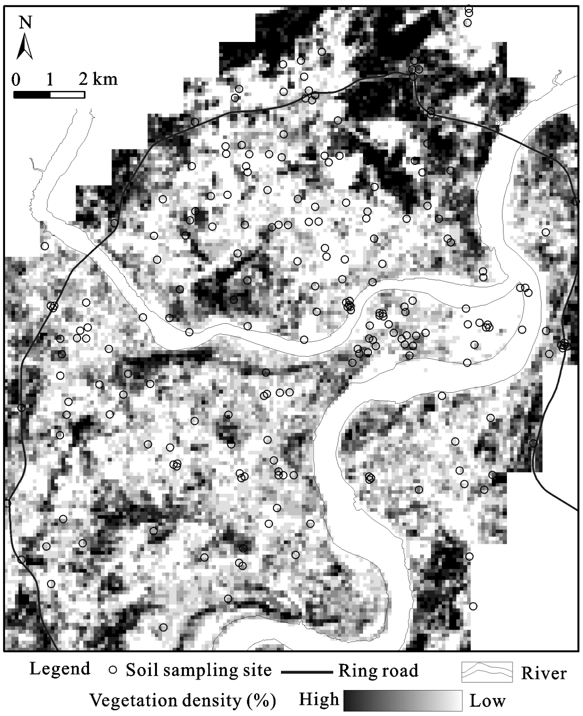

Fig. 2 Spatial pattern of vegetated areas and location of soil sampling sites in study area

mate volumetric method (LY/T 1237-1999). Soil bulk density was obtained by the gravimetric method (NY/T 1121.4-2006).

2.3 Calculation of SOC density and storage

SOC density measures the content of SOC in a fixed horizon, such as 0–20 cm. The SOC density was calculated by the equation as follows (Xu *et al.*, 2007; Ni *et al.*, 2009):

$$SOCD = SOC \times \gamma \times H \times 10^{-2} \quad (1)$$

where $SOCD$ is the SOC density (kg/m^2); SOC refers to SOC (g/kg); γ represents bulk density (g/cm^3); H is depth of soil (cm).

More intense soil sampling results in better estimated values, but is expensive. Spatial interpolation schemes allow a robust estimation of the SOC density to be obtained across the study area based upon the samples. Since the variables of slopes, types of green land or urbanized periods would cause spatial variability in SOC density in urban topsoil, those variables, easier to measure than the SOC density, can be used as geographic assistant information in the Kriging interpolation method. Three models of Kriging were tested to interpolate the value of the SOC density: using slopes, green land types, and urbanized periods as an assistant covariate. The SOC density of a sample was divided into two parts, the average value and the residuals for each sample type, which was calculated as follows (Fan *et al.*, 2011):

$$SOCD_{kj} = \mu_k + r_{kj} \quad (2)$$

where $SOCD_{kj}$ is the SOC density (kg/m^2) of sample j for soil sample type k (k = 1, 2, 3, …, n); μ_k is the average $SOCD$ value (kg/m^2) for soil sample type k; and r_{kj} is the residuals of sample j for soil sample type k. In ArcGIS 9.3 software, residuals r_{kj} was used as a new variable to produce a Kriged map of residual results. The estimated $SOCD$ of sample j was the sum of the Kriged residuals and the average $SOCD$ value of sample j (Fan *et al.*, 2011):

$$SOCD^*_{kj} = \mu_k + r^*_{kj} \quad (3)$$

where $SOCD^*_{kj}$ is the estimated $SOCD$ (kg/m^2) of sample j for soil sample type k (k = 1, 2, 3, …, n); μ_k is the average $SOCD$ value (kg/m^2) for soil sample type k; and r^*_{kj} is the Kriged residuals of sample j for soil sample type k. Assessment of Kriging accuracy in the GIS Environment is to compare the cross-validation results for three Kriging models as follows: the mean prediction error should be near zero; the root-mean-square error (RMSE) should be as small as possible; the RMSE should be near average standard error (ASE); the root-mean-square standardized error (RMSSE) should be approximately 1 (Jiang *et al.*, 2005). Random samples were used to observe the deviation of the Kriging results, and less deviation produced the better results.

Using the zonal statistics in GIS, vegetation density S_i and $SOCD^*_i$ at cell i with a size of 100 m by 100 m were calculated. The storage of SOC could be calculated through multiplying the vegetation fraction and the estimated SOC density, as follows:

$$SOCS = \sum_{i=1}^{n} S_i \times SOCD^*_i \quad (4)$$

where $SOCS$ represents the SOC storage (kg) across the study area; n is the number of cells with a size of 100 m by 100 m; S_i is vegetated cover area of cell i (m^2); and $SOCD^*_i$ is the estimated SOC density of cell i (kg/m^2).

3 Results

3.1 Analysis of observed SOC density

First, the variation of the SOC density across different slopes was analyzed. Five types of slopes were reclassified: 0°–2° and 2°–6° for flat areas, 6°–15° and 15°–25° for hilly areas, and >25° for mountainous areas. Figure 3a shows that the areas with a slope of 2°–6° had an average SOC density of 3.36 kg/m^2, owing to site-specific management. The areas with a slope >25°, located in urban parks and natural preserved areas with dense trees and bushes, had an average value of 3.20 kg/m^2. In contrast, hilly areas with a slope of 15°–25° had a relatively low density (2.21 kg/m^2), owing to loss of soil fertility from intense human activities on this fragile ecosystem.

Second, the differences of SOC density were given among the urbanized periods of pre-1988, 1988–2001, and 2001–2010. Figure 4 disclosed urban land use conversion based on interpreted results of Landsat TM images. It was found that Chongqing experienced rapid growth toward the north in the latest decades, especially in the Liangjiang New Area located north of the Jialing River. The results show that the SOC density was high in central urban areas and decreased in newly urbanized areas. The SOC density during the urbanized periods of pre-1988, 1988–2001, and 2001–2010 were 3.12 ± 1.73 kg/m^2, 2.57 ± 1.58 kg/m^2 and 1.87 ± 1.03 kg/m^2, respectively. A simple calculation indicates that the average SOC density during 2001–2010 was lowest, 27.4% less than that during 1988–2001, and 40.2% less than that before 1988 (Fig. 3b).

Third, the SOC density varied over different types of green land. Referring to the classification of urban green space (CJJ/T85-2002), the green spaces were divided into five types: transport green land, street green land, public open spaces, parks and gardens, and residential green land. As expected, the SOC density was relatively high in urban parks, with an average of 3.63 kg/m^2. However, the variation is very high in urban parks: the highest value was in Chongqing Zoo, averaging 15.65 kg/m^2, whereas the lowest value was in Hong En Temple Park, a newly established park, averaging 1.28 kg/m^2. It is worth noting that residential green land had a low average of 2.73 kg/m^2, which could be caused by compact living districts in hilly cities. Low density SOC was found in scattered transport and street green land, resulting from low fertilizing and watering (Fig. 3c).

3.2 Estimation of Kriged SOC density

The Kriging method was used to interpolate the residuals of the SOC density using slopes, green land types, and urbanized periods as an assistant covariate. The Kriging module provides alternative variogram models, such as spherical, exponential and Gaussian models. For these data, an exponential model was a good first choice, because its nugget/sill ratios between 25% and 75% suggest that the variable had a moderate spatial dependence and local variations could likely be captured. Figure 5 presents the Kriging results showing that, for three methods, the residuals of the SOC density decreased from the south to the north of the Jialing River, and had positive residuals in parks and a negative one in the Liangjiang New Area, which conformed to the observed pattern of the SOC density. However, there were differences from one Kriging method to another; for example, the Kriging pattern combined with slopes and green land types had a similar pattern (Fig. 5a, c), but

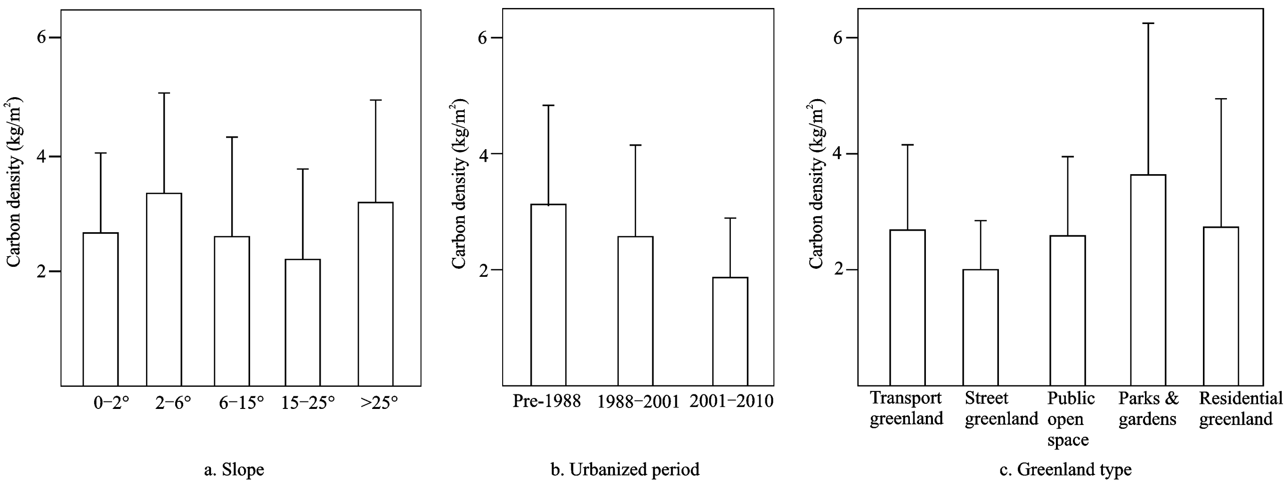

Fig. 3 Means and deviations of SOC density of different kinds of soil samples

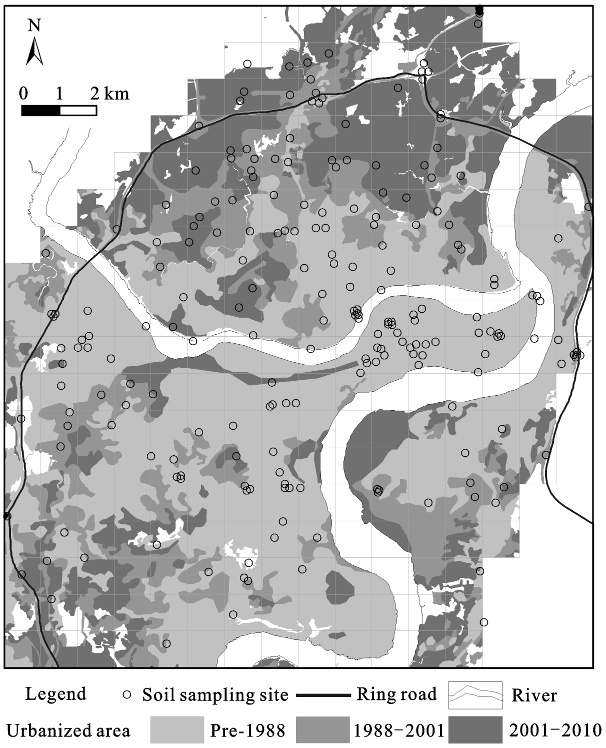

Fig. 4 Urban topsoil sampling site in different urbanized periods

the Kriging pattern combined with urbanized periods had a more fragmented pattern in the north (Fig. 5b).

Cross-validation allows comparison of estimated and true values using the information available in a sample dataset. The RMSE of the Kriging method combined with slopes was as low as 1.503, whereas the method combined with urbanized periods and green land types was higher, being 1.517 and 1.524, respectively. The ASE of the first method (1.533) was more than the RMSE, and the RMSSE (0.979) was less than 1, which indicated possibly higher estimated residuals than the true ones. In all, the first method would be a good choice. Accuracy assessment was further carried out based on ten random samples, and the deviation of estimated and true values was as low as ±0.006 kg/m^2. After that, both inverse distance weighting (IDW) and the Kriging method without assistant information were tested for comparison. The RMSEs of Kriging and IDW were 1.55 and 1.52, respectively, being higher than the previous methods.

3.3 Estimation of SOC storage

The storage of SOC is determined by the vegetation coverage and the estimated SOC density. The SOC pool in green land topsoil is considered here, while the SOC pool covered by impervious surfaces is neglected, since the covered soil lacks sources of nitrogen input combined with slow decomposition rates. The results of vegetation subtraction indicates that urban green land was mainly distributed around parks, open spaces, hilly areas and the undeveloped areas north of the ring road

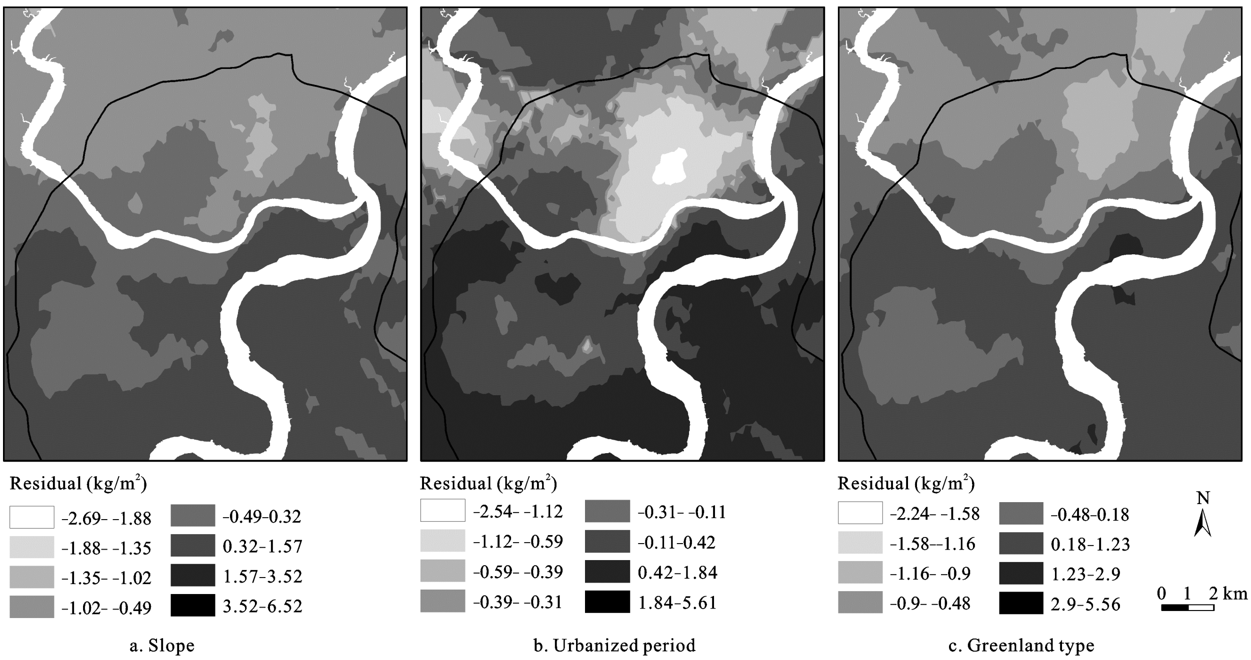

Fig. 5 Mapped SOC density residuals in urban topsoil

(Fig. 2). The vegetation cover accounted for 30.9% of the total area, with an area of 73.5 km^2. The green land area was 35.5% of the urban built-up areas in Chongqing in 2010, as reported by the Chongqing Bureau of Parks and Woods. Considering the high density of buildings, the figure of vegetation coverage was probably reliable. Using Equation (3), the estimated SOC density was calculated by the Kriging model with slopes as a secondary variable. From Equation (4), the result of cell calculation demonstrated that the storage of SOC in urban topsoil was 0.192 Tg (1 Tg = 10^{12} g) for all green land across the study area, with an average SOC density of 2.61 kg/m^2. As reported by Huang *et al.* (2005), purple and yellow soil are the most common soil types in Chongqing, with an average SOC density of 2.21 kg/m^2 and 3.88 kg/m^2, respectively, which is in accordance with the present results. The whole of Chongqing, with an area of 82 400 km^2, had 0.273 Pg storage of SOC in topsoil to 0–20 cm, according to the results estimated by Huang *et al*. (2005). The storage of SOC in this study area occupied approximately 0.07% of the SOC pool in the whole of Chongqing. However, urban soil management has become a growing concern when considering its potential effects on the environment during rapid urbanization.

4 Discussion

The SOC density in topsoil of hilly cities is likely to be lower than that of cities on the plains. The results of this study show that 15°–25° slope areas accounted for nearly half of the study area, but the SOC density in those areas was as low as 2.21 kg/m^2 and less than the average value of 2.61 kg/m^2. This reflects the fact that human activity can exacerbate the risk of soil erosion and make soil less able to hold water and nutrients, especially for the sloping areas such as hills, gullies, and mountainous fringes. More evidence was the low density SOC in the residential green land of Chongqing, only being 2.73 ± 1.90 kg/m^2, which could be explained by dense buildings and sparse, scattered vegetation in residential zones. The SOC density in residential spaces of cities on the plains would be much higher. For example, Baltimore and Chicago in the United States had an SOC density of 12.2 ± 1.1 kg/m^2 and 16.3 ± 1.6 kg/m^2, respectively, in 0–20 cm of residential grass (Pouyat *et al.*, 2006), and Shanghai had a density of 23.9 kg/m^2 in 0–30 cm (Liu, 2009). Furthermore, the average SOC density in the study area during 2001–2010 (the period of most rapid urbanization) was lowest, 27.4% less than that during 1988–2001, and 40.2% less than that before 1988. Chongqing has a more fluctuated SOC density than Shanghai (Xu *et al*., 2011), since the average SOC density during 2000–2005 in Shanghai was only 6.80% less than that during 1980–2000, and 36.90% less than that before 1980 (Xu *et al.*, 2011). This reflects that urban development and its land use conversion puts intensive influences on the SOC pool in hilly cities. Strategies of accumulating SOC in Chongqing should integrate nutrient management and waste recycling for restoring soil with green coverage increment, toward the objective of national model cities for environmental protection.

Second, the high spatial variability of the SOC density for hilly cities means that Kriging results need to be improved by incorporating assistant information such as terrain. In general, urban soils consist of various parent materials owing to soil mixing, waste material importing and contamination. They are also highly disturbed when native vegetation is cleared or destroyed during urban development (Pouyat *et al.*, 2002; Lorenz *et al.*, 2006). For the purpose of saving cost and enhancing accuracy, the easily measured variables could be used as geographic assistant information in the Kriging interpolation method. The results of three Kriging models indicate that variables such as terrain, vegetation and human activities are appropriate. The Kriging results combined with slope had especially good performance compared with the results of IDW or Kriging without a secondary covariate. It is worth noting that estimation of the SOC pool in rural soils could be calculated by the SOC density and the percentage of soil types (Ni *et al.*, 2009), while it is not appropriate in the estimation of the urban SOC pool as mixed disturbances and input of industrial organic waste and garbage diversify the sources of the urban SOC pool (Xu *et al.*, 2011). There could be an uncertainty in this paper, considering the high variability of urban topsoil and the significant but neglected variables. In addition, the relationship between soil sample density and the estimated accuracy still needs to be studied (Fan *et al.*, 2011).

5 Conclusions

Based on soil sample collection and remote sensing, the storage and density of SOC in urban topsoil were estimated and the following conclusions were drawn:

(1) The SOC density exhibited high spatial variability in the urban topsoil of Chongqing, varying between different slopes, different types of green land and different urbanized periods. The flat areas with a slope of 2°–6° had a high SOC density in topsoil (averaging 3.36 kg/m^2), the hilly areas with a slope of >25° averaged 3.20 kg/m^2, and the sloping areas of 15°–25° ranked last (averaging 2.21 kg/m^2). The newly developed areas during 2001–2010 to the north of the Jialing River had a lower SOC density than the existing areas before 1988 in the south, which can be indicated from an average SOC density of 1.87 kg/m^2 and 3.12 kg/m^2 , respectively. Urban parks and gardens had a high SOC density (averaging 3.63 kg/m^2) than other green lands, and residential green land had a low average of 2.73 kg/m^2.

(2) For hilly cities, the variability of terrain pattern affects the distribution of SOC. The Kriging method combining slope with SOC density had a high accuracy, with a RMSE as low as 1.503, while the method combining green land types with SOC density had a higher RMSE. The interpolated results show that the SOC density to the north of the Jialing River was higher than that in the south. The vegetated areas were estimated to amount to 73.5 km^2 across the study area, with an SOC storage of 0.192 Tg and an average density of 2.61 kg/m^2.

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