Topsoil Organic Carbon Variability in Residential Land of Rapidly Urbanizing Areas and Its Influencing Factors: A Case Study of Nantai Island, Fuzhou (Postprint)

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Abstract

Based on residential land extraction for Nantai Island (Cangshan District) of Fuzhou City from high-resolution imagery, 50 sample quadrats were randomly selected from a 30 m × 30 m grid covering the study area for surface soil sampling to analyze the variation characteristics of soil organic carbon density (SOCD) in the topsoil of residential land and its influencing factors in this rapidly urbanizing region. The results show that: under intense human activity disturbance, soils in urban residential areas exhibit pronounced spatial variation characteristics, with a mean SOCD of 33.814 t/hm² and a coefficient of variation of 72.8%. The SOCD in the 0–20 cm soil layer of suburban village residential land is 72% higher than that of urban residential land, indicating that in-situ urbanization of villages will result in decreased soil carbon storage. However, no significant differences in topsoil organic carbon content and density are observed between urban residential communities with construction ages of 0–5 years and 5–10 years, with significant improvement occurring only when construction age reaches 10–15 years. The greening environment management quality index for urban residential areas, constructed based on factors including humidity, heat, greening rate, and property management fees, demonstrates significant positive correlations with topsoil organic carbon content and density in urban residential areas and significant negative correlation with soil bulk density, representing another major factor influencing SOCD variation in rapidly urbanizing regions.

Full Text

Variability of Soil Organic Carbon and Factors Affecting It in Residential Lands in a Rapidly Urbanizing Area: A Case Study of Nantai Island in Fuzhou City, China

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Abstract

Based on high-resolution imagery extraction of residential land in Nantai Island, Fuzhou City, this study conducted surface soil sampling from a 30 m × 30 m grid covering the study area to analyze the characteristics and influencing factors of soil organic carbon density (SOCD) in residential lands within this rapidly urbanizing region. Under intense human activity disturbance, urban residential soils exhibited significant spatial heterogeneity, with an average SOCD of 33.814 t/hm^2 and a variation coefficient of 72.8%. The SOCD in the surface layer (0–20 cm) of suburban rural residential land was 72% higher than that of urban residential land, indicating that in-situ urbanization of rural villages would lead to declines in soil carbon stocks. Both SOC content and density in the surface layer were significantly higher in housing developments built 10–15 years ago compared to those less than 10 years old, though no significant differences were observed between 0–5 year and 5–10 year developments. A composite index developed in this study for urban residential green space management quality, which combined humidity, heat, green coverage ratio, and property management fees through principal component analysis, showed significant positive correlations with SOC content and density, and negative correlation with bulk density. Therefore, residential green space management represents another key factor affecting SOCD variation in rapidly urbanizing areas. Although the conversion of rural residential land to urban residential land will lead to SOCD declines due to reduced exogenous organic material input, the living environment has been improved, and green space management also contributes to the improvement of urban soil quality.

Keywords: rapid urbanization; residential land; soil organic carbon density; Fuzhou City

1. Study Area Overview

Cangshan District in Fuzhou is located in the southern part of the city (25°15 - 26°39 N, 118°08 -120°31 E), covering the entire Nantai Island with an area exceeding 150 km^2 and a population of approximately 1.03 million, accounting for 26.4% of Fuzhou’ s total population. The island is surrounded by the Min

River, with a river length of 27.3 km and additional islet area of 10.3 km^2. Due to the rapid development of the Jinshan area in western Nantai Island, Nantai Island has gradually become an important residential area in Fuzhou. The region features a south subtropical maritime monsoon climate with distinct seasonal precipitation variation. The average annual precipitation is 1,395.6 mm, with 73.6% concentrated in the summer half-year. The average annual rainfall days number 142.3, average annual sunshine hours are 4,425.9 h, and average annual relative humidity is 58.1%.

2. Sample Collection and Processing

Using ENVI 5.1 remote sensing software, SPOT 6 imagery (March 7, 2014) was processed with Pan Sharpening to achieve a spatial resolution of 1.5 m. Visual interpretation was employed to extract residential land in the study area, which was further subdivided into urban residential land and rural village housing. According to current land use classification standards, rural homesteads and urban residential land were merged into a single category because their colors and textures are very similar in remote sensing images. While visually interpreting and vectorizing urban land use from the SPOT 6 imagery and soil type maps, a 30 m × 30 m grid was created for the entire study area. Using ArcToolbox, grids completely falling within residential land boundaries were extracted, and these corresponding grids served as randomly selected field soil survey plots. If surface soil could not be obtained in individual sampling grids, they were moved to the nearest grid. Figure 1 [Figure 1: see original paper] shows the spatial distribution of residential land and soil sampling points in Nantai Island, Fuzhou.

Field surveys were conducted in May 2014. A soil auger with 5 cm diameter was used to collect samples. Within each plot, 5–8 sampling points were distributed as uniformly as possible. Samples were collected from green spaces or bare soil at depths of 0–10 cm and 10–20 cm. A ring knife was used to collect samples for bulk density determination and to calculate the impervious surface percentage (ISP) of the plot. Soil samples were air-dried in the laboratory, passed through a 2 mm sieve, and stored for analysis. Since a considerable portion of soil samples contained construction waste and bricks, inorganic carbon removal was necessary. Soil samples were treated with 1 mol/L HCl, heated on an electric hot plate until nearly dry, then transferred to an oven and dried to constant weight. Finally, a carbon-nitrogen elemental analyzer (ELEMENTAR Vario EL III CN) was used to determine soil organic carbon (SOC) and total nitrogen (TN).

3. Data Compilation and Analysis

ArcGIS 10.3 software was used to compile the measured soil properties and related geographic information database. To explore the impact of urban residential area management quality, corresponding variables were obtained from aspects of heat, greening rate, and property management level. Landsat 8 imagery (September 2014) was radiometrically corrected and used to calculate brightness temperature as a heat factor. The tasseled cap transformation method was applied to derive wetness index, which is sensitive to both soil moisture and vegetation. Residential districts with fluvo-aquic soil type were selected, and their residential community vector polygons were delineated to extract average brightness temperature and wetness index. Data on residential community construction time and property management fees were obtained from real estate websites (http://esf.fz.fang.com/map/). SPSS 19.0 was used for descriptive statistics, principal component analysis, and variance analysis with multiple comparisons.

Soil organic carbon density (SOCD) typically refers to SOC storage per unit area per unit depth. Since urban development often results in missing surface soil due to impervious surface coverage, this study introduced ISP to correct SOCD calculations for urban surface soils:

$$SOCD_i = C_i D_i H_i (1 - I)$$

where $SOCD_i$ (t/hm^2) is the soil organic carbon density, k is the number of soil layers, H_i is the thickness of the i-th layer (cm), C_i is the SOC content of the i-th layer (g/kg), D_i is the bulk density of the i-th layer (g/cm^3), I is the impervious surface percentage (ISP) in the plot (%), and δ is the percentage of gravel larger than 2 mm. This study divided samples into two layers, each 10 cm thick.

1. SOCD in Random Sampling Grids

The SOCD data for surface soil (0–20 cm) in Nantai Island residential land, as well as log-transformed and square root-transformed data, all followed normal distribution. The average SOCD was 33.814 t/hm^2 with a variation coefficient of 72.8%, indicating moderate spatial variability. This demonstrates that under intense human activity disturbance, urban residential soils exhibit strong spatial heterogeneity. The ISP ranged from 0.22 to 0.708, representing the proportion of surface soil replaced by impervious surfaces in randomly selected plots, confirming that incorporating the ISP parameter for urban area sampling meets random sampling requirements.

2. Differences Between Urban and Rural Residential Land

The study area contained both urban residential land and rural village residential land, with areas of 2,277.67 hm^2 and 2,080.78 hm^2, respectively. The average SOCD (0–20 cm) of rural residential land (43.488 t/hm^2) was significantly higher than that of urban residential land (25.256 t/hm^2). Although urban residential land had higher SOC content in the 0–10 cm layer, rural residential land showed significantly higher values in the 10–20 cm layer. Bulk density in rural residential land (1.219 g/cm^3 and 1.335 g/cm^3 for the two layers) was significantly lower than in urban residential land (1.328 g/cm^3 and 1.451 g/cm^3). The C/N ratio was also significantly higher in rural residential land (11.169 and 12.093) compared to urban residential land (9.785 and 10.237). These differences indicate that more exogenous organic material input and higher C/N ratios are the main reasons for higher SOCD in rural residential land. In terms of variability, urban residential land showed higher variation coefficients for SOCD (66.6% and 76.7% for the two layers) compared to rural residential land (65.7% and 72.0%). Table 1 compares soil properties between urban and rural residential lands.

2. Residential Areas of Different Construction Ages

Samples with fluvo-aquic soil were grouped by residential community construction age. Soil pH in Cangshan District remained neutral to weakly alkaline and did not change significantly with soil formation time. SOC content and density in the 10–15 year group were significantly higher than in communities less than 10 years old, though no significant differences existed between 0–5 year and 5–10 year groups. Compared to older rural housing, urban residential land requires longer accumulation time for soil carbon stock recovery. The 10–15 year group showed SOC content of 14.126 g/kg and SOCD of 26.578 t/hm^2, representing increases of 12.8% and 31.5% respectively compared to the 0–5 year group. Table 2 shows differences in surface soil (0–20 cm) properties among residential districts of different ages.

3. Relationship Between Urban Residential Area Management and Plot Soil Properties

Four indicators related to residential green environment management quality (wetness, bright temperature, green coverage ratio, and property management fees) were analyzed using principal component analysis. The first principal component (PC1) had an eigenvalue greater than 1 and explained 62.77% of the variance, with factor loadings of 0.765, -0.754, 0.779, and 0.866 for the four indicators, respectively. PC1 was used as a composite index representing urban residential green space management quality. This index showed significant positive linear relationships with SOC content and density ($R^2 = 0.513$, $p < 0.05$ and $R^2 = 0.562$, $p < 0.01$, respectively) and negative correlation with bulk density, though the latter was not statistically significant. Higher quality green environment management, objectively manifested as higher greening rates and humidity with lower surface temperatures, promotes soil loosening to some extent. Figure 3 [Figure 3: see original paper] illustrates the linear relationships between the composite management quality index and surface soil parameters.

1. Variability of Urban Soil Organic Carbon and Its Implications for Regional Carbon Stock Prediction

High spatial variability in urban soils, combined with differences in urban development stages and land use backgrounds, creates considerable uncertainty in urban soil carbon stock estimation. The SOCD in Nantai Island residential land showed variation coefficients exceeding 70% and extreme differences ranging from 6.667 to 85.689 t/hm². This variability is similar to early representative studies in Baltimore, USA and Stuttgart, Germany. Urban residential land SOCD (25.256 t/hm²) was lower than Beijing' s Fifth Ring Road residential green space (54.4 t/hm²) and Baltimore residential turf (45.5 t/hm²), mainly because rapid urban construction in recent years removed or replaced vegetation ecosystems and surface soils, reducing organic matter input. The assumption of surface soil disappearance under impervious surfaces, combined with the widespread distribution of fluvo-aquic soils with loose structure, also contributed to lower calculated values. Urban areas exhibit obvious landscape spatial heterogeneity due to 镶嵌着 shape and size variations of impervious surfaces, green spaces, and water bodies, which profoundly influence soil spatial variability and carbon pool size. Traditional soil mapping often excludes urban areas or only includes parks and unvegetated zones, failing to recognize the complex distribution characteristics of urban soils. The concept of "urbanized soil space" as a combination of soil and non-soil components in different proportions provides theoretical basis for introducing impervious surface percentage in SOCD calculations.

2. Impacts of Rural In-situ Urbanization and Anthropogenic Management

High spatial variability in urban soils requires auxiliary information to improve prediction accuracy. Rural residential land SOCD was 72% higher than urban residential land. Most rural residential areas have poor environmental sanitation conditions, with random waste accumulation and improper sewage discharge, resulting in substantial anthropogenic input of exogenous carbon and nitrogen into soils. When rural land undergoes rapid in-situ urbanization, SOC stocks will significantly decline. Similar trends show that urban areas in Boston and Syracuse had SOC stocks 2–3 times lower than before urbanization, with increased road density being a major cause of carbon loss. However, some studies show higher urban SOC stocks along urban-rural gradients, such as in Chicago and Auckland where urban areas were 1.5 times higher than suburban rural areas. These contradictory views mainly result from differences in land use background and time factors. Different land use histories lead to varying initial carbon density values, and carbon accumulation rates differ after urban vegetation planting. Like farmland during initial fallow stages, extending the period promotes carbon accumulation. Although conversion of rural to urban residential land reduces exogenous carbon input, it greatly improves living environment sanitation, and green space management contributes to continuous soil quality improvement. Studies show that urban residential green spaces with higher management levels have carbon densities more than double those of newly built residential areas.

4. Conclusion

The average SOCD in Cangshan District residential land was 33.814 t/hm² with a variation coefficient of 72.8%, indicating moderate spatial variability under intense human disturbance. Rural residential land SOCD (0–20 cm) was significantly higher than urban residential land, with more exogenous organic material input and higher C/N ratios being the main reasons. Urban residential land SOC content and density showed no significant differences among newly built communities (<10 years), but only became significantly higher in 10–15 year-old communities, while C/N ratios showed no significant changes. This indicates that urban residential land requires more than 10 years of stabilization for significant SOC accumulation. The first principal component from PCA, representing urban residential green space management quality, showed significant positive correlations with SOC content and density, indicating that residential green space management is another important factor affecting SOCD variation in rapidly urbanizing areas.

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Note: Figure translations are in progress. See original paper for figures.