Urban–rural gradients in soil nutrients beneath Chinese pine (*Pinus tabulaeformis* Carr.) are affected by land-use

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Accepted: 14 January 2022 / Published online: 26 January 2022
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Abstract
Urban–rural gradients of soil nutrients may be affected by many factors including land use, vegetation cover, and management. In this study, focusing on one vegetation type (Chinese pine, *Pinus tabulaeformis* Carr.) to exclude the effects of vegetation cover, we investigated soil nutrients in three land-use types (neighborhoods, parks and roadsides) along urban–rural gradients in Beijing, China, to explore the differences in soil nutrients across land-use types and the changes of soil nutrients along the urban–rural gradient. Soil nutrients (organic carbon, calcium and magnesium) are significantly higher in neighborhoods and parks than in roadsides, while soil nutrients (except for magnesium) showed no significant differences between in neighborhoods and in parks. Interestingly, soil moisture, nitrate-nitrogen, calcium, magnesium, and available phosphorus and potassium all decreased along urban–rural gradients in parks, while only soil available phosphorus did so in neighborhoods and none soil variables studied showed this trend in roadsides. Thus, land use plays an important role in modifying urban–rural gradients of soil nutrients.

Keywords Chinese pine · Land-use types · Soil nutrients · Urban–rural gradients

Introduction

Urbanization affects the biological, physical and chemical properties of soils and the processes that affect them (Pouyat et al. 2010; Herrmann et al. 2018). Gradients in soil properties have been studied at the scales of patches (Jenerette et al. 2010), cities (Pouyat et al. 2006, 2010), regions (Pouyat et al. 2007; Li et al. 2013), and globally (Pouyat et al. 2006). The urban–rural gradient paradigm characterizes variation in soils with respect to the degree of urbanization as measured by land-use intensity (Su et al. 2019), style of land management (Mao et al. 2014), particular microenvironments (Liu et al. 2007), and/or the flora and fauna that compose soils (Zhu and Carreiro 1999; Zhao et al. 2010). This paradigm is considered useful for describing effects of urbanization on soil nutrients due to its simplicity and effectiveness (Bennett 2003; Vasenev et al. 2013; Chen et al. 2014; Meng et al. 2018).

Previous studies have described how urban–rural gradients of soil nutrients are influenced by many factors including the geographical locations of study areas (Bennett 2003; Li et al. 2013), soil properties and depths (Baxter et al. 2002; Vasenev et al. 2013), land-use types (Bennett 2003; Foti et al. 2017), vegetation types (Zhao et al. 2007), and how the land is managed (Foti et al. 2017). Differences in management practice, soil history, the amounts and nutrient content of leaf litter (reflecting vegetation type), and the depth and density of plant roots can all affect the soil properties and thus the direction and slope of urban–rural gradients in soil properties (Zhao et al. 2007; Lorenz and Lal 2009; Pouyat et al. 2010; Foti et al. 2017). Foti et al. (2017) reported a trend: although physical and chemical properties of woodland soils varied along urban–rural gradients, such gradients were attenuated under lawns where soils are more actively managed, e.g., by regular fertilization.

Studies of the same city sometimes differ in which urban–rural gradients they show, even for the same soil
nutrient (Table 1). To obtain more consistent results, some researchers control either for land-use type or vegetation type as they explore urban–rural gradients in soil nutrients (Pouyat et al. 1995; Bennett 2003; Kaye et al. 2008).

In Phoenix, USA, Davies and Hall (2010) found that controlling for differences in land-use type (desert yards) but not in vegetation type reduces urban–rural gradients in soil moisture, organic matter and inorganic nitrogen. In New

| Location            | Land-use types                                                                 | Factors controlled \(^{(1)}\) | Soil nutrients                   | Urban–rural gradients | References                      |
|---------------------|-------------------------------------------------------------------------------|-------------------------------|----------------------------------|-----------------------|---------------------------------|
| Beijing, China      | Neighborhood, park, roadside, industrial, institutional, road greenbelt, forest | No                            | Moisture content                | Positive              | Mao et al. 2014                 |
|                     |                                                                               |                               | Organic carbon                  | Positive              |                                 |
|                     |                                                                               |                               | Total nitrogen                  | Positive              |                                 |
|                     |                                                                               |                               | Available phosphorus             | Positive              |                                 |
|                     |                                                                               |                               | Available potassium             | Positive              |                                 |
| Hefei, China        | Street, campus, park                                                          | Vegetation                    | Ammonium-nitrogen               | Positive              | Zhang et al. 2010a              |
|                     |                                                                               |                               | Nitrate-nitrogen                | Negative              |                                 |
| Nanjing, China      | Neighborhood, park, roadside, square, campus, vegetable garden                | No                            | Total phosphorus                | Negative              | Yuan et al. 2007                |
|                     | Neighborhood, park, roadside, industrial, agricultural, traffic, municipal, others | No              | Total phosphorus                | Near zero             | Zhao et al. 2007                |
|                     |                                                                               |                               | Available potassium             | Negative              |                                 |
|                     |                                                                               |                               | Total potassium                 | Positive              |                                 |
| Nanchang, China     | NA \(^{(1)}\)                                                                 | No                            | Ammonium-nitrogen               | Positive              | Chen et al. 2014                |
|                     |                                                                               |                               | Nitrate-nitrogen                | Negative              |                                 |
|                     |                                                                               |                               | Available phosphorus             | Negative              |                                 |
|                     |                                                                               |                               | Total phosphorus                | Negative              |                                 |
| Hangzhou, China     | Residential, agricultural, commercial                                         | No                            | Total phosphorus                | Negative              | Zhang 2004                      |
| Hubei, China        | Neighborhood, park, roadside                                                   | No                            | Available phosphorus             | Positive              | Li et al. 2013                  |
|                     |                                                                               |                               | Organic matter                  | Positive              |                                 |
| Chengdu, China      | Neighborhood, park, traffic, industrial                                        | No                            | Total phosphorus                | Negative              | Li et al. 2018                  |
| New York, USA       | NA                                                                             | Vegetation                    | Ammonium-nitrogen               | Near zero             | Zhu & Carreiro 1999            |
|                     |                                                                               |                               | Nitrate-nitrogen                | Negative              | Pouyat et al. 2002              |
|                     |                                                                               |                               | Organic carbon                  | Negative              | Baxter et al. 2002              |
|                     |                                                                               |                               | Ammonium-nitrogen               | Positive              |                                 |
|                     |                                                                               |                               | Nitrate-nitrogen                | Near zero             | Lovett et al. 2000              |
|                     | Park, field station, nature preserve, environmental research organization     | Land-use and vegetation       | Ammonium-nitrogen               | Negative              |                                 |
|                     |                                                                               |                               | Nitrate-nitrogen                | Negative              |                                 |
|                     |                                                                               |                               | Calcium                         | Negative              |                                 |
|                     |                                                                               |                               | Magnesium                       | Negative              |                                 |
| Phoenix, USA        | Desert, neighborhood, industrial, river gravel, agriculture                    | No                            | Ammonium-nitrogen               | Near zero             | Hope et al. 2005                |
|                     | Desert                                                                        | Land-use and vegetation       | Nitrate-nitrogen                | Near zero             | Davies & Hall 2010              |
|                     |                                                                               |                               | Moisture content                | Negative              |                                 |
|                     |                                                                               |                               | Organic matter                  | Negative              |                                 |
|                     |                                                                               |                               | Ammonium-nitrogen               | Negative              |                                 |
|                     |                                                                               |                               | Nitrate-nitrogen                | Negative              |                                 |
| Dane, USA           | Neighborhood                                                                   | Land-use                       | Total phosphorus                | Near zero             | Bennett 2003                    |
| London, England     | NA                                                                             | No                            | Total phosphorus                | Negative              | Meng et al. 2018                |
| Moscow, Russian     | Industrial, residential, recreational                                          | No                            | Organic carbon                  | Negative              | Vasenev et al. 2013             |

\(^{(1)}\) No indicated that neither vegetation nor land-use were not controlled
York, USA, Zhu and Carreiro (1999), Baxter et al. (2002), and Lovett et al. (2000) did the opposite, controlling for variation in vegetation type (looking only at oak stands) but not in land-use type and found the opposite result, namely increased urban–rural gradients in soil ammonium-nitrogen and nitrate-nitrogen (Table 1). Controlling for land-use and vegetation types thus appears to improve the precision with which we can assess urban–rural gradients in soil nutrients, even as we remain uncertain about just how land-use and vegetation affect these gradients.

Because many pedogenic factors are changed by urbanization, there are inconsistencies in previous results about the influence of urbanization on soil nutrients. In this study, we excluded the influence of vegetation by focusing our study on one vegetation type of pine, and sampled soils in three land-use types (neighborhoods, parks, and roadsides) along the urban–rural gradient. It will help identify the major factors influencing soil nutrients along urban–rural gradient. We try to answer two questions: (1) How do soil nutrients differ among different land-use types? (2) Are there clear urban–rural gradients in soil nutrients and do these differ among land-use types? Neighborhoods, parks, and roadsides are major land uses in both urban and rural areas in Beijing, China (Zhao 2010; Kuang 2012). To control for the influence of vegetation type on soil nutrients along the urban–rural gradient, we investigated only sites covered by one vegetation type: Chinese pine (Pinus tabulaeformis Carr.). This coniferous tree is endemic to northern China and a dominant species in the region. It is widely planted in both urban and rural areas because of its high esthetic value and its ability to thrive in harsh habitats (Zheng and Fu 1978; Zhao 2010). We measured soil nutrients beneath Chinese pine in 15 neighborhoods, 25 parks and 24 roadsides that spanned broad urban–rural gradients, providing a clean design for a “natural” experiment with three “treatments” (Diamond 1983).

Methods

Study sites

This study was conducted in Beijing (39°28′-41°25′N, 115°25′-117°30′E), the largest metropolis of northern China. By 2020, the population of Beijing has reached 21.89 million (the 7th National Census Bulletin of China posted by http://www.gov.cn). The altitude of the built-up area of Beijing ranges from 20 to 60 m (Zhang et al. 2010b). The city has temperate humid monsoonal continental climate with a mean annual temperature of 11–12 °C and mean annual precipitation of 500 mm. Dominant native soils in Beijing are cinnamon soils and fluvo-aquic soils with parent materials consisted of weathering rocks and loose quaternary sediment (Liu et al. 2016). The native vegetation is characterized by warm temperate deciduous broad-leaved forests.

In July 2016, we set up a south-north transect running through the city center (Fig. 1). The transect spans quickly urbanizing regions as well as rural areas belonging to Beijing administratively (Mao et al. 2014; Peng et al. 2016). Because the city of Beijing has been expanding concentrically (Peng et al. 2016), the distance of sites from the city center was used to characterize the urban–rural gradient. Along this transect, we studied soils in Chinese pine forests located in 15 neighborhoods, 25 parks and 24 roadsides (Fig. 1 and Table 2). We had two considerations in choosing these sites: (1) the cover of Chinese pine forests was more than 100 m²; and (2) sites were spaced at least 1-km apart. These Chinese pine stands averaged 22 years old. The average height and diameter at breast height were 5.85 m and 16.62 cm, respectively.

Soil sampling and soil nutrient analysis

At each site, we sampled surface soils (0–20 cm) in four plots that were 50 cm from the trunk then mixed these to obtain a combined sample for analysis. The soil samples were oven-dried to constant weight at 105 °C for 72 h. Percent soil moisture (SM) was calculated from the weight difference between wet and dry soil per unit dry soil (Lu 2000). We measured soil organic carbon (SOC) using the dilution heat K2Cr2O7 oxidation volumetric method (Lu 2000; Yu et al. 2010). Soil ammonium-nitrogen (NH4+-N) and nitrate-nitrogen (NO3--N) were extracted using 1.0 mol/L potassium chloride and then analyzed via flow injection analysis (Lachat QuikChem, Lachat Instruments, Colorado, USA) (Lu 2000; Yu et al. 2010). Soil available phosphorus (AP) was derived from samples digested with 0.5 mol/L pH 8.5 NaHCO3 and analyzed using Mo-Sb colorimetry (Lu 2000; Yu et al. 2010). For soil available potassium (AK), we digested samples with 1.0 mol/L pH 7 CH3COONH4 and determined concentrations using ICP-OES (Prodigy, Leeman, USA) (Lu 2000; Yu et al. 2010). Soil calcium concentration (Ca) and magnesium concentration (Mg) were determined using ICP-OES (Prodigy, Leeman, USA), following closed HNO3/HCl/HF digestion in a microwave oven (Chen et al. 1999).

Data analysis

All statistical analyses were performed using the R language (R, version 3.5, http://www.R-project.org). Because NO3--N, AP, AK, Ca and Mg were not highly skewed, we normalized their distributions using a log10 transformation before analysis. We first used ANOVA models to test whether soil properties varied among the land-use types. We used the Tukey’s HSD test to compare resulting estimated differences in soil property values between particular land-use types. We adjusted
Table 2  Definition and characteristics of land-use types studied

| Land-use types | Neighborhoods | Parks | Roadsides |
|----------------|---------------|------|-----------|
| **Panoramic photos** | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| **Description** | Green spaces in neighborhoods, mainly serving the community residents, with functions of providing shade and recreational places for residents, etc | Green spaces in public parks, open to the public, with recreation as the main function, also with functions of ecology, landscape, education, etc | Green spaces along roads, with functions of beautifying roads and reducing traffic noise, solid and gaseous pollution, etc |
| Land use unit studied | 10 (1.3 – 40) ha | 57 (1.8 – 380.4) ha | 37 (10 – 90) m |
| Sampling patch | > 100 m² | > 100 m² | > 100 m² |
| Spaces between pines (m) | 3 – 5 | 3 – 5 | 3 – 5 |
| Pine age (year) | 23 (12 – 38) | 23 (9 – 44) | 20 (11 – 34) |
| Pine height (m) | 5.8 (2.2 – 10.2) | 5.9 (2.5 – 12.3) | 5.9 (1.6 – 10.6) |
| Diameter at breast height of pine (cm) | 16.9 (7.1 – 32.9) | 18.1 (7.6 – 34.7) | 14.9 (7.0 – 26.8) |

The data in columns of land use unit studied, and pine space, age, height and diameter at breast height were offered in form of mean (min–max)
the p values from these Tukey-HSD tests using the Benjamini and Hochberg’s false rate of discovery method in the ‘multcomp’ package in R (Benjamini and Hochberg 1995). We then applied simple linear regression models using the ‘lm’ function in R to test for urban–rural gradients in soil properties. We compared full models with null models which included only the intercept, using likelihood ratio tests with the function ‘anova’ to measure the significance of each linear model.
Results

Soil nutrient contents among land-use types.

Land-use types differed in soil nutrient levels in these Chinese pine stands. In particular, levels of SOC, Ca and Mg under Chinese pines growing within neighborhoods and parks were appreciably higher than levels of these nutrients in roadside areas \( (P < 0.01, \text{Fig. 2}) \). Neighborhoods had 62%, 113%, and 168% more SOC, Ca, and Mg, respectively, than roadways while parks had 36%, 70%, and 81% more. Neighborhoods also had 47% higher levels of soil NO3-N than roadways \( (P < 0.05, \text{Fig. 2D}) \) and 168% higher soil Mg than parks \( (P < 0.01, \text{Fig. 2H}) \).

Urban–rural gradients in soil nutrients

Conspicuous and consistent urban–rural gradients in soil nutrients exist in Beijing. Overall, and in all particular cases that were significant, nutrient levels decline along the urban–rural gradient across park lands. SM (slope: -0.630; \( R^2 \): 0.52; \( P: < 0.01 \); Fig. 3A), NO3-N (slope: -0.027; \( R^2 \): 0.34; \( P: < 0.01 \); Fig. 3D), AP (slope: -0.033; \( R^2 \): 0.29; \( P: < 0.01 \); Fig. 3E), AK (slope: -0.025; \( R^2 \): 0.50; \( P: < 0.01 \); Fig. 3F), Ca (slope: -0.036; \( R^2 \): 0.41; \( P: < 0.01 \); Fig. 3G) and Mg (slope: -0.042; \( R^2 \): 0.31; \( P: < 0.01 \); Fig. 3H) significantly decreased along the urban–rural gradient for parks. Only soil AP (slope: -0.044; \( R^2 \): 0.41; \( P: < 0.01 \)) significantly decreased along the urban–rural gradient in neighborhoods (Fig. 3E). SOC and NH4+-N did not change significantly along the urban–rural gradient for all land-use types studied. There were no significant changes in soil variables studied along the urban–rural gradient for roadsides.

Discussion

Urbanization has exerted profound effects on ecosystems. Soil, as the main source of water and nutrients for plant growth, is critical to plant growth and development, and as the main component of the ecosystem, plays great roles in urban ecosystem functions (e.g., primary productivity and material cycles) and services (e.g., cooling, flood reduction, carbon sequestration). So the investigation of the effects of urbanization on soil nutrients is very important to understand the effects of urbanization on ecosystems. The urban–rural gradient is a basic feature of the urban spatial pattern (McDonnell and Pickett 1990), and represents the process of urbanization. Changes of soil properties along the urban–rural gradient can not only reflect the impact of urbanization on the soil, but also determine urban ecosystem functions and services (O’Riordan et al. 2021). Existing studies have shown that changes in soil properties along the urban–rural gradient are inconsistent (Table 1). The reasons might be the regional differences and complex interactions of biophysical, biological and anthropogenic influencing factors. By excluding the influences of vegetation types and separating the influences of land use types on soil nutrients, this study found that urban–rural gradients of soil nutrients were different among land use types, implying that the effects of urbanization on soil nutrients were dependent on land use type.

Effects of land-use types on soil nutrient contents

Soils under different land-use types were modified by anthropogenic disturbances to different degrees (Pouyat et al. 2007; Mao et al. 2014; Li et al. 2018). In our study, soil levels of SOC, Ca and Mg in neighborhoods and parks were higher than that in roadsides (Fig. 2) as was soil NO3-N in neighborhoods (Fig. 2D). Similarly, SOC levels in neighborhoods were higher in Baltimore, USA (Pouyat et al. 2002) and Phoenix, USA (Davies and Hall 2010). Soil Ca levels in neighborhoods of Beijing, China were higher than those in other land-use types (Ma 2007). Neighborhoods and parks typically experience higher inputs of soil nutrients than roadsides as city dwellers often deliberately apply fertilizer and inadvertent fertilization occurs from pets and livestock (Hope et al. 2005; Lorenz and Lal 2009). Neighborhoods and parks are designed as mostly artificial landscapes with high plant diversity for aesthetic and recreational value while still retaining some residual vegetation (Sharpe et al. 1986; Li et al. 2006; Zhao 2010). To sustain this vegetation, more active management occurs in most neighborhoods and parks than in roadsides. This includes more frequent irrigation and the addition of chemical fertilizers (Mao et al. 2014; Li et al. 2018).

Some of these gradients are element-specific, suggesting that the mechanisms that may account for them are, too. Soil organic carbon, for example, may be related to soil age (Morisada et al. 2002; Hou et al. 2019). During the construction of neighborhoods and parks, some soils in these areas were preserved without being moved. Once built, neighborhoods and parks experience little soil disturbance. In contrast, old and broken roads are frequently rebuilt, meaning that soils in these areas may be frequently renewed or disturbed. Thus, while SOC could accumulate with age in neighborhoods and parks, this is less likely in roadsides (Mao et al. 2014; Bae and Ryu 2015). We also observed that soil Ca was higher in neighborhoods and parks. This may reflect that fact that more buildings and recreational facilities in these areas use construction materials like bricks, cement, and concrete with abundant Ca (Pouyat et al. 2007; Mao et al. 2014).
Fig. 2 Differences in soil nutrients among land-use types: (A) moisture content; (B) organic carbon; (C) ammonium-nitrogen; (D) nitrate-nitrogen; (E) available phosphorus; (F) available potassium; (G) calcium; and (H) magnesium. The letters indicated significant differences between land-use types at $P < 0.05$. 
Fig. 3 Changes of soil nutrients with the distance from city center for neighborhoods, parks and roadsides: (A) moisture content; (B) organic carbon; (C) ammonium-nitrogen; (D) nitrate-nitrogen; (E) available phosphorus; (F) available potassium; (G) calcium; and (H) magnesium. Only were regressional lines showed when their relationships were significant ($P<0.05$). ** indicated the slope was significant at the level of $P<0.01$. 

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Others have sometimes documented results that differ from ours. Mao et al. (2014) found higher levels of soil organic carbon in roadways than in neighborhoods and parks in Beijing. It is possible that in their study, the effects of land-use were confounded with the effects of vegetation type. Their study included several vegetation types, so unbalanced sampling among these might lead to the inconsistent result (Jackson et al. 2002; Zhao 2010; Guo et al. 2018; Liu et al. 2018).

**Effects of land-use types on urban–rural patterns of soil nutrients**

Urbanization tends to degrade the biophysical environment while not diminishing soil nutrients. In this study, SM, NO$_3$–N, AP, AK, Ca, and Mg were all higher in urban than in rural park lands (Fig. 3). Previous studies also found higher soil nutrients in urban areas than in rural areas, such as for soil NO$_3$–N in New York, America (Zhu and Carreiro 2004), soil AP in Beijing, China (Mao et al. 2014), soil AK in Nanjing, China (Zhao et al. 2007), and soil Ca in New York, America (Pouyat et al. 2008).

Monotonic increases in soil nutrients toward city centers could reflect several factors. First, if construction waste following the construction of buildings in urban areas was mixed into soils, concrete and cement could elevate soil Ca, Mg, TP and TK (Pouyat et al. 2007; Mao et al. 2014; Li et al. 2018). Second, intensive vegetation management practices in urban areas could increase soil nutrients, such as frequent irrigation with eutrophic reclaimed water and chemical fertilization increasing SM, SOC, TN and TP (Hope et al. 2005; Mao et al. 2014). Third, some indirect influence by the invasion of exotic earthworm (Baxter et al. 2002; Pouyat et al. 2002; Phillips et al. 2019), and/or by high soil temperatures due to heat island effect (Pouyat et al. 2010; Li et al. 2013) could facilitate the accumulation of soil nutrients by accelerating nutrient cycling.

Carbon stock is of particular importance with the global carbon cycle and climate change (O’Riordan et al. 2021) and soils are the largest carbon reservoirs of the terrestrial carbon cycle (Sheikh et al. 2009). It is generally believed that the quality of urban soils is so much degraded that the carbon storage of urban soils would be lower than that of rural soils (Chen et al. 2013; Mao et al. 2014; Liu et al. 2018; Canedolli et al. 2020). But field evidences showed that SOC in urban areas is higher than that in rural areas in New York, USA (Pouyat et al. 2002), Moscow, Russian (Vasenev et al. 2013) and Harbin City, China (Lv et al. 2016), because of management practices (e.g., fertilization, irrigation and pruning ornamental shrubs) and/or waste management (Vasenev and Kuzyakov 2018). In this study, we found that there were no significant changes in SOC along the urban–rural gradient (Fig. 3B), which suggest that the capacity of urban soils to store carbon is comparable to that of rural soils. So the effect of urbanization on SOC might be city-specific. However, adaptive urban planning and management strategies are of high urgency to enhance carbon sequestration in urban soils in face of global climate change.

An interesting result of this study is that the urban–rural gradients of soil nutrients differed among land-use types. Six out of eight nutrients decline along urban–rural gradients across parks, but only one nutrient did so for neighborhoods and none showed this trend among roadside pine stands (Fig. 3). The significant gradient of soil nutrients across parks probably reflects differences in their history and management intensity between urban and rural areas. The spatial pattern of Beijing, the capital of China, has changed little over the past 1000 years except for expanded built-up areas and denser populations. Most parks in the inner city are historical sites and little altered over their long history (Li et al. 2006). Park soils along urban–rural gradients might thus reflect an age gradient. Most parks in the city center, such as Yuetan Park (built in 1530) and Jingshan Park (built in 1928), are far older than parks away from city center, such as Olympic Forest Park (built in 2008) and Banta Country Park (built in 2011). These older parks in the city center were usually better managed and preserved. However, younger parks in the outer city have short histories and tend to be managed less as they serve fewer people spread over a relatively large area. In Beijing, neighborhoods are usually managed by property management companies, not directly by various house owners (Gao and Asami 2011; Wang et al. 2015). This may lead to homogeneous management measures (e.g., fertilization and irrigation) across neighborhoods. This may contribute to low variability of soil nutrients in neighborhoods along urban–rural gradients (Bennett 2003; Davies and Hall 2010; Polsky et al. 2014; Wang et al. 2015). Less change in soil TP across residential zones along urban–rural gradients has also been reported in Dane Country, Wisconsin, America (Bennett 2003).

Unlike parks and neighborhoods, roadways are frequently in the process of being rebuilt to meet increased traffic congestion or to cater to modern standards of design (Mao et al. 2014; Mo et al. 2017). This results in little difference in the age of roadside soils along the urban–rural gradient, perhaps explaining why significant urban–rural gradients in soil nutrients do not occur among roadsides (Foti et al. 2017).

This investigation showed that controlling for vegetation (by only sampling sites with Chinese pine cover) exposed urban–rural gradients in soil nutrients that differ among the three land use types we studied. Our analyses, however, ignored other factors that could influence soil nutrients along urban–rural gradients. Available studies have showed there are many factors that could influence soil nutrients along urban–rural gradients, including biophysical factors such as temperature and moisture (Fang
et al. 2005), impervious surfaces (Raciti et al. 2012), air quality (Gregg et al. 2003; Loya et al. 2003), nitrogen deposition (Phoenix et al. 2012), litter amount (Tóth et al. 2011), plants and soil fauna (Pouyat et al. 2010), and human disturbance (Bowd et al. 2019). Any of these factors could potentially influence the response of soil nutrients to urban–rural gradients. While we examined effects of land-use type on the urban–rural gradient in soil nutrients in Beijing, these additional factors should be investigated to improve our understanding of the forces driving urban–rural gradients in soil nutrients.

Conclusions

Many factors influence soil nutrient levels, limiting the ability of other studies to find clear and consistent urban–rural gradients in soil nutrients. Here, we controlled for vegetation cover by restricting our study to one cover type (pine forests). We also controlled for land use by examining multiple replicates of three land uses dispersed along the urban–rural gradient, allowing a balanced (“natural”) experimental design. These controls allowed us to detect and characterize conspicuous urban–rural gradients in soil nutrients primarily in parklands. This probably reflects differences in history and management intensity for parks located in urban vs. rural areas. We also found urban–rural gradients in soil nutrients for parks to be element-specific. This might reflect particular management practices (such as fertilization) or effects from human constructions (the use of cement and minerals). The former influences SOC, soil NO$_3^-$-N and AK, while the latter influences soil Ca and Mg. Because human activities are strongly related to land use, it is important to control for land-use when seeking to study the urban–rural gradients in soil nutrients.

Acknowledgements

This study was supported by the National Key Research and Development Program of China (2017YFE0127700) and the National Natural Science Foundation of China (71533005 and 41571053). We sincerely thank Donald M. Waller for his suggestion of revision and polishing language. Also, we thank the editors and reviewers for their valuable comments, which improved the manuscript.

Declarations

Ethical Approval  Not applicable.

Consent for publication  The authors consent to the terms for publication as stated by the journal and its publisher.

Competing interests  The authors have no conflicts of interest to declare.

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