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Soil Chemical and Physical Properties That Differentiate Urban Land-Use and Cover Types

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We investigated the effects of land use and cover and surface geology on soil properties in Baltimore, MD, with the objectives to: (i) measure the physical and chemical properties of surface soils (0–10 cm) by land use and cover; and (ii) ascertain whether land use and cover explain differences in these properties relative to surface geology. Mean and median values of each variable measured across all plots showed that soil properties varied considerably. Chemical properties generally varied more than physical properties. A subset of the variables measured showed a pattern with land use and cover. Potassium, P, and bulk density were the most discerning variables differentiating forest cover from land uses dominated by turfgrass cover. Soil pH differentiated residential land use and cover from the other turfgrass types. This separation may reflect differences in management, e.g., additions of fertilizer, although additional research is needed to assess the importance of management on soil properties. Differences in surface soil properties among land use and cover types could be useful when conducting urban soil surveys, at least to spatially differentiate remnant soils from highly disturbed and managed soils. Other soil properties (Al, Mg, V, Ti, Mn, Fe, Ni, and soil texture) were related to surface geology and thus unique to the Baltimore region. The importance of surface geology was contrary to our expectation that urban factors would be more important in determining the distribution of surface soil characteristics. Heavy metal concentrations did not differentiate land use and cover, suggesting that these elements are more related to other factors.

Abbreviations: CDA, canonical discriminant analysis; CT, commercial or transportation; F, forest; IU, industrial or urban open; I, institutional; MANOVA, multivariate analysis of variance; P, park or golf course; R, residential.

A majority of soil studies in urban areas have focused on highly disturbed and human-constructed soils along streets and in highly developed areas (e.g., Craul and Klein, 1980; Patterson et al., 1980; Short et al., 1986; Jim, 1993, 1998). As a result "urban soils" typically have been viewed as drastically disturbed soil material of low fertility (Craul, 1999). Yet other potentially influential factors associated with urban land transformations have received limited attention. In fact, the characteristics of soil can vary greatly across the entire urban landscape, including not only highly disturbed but also relatively undisturbed soils that are modified by management and urban environmental factors (Schleuß et al., 1998; Pouyat et al., 2003).

Pouyat and Effland (1999) recognized the importance of urban environmental and management factors and categorized the effect of each factor, together with disturbance, as direct or indirect. Direct effects include those typically associated with urban soils, such as physical disturbances, incorporation of anthropic materials, and burial or coverage of soil by fill material and impervious surfaces (Craul, 1992; Jim, 1998; Schleuß et al., 1998). Soil management practices, e.g., fertilization and irrigation, which are introduced after the initial development disturbance, also are considered direct effects. Indirect effects include the urban heat island (Oke, 1995; Mount et al., 1999), soil hydrophobicity (White and McDonnell, 1988; Craul, 1992), introductions of exotic plant and animal species (Steinberg et al., 1997; Ehrenfeld et al., 2001), and atmospheric deposition of pollutants such as N (Lovett et al., 2000), heavy metals (Orsini et al., 1986; Boni et al., 1988; Lee and Longhurst, 1992; De Miguel et al., 1997; Mielke, 1999), and potentially toxic organic chemicals (Wong et al., 2004).

In the urban landscape, these factors result in a mosaic of soil patches (i.e., relatively homogenous soils that differ from their surroundings [Forman, 1995]) that range in condition from natural soil profiles to partially disturbed profiles to made and covered soils of relatively young age (Pouyat et al., 2003). Overlain on this soil mosaic are human activities such as recreational uses and turf management practices that can further modify soil characteristics. As the soil mosaic develops, we expect highly variable soil conditions at multiple scales, the extent of which depends on the pattern of development, the range of management regimes in use, and the magnitude and pattern of environmental change, e.g., depositional gradients of atmospheric pollutants (Pouyat et al., 1995; 2003).

An understanding of the modifications of soil characteristics and how they vary spatially in urban ecosystems is needed so that the traditional agriculturally based soil survey approach and associated soil interpretations can be applied to urban landscapes (Effland and Pouyat, 1997; Galbraith et al., 1999; De Kimpe and Morel, 2000). Specifically, various soil properties need to be assessed as potential diagnostic properties and descriptors to map and classify urban modified soils (Hollis, 1991). Moreover,

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for interpretive purposes, soil plays a unique role as the brown infrastructure of urban ecosystems, e.g., water infiltration and purification (De Kimpe and Morel, 2000), much in the same way urban vegetation, or green infrastructure, does (Benedict and McMahon, 2002).

We investigated the effect of land use and cover on surface-soil properties in the City of Baltimore, MD. Land use and cover may serve as an indicator of disturbance, site history, management, and the urban environment—factors that should disproportionately affect surface rather than subsurface soil properties. If coherent and repeatable relationships between surface soil properties and land use and cover can be established, these relationships could be used to develop diagnostic properties for mapping soils in urban landscapes, although a more complete characterization of soil to a depth of two or more meters is desirable to classify and map soils in urban landscapes (Galbraith et al., 1999). The benefit of drawing a relationship between soil characteristics and land use and cover is that spatial data sets are typically available for the latter rather than the former for most urban metropolitan areas.

This research builds on a network of plots established as part of the Baltimore Ecosystem Study, a Long-Term Ecological Research (LTER) site (Pickett et al., 1997). The "extensive" plots were established to represent various patch types defined by their land use and cover (Nowak et al., 2004). We took advantage of this preexisting study design to achieve the following objectives: (i) measure the physical and chemical characteristics of surface soils in Baltimore by land use and cover type; and (ii) ascertain whether land use and cover explain differences in these properties, and if they do, determine what specific soil properties best differentiate the land-use and cover types. In addition, Baltimore is made up of two physiographic provinces of roughly equal area and thus we were able to compare soil properties measured in plots occurring in the two provinces.

Measurements of surface soil properties were expected to be influenced more by urban factors, thus land use and cover, than by surface geology due to surface disturbance, management, and the import or redistribution of soil fill material that occurs in urban landscapes (e.g., Schleuß et al., 1998). Moreover, we expected that differences in soil properties would be explained largely by land use and cover on a citywide scale, that soil properties associated with specific land uses (e.g., residential vs. commercial) would differ significantly, and that differences would be greater between land uses where direct effects predominate (e.g., commercial and industrial) than those where indirect effects dominate (e.g., remnant forest patches embedded within the urban landscape).

METHODS

Study Area

Baltimore is a historically industrial city with a population of 638 251 in the year 2000 (quickfacts.census.gov/qfd/; verified 11 Feb. 2007) and is located on the Chesapeake Bay in the Mid-Atlantic region of the USA (Fig. 1). The city is traversed by several major highways and has 31 facilities reporting chemical atmospheric releases, which amounted in 1997 to an estimated 4.9 million t of various pollutants, including Cr, Cu, Ni, and Zn (Boone, 2002). The Baltimore metropolitan area has hot, humid summers and cold winters with average annual air temperatures ranging from 14.5°C in the city to 12.8°C in the surrounding area. This difference in

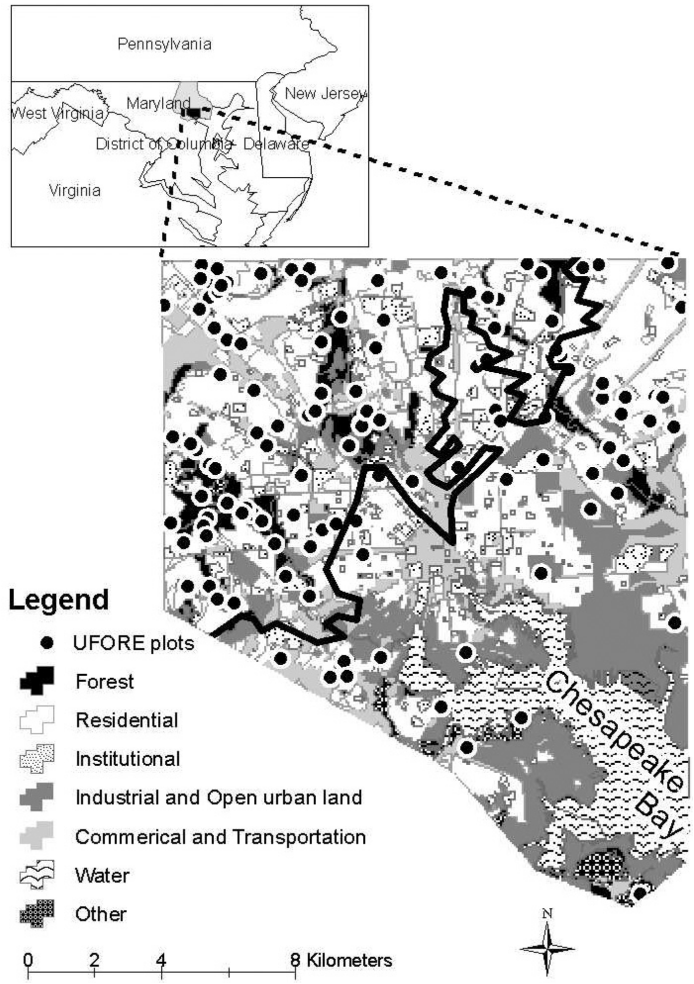

Fig. 1. City of Baltimore showing 122 Baltimore Ecosystem Study Urban Forest Effects (UFORE) plots that were sampled for soil. The fall line between the Piedmont and Atlantic Coastal Plain physiographic provinces is shown as a solid line.

air temperature is attributed to the heat island effect (Brazel et al., 2000). Precipitation is distributed evenly throughout the year for the entire study area and ranges from an annual average of 107.5 cm in Baltimore to 104 cm in the surrounding metropolitan area (NRCS, 1998).

Baltimore lies along the Chesapeake Bay 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 (Fig. 1). Most of the city is characterized by nearly level to gently rolling uplands, dissected by narrow stream valleys. The Piedmont Plateau in the city is underlain by mafic and ultramafic 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 that are underlain by either sandy or gravelly sediments or unstable clayey sediment. The dominant Coastal Plain soils in the Baltimore city area consist of Typic Hapludults. 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 dominant Piedmont soils in the Baltimore area consist of Ultic Hapludalfs. Highly disturbed soils make up >60% of the land area of the city (Pouyat et al., 2002).

Sampling Design

Plots were located within Baltimore by a stratified random sampling design using land use and cover (Fig. 1). These plots were established in 1999 as part of the Baltimore Ecosystem Study (Pickett et al., 1997) to collect data needed to calibrate the Urban Forest Effects (UFORE) model (Nowak et al., 2004). Originally, 11 land-use and cover types were delineated using 1994 digital orthophoto quarter quads of the Maryland Department of Natural Resources, and were weighted based on the aerial coverage of each type. A grid was laid over the land-use map and 202 plots were located randomly on the grid. The land-use and cover types corresponded roughly to Anderson Level II land cover classes (Anderson et al., 1976) and included commercial, industrial, institutional, transportation rights-of-way, high- and medium-density residential (no low-density residential areas were identified within city boundaries), golf course, park, urban open, unmanaged forest, and wetland.

Following Nowak et al. (2004), a circular plot with a radius of 11.35 m (0.04 ha) was reestablished at each sample location. For this study, 122 of the original 202 plots were sampled for soils (Fig. 1). Fewer plots were sampled because (i) many plots were composed of primarily impervious surface, (ii) permission was not granted to collect soil samples at a number of private residences and (iii) riparian and wetland plots were not included in this study. Due to the reduced number of plots sampled for soils, we combined medium- and high-density residential, commercial and transportation, industrial and urban open, and golf course and park types to increase the power of the statistical design. Land-use and cover types were combined that were more similar to each other in cover and management than the other types. For example, urban open and industrial plots were combined because these areas were not being managed and were not dominated by turfgrass. Moreover, the unmanaged and undisturbed forest type was not combined with any of the other types since we expected the nonforest types to be either managed or previously disturbed. The resulting number of sampled plots by land-use and cover type was: nine commercial or transportation (CT); 12 industrial or urban open (IU); 10 institutional (I); 52 residential (R); 13 park or golf course (P); and 26 unmanaged forest (F), with the CT, I, R, and P types being dominated by managed turfgrass, F by naturalized forest, and the IU by early successional herbaceous and woody vegetation.

Two techniques were used to acquire soil samples within the plots: (i) three undisturbed 5-cm-diameter by 5-cm-deep cores, used to measure bulk density; and (ii) a composite soil sample (0–10-cm depth) taken with a 2-cm-diameter stainless steel sampling probe. If present, the depth of the organic horizon was recorded but was omitted from the sample. Typically, 10 to 15 cores per plot were sampled randomly and composited from the dominant cover type within the plot. Each composite sample was air dried and sieved in the laboratory with a stainless steel 2-mm mesh sieve. The undisturbed cores were used to determine soil bulk density (Blake and Hartge, 1986). Subsamples of the dry-sieved soil were analyzed for total N with a LECO CHN-600 Analyzer (LECO Corp., St. Joseph, MI) and available Ca, K, Mg, and P using the Mehlich-1 extract, which is a double acid extraction solution of 0.05 M HCl and 0.0125 M H_2SO_4 (Mehlich, 1953) at the University of Maryland-College Park's Cooperative Extension Soil Laboratory. Use of the Mehlich-1 extract is appropriate for acidic, low cation exchange capacity soils, which are commonly found in the Baltimore metropolitan area (NRCS, 1998). Organic matter content of the mineral soil was determined by loss-on-ignition (360°C for 1 h), distribution of particle size by the hydrometer method (Wilde et al., 1972), and pH using a 1:1 soil/water mix (Orion Model 520a, Thermo Fischer Scientific, Waltham, MA). Subsamples also were digested at the Baltimore Ecosystem Study–University of Maryland-Baltimore County Laboratory using HNO_3 and HCl extraction (modified USEPA Method 3050B). These extracts were analyzed at the Cornell University's Nutrient Analysis Laboratory to determine acid-soluble Al, Ca, Co, Cu, Cr, Fe, K, Mg, Mn, Na, Ni, P, Pb, S, Ti, V, and Zn using an inductively coupled plasma optical emission spectrophotometer (SPECTRO CIROS CCD, Spectro Analytical Instruments, Kleve, Germany). Elemental data are presented as a concentration per dry weight of soil.

Statistical Analysis

To address the stated objectives of this study, we used (i) multivariate and post-hoc univariate statistical analyses to test whether soil properties differed among land-use and cover types and surface geology, and (ii) canonical discriminant analysis (CDA) using Proc CANDISC with a correlation matrix (SAS Institute, 2003) to discriminate among types, to determine what set of variables best predicted group (land use and cover) membership, and to visualize the data by condensing the multiple soil variables onto one or more axes. The CDA procedure first tests whether the land-use and cover types differ, on average, in soil characteristics using a parametric multivariate analysis of variance (MANOVA); a second test uses canonical correlation analysis to determine the successive functions and canonical roots that best discriminate between a set of class variables (land-use and cover type) and allows the visualization of the discriminate functions by plotting the discriminate scores of the individual plots. The advantage of a multivariate approach is that two or more variables that overlap considerably (i.e., are correlated) may be more distinct when examined from a multivariate point of view (Littell et al., 1996). Moreover, the multivariate approach reduces Type I errors that occur in multiple univariate tests (Quinn and Keough, 2002). To test for the possible effect of factors other than land use and cover on soil characteristics, we classified plots on the basis of their location relative to the Piedmont Plateau vs. Atlantic Coastal Plain (Fig. 1).

We used 17 elemental variables in the CDA. Soil bulk density, pH, organic matter, and total N also were included in the CDA for a total of 21 variables. The inclusion of soil variables with different units of measurement and variation warrants the use of a correlation matrix in the CDA (Jolliffe, 2002). Soil texture was not used in the CDA due to a lack of samples taken from 11 of the 122 plots. Data were transformed to stabilize the variance of individual properties where necessary. These included $\log_{10}$ for elements and square root for bulk density, total N, and organic matter. One outlier (industrial) was removed from the analysis because it was greater than three standard deviations from the mean for the metals Fe, Cr, Co, and Ni.

Once the MANOVA established that at least one of the variables assessed was different among land-use and cover types, means for individual soil properties were subjected to one-way ANOVA as a post-hoc test (SAS Institute, 2003). The ANOVA tested for the effect of land-use and cover type and physiographic province on each soil variable. Since the number of plots sampled per land-use type was weighted, Hochberg's method for unequal sample sizes was used to determine significant differences between means.

RESULTS AND DISCUSSION

Mean and median values of each variable measured across all plots revealed that soil properties in Baltimore varied widely. Chemical properties were more variable than physical properties except for soil pH (Table 1). For example, differences between minimum and maximum values of HNO_3 extractions of Ca, K, and Mg were more than 10-fold and the CV exceeded 70%, compared with 18.1 and 14.9% for sand and bulk density, respectively (Table 1). Concentrations of heavy metals also were highly variable, with CVs ranging from approximately 50% for Al to 250% for Pb.

In comparison with other soil investigations in urban landscapes, Baltimore's soils generally fell within the ranges measured, but with interesting differences. Short et al. (1986) characterized highly disturbed soils derived from fill in the National Mall in Washington, DC, which like Baltimore lies along the fall line between the Atlantic Coastal Plain and Piedmont provinces in the mid-Atlantic region of the USA. In Washington, bulk density and soil texture measurements of surface horizons generally fell within the range of soils in Baltimore. Sand content ranged from 10 to 80% and bulk density from 1.25 to 1.85 Mg m^{-3}, while sand content in Baltimore ranged from 33 to 83% and bulk densities from 0.71 to 1.74 with a mean and median of 1.18 Mg m^{-3} (Table 1). Other urban investigations of surface soils found higher bulk densities than in Baltimore, such as in Hong Kong, where two-thirds of sampled soils exceeded bulk densities of 1.6 Mg m^{-3} (Jim, 1998), and in Pullman, WA, and Moscow, ID, where bulk densities ranged between 1.4 and 1.7 Mg m^{-3} for residential soils (Scharenbroch et al., 2005). We suspect that the range in bulk density for Baltimore was larger than in these studies because soils that were not drastically disturbed, e.g., forest plots, were included in the Baltimore study.

Table 1. Descriptive statistics of soil properties sampled to a depth of 10 cm in the City of Baltimore (*n* = 122 except where noted).

Soil property	Mean	Median	Minimum	Maximum	SE	CV
						%
Bulk density, Mg m^{-3}†	1.18	1.18	0.71	1.74	0.016	14.9
pH	5.2	6.0	3.3	7.6	0.07	12.8
Organic matter, g kg^{-1}	54	51	5	130	17	34.6
Sand, %‡	53	53	33	83	0.91	18.1
Clay, %‡	17	16	6	31	0.49	30.2
N, g kg^{-1}	1.6	1.4	0.1	6.6	0.087	58.8
Acid-extractable K, mg kg^{-1}	903	759	124	4038	57	69.9
K, mg kg^{-1}	106	91	12	280	5.2	54.6
Acid-extractable Ca, mg kg^{-1}	4347	2542	32	30 528	460	117.5
Ca, mg kg^{-1}	1620	1350	18	5634	97	66.0
Acid-extractable Mg, mg kg^{-1}	2699	2164	55	10 290	190	78.3
Mg, mg kg^{-1}	155	160	21	388	4.4	31.3
Acid-extractable P, mg kg^{-1}	527	460	65	2080	31	64
P, mg kg^{-1}	90	38	5	1154	15	178.3
Acid-extractable Na, mg kg^{-1}	115	96	20	388	6.8	65.5
Acid-extractable Al, mg kg^{-1}	14 117	13 522	1418	42 097	670	52.6
Acid-extractable S, mg kg^{-1}	370	313	119	2071	20	60.5
Acid-extractable Ti, mg kg^{-1}	282	197	36	1177	21	83.6
Acid-extractable Cr, mg kg^{-1}	72.3	38	8	794	8.8	133.8
Acid-extractable Mn, mg kg^{-1}	472	422	6	2 125	31	71.9
Acid-extractable Fe, mg kg^{-1}	23 495	22 277	6540	62 580	1000	49.3
Acid-extractable Co, mg kg^{-1}	15	12	0.5	65	1.1	78.4
Acid-extractable Ni, mg kg^{-1}	27	18	5	336	3.2	131.5
Acid-extractable Cu, mg kg^{-1}	45	35	6	216	3.0	73.9
Acid-extractable Zn, mg kg^{-1}	141	81	6	1109	16	120.4
Acid-extractable Mo, mg kg^{-1}	0.5	0.3	0.01	7	0.083	201.1
Acid-extractable Pb, mg kg^{-1}	231	89	4	5 652	53	251.3
Acid-extractable Cd, mg kg^{-1}	1.06	0.89	0.003	3.1	0.066	68.4
Acid-extractable V, mg kg^{-1}	37	31	7	118	2.2	66.2

† *n* = 118

‡ *n* = 111

Although soil chemical characteristics in Baltimore generally had high CVs, soil pH had a relatively low CV of 12.8% (range 3.3–7.6; Table 1). Similarly, in predominately residential soils in Ibadan, Nigeria (population >2 million), soil pH (1:2 soil/0.1 *M* CaCl solution ratio) ranged from 5.1 to 7.6 with a CV of 15% (Gbadegesin and Olabode, 2000). In contrast, data collected in New York City's Central Park during a 20-yr period showed a wide range in soil pH (1:2 soil/water ratio), from 3.5 (pine grove) to 8.8 (street tree pit), but with a narrower range in pH (4.8–6.3) for lawn sites (Pouyat et al., 2002). For roadside soils in Hong Kong, soil pH (1:2.5 soil/water ratio) ranged from 6.77 to 9.95 with a CV of 6.2% (Jim, 1998).

Heavy metal concentrations in Baltimore fell within the range of data reported in other studies. Short et al. (1986) measured 8 *M* HNO_3–extractable Pb, Zn, Ni, Cd, and Cu in the National Mall in Washington, DC, and found mean concentrations of 209.9 (±20.2), 87.8 (±11.8), 13.1 (±0.9), 0.57 (±0.05), and 30.4 (±3.8) mg kg^{-1} in the surface horizon, respectively. These concentrations are comparable to the mean concentrations found in Baltimore but with lower variance, which again may be due to the inclusion of undisturbed soils in the Baltimore sampling design. Mielke et al. (1983) sampled 422 garden soils in Baltimore and found median concentrations of 100, 92.0, 2.8, 0.56, and 17.3 mg kg^{-1} for 1 *M* HNO_3–extractable Pb, Zn, Ni, Cd, and Cu, respectively, which are comparable to findings in this study. In the Mielke et al. (1983) study, however, maximum concentrations of the garden soils were more than twofold higher than the maximum concentrations measured in our study. This discrepancy can be explained by differences in sampling intensities, as they found only a few highly contaminated garden soils among the 422 sampled, relative to the much lower number of garden soils included in our study.

To assess the potential fertility of soils in Baltimore, we compared the median levels of the elements measured in this study with fertilizer recommendations in the literature. Whitcomb (1987) recommended available soil concentrations for horticultural soils of 300 to 1000, 74 to 150, 100 to 500, and 30 to 60 mg kg^{-1} for Ca, K, Mg, and P, respectively, compared with median available (Mehlich-1 extractant) concentrations of 1350, 91, 160, and 38 mg kg^{-1} found in Baltimore soils (Table 1). Thus, it is apparent that in many of the plots sampled, Baltimore soils have sufficient nutrient levels to support plant growth, and in the case of Ca, excessive, given the recommended ranges. Although these data suggest that soils in Baltimore for the most part have the potential to be highly productive for plants, the maximum or minimum range of measurements of other soil

Table 2. **Results of a multivariate analysis of variance that tested for the significance of a set of 21 variables among land-use and cover types and physiographic province.**

Source	Wilk's λ	*F*	Denominator df	*P*
Land use	0.10770	2.58	469	< 0.0001
Province	0.45670	5.61	99	< 0.0001

properties, e.g., maximum bulk density values and minimum organic matter content (Table 1), in this and other urban studies suggest that urban soils have a tendency to be poor plant growth environments (e.g., Patterson et al., 1980; Short et al., 1986; Jim, 1993, 1998).

The fact that concentrations of Ca in surface soils were high to excessive suggests that urban areas receive above-background inputs of this element. For example, 72% of the sampled plots exceeded 1000 mg kg^{-1} of available Ca, whereas non-limestone-influenced soils in the Piedmont and Atlantic Coastal Plain of Maryland have available Ca in the range of 200 to 1000 mg kg^{-1} (Soil Survey Staff, 2007). Calcium is an important constituent of atmospheric particulates in urban areas and apparently originates from construction materials such as concrete (Orsini et al., 1986; Boni et al., 1988; Lee and Longhurst, 1992; De Miguel et al., 1997), and there is evidence that urban land uses associated with high amounts of concrete such as transportation rights-of-way and vacant lots may be a source of urban dust to natural areas adjacent to them. Lovett et al. (2000) measured a strong gradient of Ca deposition into oak (*Quercus* spp.) forest stands along an urban–rural gradient in the New York City metropolitan area with the urban stands receiving up to three times greater throughfall loadings than in suburban and rural stands. Along the same urban–rural gradient, Pouyat et al. (1995) found that soil Ca and total salt concentrations were significantly higher in urban than in suburban and rural forest patches, and that these concentrations were positively correlated with road density and traffic volume. Consistent with these findings, Bloemen et al. (1995) found in Osnabrück, Germany, that pH was much higher for turfgrass and woodland soils within the boundaries of the city than for the same cover types in surrounding areas, though they did not report on Ca concentrations.

Although these results suggest that highly urbanized areas may act as sources of these elements on a regional scale, depositional gradients also may be occurring within cities. Tanner and Fai (2000) measured the concentrations of major cations in bulk deposition at 17 locations in Hong Kong and found that these concentrations varied spatially by factors up to 65. They attributed variations in bulk deposition of Ca to soil parent material and dust from construction materials (Tanner and Fai, 2000; Tanner and Wong, 2000).

Effect of Land Use and Cover

Land use and cover was significantly differentiated by the 21 soil variables used in the CDA ($P < 0.0001$ using MANOVA; Table 2). The CDA showed that the first and second factors accounted for 49.7 and 28.0% of the variation, respectively, for a total of 77.7%. Positive coefficients for the first variate were related with high concentrations of K and P and high bulk densities (Fig. 2). The first variate separated forest cover from the other land-use and cover types, with the F plots corresponding to negative coefficient values, or lower concentrations of K and P, and lower bulk densities (Fig. 3). The second variate was related to soil pH and appeared to vary across land-use and cover types with predominately turfgrass cover (Fig. 2 and 3). A negative coefficient of this variate (lower pH) tended to correspond to the residential (R) type, while positive coefficients (higher pH) generally corresponded to CT and I types (Fig. 3). Of the 52 R plots, 43 fell below the origin on the second variate axis (Fig. 3).

In the ANOVA, differences were significant at $P < 0.05$ among land-use and cover types for 6 of the 21 variables. These results should be interpreted with caution, however, due to the possible inflation of Type I errors for these variables: pH, bulk density, and concentrations of K, P, Na, and Al (Table 3). For pH, mean values were lowest for the F types (pH = 5.7) and highest for CT types (pH = 6.8; Table 3). Consistent with the separation of plots along the first and second variates in the CDA, mean differ-

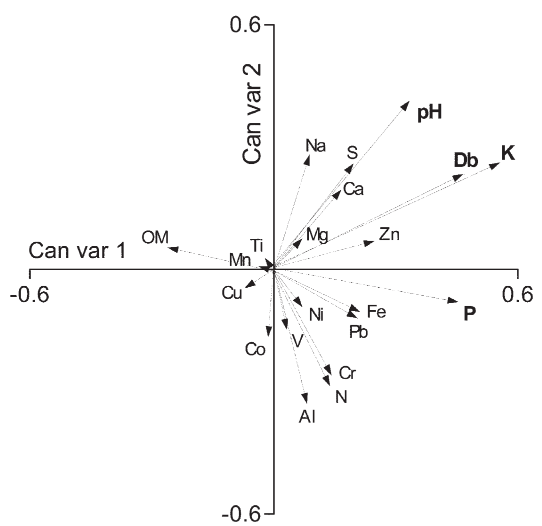

Fig. 2. Vector diagram showing positive and negative correlations of 21 soil variables to the first and second canonical variates (Can var) derived from a canonical discriminant analysis procedure to discriminate plots by land use and cover in Baltimore. Highest correlating variables to the canonical variates are in bold type; OM = organic matter, Db = bulk density.

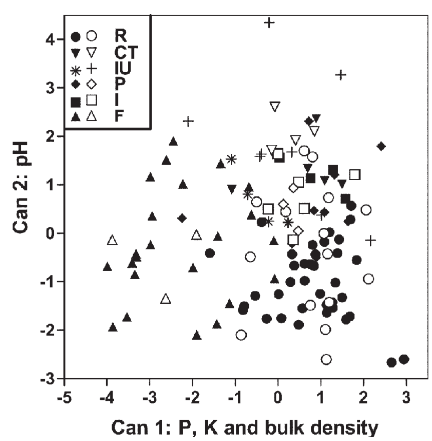

Fig. 3. Scatter plot of first and second canonical variates (Can) of a canonical discriminant analysis procedure using 21 soil variables to discriminate plots by land-use type in Baltimore (R = residential, CT = commercial or transportation, IU = industrial or urban open, P = park or golf course, I = institutional, and F = forest). The first canonical variate was correlated to P, K, and bulk density and the second variate to pH. Piedmont plots are the solid symbols and the star sign, and the Coastal Plain plots are the open symbols and the plus sign.

Table 3. Mean (±SE) surface soil properties (0–10 cm) for land-use classes and ANOVA P values.

Soil property	Land use†						ANOVA
	CT	IU	F	P	R	I	*P*
Bulk density, Mg m^{-3}	1.3 ± 0.058 a‡	1.2 ± 0.074 ab	1.1 ± 0.037 b	1.2 ± 0.027 ab	1.2 ± 0.019 a	1.3 ± 0.067 a	0.0009
Sand, %	56 ± 3.5	63 ± 4.4	54 ± 2.1	51 ± 2.2	51 ± 1.3	53 ± 1.5	NS§
Silt, %	27 ± 2.5 ab	23 ± 3.2 a	32 ± 1.7 b	33 ± 2 b	30 ± 0.83 ab	29 ± 1.7 ab	0.0117
Clay, %	17 ± 1.5 ab	15 ± 1.6 ab	14 ± 1.2 a	16 ± 0.81 ab	19 ± 0.73 b	17 ± 1.1 ab	0.0036
pH	6.8 ± 0.23 a	6.3 ± 0.33 ab	5.7 ± 0.16 b	6.4 ± 0.16 ab	6.0 ± .082 b	6.4 ± 0.22 ab	0.0007
OM, g kg^{-1}	55 ± 4.6	53 ± 9.5	61 ± 4.6	59 ± 3.7	50 ± 1.7	48 ± 5.6	NS
N, g kg^{-1}	1.3 ± 0.18	1.5 ± 0.34	1.6 ± 0.26	1.6 ± 0.12	1.8 ± 0.11	1.5 ± 0.34	NS
Al, mg kg^{-1}	12 620 ± 2191 ab	9560 ± 1743 a	13 238 ± 1013 ab	15 112 ± 1793 ab	15 840 ± 1185 b	12 962 ± 2528 ab	0.0474
P, mg kg^{-1}	497 ± 76 ab	706 ± 192 ab	373 ± 58 a	486 ± 30 ab	592 ± 41 b	453 ± 68 ab	0.0035
S, mg kg^{-1}	419 ± 60	574 ± 156	330 ± 44	346 ± 15	340 ± 14	342 ± 29	NS
Ti, mg kg^{-1}	316 ± 86	218 ± 45	324 ± 62	269 ± 43	259 ± 26	356 ± 110	NS
Cr, mg kg^{-1}	50 ± 16	98 ± 64	53 ± 11	91 ± 26	83 ± 11	33 ± 6	NS
Mn, mg kg^{-1}	514 ± 129	425 ± 75	503 ± 69	629 ± 144	439 ± 42	377 ± 71	NS
Fe, mg kg^{-1}	23 060 ± 4287	21 708 ± 3166	20 142 ± 1919	24 729 ± 2540	25 681 ± 1807	21 777 ± 3124	NS
Co, mg kg^{-1}	11 ± 2.2)	10 ± 2.6	14 ± 1.8	19 ± 3.7	16 ± 1.9	12 ± 2	NS
Ni, mg kg^{-1}	20 ± 2.	20 ± 4	20 ± 1.6	34 ± 6.6	33 ± 7.1	18 ± 2.7	NS
Cu, mg kg^{-1}	37 ± 4.3	55 ± 16	51 ± 9.2	39 ± 4.8	43 ± 3.3	37 ± 7	NS
Zn, mg kg^{-1}	154 ± 31	304 ± 104	103 ± 24	93 ± 14	145 ± 21	86 ± 12	NS
Pb, mg kg^{-1}	226 ± 84	258 ± 104	113 ± 30	109 ± 28	340 ± 118	103 ± 35	NS
Na, mg kg^{-1}	214 ± 29 a	120 ± 24 ab	119 ± 19 b	108 ± 15 ab	101 ± 7.6 b	95 ± 16 ab	0.0180
Mg, mg kg^{-1}	3966 ± 993	2031 ± 351	2599 ± 406	2896 ± 446	2556 ± 292	3107 ± 861	NS
K, mg kg^{-1}	1177 ± 190 a	924 ± 148 ab	561 ± 98 b	1038 ± 140 a	924 ± 89 a	1239 ± 284 a	<0.0001
Ca, mg kg^{-1}	6491 ± 1766	6529 ± 1931	4148 ± 1189	3677 ± 710	3603 ± 610	5051 ± 1876	NS
V, mg kg^{-1}	35 ± 7	29 ± 6.2	36 ± 4.8	35 ± 4.4	40 ± 3.7	37 ± 8.8	NS

† CT, commercial or transportation; IU, industrial or urban open; F, unmanaged forest; P, park or golf course; R, residential; and I, institutional.

‡ Means with different letters were significantly different.

§ NS, not significant at the $\alpha = 0.05$ probability level.

ences were significant between the CT and R, and CT and F types ($P = 0.042$ and 0.001, respectively, using Hochberg's test).

Similar to soil pH, the F type measurements of bulk density differed significantly from the CT, R, and I land-use and cover types ($P = 0.017$, 0.006, and 0.010, respectively, using Hochberg's test). The F type had the lowest mean bulk density (1.1 ± 0.058 Mg m^{-3}) while the I type had the highest (1.3 ± 0.067 Mg m^{-3}; Table 3).

Potassium showed a similar pattern to that of pH. Concentrations of K were as much as 2.2 times greater in the I type (1239 ± 284 mg kg^{-1}) than in the other land-use and cover types (Table 3). Potassium differences were significant ($P < 0.05$) between the F and the CT, P, R, and I land-use and cover types. The F type also had a relatively low P concentration (373 ± 58 mg kg^{-1}) and was 1.9-fold lower than the IU type. Sodium was more than twice as high in the CT type (214 ± 29 mg kg^{-1}) than in the other types and differed significantly between F and R types ($P = 0.0094$ and 0.086, respectively, using Hochberg's test). None of the heavy metals measured in this study was statistically significant ($P < 0.05$) in the ANOVA, with one exception: Al concentrations were 1.7 higher in the R than in the IU land-use and cover type ($P = 0.035$, using Hochberg's test).

The results of the MANOVA and CDA suggest that, for a subset of the soil variables measured, primarily K, P, bulk density, and pH, stratification by land-use and cover classes explained up to 77% of the differences found at the citywide scale (Table 2, Fig. 3). In particular, the F plots were separated with little overlap from what are predominately turfgrass cover types (CT, P, R, and I types) by the first variate in the CDA, which explained almost 50% of the variation in the data. Moreover, the F plots significantly differed from the CT, P, R, and I types in concentrations of P and K and bulk density in several pairwise comparisons in the post-hoc Hochberg tests (Table 3).

Land use and cover often are used as a class variable to stratify sampling in urban landscapes (e.g., Nowak et al., 2004; Blume, 1989) with the supposition that the classification categories used, such as those in the Anderson Level II system, represent differences in management, disturbance, cover, and for soil investigations, sources of contamination. Our analysis suggests that surface soil properties of the six land-use and cover types were discriminated best by properties most likely to be affected by the presence or absence of turfgrass management activities (e.g., liming and fertilization) and surface site disturbance. For example, in the CDA, the variables most discriminating were K, P, and bulk density, which separated F type soils (undisturbed and unmanaged) from more typical urban soils (disturbed and managed soils). In addition, the CDA results were supported by the ANOVA multiple means tests, where K and P concentrations and bulk density significantly differed among land-use and cover types, with the F types having the lowest concentrations of K and P and lowest bulk density (Table 3). Forest soils generally are not managed or disturbed, so bulk densities are lower. Also, these soils receive fewer added elements (particularly P and K from fertilizer) than soils undergoing turfgrass management.

While the F types were clearly separated from land-use and cover types dominated by turfgrass, the separation among the turfgrass cover types was not as strong. The second variate explained 28% of the variation, showing considerable overlap among most of the turfgrass cover types (Fig. 3). The R types, however, clustered below the origin of the second variate axis, suggesting that these plots were differentiated from the other turfgrass types by having more acidic soils. Moreover, the post-hoc ANOVA tests showed that the R types had significantly lower pH and higher Al concentrations than the CT type, with similar relationships to the IU, P, and I types, though these differences were not separable given the statistical power of the study design (Table 3).

The separation of the R type from the CT type and less so with the other turfgrass types may be due to differences in management regimes or other site factors related to the land-use and cover types, e.g., site history (Qian and Follett, 2002) and juxtaposition to built environments such as roads and construction zones (De Miguel et al., 1997), the latter of which may explain the higher Na concentrations and pH in the CT type (Table 3). By contrast, other factors may be increasing the overlap of plots in the scatterplot (Fig. 3), e.g., such as differences in time since development, which has been shown to differentiate older (>40 yr since development) from younger urban soils (e.g., Golubiewski 2006; Scharenbroch et al., 2005). Another factor associated with turfgrass management is the application of lime ($CaCO_3$). As with fertilizer, it is common to apply lime to turfgrass as an amendment to adjust soil pH. A survey of homeowners in a suburb of Baltimore, however, revealed that only about 15% of homeowners applied lime to their lawns (n = 59; J. Russell-Anelli, I.D. Yesilonis, and R.V. Pouyat, unpublished data, 2003). Excessive fertilizer application into lawns from which clippings are removed and to which no lime is added also could explain the lower soil pH in the R type plots (e.g., Barak et al., 1997). Surveys of residences in Baltimore County showed that between 50 and 70% of residents fertilize their lawns, applying between 60 and 110 kg N ha^{-1} yr^{-1} (Law et al., 2004).

Unlike the soil properties mentioned above, heavy metals were not related to land use, given the power of the study design. The lack of importance in the CDA of heavy metals and the lack of statistically significant differences among land-use and cover types suggest that sources of heavy metal contamination were not detectable at the scale of observation and sampling intensity used in this study.

Comparisons of land use in this study suggest that urban direct effects resulted in greater changes in soil characteristics than indirect effects; that is, differences between land uses affected by predominately environmental factors (indirect), e.g., the F type, in contrast with disturbance (direct), e.g., the CT type, are larger than differences between land-use types affected primarily by disturbance and management (Table 3). With this study we were unable to compare unmanaged forest plots embedded within rural and urban areas, but other studies have shown that urban environments can affect soil properties in forest patches along urban–rural environmental gradients in the metropolitan areas of New York City (Pouyat et al., 1995), Asheville, NC (Pavao-Zuckerman, 2003), and Louisville, KY (M.M. Carreiro, R.V. Pouyat, and C. Tripler, unpublished data, 2005).

Table 4. Total canonical structure of a canonical discriminant analysis of 21 soil variables measured for soils in Baltimore to discriminate between the Piedmont Plateau and Atlantic Coastal Plain physiographic provinces.

Soil property	Canonical coefficient
Bulk density, Mg m^{-3}	−0.163226
pH	−0.194577
Organic matter, g kg^{-1}	0.224740
N, g kg^{-1}	0.115856
Acid-extractable K, mg kg^{-1}	0.225551
Acid-extractable Ca, mg kg^{-1}	0.138771
Acid-extractable Mg, mg kg^{-1}	0.623891
Acid-extractable P, mg kg^{-1}	0.035758
Acid-extractable Na, mg kg^{-1}	0.237567
Acid-extractable Al, mg kg^{-1}	0.876830
Acid-extractable S, mg kg^{-1}	−0.111382
Acid-extractable Ti, mg kg^{-1}	0.722716
Acid-extractable Cr, mg kg^{-1}	0.503410
Acid-extractable Mn, mg kg^{-1}	0.678600
Acid-extractable Fe, mg kg^{-1}	0.727365
Acid-extractable Co, mg kg^{-1}	0.814515
Acid-extractable Ni, mg kg^{-1}	0.578627
Acid-extractable Cu, mg kg^{-1}	0.335590
Acid-extractable Zn, mg kg^{-1}	−0.130812
Acid-extractable Pb, mg kg^{-1}	−0.192005
Acid-extractable V, mg kg^{-1}	0.777709

Effect of Physiographic Province

Physiographic province was significantly differentiated by the 21 soil variables used in the CDA (P < 0.0001 using MANOVA; Table 2). The CDA showed that positive coefficients for the canonical variate were related with high concentrations of Al, Co, Fe, Ti, and V (Table 4). The variate separated the two geologic provinces, with lower values corresponding to the Atlantic Coastal Plain and higher values to the Piedmont Plateau (Fig. 4).

In the ANOVA, differences were significant at P < 0.05 between the geologic provinces for 10 of the 17 chemical variables measured: Al, Co, Cr, Cu, Fe, Mg, Mn, Ni, Ti, and V (Table 5). For Al, Fe, Mg, Ni, Ti, and V, differences were nearly twice as high for the Piedmont Plateau as for the Atlantic Coastal Plain (Table 5). These differences continued even when F type plots (by definition undisturbed) were removed from the analysis.

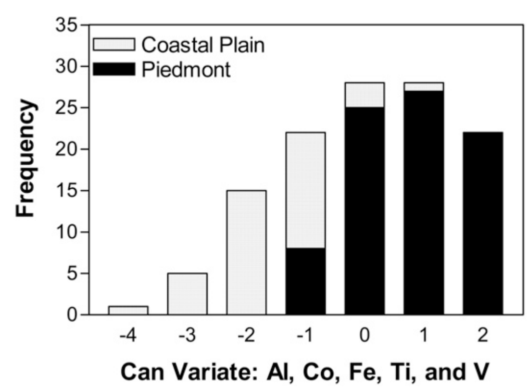

Fig. 4. Frequency histogram of canonical variate of a canonical discriminant analysis procedure using 21 soil variables to discriminate plots by geophysical province in Baltimore. Each bar represents the frequency of plots falling within a ±0.5 range of canonical coefficient values. The canonical variate was correlated to contents of Al, Co, V, and Ti.

These results suggest that differences in the elemental composition of parent material associated with the Piedmont Plateau and Atlantic Coastal Plain may largely explain the spatial variation of primarily Al, Co, Ti, and V, and, to a lesser extent, Cr, Cu, Fe, Mg, Mn, and Ni. Parent material in this region of the Piedmont Plateau is composed of mafic and ultramafic rock types that are rich in Al, Co, Cr, Cu, Fe, Mg, Mn, Ni, and V (Sparks, 1995). Of the elements that statistically differed between physiographic provinces, only Ti cannot be associated with mafic rock types. In addition to the original 21 variables, we compared sand, silt, and clay particle-size fractions between provinces (Table 5). In all cases, differences between the Piedmont Plateau and the Atlantic Coastal Plain were highly significant ($P < 0.01$ using Hochberg's test). The Atlantic Coastal Plain had soils that were more coarse textured (mean sand fraction = 58%) than the Piedmont Plateau soils (mean sand fraction = 51%), which is consistent with the differences in parent material between two provinces (Table 5).

A strong influence of parent material on several trace metals in a highly disturbed landscape with many potential contaminant sources of these metals was contrary to our expectation. Regional studies have shown that parent material does have an influence on spatial patterns of trace metals; however, these studies included both urban and nonurban areas (Bityukova et al., 2000; Facchinelli et al., 2001). In the Baltimore study, soils were sampled only within the city's boundaries. Therefore, in our sample area, large volumes of soil were disturbed, added, or removed with time such that the native soil has become highly modified or buried by fill materials. Moreover, Baltimore is an old industrial city that has many sources of pollutants. Based on a soil survey of Baltimore, we estimate that >60% of the mapped soils are highly disturbed or covered by impervious surfaces with an additional 20% influenced by management or moderate disturbances (Pouyat et al., 2002). Our results show that, despite these changes, properties of the native soil continue to persist, specifically soil texture and a suite of trace metals associated with mafic and ultramafic parent material. The continued strong relationship between native parent material and these variables suggests that the transport and movement of soil within the Baltimore landscape occurred at short distances; however, the fact that other soil properties did not vary by the native parent material, such as the variables shown to differ among land-use and cover types (pH, P, K, and bulk density), suggests that urban factors also had an affect on the spatial pattern of surface soil characteristics in Baltimore.

Table 5. Soil property means (0–10 cm) and ANOVA results by physiographic province for 122 plots sampled in the City of Baltimore (*n* = 82 and 40 for the Piedmont and Atlantic Coastal Plain geophysical provinces, respectively).

Soil property	Physiographic province		ANOVA
	Piedmont	Coastal Plain	*P*
Bulk density, Mg m^{-3}	1.17	1.22	0.189
pH	6.0	6.3	0.117
Organic matter, g kg^{-1}	56	50	0.069
Sand, %†	51	58	<0.001
Silt, %†	32	26	<0.001
Clay, %†	18	16	<0.01
N, g kg^{-1}	1.63	1.61	0.352
Acid-extractable K, mg kg^{-1}	986	735	0.068
Acid-extractable Ca, mg kg^{-1}	4 529	3 972	0.264
Acid-extractable Mg, mg kg^{-1}	3 246	1 577	<0.001
Acid-extractable P, mg kg^{-1}	523	535	0.774
Acid-extractable Na, mg kg^{-1}	120	104	0.055
Acid-extractable Al, mg kg^{-1}	17 082	8 038	<0.0001
Acid-extractable S, mg kg^{-1}	350	404	0.371
Acid-extractable Ti, mg kg^{-1}	354	134	<0.0001
Acid-extractable Cr, mg kg^{-1}	82	52	<0.0001
Acid-extractable Mn, mg kg^{-1}	578	255	<0.0001
Acid-extractable Fe, mg kg^{-1}	27 507	15 269	<0.0001
Acid-extractable Co, mg kg^{-1}	19	6.8	<0.0001
Acid-extractable Ni, mg kg^{-1}	32	16	<0.0001
Acid-extractable Cu, mg kg^{-1}	48	38	0.006
Acid-extractable Zn, mg kg^{-1}	127	171	0.293
Acid-extractable Mo, mg kg^{-1}	0.35	0.7	<0.0001
Acid-extractable Pb, mg kg^{-1}	220	254	0.122
Acid-extractable Cd, mg kg^{-1}	1.2	0.9	0.043
Acid-extractable V, mg kg^{-1}	45	20	<0.0001

† Variables not included in canonical discriminant analysis.

CONCLUSIONS

Results of this study suggest that properties of surface soils can vary widely in urban landscapes, making it difficult to define or describe a typical "urban soil." Regardless of the wide range in measured soil properties, a subset of the variables measured (K, P, bulk density, and pH) showed a discernable pattern with land-use and cover types used in this analysis. Differences were greatest and most frequent between land-use and cover types dominated by direct or indirect urban effects (e.g., forest vs. residential). Potassium, P, and bulk density were the most discerning variables differentiating forest cover from land uses dominated by turfgrass cover, which may be due to lawn fertilizer and the intensity of use occurring in residential areas. Likewise, soil pH differentiated residential areas from other land-use and cover types dominated by turfgrass, which may reflect differences in management intensity and juxtaposition to built environments. Unlike soil properties related to turfgrass management, heavy metal cations did not differ among land-use or cover types, suggesting that these elements are more related to site history and the spatial arrangement of contaminant sources in urban landscapes.

The differences in surface soil properties among land-use and cover could be useful in conducting urban soil surveys, at least to spatially differentiate remnant soils from highly disturbed and managed soils. Moreover, those soil properties associated with fertilizer applications (K and P) and intensity of use (bulk density), may be useful as diagnostic properties to differentiate human impacts on surface soil characteristics in urban landscapes. Since these properties are potentially related to management activities that typically occur in urban landscapes, we suggest that comparable studies in other cities will show similar results. Soil pH also may serve to differentiate among land-use types dominated by turfgrass cover; however, additional research is needed at finer resolutions and under more controlled conditions to assess the importance of turfgrass management practices on soil pH and other properties.

A subset of the variables measured, primarily Al, Co, Fe, Mn, Ti, V, and soil texture, was related to the surface geology of the study area and is therefore unique to the Baltimore region. The importance of natural soil-forming factors, in this case parent material, was contrary to our expectation that urban factors would be more important in determining the spatial distribution of surface soil characteristics. Although a significant proportion of Baltimore's land area has been disturbed through urban development, these disturbances resulted in the movement of soil materials for only short distances, suggesting the continued importance of surface geology in determining the spatial distribution of at least some soil properties in urban landscapes.

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