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RESEARCH ARTICLE

Response of forest soil properties to urbanization gradients in three metropolitan areas

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Abstract We investigated the effects of urban environments on the chemical properties of forest soils in the metropolitan areas of Baltimore, New York, and Budapest. We hypothesized that soils in forest patches in each city will exhibit changes in chemistry corresponding to urbanization gradients, but more strongly with various urban metrics than distance to the urban core. Moreover, differences in parent material and development patterns would differentially affect the soil chemical response in each metropolitan area. Results showed that soil chemical properties varied with measures of urban land use in all three cities, including distance to the urban core, which was an unexpected result. Moreover, the results showed that the spatial extent and amount of change was greater in New York than in Baltimore and Budapest for those elements that showed a relationship to the urbanization gradient (Pb, Cu, and to a lesser extent Ca). The spatial relationship of the soil chemical properties to distance varied from city to city. In New York, concentrations of Pb, Cu, and Ca decreased to approximately background concentrations at 75 km from the urban core. By contrast, concentrations of these elements decreased closer to the urban core in Baltimore and Budapest. Moreover, a threshold was reached at about 75% urban land use above which

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concentrations of Pb and Cu increased by more than twofold relative to concentrations below this threshold. Results of this study suggest that forest soils are responding to urbanization gradients in all three cities, though characteristics of each city (spatial pattern of development, parent material, and pollution sources) influenced the soil chemical response.

Keywords Baltimore · Budapest · Calcium · Copper · Heavy metals · Lead · New York · Urban soil · Urbanization gradient

Introduction

Soils may serve as a useful indicator of the long-term accrued effects of urban environments (McDonnell et al. 1993; Pouyat and Effland 1999). Soils are sinks for airborne chemicals because they are typically rich in exchange sites associated with clay lattices and organic matter. Airborne chemicals that are not retained in the soil and move through the profile can induce changes in soil chemical properties (Johnson and Cole 1980). Thus, as chemicals accumulate or pass through soils, the effects of airborne chemicals become measurable with time. Understanding these relatively rapid changes in forest soil properties is important, since they can lead to responses in soil community structure and in more chronic stages, alterations of ecosystem processes and forest vigor (Ohtonen and Markkola 1991; McDonnell et al. 1997).

The gradient approach has been used to investigate the effects of urban environmental changes on soil properties and fauna in remnant forest patches (Sadler et al. 2006; Carreiro et al. in press; Pouyat et al. in press). The use of the environmental gradient paradigm to investigate responses of forest ecosystems to urban land-use change was first proposed by McDonnell and Pickett (1990). The environmental gradient paradigm was popularized by Whittaker (1967) as a method for examining changes in plant species composition along elevation gradients. The method assumed that environmental variation along elevation gradients is ordered in space and that the spatial pattern of the environment constrained the occurrence of plant species (McDonnell and Pickett 1990). In applying the paradigm to urban landscapes, McDonnell and Pickett suggested the term *urban–rural land-use gradient* (heretofore referred to as *urbanization gradient*) to describe environmental gradients caused largely by variations in land use.

Urbanization gradient analyses can either be direct, when the underlying urban environmental factor is ordered linearly in space, or indirect, when a gradient of underlying factors is organized noncontinuously across the landscape (McDonnell et al. 1993). In both cases, the use of multivariate statistical techniques is necessary when several response variables are of interest and when several environmental factors vary along the gradient (Pouyat et al. in press). In the case of soil responses to urbanization gradients, multivariate statistical methods are used to relate several soil variables to either the distance from the urban center or to various metrics of urban land use, e.g., percentage of urban land-use cover or population density (e.g., Pouyat et al. 1995). In the former case, distance is an easily calculated value that is used as a surrogate variable for the urban factors. However, because of the patchiness of urban development patterns, distance may not be as representative of an urbanization gradient as a quantifiable metric such as road or population density (Theobald 2004; Hahs and McDonnell 2006).

A challenge of quantifying urbanization gradients and the underlying environmental factors associated with them is separating the effect of nonurban and urban environmental factors, particularly with investigations of soils (Pouyat et al. in press). Jenny (1941) described soil formation as a combination of state factors that include climate (*cl*), organisms (*o*), parent material (*pm*), relief (*r*), and time (*t*), where the characteristics of any given soil, S, are the function

$$S = f(cl, o, pm, r, t) \quad (1)$$

To recognize the potential effect of humans on soils, Amundson and Jenny (1991) and Pouyat and Effland (1999) proposed the inclusion of a sixth or anthropogenic factor *a*, such that

$$S = f(a, cl, o, pm, r, t) \quad (2)$$

If any of the factors in Eq. 1 vary along an urbanization gradient, there is the potential for a confounding effect, e.g., differences that may occur in parent material (Pouyat et al. in press). However, in situations where all of the nonurban factors are constant, the effect of a in Eq. 2 can be independently assessed. Pouyat and Effland (1999) proposed that urbanization gradients can create situations in which the anthropogenic factor a (in this case, an urban factor) varies for relatively short distances (<100 km) so that it is possible to hold the remaining factors as constant as possible, i.e., an "anthroposequence," where

$$S = f(a)_{cl,o,pm,r,t} \quad (3)$$

With this approach, the null hypothesis is represented by no detectable differences in the response variables along the urbanization gradient (Pouyat and Effland 1999).

To investigate the relative importance of urban environmental factors (a) versus parent material (pm) on soil chemistry, we compared urbanization gradient results of separate studies conducted in the Baltimore, New York, and Budapest metropolitan areas. These metropolitan areas differ in population densities, surface areas, surface geologies, and transportation systems. The gradient analyses in New York and Baltimore utilized previously published data (Pouyat et al. 1995; Szlavecz et al. 2006), of which a subset are analyzed in this article to make comparisons to newly acquired data from the Budapest metropolitan area. For all three cities, we compared a common set of 15 soil properties in hardwood forest remnant stands. In the case of New York, the forest patches were situated on surface geology of the same type, and thus approximated an anthroposequence along an urbanization gradient of 0-125 km, whereas in Baltimore and Budapest the surface geology differed along a 0–30 and 0–20 km gradients, respectively.

The following factors were compared among the three areas: (1) soil chemical properties that significantly changed across the urbanization gradient; and (2) relationship of individual soil chemical properties with distance to the urban core and with various urban metrics. We hypothesize that all three metropolitan areas will exhibit changes in forest soil chemical properties along their respective urbanization gradients and that these changes will be more related to changes in measures of urban land use than with distance to the urban core. Moreover, we hypothesize that the New York gradient will have affects on soil properties at greater distances from the urban core but with a similar amount of change (e.g., metal contamination) as the other two cities. Finally, we expect the response to the urbanization gradient to be confounded by the effects of differences in parent material occurring in the Baltimore and Budapest metropolitan areas.

Study areas

The Baltimore, MD, metropolitan area encompasses five counties with an area of 1,200 km^2 along the Chesapeake Bay in the Mid-Atlantic Region of the United States. Historically, the city has had an industrially based economy. Emissions from industrial sources have substantially decreased since the enactment of the Clean Air Act and the concurrent loss of manufacturing industries beginning in the early 1970s. The metropolitan area has had a population increase to 2.5 million people, while Baltimore has had a population decrease of 11.5% (736,014–638,614) between 1990 and 2000.

Baltimore lies between two physiographic provinces: the Piedmont Plateau and the Atlantic Coastal Plain. The north–northeast trending fall line separates the two provinces, dividing the city approximately in half. The Piedmont Plateau in the Baltimore metropolitan area is underlain by mafic, gneiss, and schist rock types (Crowley and Rhinhardt 1979). The Coastal Plain in the city is underlain by much younger, poorly consolidated sediments. Soils in the Coastal Plain of the city are very deep, somewhat excessively drained and well drained upland soils underlain by either sandy or gravelly sediments or unstable clayey sediment. Soils in the Piedmont Plateau of the Baltimore region are very deep, moderately sloping, well drained upland soils that are underlain by semi-basic or mixed basic and acidic rocks (NRCS 1998).

The study area of the New York urbanization gradient includes contrasting land uses extending from Bronx County, NY (New York City) north to sites in Westchester County, NY, and Litchfield County, CT (McDonnell et al. 1997). The New York metropolitan region encompasses 31 counties (41,000 km^2) with a population of more than 20 million while the city has maintained a population of approximately 8 million (Flores et al. 1998). New York is the financial center of the world and has, since the beginning of the industrial revolution, a history of industrial manufacturing.

The Bronx study area constitutes the southern portion of the Northeastern Upland Physiographic Province. The bedrock consists of highly metamorphosed and dissected crystalline rocks that are composed of schist, granite and gneiss (Schuberth 1968). Soils in the study area are classified as Typic or Lithic Dystrochrepts, coarse-loamy, mixed, mesic subgroups. The soil types included in the study are well drained, moderate to shallow sandy loam soils situated on gently sloping terrain (Hill et al. 1980).

Budapest has a longer and more diverse history than both Baltimore and New York. The first recorded settlement dates back to 89 AD. The major parts of the city (Buda, Pest, and Obuda) were unified in 1867, and by this time Budapest had become a regional economic center. The rapidly growing population peaked in the 1970s with over 2 million people, but then the trend reversed as the city lost population to the surrounding areas (Enyedi 1988). Currently, with 2.5 million people, the Budapest metropolitan area is the largest in Central-Eastern Europe. The present city boundary was established in 1950 and the total metropolitan area encompasses 525 km^2. Similar to Baltimore and New York, Budapest has a history of industrial manufacturing dating back to the second half of the 19th century. However, unlike Baltimore and New York, air pollution controls have been in use only since the early 1990s compared to 1970 in the U.S.

The Budapest metropolitan area is divided by the Danube River, which separates the two major parts of the city, Buda and Pest. Buda and Pest roughly coincides with the two major geological formations in the region. The Buda Hills are underlain by Karst topography and loess. The Karst topography is made up of primarily limestone and dolomite and occupies about 40% of the Buda Hills area while loess occupies about 50% of the area.

Materials and methods

In all three metropolitan areas, forest stands were selected using aerial photographs, topographic maps, and prior knowledge of each metropolitan area (Pouyat et al. 1995; Szlavecz et al. 2006). To comply with the assumptions of an anthroposequence, we attempted to locate stands that were of equivalent size (size $\geq$ 2 ha); had similar overstory species composition (deciduous in all cases); within slopes of <15%, stand age of 60+ years; and no visual signs of recent human disturbance. However, it was impossible to locate stands occurring on similar surface geologic types within Baltimore and Budapest.

In Baltimore, stands were located in an urban, suburban, or rural settings based on political and geographical boundaries and then were measured for distance from the city center (Inner Harbor). Six stands were located in Baltimore within 9 km from the city center on gabbro rock types: Cross Keys (CK), Cylburn Arboretum (CA), Druid Hill (DH), Hillsdale Park (HD), Leakin Park (LP), and Pimlico (PM). Three stands were located at the Baltimore City and County border and were approximately 10–14 km from the city center on coastal plain and gneiss/schist rock types: Druid Ridge Cemetary (DC), Mount Pleasant Park (MP), and Robert E. Lee Park (RL). Five stands were located >19 km from the city center on primarily gneiss/schist rock types: Gunpowder Falls (GF), Liberty Reservoir North (LN), Liberty Reservoir South (LS), Loch Raven Reservoir (LR), and Oregon Ridge Park (OR).

In each stand, a series of 0.04 ha circular plots (11-m radius) were randomly established for soil sampling. Three plots were established for stands <100 ha and five plots were established for stands >100 ha. At each plot a composite soil sample (0–10 cm) of six 5-cm diameter cores was collected using a stainless steel sampling device.

In New York, nine oak stands were selected along the transect each with three 20 $\times$ 20-m plots. In the Bronx, NY, stands were located in Pelham Bay Park (PBP), Van Cortlandt Park (VCP), and the New York Botanical Garden (NYBG). In Westchester and Litchfield Counties, between 25 and 125 km north of New York, stands were located at increasing distances from the urban core (Central Park, Manhattan) in Saxon Woods State Park (SWP), Mianus River Gorge Reserve (GRM), Mountain Lakes Park (LPM), Housatonic State Forest (HSF), Mowhawk State Forest (FSM), and Masadonia State Park (MSP). Four 5 $\times$ 5-m subplots were selected randomly for sampling within each plot, for a total of 12 sample locations in each stand. Mineral soil was sampled to a depth of 10 cm using a standard 2-cm-diameter stainless steel sampling probe. Approximately 10 cores were composited for each subplot.

In Budapest, forest stands were located in both urban and rural areas on both major geological types of the region allowing for a within-city comparison of urbanization gradients. Six stands were established in each geologic type for a total of 12 stands. In Buda, the stands included, in increasing distance from the urban core, Budakeszi (BK); Csilleberc (CS); Normafa (NF); Viranyos (VY); Kamaraerdo (KM); and Pilicsaba (PC). Likewise, stands in Pest included in increasing distance from the urban core, Orczy Kert (OZ); Obudai Sziget (OB); Paskomliget (PK); Peterhalmi Erdo (PT); Akadademia Kiserdo (AK); and Cinkotai Kiserdo (CK).

At each stand, three plots were randomly chosen both in terms of direction and in terms of distance from a point in roughly the middle of the stand. In each plot, three soil samples were taken at a depth of 0–10 cm using a 5 cm diameter coring device. These soil subsamples formed a triangle with the points 5 m apart. The subsamples taken in each plot were combined for each of the three plots (total of 3 samples per stand).

Calculating measures of urban land-use

Methodology for calculating measures of individual urban features (heretofore referred to as urban metrics) used in the current study was developed for the New York City metropolitan area (Medley et al. 1995). These metrics included the length of roads and highways (Rdden, reported on a per km^2 basis); percent urban land use (Purban); population density (Popden, reported as number of people per km^2); and traffic volume on major roads and highways (Trafvol, reported as number of vehicles day^{-1}) that occurred within 2 km in each direction of each stand (16 km^2 total area). We calculated the same urban metrics in Baltimore but were unable to obtain data to calculate road density, population density, and traffic volume in the Budapest metropolitan area.

Soil analysis

Mineral soil samples for all sites were air dried, ground, and sieved using a 2-mm mesh screen. Organic layers were omitted from the samples. A subsample of mineral soil was analyzed to determine acid soluble Co, Cr, Cu, Mn, Ni, Pb, and Zn. For Baltimore and Budapest, acid soluble Al, Ca, K, Mg, and P also were measured. Subsamples were ashed for 4 h at 475°C and digested with 7.7 N HNO_3 for 25 min. Additionally, available P, K, Ca, Mg, and Al were analyzed using Morgan solution and Mehlich-1 solution extractions for the New York and Baltimore samples, respectively. Soil active acidity was measured on a 2:1 water soil mixture for the New York samples and a 1:1 mixture in Baltimore and Budapest samples. Percent organic matter of mineral soil was determined by loss on ignition (475°C for 4 h). See Szlavecz et al. (2006) and Pouyat et al. (2007) for more details of the soil analyses.

Statistical analysis

Prior to the correlation with distance and the urban metrics, the soil data were submitted to a Principal Component Analysis (PCA) using the SAS package (SAS Institute, version 9.1) to generalize the soil variables and to ordinate the plots. Because units of measurement were not consistent among all variables, the PCA was conducted on a correlation matrix, thereby emphasizing relative variation in the data (Pielou 1984).

To determine the soil chemical properties that were responding to the urbanization gradient, the first three principal components and individual soil variables were correlated with distance to the urban core or an urban metric using Spearman correlation (SAS Institute, version 9.1). Soil variables that showed a significant relationship to either distance or Purban in more than one city were then used in a comparison of those cities. Due to the differences in extraction method for P, K, Ca, Mg, and Al between New York and Budapest, comparisons of these variables were not made for these cities. City comparisons were accomplished using linear regression by relating each response variable against distance to the urban core and Purban—measures that were available for all three cities. The linear regressions against distance or Purban were made using the equation,

$$N = a + bF \tag{4}$$

which Richardson and Edmonds (1987) adapted from Jenny (1941) state factor equation. For this analysis, N is a principal component or individual soil variable, F is distance to urban core or Purban (a in Eqs. 2 and 3), and b is the slope over distance or the range of the factor measured along the urbanization transect. The slope of the linear regression and coefficient of determination (r^2) represent the relative influence and importance of the state factor (in this case urban metric or distance) on the observed soil property (Richardson and Edmonds 1987). Moreover, the y-intercept represents the amount of change (positive or negative) in the soil property, assuming the baseline value is represented by the rural measurement of a soil property. Furthermore, the x-intercept in a linear regression approximates the distance from the urban core in which there is a measurable urban effect. Soil variables that statistically varied along each urbanization gradient were compared across the cities for their x- and y-intercepts and slope.

Data were transformed ($\log_{10}$) to stabilize the variance of individual properties where necessary and used to determine the coefficient of determination and the P values of the linear regression analyses, whereas non-transformed data are shown in the scatter plot diagrams and used to determine slope and x- and y-intercepts. The GF stand in Baltimore had one of five plots removed as an outlier because the plot increased the standard deviation of Pb levels for the stand by 30-fold compared to the standard deviation without the plot.

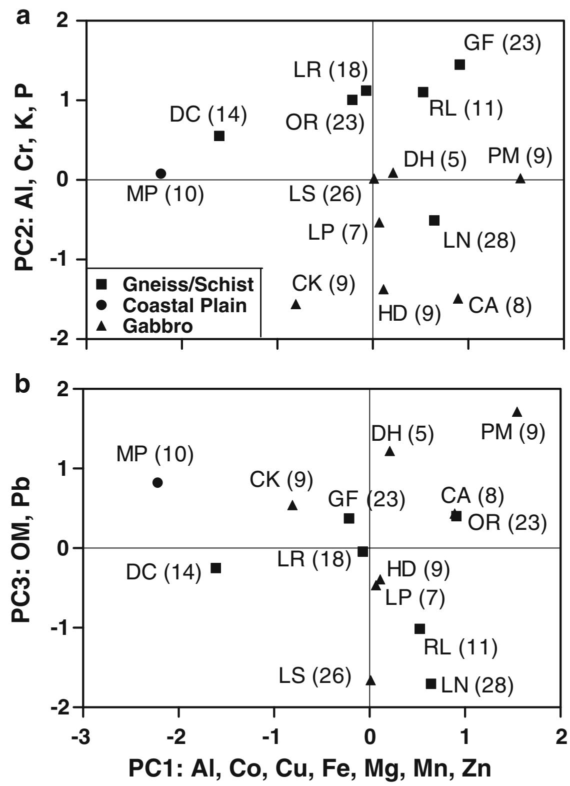

Fig. 1 Scatter plots of the (**a**) first and second principal components (PC1 and PC2) and (**b**) the first and third components (PC1 and PC3) of a principal component analysis procedure using 15 soil variables and 14 stands in Baltimore. PC1 was correlated to Al, Co, Cu, Fe, Mg, Mn, and Zn; PC2 was correlated to Al, Cr, K, and P; and PC3 was correlated to OM and Pb. Stands that fell on gneiss/schist are squares, on the Coastal Plain are circles; and on gabbro are triangles. An individual stand's distance to the urban core is represented parenthetically in km

Results and discussion

Baltimore

A complex pattern was found in the distribution of stands obtained from the PCA of soil properties in the Baltimore metropolitan area (Fig. 1). Approximately 83% of the variation was accounted for by the first three components of the PCA with the first principal component (PC1) explaining 45% of the variation (Table 1). Positive loadings of PC1 corresponded to high concentrations of primarily trace elements (Al, Co, Cu, Fe, Mg, Mn, and Zn) (Table 1). The second and third principal components (PC2, PC3) accounted for 24.8 and 13.4% of the variation with PC2 positively loaded with Al, K, and P and negatively loaded with Cr. The third principle component had positively loaded with Pb and organic matter (Table 1). There was no apparent relationship in the PC1 and PC2 scatter plot with distance to the urban core (Fig. 1a). However, PC1 appears to separate the only stand located on the Atlantic Coastal Plain (stand MP) from those on the Piedmont Plateau, while PC2 separates stands located on parent material made up of gabbro rock types from those on gneiss and schist rock types (Fig. 1a). The third principal component appears to separate stands in highly urbanized areas with those that are embedded in rural areas, with one exception, stand OR (Fig. 1b).

Neither PC1 nor PC2 were significantly correlated to distance from the urban core or any of the urban metrics (Table 2). However, PC3 varied negatively with distance to the urban core ($r = -0.538$, $P = 0.047$), and positively in order of importance with Purban, Rdden, and Popden (Table 2). Soil properties that were not strongly related to PC3, but

Table 1 Principal component loadings from a PCA of soil element concentrations in Baltimore ($n = 14$ stands), New York ($n = 9$ stands), and Budapest ($n = 12$ stands)

Variable	Principal components								
	Baltimore			New York			Budapest		
	1	2	3	1	2	3	1	2	3
Al	**0.76**	**0.58**	0.00	−0.13	−0.32	−0.44	**0.88**	−0.41	0.20
Ca	0.59	−0.57	−0.01	**0.89**	0.26	0.00	0.31	**0.89**	0.23
Co	**0.85**	−0.17	0.25	−0.24	**0.76**	−0.50	**0.94**	−0.29	0.17
Cr	0.48	**−0.79**	0.21	0.60	0.57	−0.55	**0.95**	−0.12	0.00
Cu	**0.79**	−0.05	0.44	**0.80**	0.02	0.03	0.68	0.60	−0.35
Fe	**0.81**	0.41	0.27	0.40	−0.39	**0.64**	**0.94**	−0.30	0.15
K	0.25	**0.84**	−0.43	**0.79**	0.31	−0.03	**0.94**	−0.28	0.12
Mg	**0.80**	−0.11	−0.45	**0.95**	0.13	0.18	0.53	**0.75**	0.21
Mn	**0.92**	0.19	0.06	−0.64	0.59	0.21	**0.90**	−0.35	0.10
Ni	0.73	−0.50	0.19	**0.82**	0.47	−0.18	**0.97**	−0.15	0.19
OM	−0.38	0.51	**0.69**	**0.85**	−0.13	−0.28	**0.94**	−0.05	−0.08
P	0.38	**0.71**	0.27	−0.27	**0.79**	0.44	0.59	**0.74**	−0.12
Pb	−0.34	−0.26	**0.77**	**0.91**	−0.16	0.26	**0.72**	0.14	**−0.68**
pH	0.68	−0.51	−0.31	−0.47	**0.75**	−0.01	−0.01	**0.80**	0.41
Zn	**0.86**	0.43	0.04	0.22	**0.71**	**0.57**	**0.93**	0.20	−0.18

Bold numbers represent elements that load on the principal component as determined by the eigenvalue

Table 2 Spearman correlation matrix between elements, urban metrics, and distance from the urban core ($n = 14$ stands) in Baltimore

	Distance	Purban	Popden	Trafvol	Rdden
Distance	1	−0.72**	−0.89***	−0.72**	−0.90***
Purban	−0.72**	1	0.78***	0.69**	0.85***
Popden	−0.89***	0.78***	1	0.56*	0.98***
Trafvol	−0.72**	0.69**	0.56*	1	0.63*
Rdden	−0.90***	0.85***	0.98***	0.63*	1
PC1	−0.090	−0.14	−0.046	−0.037	−0.037
PC2	0.37	−0.27	−0.27	−0.30	−0.24
PC3	−0.54*	0.72**	0.63*	0.38	0.70**
Ca	−0.53	0.35	0.28	0.49	0.31
K	0.67**	−0.74**	−0.66*	−0.62*	−0.67**
Mg	0.29	−0.50	−0.51	−0.36	−0.52
OM	0.051	0.34	0.15	−0.051	0.21
Pb	−0.80***	0.92***	0.80***	0.68**	0.87***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively

showed a significant relationship to distance or an urban metric, included K and Pb, which were negatively and positively related in order of importance to Purban, Rdden, and Popden (Table 2). The relationship of K and Pb concentrations contrasted with distance to the urban core with K being positively related ($r = 0.674$, $P = 0.008$) and Pb being negatively related ($r = -0.80$, $P = 0.001$) to distance.

Distance to the urban core was negatively and highly correlated to the other urban metrics (Table 2). Of the metrics used, Trafvol and Purban exhibited the least importance to distance; nonetheless, distance still explained more than 70% of the variation of these two metrics. Moreover, Purban showed the strongest relationship with Pb and K using Spearman correlation (Table 2).

The Baltimore results show the difficulty in measuring an urbanization gradient effect in soils that developed from different parent material, particularly with respect to soil chemical properties. In other words, the statistical comparisons of soil chemical properties were dominated by differences in mineralogy rather than environmental differences that may have occurred along the urbanization gradient. The first principal component (PC1) separated stand MP the only stand occurring on the Atlantic Coastal Plain, from the other stands (Fig. 1). The soil variables that were associated with PC1 (Fe, Al, Co, Cu, Mg, Mn, and Zn) are associated with mafic and ultra mafic rock types. These soil chemical properties were found in a separate study to differ between the Atlantic Coastal Plain and Piedmont Plateau provinces within Baltimore (Pouyat et al. 2007). Stand DC also was clustered with stand MP, and according to soil survey maps, is situated on a Glenelg urban-complex map unit, which may contain imported fill material (NRCS 1998). Whatever the case, the Glenelg and Coastal Plain soil tended to be more acidic compared to the other stands and had relatively low concentrations of Co, Fe, Mn, Mg, Ni, and Zn.

The second principal component clearly differentiated stands by parent material but at a finer scale than the regional differences in parent material exhibited by PC1. Stands associated with negative and positive loadings on PC2 are located on gabbro and gneiss/schist rock types, respectively, while PC1 separated the Atlantic Coastal Plain and the Piedmont Plateau (Fig. 1a). The second principal component also may be confounding the effect of the urbanization gradient. Potassium (K) was the strongest loading variable on PC2; K was strongly and negatively related to the urban metrics and positively related with distance to the urban core. Soils that have developed on gneiss/schist rock types tend to have higher K concentrations than those forming on gabbro types (Fig. 1a).

The third principal component provided some separation between stands on the urbanization gradient regardless of parent material, suggesting that the variables loading on this component (Pb and organic matter) may be responding to an urban environmental factor. Lead in particular appears to explain the separation of stands, which is reflected by this element's significant positive correlations with the urban metrics, particularly Popden and Rdden, and a negative relationship with distance to the urban core (Table 2). By contrast, organic matter did not significantly relate to any of the urban metrics or distance to the urban core. However, organic matter was negatively related to soil pH ($r = -0.684$, $P = 0.007$ using Spearman correlation). Soil pH along the Baltimore gradient ranged from 3.8 to 5.1; these results may have biological significance to soil organisms and thus decay rates of organic matter. For example, Szlavecz et al. (2006) found earthworm biomass and density was negatively related to soil pH in these stands.

New York City

A clear pattern was discernable in the distribution of stands obtained from the PCA of soil properties in the New York City metropolitan area (Fig. 2). Approximately 83% of the variation was accounted for by the first three components of the PCA, with PC1 accounting for 43% of the variation (Table 1). Positive loadings of PC1 corresponded to high concentrations of metals (Cu, Ni, and Pb), high organic matter concentration, and high concentrations of base cations (Ca, Mg, K) (Table 1). Stands located closer to the urban core had positive loadings on PC1, with stands located beyond 25 km of the urban core having negative loadings (Fig. 2). The second and third principal components (PC2, PC3) accounted for 24 and 13% of the variation, respectively, with PC2 corresponding to positive loadings of Co, P, pH, and Zn; and PC3 corresponding to positive loadings of Fe and Zn (Table 1). There was no apparent relationship between distance to the urban core and PC2 and PC3 in the principal component scatter plots (Fig. 2a, b).

The first principal component was strongly and negatively related to distance from the urban core ($r = -0.88$, $P < 0.01$), while the urban metrics were strongly and positively related to PC1 in order of importance: Trafvol ($r = 0.867$, $P < 0.01$), Purban ($r = 0.820$, $P = 0.007$), Rdden ($r = 0.817$, $P = 0.007$), and Popden ($r = 0.733$, $P = 0.025$) (Table 3). Variables that were not strongly related to the first three principal components, but showed a significant relationship to distance or urban metrics

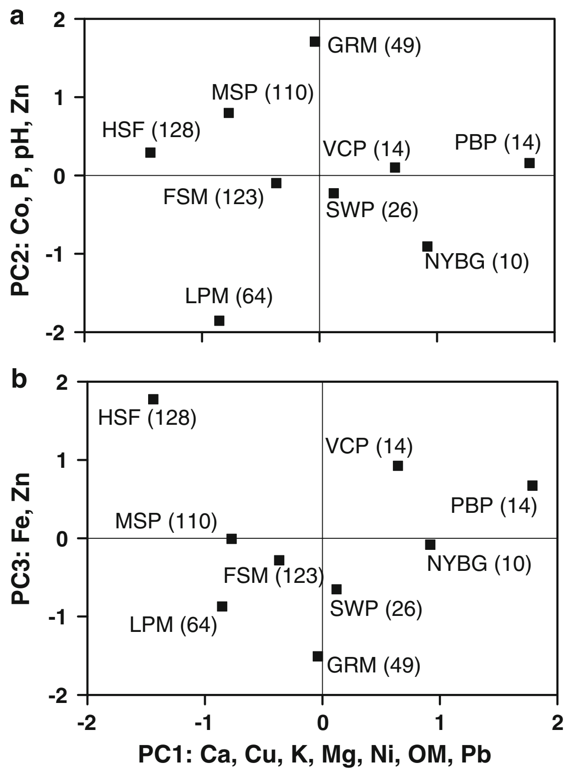

Fig. 2 Scatter plots of the (**a**) first and second components (PC1 and PC2) and (**b**) the first and third components (PC1 and PC3) of a principal component analysis procedure using 15 soil variables and nine stands in New York. PC1 was correlated to Ca, Cu, K, Mg, Ni, OM, Pb; PC2 was correlated to Co, P, pH, and Zn; and PC3 was correlated to Fe and Zn. An individual stand's distance to the urban core is represented parenthetically in km

included pH and concentrations of P and Co, which were negatively related to Rdden ($r = -0.683$, $P = 0.0424$) (Table 3). All of the urban metrics were highly and negatively related (Spearman correlation coefficients of >0.90) to distance to the urban core.

The results in New York clearly show the importance of keeping soil parent material as constant as possible among observations when comparing soil chemical properties along urbanization gradients (i.e., an anthroposequence). The New York urbanization gradient results were not surprising since similar results were found using a larger, 23 variable data set in previous studies (Pouyat and McDonnell 1991; Pouyat et al. 1995). Using the smaller 15 variable data set in the current analysis, a total of seven variables (Ca, Cu, K, Mg, Ni, Pb, and organic matter) loaded heavily on PC1, which in turn showed a strong positive relationship with the urbanization gradient (Fig. 2).

Correlations of individual soil properties with the urban metrics or distance to the urban core were consistent with variables that loaded onto PC1 except for P and soil pH, both of which had a negative relationship with Rdden (Table 3). It is unclear as to the nature of these relationships; however, there is some evidence that P availability (as opposed to total P measured in this study) declines toward the urban end of the New York City urbanization gradient (Baxter et al. 2002). The authors suggested, but were unable to prove, that the lowered availability in P was due to higher earthworm activity and N deposition rates in the urban rather than in the rural stands. In addition, soil pH was significantly related to PC1 in the earlier 23 variable analysis, though the differences occurring along the gradient (4.2–4.5) were not considered biologically significant (Pouyat et al. 1995). Measurements of acidic deposition along the New York City urbanization gradient suggested that although N and sulfur throughfall inputs were up to three times higher in the urban than in the rural stands, the pH of the input was neutralized by enhanced Ca and Mg inputs (Lovett et al. 2000).

Budapest

A complex but discernable pattern was found in the distribution of stands obtained from the PCA of soil properties in the Budapest metropolitan area (Fig. 3). Approximately 94% of the variation was accounted for by the first three components of the PCA, with PC1 accounting for 63.4% of the variation (Table 1). Positive loadings of PC1 corresponded to high concentrations of several elements (Al, Co, Cr, Fe, K, Mn, Ni, Pb, and Zn) and high organic matter concentration (Table 1). Stands located closer to the urban core had positive loadings on PC1, whereas sites located beyond 7 km of the urban core had negative loadings (Fig. 3). The second and third principal components (PC2, PC3) accounted for 24 and 7% of the variation, respectively, with PC2 corresponding to positive loadings of Ca, Mg, P, and pH; and PC3 corresponding to positive loadings of Pb (Table 1). The second principal component appears to distinguish stands nearer the urban core, but this pattern only occurs within each geological type. For example, both Pest (solid squares in Fig. 3a)

Table 3 Spearman correlation matrix between elements, urban metrics, and distance from urban core ($n = 9$ stands) in New York

	Distance	Purban	Popden	Trafvol	Rdden
Distance	1	−0.92***	−0.92***	−0.97***	−0.93***
Purban	−0.92***	1	0.96***	0.93***	0.88**
Popden	−0.92***	0.96***	1	0.92***	0.93***
Trafvol	−0.97***	0.93***	0.92***	1	0.90***
Rdden	−0.93***	0.88**	0.93***	0.90***	1
PC1	−0.88**	0.82**	0.73*	0.87**	0.82**
PC2	0.32	−0.16	−0.37	−0.25	−0.53
PC3	0.017	0.18	0.18	0.050	0.017
Ca	−0.72*	0.72*	0.57	0.67*	0.63
Co	0.50	−0.58	−0.73*	−0.48	−0.68*
Cu	−0.88**	0.78*	0.73*	0.88**	0.72*
K	−0.30	0.35	0.18	0.30	0.33
Mg	−0.85**	0.84**	0.72*	0.82**	0.77*
OM	−0.67*	0.53	0.47	0.67*	0.68*
P	0.55	−0.38	−0.53	−0.45	−0.68*
Pb	−0.85**	0.80**	0.78*	0.85**	0.88**
pH	0.48	−0.44	−0.60	−0.57	−0.68*

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively

representing the eastern side of the city, and Buda (solid diamonds in Fig. 3a) representing the western part of the city have higher loadings for those stands nearer the urban core. By contrast, PC3 does not appear to differentiate stands with respect to their distance to the urban core (Fig. 3b).

The first principal component was strongly and negatively related to distance from the urban core ($r = -0.734$, $P < 0.01$), while PC2 was strongly and positively related to Purban ($r = 0.705$, $P = 0.010$) suggesting that each of these components may represent an urbanization gradient effect. Consistent with these results, distance was strongly and negatively correlated to Ca, Co, Cr, K, Mg, P, Pb, Zn, and organic matter, and Purban strongly and positively related to Ca, Cu, P, and pH (Table 4). Organic matter, in turn, was very strongly correlated with elemental concentrations of Al, Co, Cr, Fe, K, Mn, Ni, P, Pb, and Zn with an $r \geq 0.622$ and $P < 0.05$ using Spearman correlation (not shown), which represent many of the variables corresponding to PC1 (Table 1).

Similar to Baltimore, the Budapest urbanization gradient results were confounded by differences in parent material; however, due to the distribution of stands on the two major geological types in the region, it was possible to distinguish between the effects of parent material and the urban environment (Fig. 3a). The first principal component in particular appears to correspond to an urban environmental effect, since this component clearly separated urban and rural ends of the gradient regardless of the parent material type and was negatively related to distance ($r = -0.734$, $P = 0.007$) (Fig. 3). However, PC1 was not significantly related to Purban even though Purban was significantly related to distance to the urban core ($r = -0.684$, $P = 0.014$).

The interaction of parent material with an urban effect is most visible in the scatter plot of PC1 and PC2, which shows separate clusters of urban and rural stands corresponding to each of the major geological types (Fig. 3a). Based on this observation, PC2 (Ca, Mg, P, pH) appears to represent a subset of parent material types occurring in the region and clusters the Buda and Pest types more strongly than the PC1 and PC3 scatter plot. In particular, the Buda stands occur below the origin on the PC2 axis (Fig. 3a). The second principal component also was highly correlated with Purban, which for Ca, Mg, and soil pH could reflect the potential for high inputs of these base cations at the urban end of the gradient (e.g., Bytnerowicz et al. 1999; Lovett et al. 2000). In addition, Purban was highly correlated with Cu ($r = 0.646$, $P = 0.023$) a relationship that also was found in the New York City urbanization gradient (Tables 3 and 4).

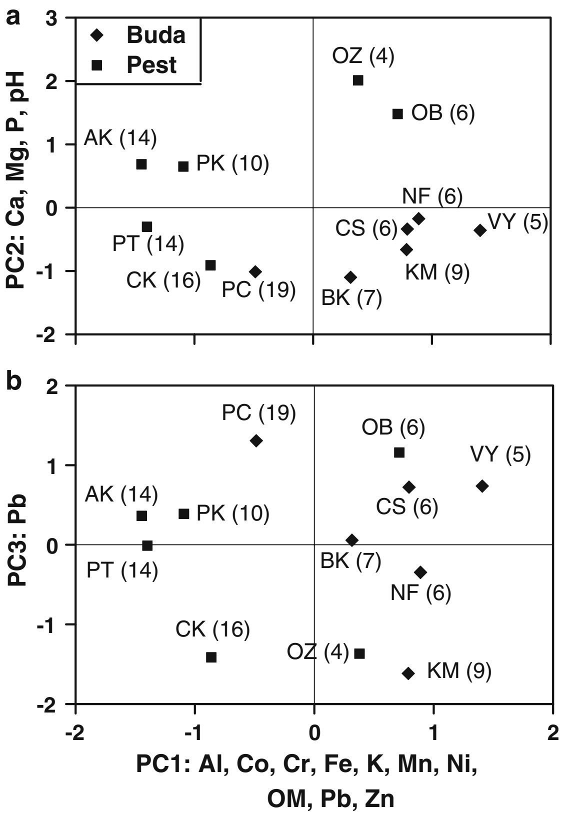

Fig. 3 Scatter plots of the (**a**) first and second principal components (PC1 and PC2) and (**b**) the first and third components (PC1 and PC3) of a principal component analysis procedure using 15 soil variables and 12 stands in Budapest. PC1 was correlated to Al, Co, Cr, Fe, K, Mn, Ni, OM, Pb, and Zn; PC2 was correlated to Ca, Mg, P, pH; and PC3 was correlated to Pb. Stands located in Buda are diamonds and in Pest are squares. An individual stand's distance to the urban core is represented parenthetically in km

The third principal component was not related to distance to the urban core or Purban, although the variable loading on this component (Pb) was found to be related to urban environments in all three cities. The PC1 and PC3 scatter plot differentiates urban versus rural stands along the PC1 axis; however, PC3 essentially separates the CK and PC stands and the KM and OB stands at the rural and urban ends of the gradient, respectively, with the PC and OB stands having higher Pb concentrations than the other stands (Fig. 3b). Therefore, the pattern represented by PC3 may reflect a secondary contamination effect that is related to a localized (<1 km scale) source of Pb.

In addition to the secondary effect of Pb, organic matter concentration, which strongly correlates with many of the variables corresponding to PC1, may be confounding the effect of the urbanization gradient. If organic matter concentration is the cause of the variation explained by PC1, and if this variable is responding to a non-urban environmental factor, it is less likely that PC1 is related to an urbanization gradient (Fig. 3). However, studies of urbanization gradients have shown higher organic matter concentrations in forest soils in the urban than in the rural end of the gradient, a response suggested to be related to negative effects of pollution on decomposer organisms (Inman and Parker 1978; Ohtonen and Markkola 1991). With the current analysis, the cause of the organic matter response to the urbanization gradient in Budapest cannot be determined.

Table 4 Spearman correlation matrix between elements, urban metrics, and distance from urban core ($n = 12$ stands) in Budapest

	Distance	Purban
Distance	1	−0.68*
Purban	−0.68*	1
PC1	−0.73**	0.25
PC2	−0.45	0.71*
PC3	0.02	−0.11
Ca	−0.62*	0.63*
K	−0.62*	0.053
Mg	−0.86***	0.56
OM	−0.76**	0.22
Pb	−0.71**	0.39
Cu	−0.90***	0.65*

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively

City comparisons

Regressions of individual response variables against distance to the urban core and Purban were computed to compare urbanization gradient responses across the three cities (Table 5). Only response variables that were significant to Purban or distance to the urban core in at least two of the cities were considered. These comparisons were meaningful because of the strong statistical relationship that was found between distance and the urban metrics. Lead was the only response variable that showed a significant response to distance in all three cities. Other variables compared between at least two of the cities included

Table 5 Linear regression equation components by individual city, element, and distance from urban core or Purban

City	Variable	Metric	Slope	Y-intercept	X-intercept	r^2	*P* value
Baltimore	Pb	Distance	−2.2 ± 0.59	77 ± 9.7	34	0.54	0.0027
New York[a]	Pb	Distance	−0.7 ± 0.18	100 ± 14	150	0.65	0.0090
New York[b]	Pb	Distance	−1.7 ± 0.35	130 ± 13	72	0.86	0.0079
Budapest	Pb	Distance	−1.4 ± 0.64	40 ± 6.8	29	0.33	0.052
New York[a]	Cu	Distance	−0.14 ± 0.052	29 ± 4.0	206	0.51	0.030
New York[b]	Cu	Distance	−0.39 ± 0.096	35 ± 3.4	90	0.81	0.015
Budapest	Cu	Distance	−1.6 ± 0.57	28 ± 6.0	17	0.44	0.019
New York[a]	Ca[c]	Distance	−1.1 ± 0.45	160 ± 34	137	0.49	0.037
New York[b]	Ca[c]	Distance	−2 ± 1.5	190 ± 55	81	0.36	0.21
Baltimore	Ca[c]	Distance	−4 ± 1.3	120 ± 21	31	0.44	0.0098
New York[a]	Cu	Purban	0.19 ± 0.061	13 ± 3.3	−73	0.57	0.018
Budapest	Cu	Purban	0.3 ± 0.11	−5 ± 6.4	16	0.48	0.013
Baltimore	Pb	Purban	0.6 ± 0.15	8 ± 10	−14	0.56	0.0021
New York[a]	Pb	Purban	0.9 ± 0.17	22 ± 9.4	−25	0.80	0.0012
New York[b]	Pb	Purban	1 ± 0.32	20 ± 21	−17	0.70	0.037

[a] The regression variables include the New York rural sites

[b] The regression variables do not include the New York rural sites

[c] Available calcium

Cu and Ca. We did not consider the comparison of K concentrations between Baltimore and Budapest since this element was likely related to variations in parent material in the Baltimore metropolitan area and thus not the result of an urban effect (Fig. 1).

For the NYC regression analysis, the lowest concentration of Pb in soil was reached at about 75 km and thus the inclusion of the more rural plots would necessitate a curvilinear function (Fig. 4a). Therefore, regressions were run with and without the rural plots, though the scatter plot and regression line (linear = solid; polynomial 2nd order = dashed) are shown with the rural plots excluded in the three city comparison (Fig. 4a). Whatever the case, Pb concentrations were negatively related with distance to the urban core in all three cities (Fig. 4a). The linear response of Pb to distance was in order of importance (i.e., coefficient of determination or r^2) for New York ($r^2 = 0.86$, $P = 0.008$), Baltimore ($r^2 = 0.54$, $P = 0.003$), and Budapest ($r^2 = 0.33$, $P = 0.052$). The curvilinear response was $R^2 = 0.97$, 0.55 and 0.33 for New York, Baltimore, and Budapest, respectively.

Of the three cities, New York had the highest and Budapest the lowest x and y-intercepts in the Pb regressions (Table 5, Fig. 4a). The y-intercept of the regression line indicates the level of contamination and was projected to be more than threefold and 37.3% higher in the New York than in the Budapest and Baltimore stands, respectively. Both New York and Budapest had regression lines of similar slope (−1.74 and −1.42) with Baltimore (−2.2) having a greater slope than New York and Budapest, respectively. The urbanization gradient effect extended to more than a twofold greater distance in New York (x-intercept = 72 km) than in the other two cities (x-intercept = 34 and 29 km in Baltimore and Budapest, respectively) (Table 5). In New York, the curvilinear relationship was more strongly related to distance than the linear regression, suggesting a more rapid drop in Pb concentration (therefore steeper slope) before reaching a more gradual slope with increasing distance to the urban core (Fig. 4a).

Copper also showed a significant response to distance in New York ($r^2 = 0.81$, $P = 0.015$ linear and $R^2 = 0.89$ curvilinear responses without rural sites) and Budapest ($r^2 = 0.44$, $P = 0.019$ linear and $R^2 = 0.57$ curvilinear responses) (Table 5, Fig. 4b). As with the Pb response to distance, the lowest concentration of Cu was reached at 63 km from the urban core in New York (Fig. 4b). Unlike the comparison of the Pb response between New York

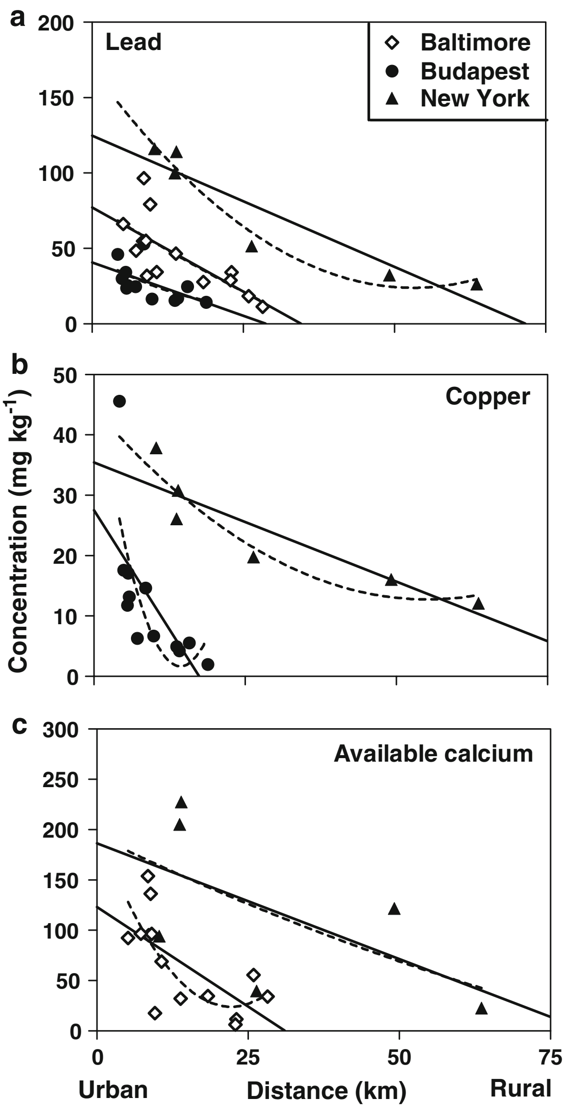

Fig. 4 Scatter plots and regressions of elemental concentration (mg kg^{-1}) versus distance from urban core (km) for (**a**) lead, (**b**) copper and (**c**) available calcium. Baltimore stands are presented by open triangles, Budapest by circles, and New York by triangles. Solid line represents linear and dashed line curvilinear responses. The New York regression does not include the rural stands. See Table 5 for linear and the text for curvilinear statistical results

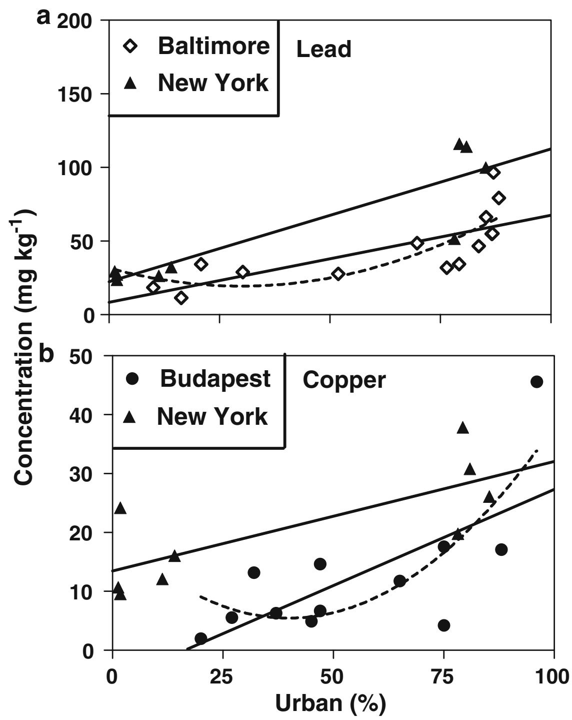

Fig. 5 Scatter plots and linear- and curvilinear- (2nd order polynomial) regressions of elemental concentration (mg kg^{-1}) of (**a**) lead and (**b**) copper versus Purban. Baltimore stands are represented by open diamonds, Budapest by circles, and New York by triangles. Solid line represents linear and dashed line curvilinear responses. The r^2 values for the linear regressions are found in Table 5. The New York regression includes the rural stands. The curvilinear R^2 values for Baltimore and Budapest are 0.66 and 0.63, respectively. The curvilinear R^2 values were not determined for New York because of the lack of stands with intermediate percentages of urban land use, i.e., sites with Purban values between 15% and 75%

and Budapest, the linear regression line of Cu had a 75% steeper slope in Budapest than the slope measured along the New York urbanization gradient. The shallower slope in New York is the result of an almost fivefold greater distance (x-intercept) and only slightly higher projected level of Cu contamination (y-intercept) than in Budapest (Fig. 4b). In both cities, the curvilinear was more strongly related than the linear relationship suggesting a more rapid drop in concentrations and thus steeper slopes within a 25 km distance to the urban core.

In the city comparisons, both Pb and Cu were significantly related to the proportion of urban land use within a 16-km^2 area of each stand, or Purban (Fig. 5). Lead was significantly related to Purban along the Baltimore and New York urbanization gradients ($r^2 = 0.56$, $P = .002$ and $r^2 = 0.80$, $P = 0.001$, respectively) (Table 5). In Baltimore a curvilinear relationship ($R^2 = 0.66$ using a 2nd order polynomial) best explains the response (dashed line in Fig. 5a). Through visual inspection, a threshold in Pb concentrations occurs at approximately a Purban of 75% (Fig. 5a). Moreover, the range in Pb concentrations beyond this threshold ranges from approximately background levels to the most contaminated levels for both cities. Likewise, Cu was significantly related to Purban in Budapest and New York with a threshold occurring at a Purban of approximately 75% (Fig. 5b).

The city comparison results only partially supported our hypothesis that there would be a greater spatial extent of soil contamination in the New York than in the Baltimore and Budapest metropolitan areas (i.e., higher x-intercept), while there would be no difference in the amount of contamination in the most urban-influenced stands (i.e., similar y-intercepts). The results of this study clearly show that the spatial extent of contamination in New York was far greater than in Baltimore and Budapest for those elements that showed a relationship to the urbanization gradient (Pb, Cu, and to a lesser extent Ca). This was expected since the New York metropolitan area spreads across parts of three states and has a population of more than 20 million people compared to populations of 2.5 million in Baltimore and Budapest metropolitan areas. The fact that the urbanization gradient was extended to 125 km from the urban core in New York to reach more rural communities compared to 28 and 19 km in Baltimore and Budapest, is a reflection of how much more expansive urban development is in New York than the other metropolitan areas.

An interesting result of this analysis is that the New York urbanization gradient could have been shortened from 125 km to approximately 80 km to capture the response of soil chemical variables used in this analysis (Fig. 4). In contrast to the distance relationships among the cities, there was a fairly consistent relationship between response variables with respect to Purban across the urbanization gradient. Specifically, an apparent threshold was reached at a Purban of 75% in which the concentrations of Pb and Cu were more than twofold higher than concentrations at lower values of Purban, though a more rigorous spatial analysis is required to test this observation (Fig. 5).

The higher levels of Pb and Cu contamination in New York, compared to the other cities, were unexpected. All three cities had developed heavy industries during the industrial revolution from the mid-1800s through the 20th century, though in the United States emissions from heavy industry were greatly reduced after the authorization of the Clean Air Act in the early 1970s compared to the institution of emission controls in Budapest in the early 1990s. However, an important distinction between Budapest and the U.S. cities may be the volume of vehicular traffic. We were unable to locate traffic volume data in Budapest, but suspect that car ownership and the volume of traffic in Budapest is significantly lower than the U.S. cities. Comparisons of traffic volume between New York and Baltimore suggest that even among U.S. cities, New York has a relatively high volume of traffic (up to 91,494 vehicles day^{-1}). Indeed, of the urban metrics measured, Trafvol explained the most variation in PC1 along the New York urbanization gradient (Table 3).

Both Pb and Cu contamination have been associated with the use of automobiles and other vehicles in urban areas (Van Bohemen and Janssen Van De Laak 2003; Zhang 2006; Yesilonis et al. 2008). Results of this and other studies suggest that Pb and Cu can be deposited within remnant forests beyond the 30 m extinction plume of roadways, which in turn suggests that a regional pattern (tens of km) of deposition may exist for these metals (Pouyat et al. 1995). Moreover, Pb and Cu can bind with organic matter and thus accumulate in surface horizons of forest soils (Johnson et al. 1982).

In comparison to Pb and Cu, Ca showed a similar response in Baltimore and New York with slightly higher concentrations in stands at the urban end of the gradient (Fig. 4c). It is unclear if the Ca response in Budapest is due to an urban or parent material effect because of the presence of limestone bedrock in the Budapest metropolitan area. Calcium is an important constituent of atmospheric particulates in urban areas that originates from construction materials such as concrete (Lee and Longhurst 1992; De Miguel et al. 1997). It has been shown that Ca deposition is elevated in urban areas at various scales of deposition (Tanner and Fai 2000; Juknys et al. 2007). At a regional scale (tens of km), Lovett et al. (2000) measured a gradient of N and Ca deposition into the stands along the New York urbanization gradient with the urban stands receiving up to three times greater throughfall loadings than in the rural stands. These inputs fell off in the suburban stands 45 km from the urban core, which the authors suggested was due to the reaction of acidic anions with larger alkaline dust particles (Ca^{2+} and Mg^{2+}) that precipitated closer to the city. Similar results were found for the Louisville and Los Angeles metropolitan areas where both N and base cation deposition occurred at higher rates in stands at the urban end of an urbanization gradient (Bytnerowicz et al. 1999; Carreiro et al. in press).

Comparison of urban metrics and distance

Distance to the urban core was negatively related to Purban in all three cities with New York explaining 92% of the variation compared to 72 and 68% in Baltimore and Budapest, respectively (Tables 2–4). For all three cities, all of the urban metrics were significantly related to distance to the urban core with Spearman coefficients of at least 0.67.

Distance to the urban core was an unexpectedly good surrogate for the urban metrics, particularly in New York where all of the metrics were highly related to distance (correlation coefficients above 0.90), while in Budapest the only urban metric calculated (Purban) was negatively related to distance ($r = -0.684$, $P = 0.014$) (Table 4). The strong relationship between distance to the urban core and the urban metrics was unexpected since urban development patterns are typically discontinuous and thus patchy at the scale of less than one to several kilometers (e.g., Luck and Wu 2002). However, at the scale in which the urban metrics were measured in this study (16 km^2) discontinuities at a finer scale would have been averaged over the area measured, thus generating a close relationship between distance and the urban metrics.

Conclusions

Results of this study suggest that forest soils are responding to urbanization gradients in all three cities, though features of each city (spatial pattern of development, pollution sources, parent material, and site history) may have influenced the soil chemical response. The changes measured along the gradients appear to result from locally derived atmospheric pollution, perhaps from vehicle use, which was more extreme at the urban end of the gradient, particularly in New York. Distance was a surprisingly good predictor of soil chemical responses in comparison to the more data intensive metrics used in this study. However, the use of distance as a surrogate variable may be sensitive to the scale of measurement, which apparently for the 16-km^2 area used in this study generated a close relationship between distance and the urban metrics.

The deposition of Pb, Cu, and to a lesser extent Ca, at the urban end of each gradient appears to occur at a scale of >30 m to kilometers, since all stands were greater than 30 m from the nearest road. This result suggests that vehicle emissions may affect forest patches beyond a distance from roads that was previously assumed. Therefore, the soil chemical differences measured along the gradient may be regarded as an urban regional phenomenon with vehicle emissions as the likely source. Moreover, the spatial extent of urban development should determine how far from the urban core the depositional pattern will occur, which we hypothesized would vary among the three cities. Indeed, the relationship of Pb and Cu contamination along each urbanization gradient supported the hypothesis that each city will vary in extent of contamination from the urban core because of differences in growth pattern. On the other hand, the hypothesis that contamination occurring at the urban end of the gradient would not vary appreciably among cities was not supported, as New York had significantly greater accumulations of Pb and Cu than the other cities. A result that is likely due to differences in transportation networks and the volume of traffic among the cities.

Finally, results of this study suggest that the “anthroposequence,” which is conceptually similar to the use of chronosequences and toposequences in soil genesis studies, is a useful approach to investigate urban environmental effects on forest soils. The results found in Baltimore and Budapest show the importance of keeping differences in parent material to a minimum in the selection of study sites along urbanization gradients. Nonetheless, significant relationships were found in all three cities regardless of differences in parent material. Lead, in particular, was found to vary along each urbanization gradient. Hence, even with differences in parent material, investigations of soil environmental gradients may be informative with elements such as Pb, which do not appreciably vary in concentration among common rock types. By contrast, for base cations such as Ca and K, which may vary highly among rock types, differences in parent material will have a confounding effect.

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