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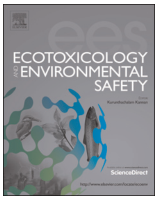

Effects of land use intensity on the natural attenuation capacity of urban soils in Beijing, China

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A B S T R A C T

Urban soils are major sinks that provide the services of attenuating and detoxifying environmental pollutants. This significant ecosystem service of urban soil can be evaluated by the natural attenuation capacity (NAC). In this research, we develop a method to calculate the natural pollutant attenuation capacity of urban soils on the basis of 5 chemical and physical measurements. By selecting municipal parks soils for reference, we assessed the spatial and temporal changes of NAC in Beijing city soils under influences of rapid urbanization. Results indicated that NAC was increasingly impacted by land use in the order: parks < schools < woods < residential areas < traffic areas. Sealed area rate and construction age are two main factors affecting the urban soil NAC. However, their roles are opposite. It would take dozens of years to reach the maximum soil NAC by soil self-recovery. The spatial distribution of NAC in Beijing built-up area resembled the age of urbanization. Regional hot spots of NAC corresponded to the land use distribution and the urbanization progress in Beijing city. The developed index can be used to assess the impacts of urbanization on soil ecosystem services of natural attenuation of contaminants.

1. Introduction

Worldwide, the urban population has reached 52% and is expected to rise at 0.5–0.87% per year for the next 50 years. China is in the midst of an incredibly rapid process of urbanization. Shanghai, Beijing and Guangzhou are amongst the 10 most densely populated metropolis of the world. Energy and resource consumptions and waste and pollutant emissions are intense in urban areas (Pataki et al., 2011). The urbanization processes drastically affect the indigenous soil ecological template (Kaye et al., 2006; Pavao-Zuckerman, 2008).

The risks of environmental harms associated with depositions of urban pollutants may be indicated by the extent of ecosystem services (Faber and Wensem, 2012; Galic et al., 2012; Nienstedt et al., 2012; Pataki et al., 2011; Thomsen et al., 2012). Ecosystem services benefit men gain from their habitat, including benefits of providing provisions, regulations, and cultural stimulations and auxiliary services that compliment the primary eco-functions (Millennium Ecosystem Assessment, 2005). Urban soils are major sinks that provide the services of attenuating and detoxifying environmental pollutants (Dominati et al., 2010;NRC, 2000).

Soils possess the ability to reduce the mass, toxicity, mobility, volume, and/or concentration of incoming pollutants. This ability is deployed through reactions of biodegrading, dispersing, adsorbing, diluting, volatilizing, stabilizing, and transforming the soil borne pollutants (US Environmental Protection Agency; EPA, 1999). The significance of a reaction is dependent on properties of soils and the nature of pollutants. Van Wijnen et al. (2012) articulated the natural attenuation capacity (NAC) of soils with respect to their ability to biodegrade organic contaminants. The resulting model included multiplying effects of 3 microbial indicators, i.e. functional microbial activity, potential carbon mineralization rate, and potential mineralization rate of organic nitrogen, and 3 abiotic indicators, i.e. soil organic matter content, soil pH, and phosphorus content as proxy indicators (Van Wijnen et al., 2012).

Identifying proper pollutants and employing appropriate metrics would be challenging for assessing natural pollutant attenuation capacities of urban soils as they undergo changes due to rapid urbanization, and there are many pollutants and potential indicators for natural pollutant attenuation capability of soils (van Wijnen et al., 2012). In China, heavy metals and polyaromatic hydrocarbons (PAHs) are the most persistent pollutants in the urban areas. Therefore, the soil's filtering and immobilizing reactions are more relevant than the degrading and destructing reactions in deciding the soil attenuation capacities. The

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concentrations of soluble heavy metal and PAHs in soils might be correlated to solid-solution dissociation constant, K_d, which in turn were functions of organic matter content, clay content, and pH of soils (Sauve et al., 2000). In this regard, the soils' pH and organic matter and clay contents would be the appropriate metrics to assessing natural pollutant attenuation capacity of urban soils.

In this research, we developed a method to calculate the natural attenuation capacity of urban soils by modifying the ecosystem-service performance index proposed by Rutgers et al. (2008) and Van Wijnen et al. (2012). Proper soil property parameters and reference values were selected to evaluate the impacts of urbanization on the NAC of urban soils. Beijing is used as a case to illustrate spatial and temporal changes of NAC in soils across the city with respect to the attributes of urbanization.

2. Methods and materials

2.1. Calculation of natural attenuation capacity

The ecosystem services are not well defined quantitatively (Luck et al., 2009; van Wijnen et al., 2012). Rutgers et al. (2008) and Van Wijnen et al. (2012) calculated the ecosystem-service performance index (EPX) of soil using the following equation:

$$\mathrm{EPX}=10^{-\left[\frac{+\log\left|\left(\frac{\mathrm{VAR}^{i}_{obs}}{\mathrm{VAR}^{i}_{ref}}\right)\right|+\cdots-\log\left|\left(\frac{\mathrm{VAR}^{j}_{obs}}{\mathrm{VAR}^{j}_{ref}}\right)\right|}{n}\right]} \quad (1)$$

where $\mathrm{VAR}^{i\ldots j}$ are soil parameters from i to j that contribute to EPX of soils. Subscripts *obs* and *ref* denote the parameter's observed and reference values, respectively (Rutgers et al., 2008). The symbol n denotes number of parameters in the computation. Generally, 4–6 parameters with the highest scores were selected among a group. The reference values represent a "maximum ecological potential", which could be brought forward by independent measurements and/or evaluations by professional panels.

For the natural attenuation capacity (NAC) of urban soils, we selected 5 soil property parameters (Table 1) that may determine the fate of heavy metals and PAHs in soils, namely soil organic carbon content (SOC), clay content (Clay), bulk density (BD), pH measured in pore water (pH), and total soil N contents (TN). The soil total N content was included as a supplemental parameter to clay and organic carbon contents of soils (Hassink, 1997). For biodegradation of organic pollutants (Eq. (1)), the contributing parameters had multiplying or dividing effects toward ecosystem-service performance index (EPX). The soil's capacity to react with or attenuate heavy metals and PAHs are additive in nature. It is the sum of surface reaction sites in [soil organic matters + clays + organic N]. In addition, the capacities are also susceptible to the multiplying/dividing influences of the soil's pH and bulk density that respectively adjust the attenuation capacity up and down and account for the net soil mass per unit volume. Eq. (1) was modified accordingly to obtain the natural pollutant attenuation capacity of urban soils (NAC):

$$\mathrm{NAC}=10^{\left[\frac{\log\left(\frac{\mathrm{SOC}}{\mathrm{SOC}_{ref}}+\frac{\mathrm{Clay}}{\mathrm{Clay}_{ref}}+\frac{\mathrm{TN}}{\mathrm{TN}_{ref}}\right)+\log\left(\frac{\mathrm{pH}}{\mathrm{pH}_{ref}}\right)-\log\left(\frac{\mathrm{BD}}{\mathrm{BD}_{ref}}\right)}{3}\right]} \quad (2)$$

In the above equation, the variables had all been defined. They represent the key soil parameters under the current land use. The variables with subscript *ref* refer to the reference value representing the parameters when the NAC of the soil is at its optimal. We used the arithmetic average of soils obtained at the public parks in Beijing for the reference values per reasoning in van Wijnen et al. (2012).

2.2. Study area and soil sampling

Beijing as a human habitat dates back for more than 3000 years. The built-up area now covers about 700 km^2. Starting from the city center, the city expands over time and outward and is encircled by 5 concentric ring roads, the traffic thorough fares. The urbanization began from the central area inside the 2nd ring road, then sequentially toward the north, west, east and south directions (Fig. 1).

Soils were sampled according to a 1 min latitude × 1 min longitude (approximately 1.9 km × 1.0 km) grid. One composite sample was obtained inside a 500 m × 500 m representative landscape of each grid. In this manner, two hundred thirty three 0–10 cm surface soil samples were collected. Each sample was composed of 5 subsamples of the four corners and the center point in a 10 m × 10 m square. Among them, 25 were from public parks, 58 from traffic areas, 53 from schoolyards and public areas, 28 from agricultural and wooded area (excluding parks), and 69 from residential areas (Fig. 1). These habitats were chosen based on the dominated landscape in each grid.

2.3. Measurements of soil parameter and paved area

Soil parameters were determined as described in Wang et al. (2011), Wang et al. (2012) and Peng et al. (2011). Soil organic carbon contents were determined using HCl treated method (Nam et al., 2008). Briefly, soil samples were treated with 1 M HCl for 24 h to decompose carbonate associated carbon. And then, the treated soil was dried at 60 °C before determination of carbon content by an elemental analyzer (Elementar, Hanau Germany). Soil pH was determined in distilled water at a soil-to-solution ratio of 1:2.5. Surface soil (0–10 cm) bulk density was determined using stainless cutting rings (100 cm^3). The ring soil samples were dried at 105 °C for 24 h to calculate bulk density. Five repeats were sampled for each 10 m × 10 m. Clay content was determined using a laser particle size analyzer and calculated according to the USDA soil classification scheme. Total nitrogen content was measured using an elemental analyzer (Elementar, Hanau Germany).

The percentage of impervious paved area of the 500 m × 500 m sampling grids was identified using GIS Arcgis 9.3.

Table 1
Key soil parameters used in NAC calculation, their ranges and ecological processes involved.

Soil parameters	Range	Ecological process involved
Soil organic carbon content (SOC) (%)	0.241–5.11	Adsorption of heavy metals and PAHs in soils and degradation of PAHs
Clay content (Clay) (%)	2.51–17.7	Adsorption of heavy metals in soils
Bulk density (BD) (g/cm^3)	0.968–1.77	Leaching of heavy metals and PAHs
pH measured in pore water (pH)	7.06–8.4	Adsorption of heavy metals and biodegradation of PAHs
Total soil N contents (TN) (%)	0.031–0.205	Supplemental parameter to clay and organic carbon contents of soils