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ScienceDirect
Catena 69 (2007) 74–81
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Establishing a spatial grouping base for surface soil properties along urban–rural gradient—A case study in Nanjing, China

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Abstract

Conventional classification systems based on vegetation and land use are frequently used to characterize or describe urban soils to determine the influence of urbanization on soils. In this study, the sensitivity of different grouping methods in reflecting soil variations along an urban–rural gradient was compared. The objective of this study was to determine the most sensitive grouping system in depicting and explaining variations of soil attributes around an urban area. Grouping methods, including urban–rural division, in situ vegetation type, land use types in different scales and numerical clustering, were compared for both single soil attributes and "soil set" defined by multiple variables. The result shows urbanization has a strong impact on many soil properties, especially that of gravel content, sand content, pH, phosphorus and soil compaction. In terms of the variations of soil attributes, in situ vegetation type is the most sensitive in comparison with local land use types and district-viewed land use types. In other words, soil properties in this study are not sensitive to coarser spatial resolution. Therefore, it's hard to interpret the spatial variation of urban soil by regular methods using natural soil-landscape paradigm. Furthermore, vegetation would best proxy the delineation of single attribute of urban soils. Numerical clusters effectively reflect the land use types and their change during urbanization. All clusters were interpreted as different sets with practical meanings: soil in abandoned greenbelt, soil in ill-managed greenbelt, soil in new vegetable land, extreme urban conditioned soil, soil in well-managed greenbelt, soil in highly mellowed vegetable land, soil in common urban–peri-urban greenbelt and weak-urban-impacted soil. They can be used as bases for soil regionalization in urban and peri-urban environment.

Keywords: Urban soil; Urbanization; Land use; Vegetation; Grouping method

1. Introduction

Research comparing urban soils to their rural counterparts has largely been neglected (Thornton, 1991). As an important component in urban ecosystem, which is closely related to other components such as air dust (Marcazzan et al., 2003), surface water (Susanna et al., 2002), ground water (Collin and Melloul, 2003), and soil fauna and flora (Jim, 1998; Crouau et al., 2002; Stephen et al., 2003; Peter et al., 2005), soils in urban areas are attracting more and more attention (Beyer et al., 1995). Although soils in urban areas are characterized by unique features in the process of urbanization (Paterson et al., 1996), there is no universally accepted classification system for urban soils, which is comparable to the classification system of rural or natural soils. Burghardt (1994, 1997) brought forward a classification system for soils in urban and industrial area which is mainly based on substrate features. Most of current soil classification systems cannot accurately describe urban soils although some of them give very rough descriptions (ISSS-ISRIC-FAO, 1998; Soil survey staff, 1998; CRG-CST, 2001). So, many studies about soil changes in the urbanization process characterized or described soils with conventional classification systems of vegetation (i.e. soils covered by lawn) (Guan et al., 1998; Davydova, 2005) or land use (i.e. soils in residential area) (Pouyat et al., 2002; Chirenje et al., 2003; Zhu and Carreiro, 2004). The definitions of land use or vegetation implied possible impacts on soils caused by specific land use type or vegetation type. But the impacts on soils are various during

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doi:10.1016/j.catena.2006.04.017

the urbanization process, such as sealing, intensive disturbance, mix of building and daily rubbish, sedimentation of air dust, and infiltration of sewage. So, the soil differences among land use types or among vegetation types cannot be simply thought as the proprietary results caused by different land use or vegetation types. It is difficult to quantitatively evaluate the contributions of different factors on soil changes during the urbanization process because of the absence of long-term observation. Furthermore, those systems about land use and vegetation are often static concepts without clear definition of spatial resolution, while soil changes and their factors are closely related to spatial scale. In spite of a lot of results in such studies, the major factors causing the spatial variation of urban soils have not been well addressed and distinguished. Conventional grouping systems often fail to tell the density and trend of soil changes under urbanization. The specific soil and landscape relations that are fundamental to soil classification and mapping, remain as a task to be done for urban environment. Constructing a rational classification system in relation to environmental parameters for urban soils is urgently needed.

General properties of urban soils are important indicators of the urban environment (Paterson et al., 1996; Huinink, 1998; Zhang et al., 2005). The aim of this study is to determine a most suitable grouping system for depicting and explaining the variations of soil properties along an urban–rural gradient in Nanjing, China. Vegetation and land use types at different scales were compared for both single soil properties and multivariable clusters.

2. Materials and methods

2.1. Study site and soil sampling strategy

Nanjing, the capital of Jiangsu province, is a city with more than 2000 years of history, located in the lower reaches of the Yangtze River (Fig. 1). The population of the main urban area is about 2 million. The main urban area of Nanjing was 32 km^2 in 1947, 108 km^2 in 1978, 144 km^2 in 1997 and nearly 200 km^2 in 2000 (He and Cui, 2000). Some new urban areas were developed rapidly in recent years such as the Hexi district in the west part of the main city, Jiangning district in the south part and Xianlin in the east part (Zhou et al., 2002). At the same time, the old urban area is undergoing intensive renewal and reconstruction, a phenomenon similar to most other cities in China. The main soil parent material of urban Nanjing is the Yangtze River alluvium. The dominant soils in and around Nanjing are Eutric and Mollic Gleysol and Gleyic Luvisol with inclusions of Planosol and Eutric Fluvisol (SSGN, 1987). The dominant natural vegetation is deciduous broadleaved forest. Most of the forest vegetation is focused in specific spots such as the Purple Mountain, Qingliangshan Park, Yuhuatai Park and some vegetable farms. In the main urban area, there is less green land (Zhou

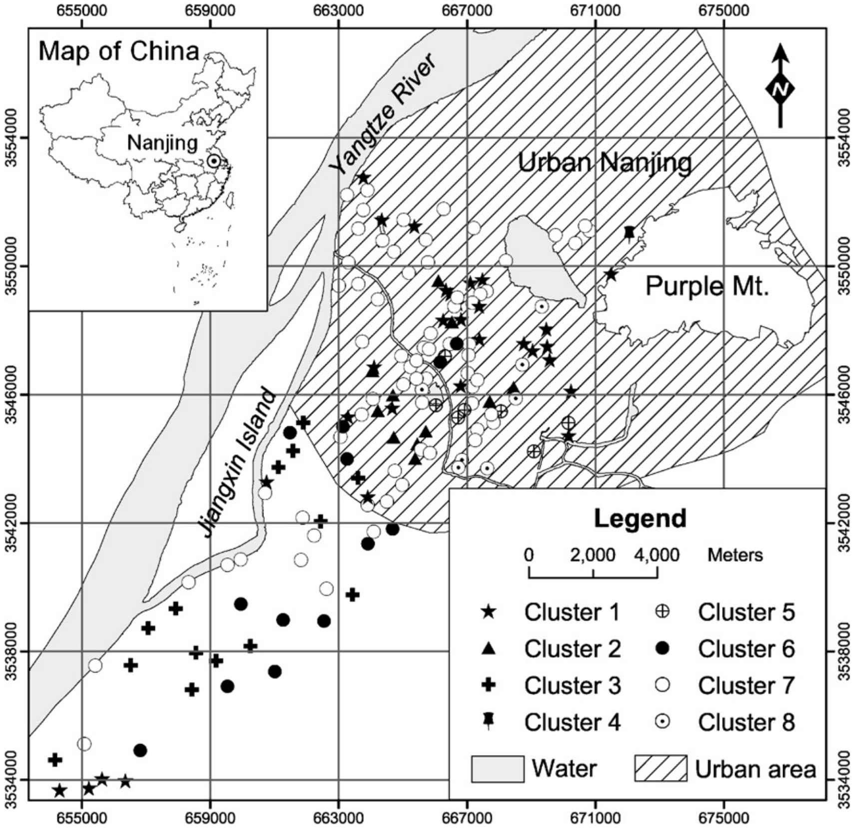

Fig. 1. The location of the study site and distribution of soil sampling sites.

et al., 2002). A lot of vegetable farms are distributed around the urban area, with industrial plants spotted among them. Outside the area of vegetable growing are paddy fields.

In this study, one urban–suburban–rural gradient located in the southwest part of Nanjing was selected. The length of the band is 24.8 km, the width 9 to 3 km gradually narrowing from urban to rural. Beginning in the spring of 2003, a systematic soil investigation of urban Nanjing was carried out. One net layer with 200 units of 1 km × 1 km size was overlapped with a map of the studied region. The number of sample sites was proportional to the size of the specific land use. 6–8 soil sampling sites were taken in each square unit for urban area, 4 for peri-urban and 2 for rural area. More samples were collected in the urban area because the spatial variation of the urban soil is presumably greater than that of rural soil, and we had very limited knowledge about soils in the urban area. A total of 157 soil sampling sites were chosen and the number of samples approximately equals the types of land use and vegetation in this study (Fig. 1). Soil samples were taken from the surface 10 cm and from 10 to 30 cm depth at each sampling site.

2.2. Laboratory analysis

All soil samples were collected by stainless-steel tools, were air-dried, ground with carnelian mortar, and sieved through 10, 60 and 100 mesh nylon sieves. Soil pH value, total organic carbon (TOC), total phosphorus (TP), available phosphorus (AP), total potassium (TK), available potassium (AK) and total iron (TFe) were measured according to ISSAS (1978). Particle size distribution was determined by a laser analyzer (LS230, Beckman Coulter). USDA soil texture system (USDA, 1993) was used for the classification of sand, silt and clay. Three replicate core samples were taken for the measurement of bulk density (BD) in the surface layer of each site (ISSAS, 1978). Gravel content (GC) includes coarse fractions >2 mm.

2.3. Statistics and GIS Software used in this study

SPSS10.0, MS EXCEL 2000, ArcView3.3, ArcGIS 8.3 were used for data analysis and data processing.

2.4. Determination of land use and vegetation information

Two levels of land use information with different spatial resolutions were adopted in this study: The local land use type was defined by the dominant land use in a 0.2 km^2 area around the soil sampling site, and the block-viewed land use type was defined by the dominant land use in an area of more than 1 km^2 around the soil sampling site.

Vegetation type reflects the information of plant species right at the sampling site. It's point-featured information in comparison to the local land use type and block-viewed land use type which were polygon-featured information. Eight types of vegetation were distinguished in this study (Table 1). Crop type and vegetable type are mainly distributed in the rural area, and others mainly distribute in the inner and peri-urban areas.

Land use types at different scales and vegetation type of each sampling site were primarily determined and recorded during the field survey according to the Chinese GB (national standard) system (MCC, 1992, 2002). Some special vegetation types, such as small artificial garden plants that are popular in urban Nanjing but there is no description in Chinese GB system, were appended. The primary classification was further revised based on the SPOT5 satellite image taken on November 2002.

3. Results and discussion

3.1. Two-group-system, urban group and rural group, a primary investigation

The study area was classified as urban part and rural part for the primary characterization of soil conditions in the study area. There were no quantitative standards to define the boundary between the urban and rural areas. One borderline was roughly delineated based on the image of SPOT5 with 2.5 m resolution. 37 sites located in the rural area, and 120 sites located in the urban area were identified. Independent *t*-test was carried out to investigate the difference of soil attributes between the urban and rural areas.

Fig. 2 shows that there are significant differences for most variables between the urban and rural soils for both layers.

Table 1
List of main vegetation and land use types determined in this study

Vegetation type		Local land use type		District-viewed land use type	
ID	Contents	ID	Contents	ID	Contents
1	Tree	1	Agricultural land	1	Urban residential zone
2	Shrub	2	Municipal land	2	Educational zone
3	Natural grass in wasteland	3	Park green land	3	Commercial zone
4	Lawn	4	Street green belt	4	Industrial zone
5	Crop	5	Industrial land	5	Recreational zone
6	Vegetable	6	Residential land	6	Agricultural zone
7	Small artificial garden plants	7	Traffic land	7	Traffic zone
8	Non-vegetation	8	Others	8	Official zone
				9	Suburban residential zone

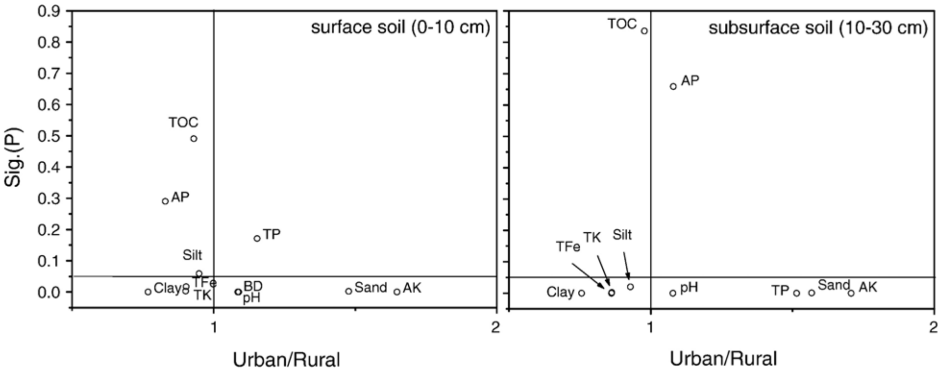

Fig. 2. Ratio of properties of urban and rural soils. Note: 1. Horizontal line in the figure means level of 95% confidence. 2. Variable dotted in the left side of vertical line means the value is lower than 1 when the content in urban soil was divided by that in rural soil, conversely if one variable dotted in the right side.

Exceptions were the AP and TOC for both layers, silt and TP for surface layer. pH, AK, sand content and gravel content in urban soils are higher than those in rural soils, while TK, TFe and clay content in urban soils are lower than those in rural soils. There is a reverse trend between the TK and AK. The content of AK in rural soils is lower than that in urban soils.

There is no significant difference in the P content between soils in the urban area and those in rural area, which is different from the results that claimed accumulations of P in urban soil (Stroganova et al., 1998; Zhang et al., 2001), but the accumulation occurred both in the urban and peri-urban soils.

The study area was located in the alluvium of the Yangtze River. This area is quite homogeneous in terms of spatial variation of soil type and soil properties. Therefore, most of the differences between soils in urban area and soils in rural area can be qualitatively explained by the influences caused by the urbanization process. For example, lime is universal and long-term used as building material, which led to higher pH for urban soils after rounds of building renovation. Lots of sands were carried into urban Nanjing, which may lead to the changes of particle size distribution for urban soils. Urbanization strongly influenced most of soil attributes listed in this study. Both surface and subsurface layers show similar changes between the urban and rural groups. AK, TP and silt content are not statistically different despite similar trends in average values. Subsurface soils presented similar trend with surface soils.

3.2. Grouping system by vegetation

Vegetation type is often used to determine the variation of urban soil in many studies. In this study, all sampling sites were divided into 8 vegetation types (Table 1). Multi-comparison analysis (Duncan) was carried out for all soil variables among these 8 categories (Table 2).

For most variables, three groups (a,b,c) with significant difference were distinguished, 4 groups (a,b,c,d) for AP and TK, 2 groups (a,b) for BD only. Significant differences exist mainly among crop, vegetable and other vegetation types. 7 out of 12 variables showed significant differences between the crop type and vegetable type. For example, the AP content is the lowest for soils of cropland (mainly paddy), but the highest for soils of vegetable land. In the urban–rural grouping system, the rural group was mainly occupied by grain crop and vegetable land, which means both the highest value and the lowest value of AP appear in the rural group. So no significant difference existed for AP content between

Table 2
Results of multi-comparison among vegetation types (depth, 0–10 cm)

Variable	Tree (15)	Shrub (24)	Natural grass (13)	Lawn (41)	Crop (5)	Vegetable (18)	Garden plant (25)	Non-vegetation (10)
pH	8.02 a	8.14 a	7.93 ab	8.16 a	6.70 c	7.36 bc	8.19 a	8.30 a
TOC g kg^{-1}	17.27 abc	21.65 ab	16.79 abc	14.69 bc	11.27 c	19.64 abc	15.99 abc	24.81 a
AP mg kg^{-1}	38.8 bcd	65.5 b	51.2 bc	38.0 c	22.6 d	129.4 a	54.9 bc	60.6 bcd
TP g kg^{-1}	2.23 bc	3.13 ab	2.95 abc	2.10 c	1.82 c	3.32 a	3.51 ab	3.98 a
AKmg kg^{-1}	154.1 ab	205.8 a	161.5 ab	166.8 ab	56.4 c	129.7 b	165.3 ab	231.2 ab
TK g kg^{-1}	21.25 bc	20.19 bcd	21.81 b	20.33 bcd	18.75 d	24.39 a	19.64 bcd	18.72 d
TFe g kg^{-1}	48.50 ab	46.75 b	48.78 b	47.41 b	42.61 ab	58.50 a	44.37 b	43.34 b
Clay %	13.8 b	12.7 b	13.1 b	13.0 b	9.8 c	18.8 a	12.2 b	11.5 bc
Silt %	65.7 ab	64.3 bc	69.9 ab	68.0 b	47.1 c	73.1 a	63.1 bc	59.2 c
Sand %	20.5 ab	22.4 ab	17.3 b	18.8 b	43.1 ab	7.2 c	24.0 ab	30.9 a
Gravel %	0.6 c	3.6 ab	1.5 bc	4.1 ab	0.7 c	0.4 c	8.2 a	3.1 ab
BD g cm^{-3}	1.38 a	1.36 a	1.37 a	1.43 a	1.33 a	1.21 b	1.41 a	1.40 a

Number in the parenthesis is the sample size of the corresponding type. Same letters in a row means no significant difference at $p<0.05$.

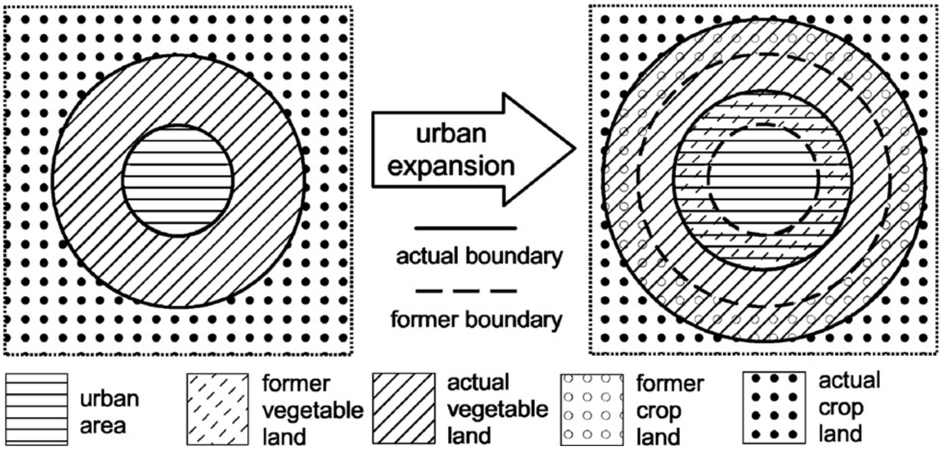

Fig. 3. Conceptual model of land use changes in the process of urbanization.

the urban group and rural group. Obviously, in comparison with the urban–rural system, vegetation grouping system can provide more detailed information about the variation of some soil attributes in the study area.

For some variables, especially the nutrient variables such as AP, soils of cropland or vegetable land possess both extreme low and extreme high values, while the soils from other vegetation types (mainly those distributed in the inner-urban and peri-urban area) contains moderate nutrient values. This phenomenon induced an implication or question: is urban soil sink or source of these nutrient elements?

Land use changes in the urbanization process lead to intensive changes of input and output mechanisms of soils around the urban area. Fig. 3 shows the conceptual model of land use changes in the process of urbanization in China. Normally, vegetables are grown around the urban area for higher profit. Because of very high input of fertilizer to vegetable land, some elements have accumulated in surface soils. With continuous urbanization, vegetable land is eventually transformed into a new urban area, with accumulated nutrients, while cropland further away becomes new vegetable land from the urban area. Under the urban environment in Nanjing, soils were frequently disturbed. Original surface soils may be mixed with deep soils. Sometimes heterogeneous soils from the rural area were introduced for planting (Lu, 2000). These may partly explain the moderate value for some variables in soils of the urban area. Further study should be carried out to determine the role of urban soil in the accumulation or release of certain substances.

3.3. Grouping system by land use

3.3.1. Local land use types (unit size 0.2 km^2)

All sampling sites were divided into 8 categories according to local land use types as illustrated in Table 1. Multi-comparison analysis was carried out for all soil variables among these 8 categories by SPSS (Table 3).

Only two groups are statistically different for 7 of 12 soil variables. No significant differences exist among land use types for 4 variables, TOC, TP, TFe, sand content. Four statistically different groups were divided for bulk density. Compared to vegetation type, fewer variables show significant difference among land use types. Obviously the classification based on the current local land use types do not reflect the changes of soils in this urban–rural gradient as detailed as vegetation types. For further detection about the

Table 3
Results of multi-comparison among local land use types (depth, 0–10 cm)

Variable	Agricultural (26)	Municipal (26)	Park green land (13)	Street green belt (14)	Industrial (13)	Residential (41)	Traffic (8)	Others (10)
pH	6.97 b	8.13 a	8.03 a	8.21 a	8.16 a	8.21 a	7.99 a	7.85 ab
TOC g kg^{-1}	17.73 a	17.17 a	24.48 a	10.64 a	23.80 a	17.01 a	13.96 a	15.01 a
AP mg kg^{-1}	102.2 a	50.3 ab	77.2 ab	39.2 b	49.2 ab	67.0 a	46.7 ab	47.5 ab
TP g kg^{-1}	3.22 a	3.46 a	3.79 a	2.27 a	2.86 a	3.12 a	2.32 a	2.28 a
AK mg kg^{-1}	115.3 b	220.8 ab	283.0 ab	144.6 b	179.5 ab	205.5 a	192.5 ab	137.0 ab
TK g kg^{-1}	22.63 a	19.40 b	19.05 b	19.89 b	20.09 b	20.58 ab	21.00 ab	22.42 a
TFe g kg^{-1}	53.67 a	50.09 a	50.22 a	47.24 a	50.19 a	44.66 a	49.00 a	51.52 a
Clay %	16.7 a	12.7 b	13.6 ab	13.0 b	12.6 ab	12.4 b	14.3 ab	13.4 ab
Silt %	67.6 ab	65.3 ab	63.9 ab	68.5 ab	64.3 ab	62.4 b	70.6 a	70.4 ab
Sand %	15.7 a	22.0 a	22.6 a	18.5 a	23.1 a	25.1 a	15.1 a	16.3 a
Gravel %	0.5 b	6.5 ab	3.5 ab	3.0 ab	4.5 ab	8.0 a	4.4 ab	3.9 ab
BD g cm^{-3}	1.23 d	1.39 abc	1.33 bc	1.44 a	1.32 cd	1.43 ab	1.43 ab	1.44 ab

Number in the parenthesis is the sample size of the corresponding type. Same letters in a row means no significant difference at $p<0.05$.

sensitivity of land use grouping system, we then tried to improve the classification by 1) subdividing the land use types, and 2) up-scaling the spatial resolution from 0.2 km^2 to more than 1 km^2, i.e., as urban functional districts.

3.3.2. Subcategories of local land use types (unit size 0.2 km^2)

As discussed previously, the local land use type grouping system, so-called "senior categories", did not provide classification of soils as detailed as vegetation grouping system did. In order to uncover the details, all "senior categories" were further divided into subcategories. For example, the residential type was divided into four subcategories (villa area, high-level apartment area, common apartment area, dense bungalow area) based on the ratio of sealed area, density of vegetation cover and the age of buildings, and the industrial type was divided into three subcategories: heavy industrial, light industrial, and mixed industrial area (MCC, 1992, 2002).

A total of 22 subcategories were introduced after excluding those subcategories with less than 5 records. The results of statistical analysis showed that there are few pairs of subcategories with significant difference between them. Only noticeable is that the content of TP in the soils of dense bungalow area is higher than that of apartment area and, the content of gravel in soils of villa area is lower than that of apartment area.

The results indicated that more detailed land use classification provided little detailed information for the grouping of urban soils from the general attributes selected in this study.

3.3.3. Urban district-viewed land use type (unit size>1 km^2)

This analysis attests to the sensitivity of soil variation to the influence of urban district-viewed land use (>1 km^2). Table 4 shows the statistical differences among district-viewed land use types for 12 variables. Only two groups can be distinguished by ANOVA for 9 of 12 variables, no significant difference exists among district-viewed land use types for other three variables. AP is an especially well-marked variable because there is no significant difference among land use types but with very high mean value range, 34.7 to 133.4 mg kg^{-1}, which means a high internal variation exists. The high inner-type-variance indicates that the influence caused by different urban functional districts is not the dominating factor of soil changes and soil variations in this study.

4. Numerical grouping system

4.1. Single soil attribute

One simple parameter was introduced to compare the difference of these different classification systems. We name it as the significant ratio *X*. If *n* groups of data with *m* variables are analyzed with multi-comparison (Duncan), there are *b* pair-groups, in which,

$$b = m^* n(n-1)/2 \qquad (1)$$

a was used to represent the number of pair-groups with 95% confidence level. So,

$$X = a/b^* 100 \qquad (2)$$

Vegetation holds the highest significant ratio of 28.0%, for local land use types and district-viewed land use types, 9.1% and 6.8%, respectively. For these three systems, the numbers of categories are similar, 8, 8, and 9, respectively (Table 1), and the results are comparable. Therefore, vegetation type is the best indicator in representing the variations of soil attributes in this study. Fewer variables showed significant difference according to the local land use types and district-viewed land use types than by in situ vegetation types. Vegetation type reflects point-specific information for the sampling site. Soil attributes in this study are not sensitive to coarser spatial resolution. Local factors brought stronger influences on urban soils, in comparison with large-scale factors.

Table 4

Results of multi-comparison among district-viewed land use types (depth, 0–10 cm)

Variable	Urban residential (42)	Educational (13)	Commercial (8)	Industrial (20)	Recreational (16)	Agricultural (25)	Traffic (16)	Official (5)	Suburban residential (6)
pH	8.18 a	8.06 a	8.03 ab	8.08 a	8.08 a	7.24 b	8.15 a	8.30 a	6.82 b
TOC g kg^{-1}	16.83 a	19.72 a	11.10 a	20.51 a	18.75 a	18.60 a	12.25 a	26.25 a	16.82 a
AP mg kg^{-1}	63.6 a	71.1 a	34.7 a	60.2 a	56.4 a	77.3 a	43.8 a	64.2 a	133.4 a
TP g kg^{-1}	3.31 a	3.00 a	2.52 a	2.90 a	3.48 a	2.89 a	2.34 a	3.97 a	3.15 a
AK mg kg^{-1}	231.7 a	228.5 ab	159.9 ab	166.6 ab	223.3 ab	116.8 b	165.2 ab	187.2 ab	112.3 b
TK g kg^{-1}	20.55 ab	19.84 ab	19.88 ab	20.99 ab	18.79 b	22.58 a	20.48 ab	19.24 ab	21.16 ab
TFe g kg^{-1}	45.13 b	51.28 ab	46.59 ab	50.94 ab	50.83 ab	53.77 a	47.84 ab	46.54 ab	49.38 ab
Clay %	12.2 b	14.0 ab	12.1 ab	13.4 ab	12.6 ab	16.1 a	13.9 ab	12.3 ab	16.1 ab
Silt %	62.5 b	66.9 ab	65.8 ab	66.9 ab	63.8 ab	66.9 ab	71.3 a	57.5 ab	71.7 a
Sand %	25.4 a	19.1 ab	22.0 ab	19.7 ab	23.6 ab	17.0 ab	14.8 b	30.2 ab	12.2 b
Gravel %	10.5 a	1.1 b	4.4 ab	3.5 ab	3.4 ab	0.5 b	3.6 ab	7.8 ab	0.3 b
BD g cm^{-3}	1.41 a	1.32 ab	1.49 a	1.36 ab	1.42 ab	1.27 b	1.42 a	1.43 ab	1.25 ab

Number in the parenthesis is the sample size of the corresponding type. Same letters in a row means no significant difference at $p<0.05$.

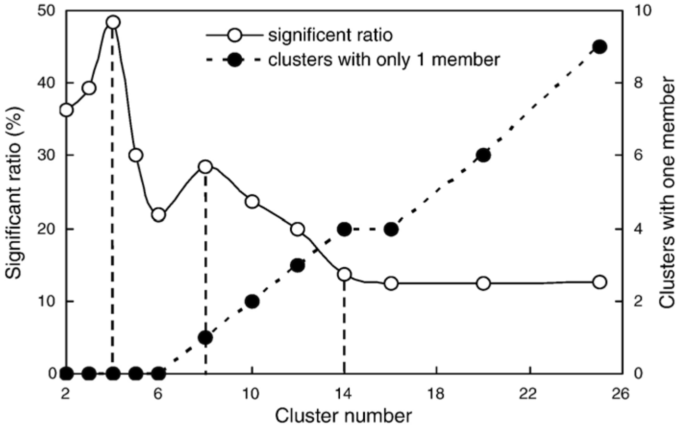

Fig. 4. Significant ratio (*X*) of the different number of clusters.

4.2. Multivariables

K-means cluster analysis (SPSS10.0) was performed for 157 sampling sites of surface layer with number of clusters objectively set from 2 to 25. Fig. 4 shows the significant ratio (*X*) against the number of the clusters. There are three critical points: the first apex occurs at 4 clusters, the second at 8 clusters and the third at 14 clusters which correspond to a higher *X* value, i.e. more sensitive in screening the sample set. 8 clusters were chosen as a basis for interpretation considering the balance between the sensing cluster numbers and significant ratio change. The distribution and interpretation result of these 8 clusters are given in Fig. 1 and Table 5.

As illustrated in Table 5, the numerical clusters obtained can be identified as some major types, based on soil characteristics especially pH, BD, Gravel content, AP and TP. These types (Table 5, column 6) approximately reflect the land use types and their change during urbanization, and they can be used as a basis for soil regionalization in urban and peri-urban environments.

Except for cluster 3, 4 and 6, there is no dominating vegetation or land use type for most of the clusters as shown in Table 5 (column 4). Therefore, vegetation or land use type cannot explain well the numerical clustering results, suggesting the complexity of the impact of urbanization. Further studies are needed to understand and to group soils and land uses in urban environments.

5. Conclusions

Urbanization imposes strong impacts on most of the soil attributes. The most remarkable influence was indicated by increased gravel, sand and pH in soils of the urban area, phosphorus accumulation in soils in the urban area and that of vegetable farm around urban area and soil compaction in urban area.

In situ vegetation type is the best indicator in delineating the variations of soil attributes in this study in comparison with local land use types and district-viewed land use types. Differences of soil attributes in this study were not sensitive

Table 5
Characteristics and explanations of clustering results

Cluster	Members	Main distribution	Major vegetation and land use features	Soil characteristics	Interpreted soil set
1	7	Urban	No dominant vegetation or land use type	Highest sand, gravel, TOC; high pH; low BD	Soil in abandoned greenbelt: received gravels, cements etc., but free from frequent human compaction.
2	11	Urban	Mainly residential (10 members), no dominant vegetation	High pH, BD, gravel; low AP, TP, TOC	Soil in ill-managed greenbelt: physically degraded such as compaction and gravel increase, bad nutrient condition.
3	14	Peri-urban	Dominantly vegetable in agricultural land (10 members)	High clay, silt, TK; low BD, TFe, TP	Soil in new vegetable land: difference in AP with cluster 6.
4	1	Urban	Lawn in municipal land	Highest pH, BD, sand, TP, TFe	Extreme urban conditioned soil: with one member only.
5	7	Urban	No dominant type	High pH, TOC, TP, AK; low BD and TFe	Soil in well-managed greenbelt: contrast to cluster 2, no obvious compaction, good nutrient condition.
6	13	Peri-urban	Dominantly vegetable (8 members) in agricultural land (10 members)	Highest AP; low BD, TFe, gravel, AK	Soil in highly mellowed vegetable land: high P accumulation.
7	67	Urban–rural diffusion	No dominant type	High pH, gravel; others in moderate	Soil in common urban–peri-urban greenbelt: largest set, with urban impact such as pH increase, gravel increase.
8	30	Mainly urban, minor rural	No dominant type	All variables in moderate	Weak-urban-impacted soil: no significant change in compaction and pH, etc.

to coarser spatial resolution. This result suggests that urban soils were changed probably more due to "point" factors than regional factors. It's hard to interpret the spatial variation of urban soil according to the existing soil-landscape paradigm. Relatively, in situ vegetation type is probably better to map single attribute of urban soil.

Numerical clusters can approximately reflect the land use types and their change during urbanization. All clusters can be interpreted as different sets with practical meaning. They can be used as a basis for soil regionalization in the urban and peri-urban environments. Vegetation or local land use type does not explain the numerical clustering results well. Further studies are needed to understand or group soils and land uses in urban environments under the impacts of urbanization.

Acknowledgements

This study was supported by the Natural Science Foundation of China (grant no. 40235054) and the Chinese Academy of Sciences (grant no. KZCX3-SW-427).

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