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RESEARCH ARTICLE

Microbial biomass carbon and enzyme activities of urban soils in Beijing

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Abstract
Introduction To promote rational and sustainable use of soil resources and to maintain the urban soil quality, it is essential to assess urban ecosystem health. In this study, the microbiological properties of urban soils in Beijing and their spatial distribution patterns across the city were evaluated based on measurements of microbial biomass carbon and urease and invertase activities of the soils for the purpose of assessing the urban ecosystem health of Beijing.
Materials and methods Grid sampling design, normal Kriging technique, and the multiple comparisons among different land use types were used in soil sampling and data treatment. The inherent chemical characteristics of urban soils in Beijing, e.g., soil pH, electronic conductivity, heavy metal contents, total N, P and K contents, and soil organic matter contents were detected. The size and diversity of microbial community and the extent of microbial activity in Beijing urban soils were measured as the microbial biomass carbon content and the ratio of microbial biomass carbon content to total soil organic carbon.
Results and discussion The microbial community health measured in terms of microbial biomass carbon, urease, and invertase activities varied with the organic substrate and nutrient contents of the soils and were not adversely affected by the presence of heavy metals at $p<0.01$. It was shown that the older and the biologically more stable part of city exhibited higher microbial activity levels than the more recently developed part of the city and the road areas of heavy traffic. It was concluded that the land use patterns in Beijing urban soils influenced the nature and activities of the microbial communities.

Keywords Beijing urban soil · Microbial community health · Microbial biomass carbon · Urease · Invertase

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1 Introduction

Soils are essential components of the terrestrial ecosystem. They support plant growth and human habitation, modulate flows of water, carbon, nutrients, pollutants, and energy, and are receptacles of wastes. As the primary media for biogeochemical cycling of carbon, nitrogen, phosphorus, sulfur, and trace elements soils play a vital role in global carbon transformations. A fully functional and diverse soil microbial community is imperative to ecological health of terrestrial environments. In urban settings, the soil comes into intimate contact with human habitation and is especially susceptible to harms by the anthropogenic intrusions (Green and Oleksyszyn 2002). As the world trains its attentions on greening planet earth, the soil resources must be rigorously preserved and urban soils being the foundation of human habitat must shoulder their shares in accommodating a low carbon society.

The properties of urban soils, in comparison to the natural and/or cultivated varieties, could be drastically altered by land clearing, cutting and filling, sealing, mixing, compaction, landscaping, and pollution (Kissiling et al. 2009; Hao et al. 2009). Lorenz and Kandeler (2006) observed that pH of urban soils might be elevated due to limestone inadvertently being introduced through discarded construction material and rubbles. The pH in 78% of the soil samples collected in Nanjing, a city approximately 200 km inland of Shanghai along the Yangtze River, were >7.5 (Wang et al. 2005). The electric conductivity (EC) and pH of the soil are chemically interrelated, as acidity may enhance dissolution of soil minerals thus causing dissolved minerals to increase in the soils (Kang et al. 2006a). Dissolution of alkali minerals in turn would modulate the soil pH. Vehicular traffic and industrial emissions caused pH of the soils to decrease and EC of the soils to increase in Lanzhou, a petroleum-based industrial city located in northwestern China (Kang et al. 2006a, b). Hu et al. (2006) reported that with urbanization the organic matter content of top soils in Daxing, an outskirt neighborhood of Beijing, increased from 1.0% in 1980 to 1.3% in 2000.

The microbial biomass and activities of natural and/or cultivated soils might be influenced by abiotic properties of soils such as water/air ratio of soil atmosphere, temperature, and concentrations of nutrients and pollutants. The interactions of these attributes along with human induced disturbances would alter the ecological processes in urban soils (Kissiling et al. 2009; Lorenz and Kankeler 2005). Indiscriminate open dumping had complicated the issues as heterogeneous mixtures of organic substrates, municipal rubbish, and construction rubbles caused microbial biomass and activity of urban soils to spatially vary (Lorenz et al. 2006). The total soil N and organic matter contents affected the microbial biomass carbon of soils in urban, forest, arable, and meadow settings (Kissiling et al. 2009; Rodríguez-Loinaz et al. 2008).

The microbial biomass carbon (MBC) normally comprised 1–5% of the total soil organic carbon (SOC; Anderson and Domsch 1986; Sparling 1992). In a well-balanced soil–plant ecosystem, the microbial biomass carbon to soil organic carbon ratio (MBC/SOC) would be fairly consistent. This microbial biomass to soil organic matter "quotient" expressed as a percentage figure was a useful indicator of microbial metabolic processes in soils. The changes in the MBC/SOC reflected inputs of organic matter, conversion to microbial carbon, decomposition of carbon, and formation of organic carbon and mineral complexes in the soils. The MBC/SOC of urban soils would decline with time before reaching a steady state that the soil organic matter initially available to microorganisms would be utilized with the residues incorporated into humic matrices (Beyer et al. 1995). Heavy metals in urban soil might impact the MBC/SOC. The MBC/SOC of soils along the traffic corridors was significantly lower than those in the park and agriculture settings (Wang et al. 2005).

The microbial biomass carbon of cropland soils in China ranged from 100 to 600 mg C kg^{-1}, and it might reach 1,500 mg C kg^{-1} in pastures (Wang et al. 2007). However, vegetative covers, waste depositions, human trampling, and pollution affected the size, activity, and composition of microbial biomass in urban soils (Bastida et al. 2008; Bhattacharyya et al. 2008; Lorenz et al. 2006; Kissiling et al. 2009; Scelza et al. 2008). Wang et al. (2007) further illustrated that in Nanjing the MBC contents of soils in public parks were the highest compared to soils under other urban land uses. Hao et al. (2009) and Lorenz and Kankeler (2005) noted that MBC contents of soils at areas of heavy vehicular traffic were relatively lower than those of other land uses in the urban surroundings. Lorenz and Kandeler (2006) suggested that frequent removal of plant litter and shortage of water supply might hamper the growth of microbial biomass in soils along corridors of heavy traffic. Further, heavy metals caused the microbial biomass carbon to decrease in affected soils (Bastida et al. 2008; Bhattacharyya et al. 2008).

Soil microbes secreted extracellular enzymes that enhanced decomposition of organic matter and transformation of nitrogen compounds (Koch 1916). The soil enzyme activities reflected the dynamics of microbial metabolic processes associated with nutrient cycling and were sensitive indicators of environmental stresses due to degradation of soil quality. Chen et al. (2008) showed enhanced activities of enzymes catalyzing metabolic reactions of C, N, P, and S cycling in soils received long-term application of reclaimed wastewater. Both enzyme activities and microbial population however might be harmed by soil-borne anthropogenic heavy metals even the chemical properties such as organic C total N contents of the soils were unaffected. The activities of urease and invertase in soils were essential in releasing simple carbons and nitrogen sources for the growth and multiplication of soil microorganisms (Balasubramanian et al. 1972). They would detect changes of metabolic activities due to adverse impacts of heavy metals in the affected soils at the cellular level (Gianfreda et al. 2005; Lorenz and Kandeler 2006).

The urease activities of the heavy metal contaminated soils were significant reduced (Moreno et al. 2003; Kandeler et al. 2000; Doelman and Haanstra 1986; Tyler 1974). In Nanjing, the urease activity of urban soil measured 2.43 mg N g^{-1} 24 h^{-1} (Hao et al. 2009) was much lower in comparison with those in natural soils, 838 mg N g^{-1} 24 h^{-1}, and agricultural soils, 779 mg N g^{-1} 24 h^{-1} (Wang et al. 2007). In urban settings, the urease activity at parks where soils were not readily disturbed was higher relative to other land uses while soils from areas of heavy vehicular traffic had considerably lower urease activities relative to other land uses (Lorenz and Kankeler 2005).

The invertase activity depended on not only concentration but also composition of soil organic matters (Gianfreda et al. 2005; Liu et al. 2007). Kandeler et al. (1999) showed that invertase activities of soils responded to incorporation of organic matter and were essential to the decomposition of organic matter and formation of humus. However, heavy metals inhibited the activities of soil microorganisms including the enzymatic processes (Chaperson and Sauvé 2007; Giller et al. 1998; Šmejkalovál et al. 2003).

Beijing, the capital of China, historically has been on the cross road of commerce, human migration, and war fares for thousands of years and is currently undergoing rapid urban redevelopment characterized by massive construction of urban infrastructures, expansion of green open spaces, and heavy foot and automobile traffics. The pace of development would not be sustainable if the ecological structure and functions including the biodiversity and fertility of soils in Beijing are irretrievably harmed. Zhao et al. (2009) have assessed the dynamics of Beijing's urban ecosystems based on ecosystem safety and health as well as substantive social and economic parameters. It is imperative that the environmental aspects of urban ecosystem sustainability in terms of structures, processes, and functions are also delineated.

To promote rational and sustainable use of soil resources and to maintain the urban soil quality, it is essential to assess urban soil ecosystem health. We hypothesized that heavy metals pollution adversely affect microbial metabolic processes in the urban soils. The sustainability of urban soil ecosystem is affected by long-term exposures to urban pollutants such as heavy metals. In this study, the microbiological properties of urban soils and their spatial distribution patterns across Beijing were evaluated based on measurements of microbial biomass carbon and urease and invertase activities of soils and their relationships with heavy metal concentrations of the soils were delineated.

2 Materials and methods

2.1 Study sites and soil sampling

The metropolitan Beijing was organized into six concentric tetragons centered at the Forbidden City and expanded outward (Fig. 1). Each ring-square was surrounded by a circular express road for automobile traffic. The investigation included essentially the entire area inside of the 5th ring-square road in which population was dense and traffic density was high. The study area covered eight separate

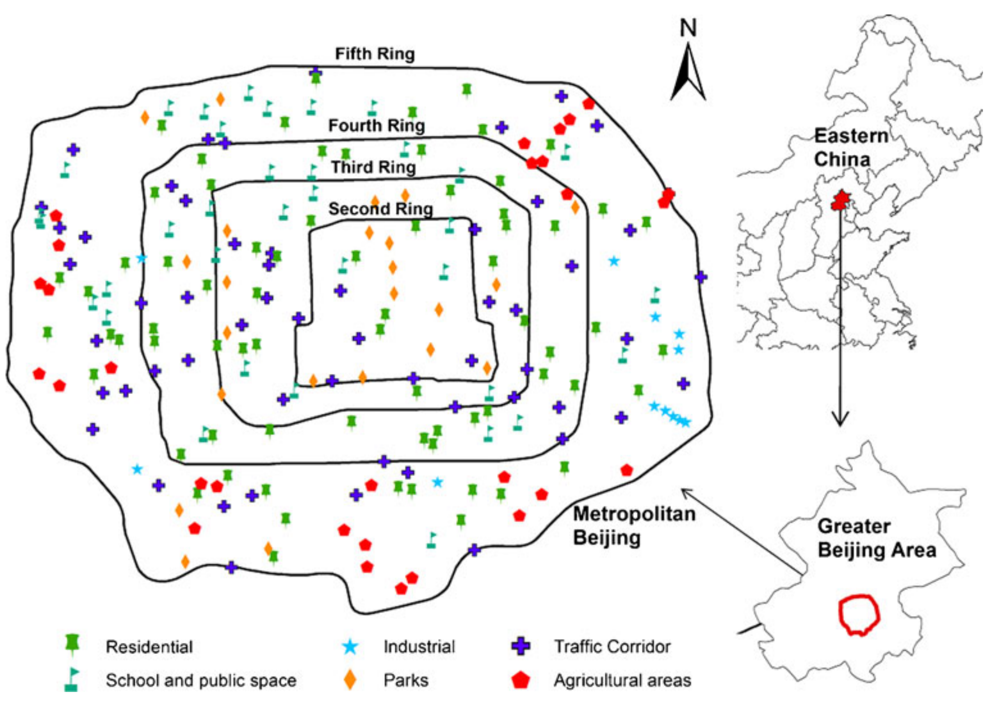

Fig. 1 Simplified map of Beijing with soil sampling locations

administrative districts of Beijing, i.e., Dongcheng, Xicheng, Chongwen, and Xunwu located inside the 2nd ring road and Chaoyang, Haidian, Fengtai, and Shijingshan located between the 2nd and the 5th ring road (Fig. 1). The study area was divided into 285 cells based on the 1 min of latitude × 1 min of longitude grids (approximately 1.9× 1.0 km). Soils representing the typical land use of each grid were selected for sampling. One composite soil sample was obtained in each cell by collecting five 0 to 10 cm depth soil cores uniformly distributed in a 10×10 m vegetated plot inside the grid. Due to restricted accesses, samples were collected only at 233 of the 285 cells. Of the 233 samples, 25 represented public parks, 58 represented traffic corridors, 38 represented schools and public areas, 28 represented agricultural production areas, 15 represented industrial areas, and 69 represented residential areas (Fig. 1).

2.2 Biochemical analyses

Samples were returned to laboratory for processing within 5 h of their collections. After removing plant residues and roots, soils were sieved at field moisture content to pass a screen with 2×2 mm openings and stored in tightly capped amber glass bottles at −25°C. Prior to the assays that included microbial biomass carbon content and urease and invertase activities, subsamples were placed in a refrigerator set at 4°C for 24 h to thaw and to restore the soil's microbial activities.

The microbial biomass carbon content was measured using the chloroform fumigation–extraction method (Vance et al. 1987). Briefly, two 10 g aliquots of the soil were chloroform fumigated while two additional 10 g aliquots were not fumigated. Afterwards, soluble carbon in the 0.5 M K_2SO_4 extracts was measured by an Elementar LiquiTOC (Germany) total carbon analyzer. Microbial biomass C was calculated from the C flush out by chloroform fumigation using a K_{EC} of 0.45.

Urease activity was determined according to Gosewinkel and Broadbent (1984). Two and a half grams of soil were mixed with 10 ml of pH=6.7 citrate buffer, 0.2 ml toluene, and 5 ml of a 10% (*w*/*v*) urea substrate solution. The mixture was diluted with 37°C distilled water to 50 ml, incubated for 24 h at 37°C, and then filtered through 0.45 μm membrane filter. Three milliliters of filtrate mixed with 4 ml of 1.35 M sodium phemolate and 3 ml of sodium hypochlorite (0.9%, *v*/*v*) and then diluted with distilled water to 20 ml. The NH_4-N of the mixture was measured at 578 nm using a photo spectrophotometer (SpectroMax Plus^{384}, USA). The urease activity was expressed in terms of mg NH_4-N g^{-1} soil·24 h^{-1}. Meanwhile, control experiments without soil and substrate were conducted to check and correct for errors caused by reagent impurity and background value of the substrate.

Invertase activity was determined by the 3, 5-dinitrosalicylic acid method as described by Frankenberger and Johanson (1983). Five grams of soil aliquot mixed with 5 ml pH=5.5 phosphate buffer, 0.2 ml toluene, and 15 ml 8% (*w*/*v*) sucrose solution and then incubated for 24 h at 37°C. Following incubation, the contents were filtrated through a 0.45 μm membrane filter. One milliliter of filtrate plus 3 ml of 3, 5-dinitrosalicylic acid reagent were mixed and heated in a boiling water bath for 5 min and then cooled in running waters for 3 min. The glucose content was measured in terms of the optical intensity (OD) of the mixture at 508 nm with a spectrophotometer (SpectroMax Plus^{384}, USA). The intervase activity was expressed as mg glucose g^{-1} soil 24 h^{-1}. Meanwhile, control experiments without soil and substrate were conducted to check for errors caused by reagent impurity and background value of substrate.

2.3 Chemical analysis

Soil samples were air-dried and sieved to analyze their basic chemical properties (<1 mm for pH determination and <0.21 mm for total C and N determination). Soil pH was determined in distilled water at a soil-to-solution ratio of 1: 2.5. Electrical conductivity of 1:5 soil-to-solution extract, calcium carbonate equivalent was determined by a manometric method. Total C and N were determined by combustion using an elemental analyzer (Elementar, Hanau Germany). Total organic C contents were determined by HCl treated method reported by Nam et al. (2008). Briefly, soil samples were weighed in a glass plate and treated with 1 M HCl for 24 h. The soil samples were then dried at 60°C prior to organic carbon determination using an elemental analyzer (Elementar, Hanau Germany). The organic matter content of the soil was obtained by multiplying the values of organic carbon by 1.724 and represented by the percentage to the soils (*w*/*w*).

Metal elements in soils were determined by the acid digestion technique reported in The Technical Specification for soil Environmental monitoring (HJ/T 166–2004). Namely, 0.25 g of 0.1 mm sieved soil samples was digested using a four-acid digestion: 10 ml HCl, 5 ml HNO_3, 5 mlHF, and 3 ml $HClO_4$. Addition digestion processes were needed with the last three acids according to the digested degree. Digested extracts were dissolved in 1:1 aqua regia and made up to 50 ml for ICP-AES analysis of Cu, Zn, Cr, Ni, Al, Fe, Na, K, Mn, Ca, and Mg and 250 ml for ICP-MS analysis of Cd, Co, and Pb.

2.4 Statistics analysis and mapping

The statistical analyses of the data including ANOVA, multiple comparison, and Pearson correlation analysis were achieved through the SPSS software (version 13.0). Prior to analyses, the data were standardized by the Box–Cox transformation to normality using Minitab 15. The spatial distributions of the microbial biomass carbon content and enzyme activities of urban soils in Beijing were mapped with support of ArcGIS 9.3 through a Kriging method in which concentration of microbial biomass carbon and urease and invertase activities soils were Napierian logarithm transformed. The outcomes overlaid on a simplified Beijing map outlining the 2nd to the 5th ring roads and soil sampling sites.

3 Results and discussion

3.1 Soil properties and metal contents

Urbanization and the underlying land uses did not significantly affect the inherent chemical properties of urban soils across Beijing (Fig. 2). The pH of urban soils in Beijing were neutral to alkaline ranging from 7.06 to 8.19, while EC varied from as low as <77.2 μs cm^{-1} to as high as >2,490 μs cm^{-1} in the 1:5 *w*/*v* soil extract (Table 1). The data dispersion was notable as indicated by standard deviations of the data we presented. Even the arithmetic mean, 194 μs cm^{-1}, leaned toward the higher end of the range. It illustrated that total dissolved salts of urban soils in Beijing were characterized by a population of soils mostly in low salinity with soils from a small number of locations showing signs of salinization. However, the salinity was not significantly different between soils representing different land use categories. The alteration of soil chemical properties by anthropogenic activities tended to be isolated and localized.

Data characterizing other attributes of soils, namely organic matter, and N, P, and K contents exhibited the similar patterns (Fig. 2). For example, the organic matter

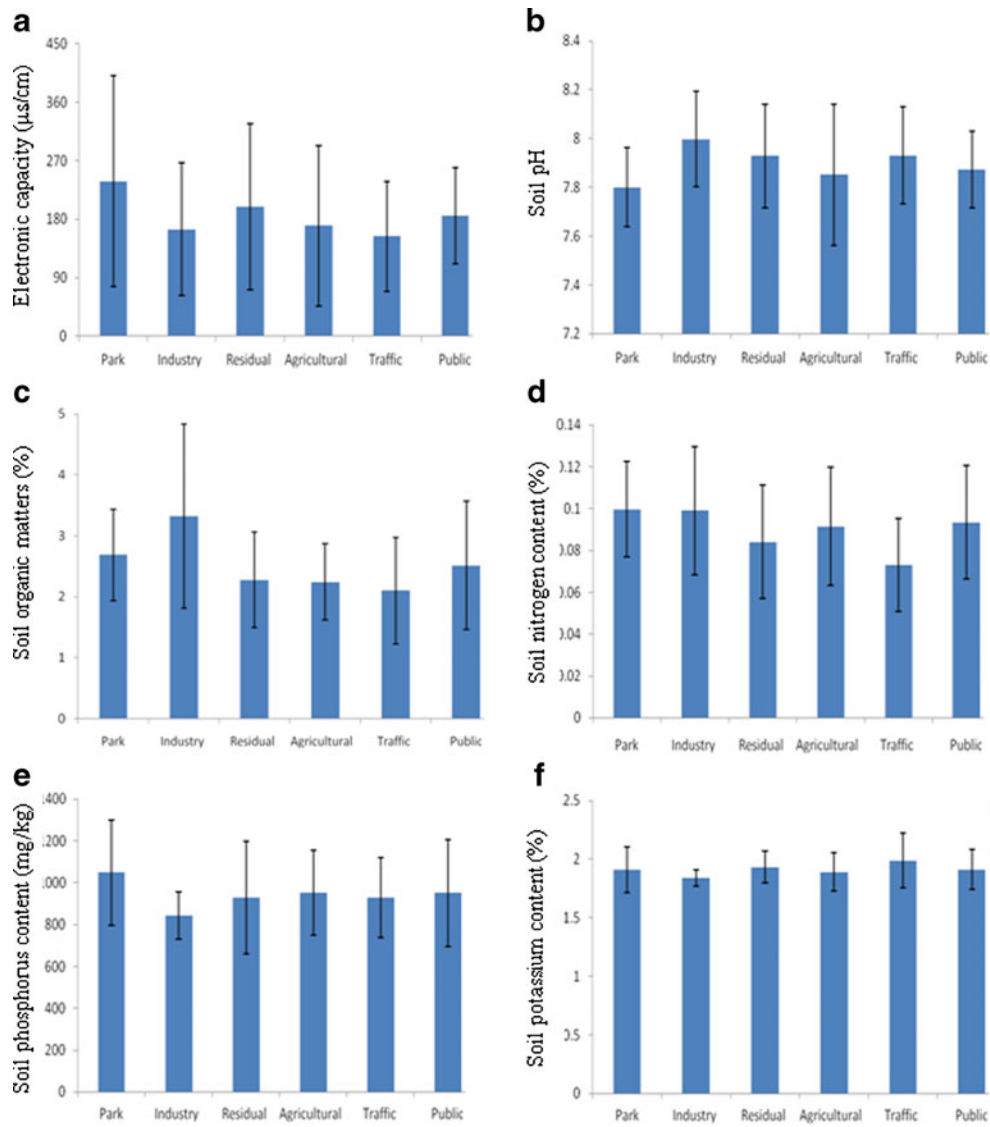

Fig. 2 Electrical conductance and pH and organic matter, N, P, and K of soils

Table 1 Descriptive statistics on selective properties of urban soils in Beijing

Soil property	Mean	Minimum	Maximum	S.D.
Total N (%)	0.088	0.03	0.20	0.029
Soil organic matter (%)	2.47	0.42	8.81	1.11
pH (1:2.5 H_2O)	8.37	6.91	8.87	0.227
Electrical conductivity (EC; μs cm^{-1})	194	77.2	2,490	190.8
Fe (%)	2.81	1.90	4.24	0.29
Ca (%)	3.51	1.35	7.16	0.93
Mg (%)	1.12	0.62	1.70	0.16
Cu	31.7	13.4	207.9	24.9
Zn	92.9	29.4	322	38.2
Pb	23.3	4.02	174	15.5
Cd	0.13	0.003	0.98	0.09

content of urban soils in Beijing varied from 0.4% to 8.8% with an overall average of 2.5% mimicking the pattern exhibited by the soil EC. The corresponding concentrations of Fe, Ca, and Mg major elements of earth's crust did not vary significantly. The human interferences did not change the background chemical matrices of the urban soil environment (Table 1).

Cadmium, copper, lead, and zinc invariably accumulate in urban soils due to the anthropogenic activities associated with transportation, commercial and industrial emissions, waste disposal, and fugitive escapes. The background concentrations of soil Cd, Cu, Pb, and Zn in Beijing were 0.119, 18.7, 24.6, and 57.5 mg/kg, respectively (Chen et al. 2004). The ranges of Cd, Cu, Pb, and Zn contents of soils in metropolitan Beijing could vary from the minimum to maximum by several orders of magnitudes (Table 1). On lower end of ranges, their concentrations were comparable to the respective baseline levels. On the higher end of the ranges, their concentrations far exceeded the respective backgrounds. The uneven distributions were indicative of the metals' transportation and deposition patterns in urban environment. Much of Beijing's soils have not been subject to heavy metal pollutions, and the areas of elevated heavy metal concentrations were relatively small.

3.2 Microbial biomass carbon

Microbial biomass carbon represented the living part of the organic matter in soils, indicative of the size and diversity of the soil microbial community. Typically, cropland soils receiving frequent inputs of carbon substrates, nutrients, and water would maintain a healthy soil microbial community. It appeared that the microbial biomass pools of the urban soils were severely stressed by limited inputs of energy, substrates, and water and possibly presence of harmful pollutants. The MBC in Beijing urban soils varied from 1.9 to 63.5 mg C kg^{-1} (Table 2), crossing the board one to two orders of magnitude lower than those of the cropland soils. The ratio of MBC/SOC in soils of different land uses were all less than those 2–4% of the cropland soils (Table 2). Relative to that of the cropland soils (Hao et al. 2009), lower microbial biomass and activities in the urban soils would signal slower biogeochemical cycling of C, N, P, and S in soils and potentially lesser available nutrients to sustain perennial urban plant population. If the urban soil environment was not constrained by inputs of energy, nutrients, and water, the seemingly small size of microbial biomass pool and low MBC/SOC would signal potential presence of toxicants such as the heavy metals harming the microbial community. While the Cd, Cu, Pb, and Zn contents of urban soils in certain parts of Beijing far exceeded the baseline levels (Chen et al. 2004), the metabolic processes of microbial community were cross the board lower than comparable metrics of the cropland soils.

The measurement of microbial biomass carbon was subject to inherently spatial variability of the fields (Broos et al. 2007). To distinguish the effects of land use categories, it is essential that the data is subject to statistical testing (Table 2). In Beijing, the microbial biomass carbon of soils may be break down into three groups in descending order of park and public areas (including schools), agricultural, industrial, and residential areas, and the heavy traffic roadside areas. When the carbon sources of the soil was accounted for, the MBC/SOC representing different land uses in descending order were public areas (including schools), agricultural and residential areas, industrial areas, and park and corridors of heavy traffic. The MBC of soils in parks was among the highest yet the corresponding MBC/SOC was ranked the lowest. Long lasting stable plant cover and seldom human disturbance had positive influences on accumulating organic matter in soils at park settings. Soils at areas of heavy vehicular traffic were also susceptible as they often were surrounded by pavement

Table 2 Microbial biomass carbon content and enzyme activities of soils in Beijing according to land use

Land use	Microbial biomass carbon (MBC; mg C·kg^{-1})	MBC/SOC[a] (%)	Urease (mg N g^{-1} soil 24 h^{-1})	Invertase (mg C g^{-1} soil 24 h^{-1})
Parks	25.9±12.8 a	1.10±0.59c	9.36±1.59 a	16.2±6.41 a
Traffic	20.1±10.9 b	1.11±0.66c	8.16±2.68 b	14.3±7.44 a
Public (Schools)	25.1±10.6 a	1.95±1.14a	8.12±2.59 b	13.1±6.22 a
Agricultural (Woods)	20.5±13.4 ab	1.60±0.84ab	7.95±2.76 b	13.8±6.81 a
Industrial	24.3±9.5 ab	1.42±0.78bc	9.28±1.47 ab	13.2±6.07 a
Residential	21.3±10.5 ab	1.69±0.78ab	8.96±1.93 ab	15.2±6.17 a
Mean	22.2	1.72	8.57	14.4
Lowest 25 percentile	1.88–14.6	0.12–1.01	1.66–7.7	0.82–9.58
Medium 50 percentile	14.6–29.1	1.01–1.68	7.7–10.1	9.58–18.9
Highest 25 percentile	29.1–63.5	1.68–6.94	10.113.6	18.932.7

The soil attribute data was tested for significant difference according to the LSD test. Same letter following values of a column indicate the soil attribute of the land uses they represented were not significantly different at $p<0.05$

[a] Soil organic carbon

that inhibited incorporation of organic matter and were lacking inputs of organic substrates, nutrients, and water that inhibited the microbial activities in the soils (Lorenz et al. 2005).

3.3 Enzyme activities

In soils where organic substrates, nutrients, and water are abundant, the urease activities have been measured at 838 and 779 mg NH_4-N g^{-1} 24 h^{-1} for native and cropland soils, respectively (Wang et al. 2007). In the urban settings of Beijing, the soil urease activities we measured, ranged from 2 to 14 mg NH_4-N g^{-1} 24 h^{-1} (Table 2), were one to almost three orders of magnitude lower than those found in crop and wild lands. Urease would catalyze the hydrolysis of urea to ammonia and carbon dioxide. Urea was the major end product of decomposing organic nitrogen in plant residues and animal excreta. Undoubtedly, the reduced microbial biomass pools of the urban soils affected the outcomes or vice versa. Among the sampling sites, soils of the parks category exhibited the highest urease activity and it was followed in descending order by soils of the residential and industrial categories and the public, agricultural, and heavy traffic categories. The urease activities were essential for mediating the transformation of soil nitrogen from organic to inorganic form allowing the soil microorganisms and terrestrial plants to utilize externally and internally generated urea as a nitrogen source. A lower lever of soil urease activity would imply either a reduced microbial biomass pool resulting in a slower rate of organic nitrogen (proteins and amino acids) oxidation or a smaller organic nitrogen substrate pool limiting the soil microbial activity. However, organic nitrogen substrates are not likely to be a constraint as organic matter contents of urban soils in Beijing had exhibited rising trends over the past several decades (Hu et al. 2006). The lower microbial biomass carbon found in Beijing urban soil would more likely be a constraint. Besides, urease activities of soils were extremely susceptible to harmful effects of heavy metals. The adverse impacts of Cd, Cu, and Zn on soil urease activities in Beijing should not be ruled out as the metal contents of sampled soils cross the board way exceeded the baseline levels.

Invertase that catalyzes the hydrolysis of sucrose was known to play a vital role in organic carbon mineralization. It would be important in breaking down plant litter in soils and formation of humic substances in soils. The invertase activities of urban soils in Beijing were within the range of soil invertase activities reported in the literature (Gianfreda et al. 2005; Liu et al. 2007). They varied from 0.8 to 32.7 mg glucose g^{-1} 24 h^{-1} and were not significantly different between the land use categories. The data complemented what the corresponding urease activities implied that lower microbial biomass carbon found in Beijing urban soil would more likely be a constraint and the invertase activities of soils were also susceptible to harmful effects of heavy metals.

3.4 Spatial distribution of microbial biomass carbon and enzyme activities

The microbial biomass carbon content and urease and invertase activities data of urban soils in Beijing were each separated into quartile categories and consolidated according to the geostatistical techniques into four consolidated quartile categories with the 1st quartile (corresponding to MBC and activities of urease and invertase in 0 to 25 percentile) being the lowest in concentrations (or activities) and 4th quartile (corresponding to MBC and activities of urease and invertase in 75 to 100 percentile) being the highest in concentrations (or activities), see Fig. 3 and Table 2. The higher are the integrated metrics, the more active is the soil microbial community. In this manner, measurements of microbial attributers of the urban soils at individual locations were linked and scaled up to illustrate the spatial pattern of soil microbial communities of the entire urban area. The metrics indicating the microbial activities of the urban soils were expected to show the influences land uses and soil pollutants across the city.

The microbial activities in terms of the integrated metrics at the city center and the north–northwest octagonal section of the city were at the top 25 percentile level in comparison to those of soils in remainder of the City (Fig. 3). Their foot prints overlapped roughly the historical capital where parks, historical relics, and public structures were concentrated, and the soils and urban landscapes associated with these locations were less susceptible to disturbances, and many had been stable for several hundred years. In addition, soils of agricultural land toward east and south also showed higher soil microbial activity.

The soil microbial activities of soils in the southwestern quartile were mostly among the lowest 25 percentile level. This section had less areas dedicated to parks and green space and several cross country highways handling heavy north–south and west–east trucking traffic that bypassed the City (Fig. 1). Similar traffic corridors in the northeast quartile exhibited comparable patterns. When the microbial community and enzymatic activities of urban soils in Beijing were deduced spatially, it showed the influences of land uses on the nature of the soil microbial communities.

3.5 Relationship between microbial and abiotic soil properties

The nature of soil microbial community might be affected by the chemical properties of soils. For urban soils in Beijing, the microbial biomass carbon content was significantly correlated with soil total N and SOM at $p<0.01$ (Table 3). It would be an indication that soil microbial biomass responded to available organic substrates and nutrients in soils and through biogeochemical cycling would provide a labile pool of carbon, nitrogen, and phosphorus in support of soil microbial community. Heavy metal contents of the soils did not appear to adversely affect the soil's microbial activities.

The urease activities of Beijing's urban soil were correlated with soil organic matter content and total N and

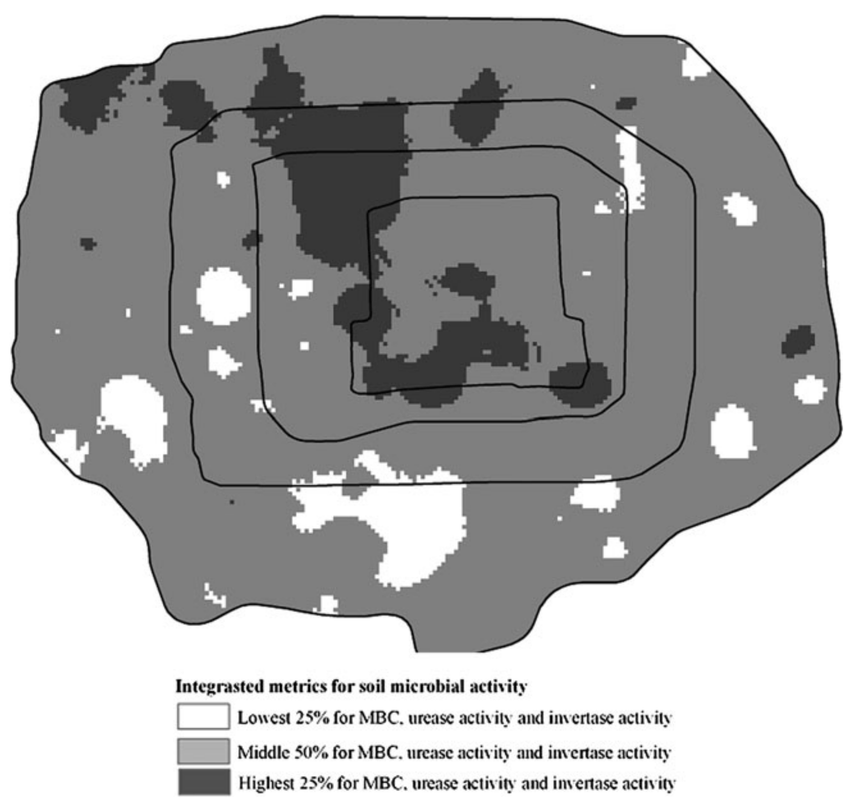

Fig. 3 Integrated spatial distributions of microbial biomass carbon (MBC), urease activity, and invertase activity of urban soils in Beijing

Table 3 Pearson correlation coefficients between microbial variables and selected abiotic properties of soils in Beijing derived from observations made at 233 locations

	SOM	TN	P	K	Fe	Ca	Mg	Cu	Cd	Zn	Pb
MBC	0.196*	0.449*	0.102	−0.083	−0.138	−0.131	−0.180	0.053	0.049	−0.010	0.148
Urease	0.411*	0.458*	0.244*	−0.130	−0.035	0.207*	0.078	0.170*	0.139	0.200*	0.211*
Invertase	0.090	0.302*	0.010	0.108	−0.024	−0.169	−0.142	0.021	0.055	−0.030	−0.013

MBC denotes microbial biomass content, *SOM* denotes soil organic matter content, *TN* denotes total N content of soil

*$p<0.01$

P at $p<0.01$ (Table 3), an indication the urease activities were tied to the microbial biomass levels as both were affected by the same soil factors. In addition, urease activities of the soils were correlated with elements Ca, Cu, and Zn at $p<0.01$. However, Ca, Cu, and Zn are either macro or micro nutrients for biota. In all, the heavy metal contents of Cd, Cu, and Zn though far exceeded the background levels of soils in Beijing; they complimented the outcomes on microbial biomass carbon data that microbial activities were not adversely affected.

The invertase activities of Beijing's urban soil were correlated with soil total N (Table 3). The remaining soil factors did not have significant effect on its activity at $p<0.01$. They are indications that essential factors such as organic substrate (i.e., soil organic matter) and nutrients (i.e., total P, Ca, Cu, Zn, etc.) were not constraints for microbial decomposition of organic matter and formation of humus in soils.

In the course of statistical analysis, it was notable that the data dispersion was considerable (Table 2) and the correlation coefficients (Table 3) explained at the most 46% of the significance. In most cases, the correlation coefficient accounted for only 15% to 20% of the significance. The remaining variances would represent potential contributing variables that were not accounted for in this study such as the soil texture and soil moisture content or simply random variations inherent to sampling, sample processing, and chemical analysis for a large-scale field study.

4 Conclusion

In urban soils, the microbial biomass carbon contents and soil urease and invertase activities are logical parameters to assess the impact of the anthropogenic activities on microbial health of urban soil environment. Based on results of our study, we conclude that:

1. The inherent chemical characteristics of urban soils in Beijing were not significantly affected by land uses. The chemical background matrices of soils were similar across the city.
2. The Cd, Cu, Pb, and Zn contents of soils in Beijing spanned wide ranges. At the lower end of the ranges, metal concentrations were comparable to the baseline levels. At the higher end of the range, metal concentrations far exceeded the respective baseline levels.
3. The size and diversity of microbial community and metabolic activity measured in terms of the microbial biomass carbon content and MBC/SOC were smaller than those in comparable native and cropland soils. The significant differences in MBC/SOC of soils of different land uses signal a variety in process governing the microbial in Beijing urban soils.
4. The microbial community health measured in terms of microbial biomass carbon, urease, and invertase activities varied with the organic substrate and nutrient contents of the soils and were not adversely affected by the presence of heavy metals at $p<0.01$.
5. When the parameters we used to assess the health of microbial community of urban soils in Beijing is mapped according to the microbial biomass carbon content and activities of urease and invertase, they showed that the older and the biologically more stable part of city exhibited higher integrated index for soil microbial activity than the more recently developed part of the city and the road areas of heavy traffic.
6. The dispersion of data is considerable and significant correlations on the average only able to explain 15% to 20% of the variations. They indicate either variables not considered in this study such as soil texture and soil moisture content were significant or the inherent errors were introduced through sampling, sample handling, and chemical analysis.
7. When the microbial activities of the urban soils in terms of the microbial biomass and activities of urease and invertase were spatially deduced, the land use patterns influenced the nature and activities of the microbial communities.

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