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Spatial variations in soil phosphorus along a gradient of central city-suburb-exurban satellite

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ABSTRACT

Urbanization has progressively intensified over the past few decades, transforming the structure and function of urban ecosystems and influencing the concentrations and spatial distributions of phosphorus (P) in the soil. This study collected 177 surface soil samples (to a depth of 20 cm) to understand the dynamics of soil P along a gradient of urbanization from a densely urbanized central city to less human-affected suburbs to a new exurban satellite in Chengdu, China. The results showed that concentrations of soil total P (TP) and its fractions (except Water-Po, NaOH-Pi, and Residual-P) in the central city and exurban satellite were significantly higher than in suburban areas ($p < 0.05$). Meanwhile, the concentrations of soil TP and its fractions (except Residual-P) significantly decreased with the increase in distance from the urban center ($p < 0.05$). These concentrations were significantly positively correlated with the densities of built-up areas and roads, and showed significant differences among different green space types. The results of generalized linear models indicated that the most decisive factors contributing to TP accumulation were the distance from urban center and green space type. Generally, green space type and density of built-up area were likely to be more crucial determinants governing soil inorganic P fractions compared with other factors, whereas the key factors affecting soil organic P fractions were varied. To conclude, urbanization is likely to lead to the accumulation of P and, thus, controlling the expansion of built-up areas and road areas is necessary to alleviate soil P accumulation in urban systems.

1. Introduction

Urbanization has rapidly intensified over the past few decades (Angel et al., 2011; Chen and Gao, 2011; Jiang and O'Neill, 2015; Merrilees et al., 2013; Takahashi et al., 2015; Villa et al., 2017). Such rapid development can transform the structure and function of urban ecosystems, thereby influencing the urban ecological environment (Haas et al., 2015; Li et al., 2017; Liu et al., 2018). With the acceleration of urban expansion, drastic disturbances, including construction projects, complex land-use patterns, high road densities, and intensive management, substantially impact the structure, quality, and function of soils as well as the cycling of soil phosphorus (P), including soil total P (TP) and its fractions (Cherubin et al., 2016; Crews and Brookes, 2014; Meng et al., 2018; Metson et al., 2015). On the one hand, excessive P input could result in elevated P concentrations in soil, which could contribute to the eutrophication of surface water, especially given the higher percentages of paved surfaces in urban areas (Huang et al., 2013; McGinley et al., 2016); on the other hand, the use of low-quality filling materials and the regular removal of plant litter can often result in the nutrient deficiency of urban soils (Jiang et al., 2016), and P scarcity has a strong influence on urban soil quality and vegetation growth. In addition, current P management approaches fail to adequately address the issues of P pollution and scarcity in urban areas (Chen et al., 2014; Cherubin et al., 2016; Roy and Bickerton, 2014). Therefore, studies have focused on improving our understanding of the distribution of soil P and its determining factors in urban systems.

Recent studies demonstrated that soil P, including TP and its fractions, is affected by urbanization (Chen et al., 2014; Metson et al., 2015; Roger et al., 2014). Some studies reported that urban and suburban soils were enriched in TP and available P (AP) compared with rural soils (Chen et al., 2014; Yuan et al., 2007). By contrast, Hales et al. (2002) demonstrated that soil AP was lower in urban than in rural soils. Meanwhile, Bennett (2003) found that concentrations of AP showed no significant differences in soils along an urban–rural gradient in Dane County, Wisconsin, USA. Following the introduction of the ‘urban–rural gradient paradigm’ (McDonnell and Pickett, 1990), researchers combined this gradient with urban soils to identify the effect of urbanization on soil TP and its fractions in many cities worldwide (Hu et al.,

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2011; Merrilees et al., 2013; Weissert et al., 2016). However, as cities have developed, there has been a tendency for previously peripheral urban areas to be become increasingly developed, both with residential and commercial areas, resulting in the formation of new urban areas in the form of satellite cities (Macgregor-Fors, 2011; Merrilees et al., 2013). However, despite this development, it is still unclear how soil TP and its fractions change along this new central city–suburb–exurban satellite gradient; such gradients might be a useful predictor of soil P because they embrace recent changes in land-use types in areas undergoing urbanization. Consequently, identifying the distribution of soil P along this gradient is crucial if we are to more fully understand the effects of urbanization on soil P.

The factors that influence the concentrations of soil TP and its fractions in urban areas have been investigated previously (Chen et al., 2014; Chen et al., 2016; Cherubin et al., 2016; Takahashi et al., 2015). Given that increasing distance from the urban center can be used as an indicator of decreasing anthropogenic influences on soil disturbance (Takahashi et al., 2015), researchers have investigated P concentrations in soils located along the direction of urban sprawl; for example, Chen et al. (2014) found that concentrations of soil TP and AP decreased with increasing distance from the urban center. Meanwhile, the densities of built-up areas and roads are also considered to be quantitative indicators reflecting environmental pressures on soil P (Berndtsson, 2014; Chen et al., 2016; Koivusalo and Sillanpää, 2013; Kuoppamäki et al., 2014). Han et al. (2011) found significantly higher net anthropogenic P accumulation in areas covered mainly by anthropogenic constructions compared with areas covered mainly by agriculture and forest. Furthermore, Kuoppamäki et al. (2014) revealed that soil TP concentrations were higher next to roads that had heavy traffic flow compared with roads that had light traffic flow in the city of Lahti, southern Finland. The distance from an urban center and densities of built-up areas and roads reflect the intensity of human disturbances, but there have been few effective modeling approaches developed to quantify explicitly the linkages between these factors and soil P content. Thus, there is the need for an accurate understanding of the response of soil P, including TP and its fractions, to these urbanization factors if we are to manage P sustainably.

Some studies also indicated that the type of green space was one of the most crucial factors affecting soil P distribution during urbanization (Cherubin et al., 2016; Cordell and Neset, 2014; Hu et al., 2011). This is because soils have been modified by human activities to various degrees (e.g., physical disturbance, coverage of soil by fill material, and management practices) under different green space types (e.g., parklands, residential, and industry). It is evident that many factors affect the accumulation and distribution of TP and its fractions in urban soils (Cherubin et al., 2016; Metson et al., 2015; Takahashi et al., 2015). However, most early studies on the effect of urban development upon soil P considered only single factors; thus, a multivariable approach is needed to address the response of soil P in relation to multiple urbanization factors (Matthies et al., 2015; Metson et al., 2015). In the present study, it was hypothesized that the urbanization processes (e.g. change of land-use types and the expansion of built-up areas and road areas) would change the accumulation and distribution of soil P; our study aimed to identify the decisive factors that determining the accumulation and distribution of soil TP and its fractions in urban systems.

Most early studies of the effects of urban development upon soil P typically considered only TP and plant-available forms of P (i.e., extractable $NaHCO_3$), but only limited data are available in relation to the occurrence of these different P fractions in urban areas (Metson et al., 2015; Roger et al., 2014). The distribution of P fractions can reflect soil composition and the status of soil degradation, enabling the quantification of the fate of native and applied P in urban systems (Aguiar et al., 2013; Riskin et al., 2013). Therefore, an accurate understanding of P pools and the different P fractions in urban area would be useful.

In this study, we measured TP and soil P fraction concentrations among soils from five green space types along a central city–suburb–exurban satellite gradient in western Chengdu, China, to investigate the effects of urbanization on soil P distribution. Our objectives were to: (1) characterize the spatial distributions of TP and P fractions along the central city–suburb–exurban satellite gradient; (2) assess the effect of distance from the urban center, density of built-up area, road density, and green space types on soil P distribution; and (3) clarify the effects of combinations of different factors in the urban system on soil P quantitatively by using generalized linear models (GLMs).

2. Materials and methods

2.1. Study area

The study area was located between the Wenjiang and Chengdu urban area (30°56′N–30°73′N, and 103°82′E–104°05′E). The area has a subtropical humid monsoon climate with an average annual precipitation of 972 mm and a mean annual temperature of 15.9 °C (Yu et al., 2015). The study area was situated on the Minjiang river alluvial plain, the soils of which are dominated by Udic Cambosol and Stagnic Anthrosols, both of which are developed from fluvial sediments. The key clay minerals in the soil are vermiculite and kaolinite (Jiang et al., 2015).

Chengdu is the capital of Sichuan Province, southwestern China. It is both an ancient city with a long history and a modern city that has undergone rapid development over the past few decades. From 1960 to 1978, the establishment of the first ring road in Chengdu connected the traditional grid-based road networks, making possible future rapid expansion of the urban internal spatial structure of the city. At the end of the 1980s, urban land-use had expanded, necessitating the construction of a second ring road. From 1996 to 2006, a more sophisticated road network was developed, with the completion of four ring roads (first ring, second ring, third ring and the outer ring) together with multiple radiating roads (Fig. 1). In 2007, Chengdu began to execute a coordinated urban–rural development project, putting into practice its vision of a spatial structure with one central city, two belts, five wedge-shaped green spaces, and six township development corridors (Qin, 2015). The six-corridor pattern was designed to help decentralize development away from the central city of Chengdu into the surrounding areas along the transportation corridors; therefore, satellite cities, such as Wenjiang, were established (Qin, 2015), resulting in a central city–suburb–exurban satellite city buffer zone between the urban center of Chengdu and Wenjiang (Liu et al., 2016; Peng et al., 2015).

In our study, the Chengdu urban center is indicated by a red star in Fig. 1, situated between the center of the city and the outer ring road, and characterized by a long history of urbanization, high population density, significant automobile transportation, and large areas of hard surfaces (e.g., pavements and roads). The area between the outer ring road to Wenjiang urban area represents a suburban area; and the Wenjiang urban area represents an exurban satellite (Fig. 1). In this central city–suburb–exurban satellite gradient, we assumed that the intensity of human disturbance decreased from the Chengdu urban center to the suburban areas, but then increased again towards the Wenjiang center.

2.2. Soil sampling

Referring to the Chinese land-use classification system (Li et al., 2015) and SPOT images with a spatial resolution of 2.5 m taken on June 1, 2015, green space types were classified as residential, attached (e.g., school yards or public areas), traffic, industrial, and park green spaces. We divided our study area into six zones according to the ring road and the boundary of Wenjiang urban area along the central city–suburb–exurban satellite gradient (Table 1). In each zone, soil samples were collected in every green space type, and the number of soil