A Global Comparison of Surface Soil Characteristics Across Five Cities: A Test of the Urban Ecosystem Convergence Hypothesis

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Abstract: As part of the Global Urban Soil Ecology and Education Network and to test the *urban ecosystem convergence hypothesis*, we report on soil pH, organic carbon (OC), total nitrogen (TN), phosphorus (P), and potassium (K) measured in four soil habitat types (turfgrass, ruderal, remnant, and reference) in five metropolitan areas (Baltimore, Budapest, Helsinki, Lahti, Potchefstroom) across four biomes. We expected the urban soil characteristics to "converge" in comparison to the reference soils. Moreover, we expected cities in biomes with more limiting climatic conditions, or where local factors strongly affect soil characteristics, would exhibit the greatest variance across soil types within and among cities. In addition, soil characteristics related to biogenic factors (OC, TN) would vary the most because of differences in climate and human efforts to overcome limiting environmental conditions. The comparison of soils among and within the five cities suggests that anthropogenic, and to a lesser degree native, factors interact in the development of soils in urban landscapes. In particular, characteristics affected by anthropogenic processes and closely associated with biogenic processes (OC, TN) converged, while characteristics closely associated with parent material (K, P) did not converge, but rather diverged, across all soil habitat types. These results partially supported the urban ecosystem convergence hypothesis in that a convergence occurred for soil characteristics affected by climatic conditions. However, the divergence of K and P was unexpected and warrants adjusting the hypothesis to account for variations in anthropogenic effects (e.g., management) that may occur within soil habitat types impacted by humans.

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Financial Disclosures/Conflicts of Interest: The idea for GLUSEEN was made possible by a Fulbright Specialist grant to R. Pouyat at the University of Helsinki. The GLUSEEN network is supported by a supplemental grant to NSF-ACI 1244820. Soil analyses were supported by the FEKUT grant (SZIE-AOTK-KK-UK 12007) of the Hungarian Ministry of Human Resources (E.H.). The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable.
Received April 29, 2015.
Accepted for publication September 9, 2015.

ISSN: 0038-075X
DOI: 10.1097/SS.0000000000000125

Key Words: Anthropogenic soils, experimental network, soil carbon, urban soils

(*Soil Sci* 2015;180: 136–145)

Urban soils provide many of the same ecosystem functions as "natural" and agricultural soils, for example, decomposition and nutrient cycling, water purification and regulation, and habitat for an enormous diversity of organisms (Giller, 1996; Pouyat et al., 2010). Nonetheless, the increasing burden of expanding urban areas, concomitant need for new infrastructure, and accommodation of greater human population densities is resulting in a worldwide alteration of these functions (Sachs, 2015). Therefore, understanding the characteristics of urban soils and how they vary is crucial to their management and restoration and ultimately to the design of more sustainable cities (Pavao-Zuckerman, 2012; Setälä et al., 2014).

A central principle in urban ecological theory presupposes that anthropogenic drivers dominate natural drivers in the control of ecosystem processes (Alberti, 1999; Kaye et al., 2006). If this assumption is true, it follows that both at regional and global scales ecosystem responses to urban land-use change should converge relative to the native systems being replaced. This "convergence" in ecosystem properties is referred to as the *urban ecosystem convergence hypothesis* (Pouyat et al., 2003; McKinney, 2006; Pickett et al., 2008). In the case of the soil system, the convergence hypothesis suggests that soil responses will converge across regional and global scales as long as anthropogenic drivers (e.g., management) dominate over natural soil-forming factors (e.g., relief). This convergence occurs because human effects on soil that are physical in nature (e.g., grading and irrigation) tend to overwhelm native factors (e.g., topography and drainage) and characteristics of soil that take thousands of years to develop. Moreover, convergence occurs because of differential human effort (e.g., water and nutrient supplements) to overcome environmental constraints on net primary productivity (NPP) and accordingly soil biological processes—the greater the limitation on these processes, the greater the effort by humans to overcome them. Hence, in a global comparison of metropolitan areas, the difference between native and anthropogenic soil will be greatest for cities located in biomes with the greatest limitations on NPP or decomposition, such as a desert or boreal forest, and for those cities with local soil-forming factors (e.g., parent material) that disproportionately affect soil development (Pouyat et al., 2010; Pouyat et al., in press).

The characteristics of urban soils vary widely and are dependent on both direct and indirect effects resulting from urban land-use and cover change. Examples of direct effects include soil disturbances such as grading (Pitt and Lantrip, 2000; McGuire, 2004; Trammell et al., 2011), management inputs such as irrigation (Tenenbaum et al., 2006; Zhu et al., 2006), and compaction through trampling (Godefroid and Koedam, 2004), whereas indirect effects include environmental changes such as the urban heat island effect (Savva et al., 2010), atmospheric deposition (Lovett et al., 2000; Rao et al., 2014), and changes in plant and animal species composition (McKinney, 2006). Early descriptions of urban soils focused mainly on highly disturbed soils exhibiting high spatial variability, massive structure (i.e., soils having no visible structure), low organic matter concentration, and contamination with toxic elements or compounds (Craul and Klein, 1980; Patterson et al., 1980; Short et al., 1986; Jim, 1993). More recent results show a greater variety of soil conditions that are often more favorable for plant growth than the preexisting native soil (Hope et al., 2005; Pouyat et al., 2007a; Davies and Hall, 2010; Edmondson et al., 2012). Adding to the complexity of soil conditions are human desires to maintain cultivated plant communities that represent the social norms of urban landscapes such as lawns and ornamental gardens (Cook et al., 2012; Kendal et al., 2012).

In contrast to increasing heterogeneity, the lag effects of site history and the propensity of residents to uniformly manage yards according to ownership boundaries may actually reduce within parcel variation of surface soil characteristics (e.g., Bennett et al., 2004; Hall et al., 2009; Raciti et al., 2011; Yesilonis et al., in press). Hence, the resultant mosaic of soil conditions necessitates a typology of soil types that can account for site history and uniformity in management, while revealing the variability that occurs across parcels within a metropolitan region (Pouyat et al., 2007b; Pouyat et al., in press). Accordingly, as per the *convergence hypothesis*, individual soil types occurring in the mosaic should differ less in their characteristics at continental and global scales than among their native counterparts when anthropogenic factors dominate natural factors of soil formation.

Therefore, as a result of the variation of anthropogenic effects on soils in urban landscapes, the comparisons described in Pouyat et al. (in press), and as will be seen in this article, represent a revision of the urban ecosystem convergence hypothesis stated previously, which assumed that anthropogenic factors have a relatively uniform effect (Pouyat et al., 2003). That is, within an urban soil mosaic, anthropogenic effects are not homogeneous from parcel to parcel (e.g., see Hope et al., 2005; Yesilonis et al., in press), and as a result, parcels with similar characteristics, and thus soil types, may vary differently from other types over continental and global scales. The net effect is that cities located in biomes with the greatest limitations on NPP and decomposition (i.e., colder or drier climates) or cities where local soil-forming factors have a disproportionate effect on soil characteristics (e.g., parent material that strongly influences soil pH) will exhibit the greatest variance across soil types within and among cities. Moreover, those soil properties strongly affected by biogenic processes, for example, organic carbon (OC) and total nitrogen (TN) (Hope et al., 2005; Zhu et al., 2006), should respond differently than properties that are strongly influenced by parent material, for example, trace elements and pH (Pouyat et al., 2007a). These differences occur because of the nature and timeframe of the anthropogenic effect; that is, biogenic processes are impacted differently than physicochemical processes by urban effects. As an example, changes in air temperature or soil moisture that occur in urban environments will affect soil microbial activity at very different temporal scales than the rate of weathering of mineral soil (hours vs. thousands of years). Similarly, soil disturbances will greatly impact soil carbon while not resulting in a measurable response in trace metal concentrations.

As part of the Global Urban Soil Ecology and Education Network (GLUSEEN), we report here on results of characteristics that are associated with both biogenic (OC, TN) and physicochemical processes (pH, available phosphorus, and potassium) of surface soils (0–10 cm) measured in four soil "habitat types" across five globally distributed metropolitan areas to test the urban ecosystem convergence hypothesis (Pouyat et al., in press). We sampled only surface soils because of the network's objective to relate soil characteristics to soil community structure and decomposition rates that are primarily relegated to surface soil horizons (Swift et al., 1979). Overall goals and objectives of GLUSEEN are reported by Pouyat et al. (in press). For this study, we address the question: How do characteristics of urban soils compare to native soils at local, regional, and global scales? Specifically, we compared surface soil characteristics of public greenspace (turfgrass [TUR]), highly disturbed or fill areas (ruderal [RUD]), undisturbed (remnant [REM]), and native (reference [REF]) soil habitat types within and among five metropolitan areas. These soil habitat types roughly corresponded to a continuum of anthropogenic effects from relatively low impacts (REF) to those largely impacted by indirect effects (REM), to types that are altered primarily by direct effects, such as in managed (TUR) and drastically disturbed (RUD) areas (Pouyat et al., in press).

We expected surface soil characteristics to "converge" differentially across four distinct biomes and by urban soil habitat type. Moreover, cities located in biomes with climatic conditions that are more limiting to NPP and decomposition (e.g., boreal-hemiboreal or semiarid) should exhibit the greatest difference between the urban influenced soils and their corresponding REF site, that is, exhibit the most convergence in native versus anthropogenic soil. At the same time, cities with the greater site limitations will exhibit the most differences among soil habitat types within a metropolitan area. Furthermore, those soil characteristics related to climatic factors, such as OC and TN, will exhibit the biggest differences.

METHODS

The Global Urban Soil Ecology and Education Network is based on a suite of soil abiotic and biotic measurements in various soil habitat types associated with urban and urbanizing landscapes on a global scale. Moreover, the network is developing protocols that are relatively simple for students and citizen scientists to execute across the diversity of soil conditions found in human settlements and urban areas around the world. Hence, the methods and study design reported in this article are part of a "proof of concept" for a global comparison of soil abiotic and biotic characteristics in the network (Pouyat et al., in press).

Study Area

This article reports on soil measurements made in GLUSEEN, which includes five cities that range in climate from boreal-hemiboreal (Helsinki and Lahti, Finland) to humid-subtropical (Baltimore, MD) and continental (Budapest, Hungary) to semiarid (Potchefstroom, South Africa) biomes (Table 1). These cities represent metropolitan areas that range in population from almost 2 million to just over 100,000 people, which covers the range in population for the majority of cities in the world. In Finland, a very large city (Helsinki) and small city (Lahti) were selected, respectively, as an interbiome comparison. In each city, soil of the same soil habitat type was sampled based on a matrix of disturbance and management levels developed for the network (Pouyat et al., in press). These included three of six possible types: low disturbance–low management, or REM soil; high disturbance–low management, or RUD soil; and high disturbance–medium management, or public turf (TUR) soil. In addition, in each city and associated metropolitan area a native soil habitat type and corresponding biome served as a "reference" (REF) for the REM category such that within city and global comparisons were possible between urban and native soil habitats (see Pouyat et al., in press, for more details on the matrix of urban soil habitat types). We inferred from these soil

TABLE 1. General Climatic and Soil Characteristics of the Five Cities Sampled in This Study

Cities	Biome	Moisture Regime	Temperature Regime	Soil Order	Parent Material
Baltimore, MD	**Humid-subtropical**	**Udic**	**Mesic**	**Ultisol**	**Mafic rock**
Budapest, Hungary	**Continental**	**Ustic**	**Mesic**	**Alfisol (Leptosol)**	**Dolomite**
Helsinki, Finland	**Boreal-hemiboreal**	**Udic**	**Mesic**	**Spodosol**	**Granite**
Lahti, Finland	**Boreal-hemiboreal**	**Udic**	**Mesic-cryic**	**Spodosol**	**Granite/till**
Potchefstroom, South Africa	**Semiarid**	**Aridic**	**Thermic**	**Aridisol**	**Shale/diabase**

habitat comparisons the effects of physical site disturbances (e.g., site grading), subsequent management activities (e.g., fertilization, irrigation), previous land-use history, imported soil materials or artifacts, and urban environmental factors on surface soil characteristics.

Baltimore, Maryland

Baltimore is a historically industrial city with a population of 620,961 in the year 2000 and is located on the Chesapeake Bay in the Mid-Atlantic region of the United States (Fig. 1). 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 air temperature is attributed to the heat island effect (Brazel et al., 2000). Precipitation is distributed evenly throughout the year and ranges from an annual average of 1,075 mm in Baltimore to 1,040 mm in the surrounding metropolitan area (Levin and Griffin, 1998). The Baltimore metropolitan region is classified by the Natural Resource Conservation Service (NRCS) as having udic moisture and thermic/mesic temperature soil regimes, respectively (Table 1).

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. 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. The sites included in this study occur on the Piedmont Plateau physiographic province. 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 (Levin and Griffin, 1998). The dominant Piedmont soils in the Baltimore area consist of Ultic Hapludalfs. Highly disturbed soils make up greater than 60% of the land area of the city (Pouyat et al., 2002). The Baltimore metropolitan region is classified by NRCS as having soils primarily in the Ultisol order (Table 1). The dominant forest tree species in the REM and REF plots sampled for this study include white oak (*Quercus alba*), red oak (*Quercus rubra*), and tulip poplar (*Liriodendron tulipifera*).

Budapest, Hungary

Budapest is a city of 1,728,000 in population (2010). The Budapest metropolitan area is divided by the Danube River, which separates the two major parts of the city, Buda and Pest. The Budapest metropolitan area has hot, dry summers and cold winters with average annual air temperature of 11.3°C. Precipitation is distributed unevenly throughout the year and ranges from an annual average of 29 mm in winter to 63 mm late spring and early

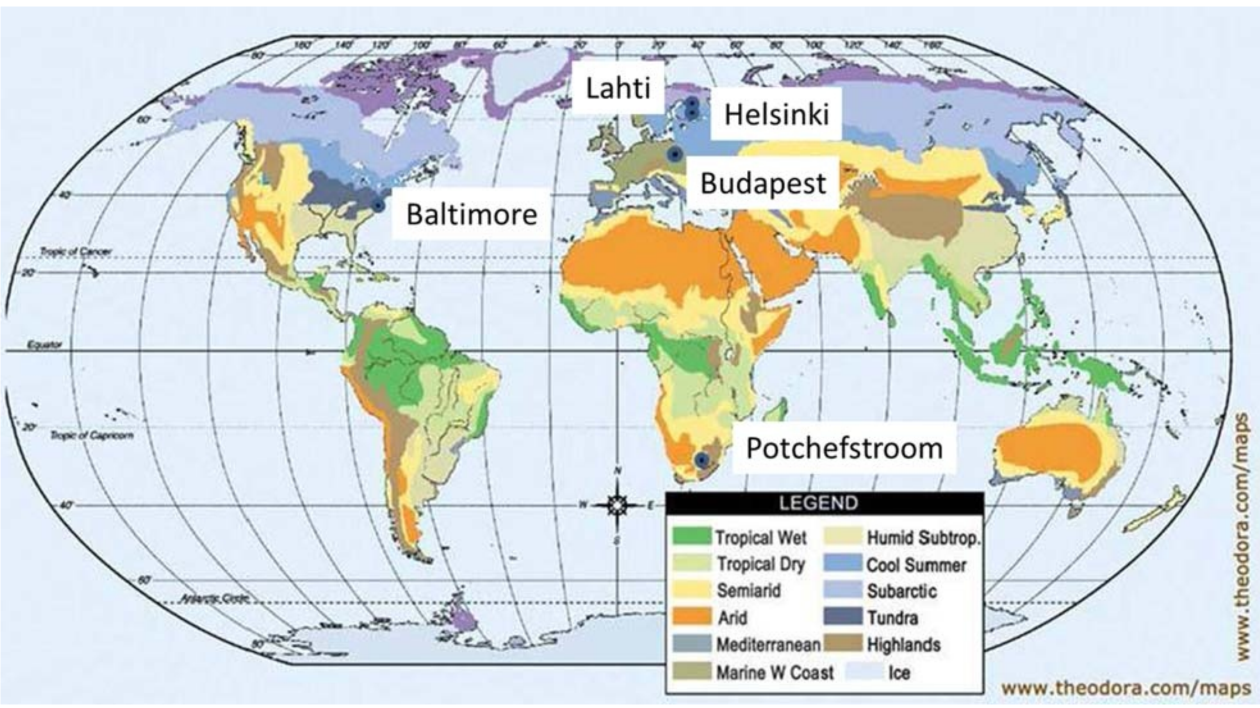

FIG. 1. Map of global climatic zones with locations of cities included in this study: Baltimore, Budapest, Helsinki, Lahti, and Potchefstroom.

summer for a total of 533 mm for a typical year (http://www.met.hu/; verified April 12, 2015).

Buda and Pest roughly coincide with the two major geological formations in the region. The area included in this study is in the urbanized area of the Buda Hills. The Buda Hills are underlain by Karst topography and loess. The Karst topography is made up of primarily limestone and dolomite and occupies approximately 40% of the land area, whereas loess occupies most of the remainder of the Buda Hills area, respectively.

The REF sites were situated in the Buda Landscape-Protection Area, which covers more than 10,000 hectares of rolling hills. The REF and REM plots were located on dry oak forest dominated by Turkey oak (*Quercus petraea*) and Sessile oak (*Quercus cerris*). The protected area surrounds Budapest from the northwest and at many points stretches into the city. The primary surface rock type is mid-Triassic dolomite, which is the oldest rock type in the Buda mountain range. Soils of the REM and REF sites are classified to the Rendzina type, which is a dark, grayish brown, intrazonal soil that has developed on carbonate rock types (e.g., dolomite, limestone, marl, or chalk). The Budapest metropolitan region is classified by the NRCS as having soils primarily in the Alfisol order (Table 1), whereas the World Soil Reference Base system classifies it as a Leptosol (Barta et al., 2009).

Helsinki And Lahti, Finland

The Helsinki region consists of a population size of approximately 1.4 million people, whereas Lahti has a population size of roughly 102,000. The mean annual temperature and average precipitation for Helsinki is 5.3°C and 682 mm, and for Lahti, 4.5°C and 636 mm, respectively. In southern Finland, winter lasts for 135 to 145 days, summer for 110 to 120 days, and temperature can vary between −35 and +35°C within a year (Finnish Meteorological Institute, http://en.ilmatieteenlaitos.fi/; verified March 12, 2015). The Helsinki and Lahti metropolitan regions are classified by NRCS as having udic moisture and mesic/cryic temperature soil regimes, respectively (Table 1).

The bedrock in Helsinki consists of microcline granite, and soil of the sites selected consists primarily of homogeneous clay and silt stratification. In Lahti, the bedrock is characterized by mica schist and mica gneiss as well as microcline granite. Soil of the Lahti sites is mostly gravel and sand till. The Salpausselkä esker, which is a terminal moraine formed in the latest ice age during the Younger Dryas era 12,000 BP, typifies the landscape in the southern part of Lahti. The Helsinki and Lahti metropolitan regions are classified by NRCS as having soils of primarily the Spodosol order (Table 1).

The REF and REM sites in both cities were Norway spruce (*Picea abies*)–dominated forest patches (Cajander, 1926), and the ground cover vegetation consisted primarily of European blueberry (*Vaccinium myrtillus*) and other succulent herbs. Canopy cover was roughly 80% or higher, and trees were at least 80 years old. Humus depth varied from 5 to 10 cm with a typical albic horizon (bleached layer below the humus layer), especially in the REF forests. In some REM forests, earthworm activity had broken the typical clear separation of the organic and mineral soil layers.

Potchefstroom, South Africa

The city of Potchefstroom in the North West Province of South Africa covers a 55-km^2 area with a population of approximately 250,000. The city is located at an altitude of 1,350 m and has a mean annual rainfall of 600 mm mainly during summer months (October to March), with average temperatures ranging between 0°C and 30°C and frequent frost in winter (www.weathersa.co.za; verified April 15, 2015). The geology is mainly quartzite, shale, and prominent volcanic elements, as well as diabase intrusions into the shale (SACS, 1980). The REF and REM sites were situated in the Rand Highveld Grassland (RHG), an endangered vegetation unit in the grassland biome of South Africa (Mucina and Rutherford, 2006). The RHG is situated on undulating plains with red or yellow, dystrophic and/or mesotrophic soil types and on rocky ridges with shallow soils (Mucina and Rutherford, 2006; Soil Classification Work Group, 1991). Nearly 50% of the RHG has been transformed by agriculture and urbanization, and only 1% is actively being conserved (Mucina and Rutherford, 2006), none of which is officially conserved as part of urban green infrastructure (van der Walt et al., 2015a). Plant functional homogenization of this vegetation type is described by van der Walt et al. (2015a) for urban areas, but van der Walt et al. (2015b) also indicated the importance of conserving these REM urban grasslands and their management processes, such as mowing to ensure self-sustaining landscapes in terms of fine-scale biophysical soil properties and processes through decomposition of litter from the remaining grass cuttings.

Soil Sampling And Analysis

A workshop was held May 2014 in Lahti to enable members of each team to discuss and confirm the consistency of their selection of sites across cities. Twenty sites per city (five replicates for each of the four soil habitat type) were identified and cross verified using photographs by sampling teams in each biome. The sites were at least 100 m apart, and plots were situated to represent the soil habitat type based on surface inspection. One rectangular plot with dimensions of 1.5 × 2 m was established per replicate site. At each plot, eight to 10 soil samples were systematically collected along the plot boundaries. Samples were collected to a depth of 10 cm using a 2.0- or 2.5-cm-diameter corer. Surface O horizons were not included in the individual cores. The eight to 10 cores were mixed and composited within the same plastic bag, then refrigerated and sent to one laboratory for analysis (see below). For the Baltimore, Budapest, and Potchefstroom samples, there was little if any Oi or Oe horizons visible in soils found in the REF or REM plots. For cities located in Finland, where Spodosols are the native soil type, there was a relatively thick Oa layer (0–10 cm) overlying a nutrient- and OC-deficient eluvial albic horizon in the REF and REM soils, and thus, it was necessary to deviate from the original protocol and include the Oa layer in each composite sample for these plots.

Soil Physical And Chemical Analyses

Soil chemical analyses were carried out in the laboratory of the Research Institute for Soil Sciences and Agricultural Chemistry of the Hungarian Academy of Sciences (Budapest) to avoid biases that may occur using different laboratory practices. After thorough mixing of individual bagged samples, each sample was air dried prior to physical and chemical analysis according to pretreatment standards (ISO 11464, 2006). Soil pH was measured in 1:2.5 soil:water suspensions for 12 h after mixing (EPA SW-846, Method 9040). Organic carbon concentration was determined by the standard ignition method (ASTM D2974-14). Total nitrogen was measured using a modified Kjeldahl method (ISO 11261, 1995). Plant-available P_2O_5 (P) and K_2O_2 (K) concentrations were extracted using AL (ammonium-lactate) (ISO 22036, 2008) and measured using inductively coupled plasma-atomic emission spectrometry (ICP-OES JY Ultima 2).

Statistical Analyses

To address the stated objectives of this study, we used a principal component analysis (PCA) as an exploratory and data reduction technique for data collected across all cities and canonical discriminant analysis (CDA) to discriminate among cities or soil habitat types, to determine what set of variables best predicted group (city or soil habitat type) membership, and to visualize the data by condensing the multiple soil variables onto one or more axes; and a univariate statistical analysis, or analysis of variance (ANOVA), to test whether soil characteristics differed within cities by soil habitat types. The advantage of a multivariate approach in the cross city analysis 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).

First, means for individual soil characteristics were subjected to one-way ANOVA to test for differences among soil habitat types within a city (SAS Institute, 2003). Data (OC, K, P, and N) were log_{10} transformed to stabilize the variance of individual properties where necessary (Table 2). A Fisher least-significant-difference test was used to determine significant differences between means. Coefficient of variation (CV) was determined for each variable by soil habitat type. The CV is a useful statistical measure for comparisons of soil variables with widely different means since the variation is normalized by the mean.

Second, the soil characteristic data for all cities were submitted to a PCA factoring in a correlation matrix using the SAS package (SAS Institute, version 8.0, 2003). Principal component analysis can take several soil properties and express them in terms of a few common components (Pielou, 1984). The first principal component (PC1) explains the maximum possible variance of the data set, the second component (PC2) explains the maximum variance subject to being uncorrelated with PC1, the third component (PC3) explains the maximum variance subject to being uncorrelated with PC1 and PC2, and so on (Usher, 1976). We used a scree plot along with the eigenvalues to determine the number of principal components that were kept.

Finally, a CDA was conducted using the Proc CANDISC procedure with a correlation matrix (SAS institute, 2003), which first tests whether the cities or soil habitat types differ, on average, in soil characteristics using a parametric multivariate analysis of variance (MANOVA), and then a second test uses canonical correlation analysis to determine the successive functions and canonical roots that best discriminate between a set of class variables (city or soil habitat type) and allows the visualization of the discriminate functions by plotting the discriminate scores of the individual plots.

For both the PCA and CDA, we used five soil variables (pH, TN, OC, and available P and K). The inclusion of soil variables with different units of measurement and variation warranted the use of a correlation matrix in both the PCA and CDA (Jolliffe, 2002).

RESULTS

Differences In Soil Habitat Types Within A City

In general, Potchefstroom had the most nutrient-poor soils in REF and REM sites, whereas in the other cities the RUD soil types tended to be the most nutrient poor (Table 2). In all cities, except Potchefstroom, OC and TN were highest in the REF and REM types with up to a 7-fold difference occurring between the REF and RUD soil habitat types in Helsinki and Lahti. For all these cities, the REF ranked higher than the REM sites for OC, except Budapest, which had the highest OC in the REM soil habitat type, a 5-fold difference. By contrast to the other cities, Potchefstroom had a roughly 2-fold greater OC in the TUR than in the other soil habitat types. In addition, soil pH in Baltimore, Budapest, and the Finnish cities had significantly higher pH in the TUR and RUD than in the REF and REM soil habitat types (a low of 4.2 and a high of 7.5 in Helsinki and Budapest, respectively), whereas Potchefstroom urban soil types exhibited higher pH than the REF types, which were not statistically significant.

TABLE 2. Chemical Properties of Surface (0–10 cm) Soil in Five Cities and Four Soil Habitat Types

Cities	Habitat Types	pH (H_2O)	Organic C (g 100 g^{-1})	Total N (g 100 g^{-1})	K_2O_2 (mg kg^{-1})	P_2O_5 (mg kg^{-1})
Baltimore	REF	5.05 (0.9) a	2.91 (0.4) b	0.17 (0.1) ab	123.31 (53.8) a	28.28 (6.7) a
	REM	5.31 (0.7) a	2.74 (0.6) b	0.19 (0) b	126.79 (86.2) a	43.36 (11.2) a
	TUR	6.35 (0.7) b	2.4 (0.7) ab	0.18 (0.1) ab	141.85 (31.9) a	149.07 (99.3) a
	RUD	7.04 (0.5) b	1.59 (0.7) a	0.12 (0) a	99.53 (33.7) a	128.84 (166.8) a
Budapest	REF	6.44 (1.3) a	8.41 (4.8) b	0.71 (0.3) b	229.25 (59.2) a	156.43 (110.4) a
	REM	7.04 (0.3) ab	10.26 (5.6) b	0.75 (0.4) b	286.81 (46.7) a	180.89 (265.9) a
	TUR	7.54 (0.2) b	2.54 (1.6) a	0.26 (0.2) a	308.64 (92.7) a	152.95 (123) a
	RUD	7.54 (0.2) b	2.3 (1.1) a	0.23 (0.1) a	287.1 (85.6) a	145.36 (122.4) a
Helsinki	REF	4.21 (0.2) a	28.65 (7.5) b	1.29 (0.4) b	433.69 (193.1) a	219.65 (76.4) ab
	REM	4.39 (0.4) a	20.23 (10.6) b	0.91 (0.5) b	332.23 (172.7) a	191.37 (63.2) a
	TUR	6.02 (0.3) b	4.87 (0.7) a	0.37 (0.1) a	290.71 (97.7) a	562.52 (387.5) b
	RUD	6.8 (0.5) c	2.13 (1.7) a	0.15 (0.1) a	276.11 (342.3) a	394.43 (343.1) ab
Lahti	REF	4.37 (0.5) a	13.14 (9) b	0.67 (0.3) c	245.13 (135.2) a	174.09 (125.2) a
	REM	4.91 (0.4) a	7.68 (2.8) ab	0.46 (0.1) bc	345.39 (186) a	99.91 (56.8) a
	TUR	5.83 (0.6) b	4.84 (3.4) a	0.31 (0.1) ab	258.21 (115.4) a	295.59 (350.6) a
	RUD	6.05 (0.4) b	2.97 (2.7) a	0.18 (0.1) a	225.3 (176.4) a	120.61 (60.1) a
Potchefstroom	REF	6.16 (0.4) a	2.42 (0.7) a	0.2 (0.1) a	357.21 (135.6) a	108.53 (160.3) a
	REM	6.7 (0.6) a	2.38 (0.8) a	0.21 (0.1) a	554.84 (76.3) ab	109.93 (74.6) a
	TUR	6.57 (0.5) a	5.57 (2) b	0.44 (0.2) b	867.64 (258.8) bc	657.15 (533.3) b
	RUD	6.68 (0.2) a	2.73 (0.3) a	0.25 (0) a	678.68 (292.6) c	358.55 (269.4) ab

Mean values (SD) of five replicate plots are shown. Data were transformed to stabilize the variance of individual properties where necessary using log_{10} transformation. Values followed by the same letter per chemical property per city were not significantly different at the 5% level.

In all cities, except Budapest, P concentrations were up to 3-fold greater in the TUR than in the other soil habitat types (Table 2). The lowest P concentrations by soil habitat type varied depending on the city, with three cities (Helsinki, Lahti, Potchefstroom) having the lowest P in the REM type and with Baltimore having by far the lowest concentrations in both the REF and REM soil habitat types (28.8 g kg^{-1}). Similar to P, K in three of the five cities (Helsinki, Lahti, Potchefstroom) had the highest concentration in the TUR type (up to 433.7 g kg^{-1} in Helsinki), whereas three cities (Baltimore, Helsinki, Lahti) exhibited the lowest concentrations in the RUD type (low of 99.5 g kg^{-1} in Baltimore).

Differences In Soil Habitat Types Among Cities

Comparison Of CV Across Soil Habitat Types

Three (pH, OC, TN) of the five soil variables measured showed a convergence as depicted by their CV, which was lower in the more disturbed soil habitat types, that is, the RUD and TUR, or those soils most affected by anthropogenic disturbance and inferred management (Fig. 2A). Both OC and TN showed the greatest convergence with CVs of roughly 75% to 95% in the REF and REM soil habitat types to approximately 25% in the TUR and RUD types. Soil pH, which is reported on a logarithmic scale, showed by far the least variation (CV of ≤20%) among all soil variables measured (Fig. 2), but also decreased toward the more disturbed and managed soils. By contrast, CVs for P and K actually slightly increased (40%–50% to 60%–75%) or "diverged" in the more disturbed soil habitat types (TUR and RUD) compared with the types representing native soil (REF and REM).

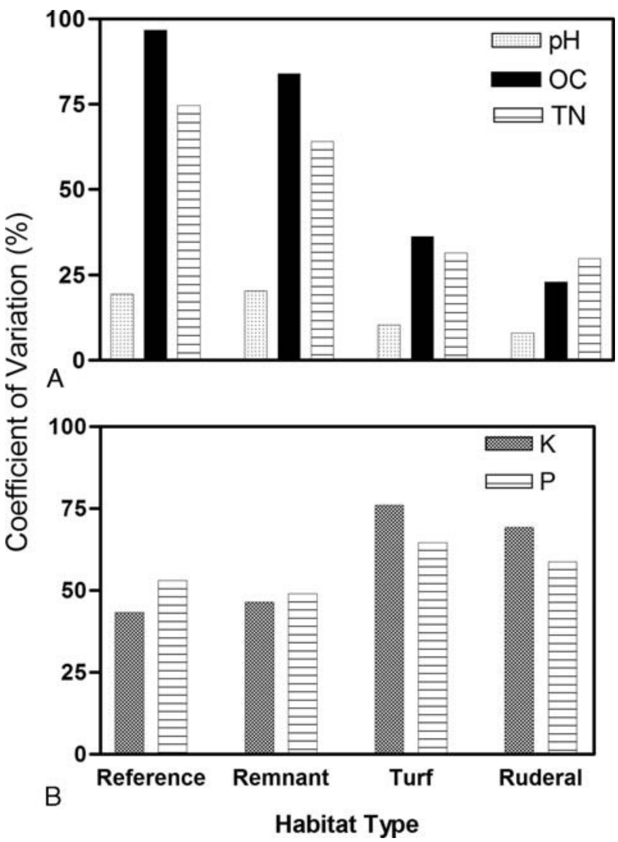

FIG. 2. The average percent CV by soil habitat type for soil characteristics exhibiting (A) convergence (OC, TN, and pH) and (B) divergence (K, P) across the five cities.

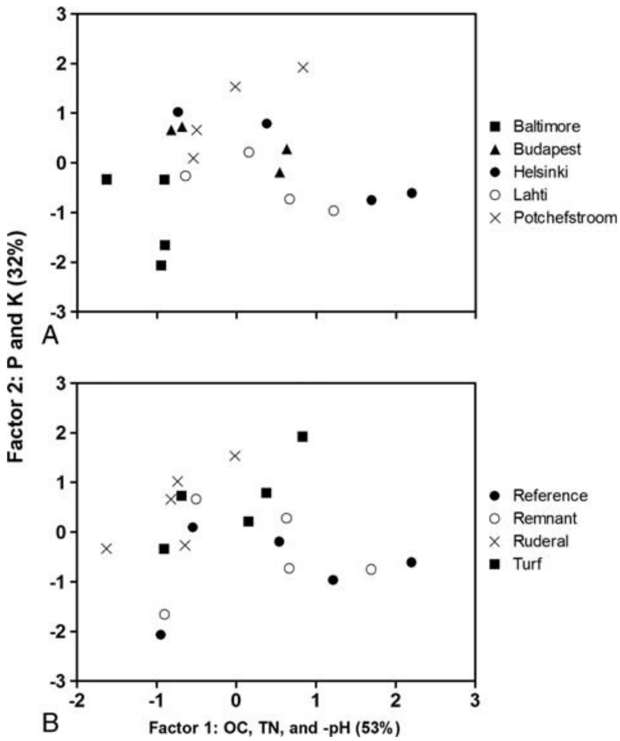

FIG. 3. Scatterplot of first (PC1) and second (PC2) principal components for the pooled data using (A) cities (Baltimore, Budapest, Helsinki, Lahti, and Potchefstroom) and (B) soil habitat types as symbols.

Comparison Across Cities: PCA

A clear relationship was discernible in the PCA for the five cities and four soil habitat types (Figs. 3A, B). Overall, 85% of the variation was explained by the first two components of the PCA, with PC1 accounting for 53% of the variation and PC2 32%. Positive loadings of PC1 corresponded to OC and TN and negative loadings to pH, whereas positive loadings of PC2 corresponded to P and K. Inspection of the scatterplot for the first two components (PC1 and PC2) with symbols representing each city showed a clustering of Baltimore sites to the left and below the origin (negative loadings of PC1 or lower concentrations of OC and TN and higher pH), whereas the other cities clustered to the right and above the origin (positive loadings or higher OC, TN, P, and K and lower pH) (Fig. 3A). We interpret the relationship of the city sites along both axes to local factors such as parent material, climate, or some other factor unique to the location of the city.

By contrast, inspection of the scatterplot representing each soil habitat type shows the relationship of habitat types more dominated by anthropogenic factors (RUD, TUR) versus habitat types less influenced by human activities (REM, REF). The RUD and TUR sites form a relatively tight cluster to the left and above the origin (higher OC, TN, and pH), whereas the REM and REF sites are dispersed widely across the scatterplot (Fig. 3B). We interpret the relationship of soil habitat types along both axes to anthropogenic factors such as management and disturbance. Moreover, the wide distribution of the REM and REF sites relative to the RUD and TUR sites (Fig. 3B) and the apparent clustering of cities (comparing Figs. 3A and B) around RUD and TUR sites appear to support our hypothesis that for this global comparison of cities native soils differ more than soil types effected by anthropogenic factors.

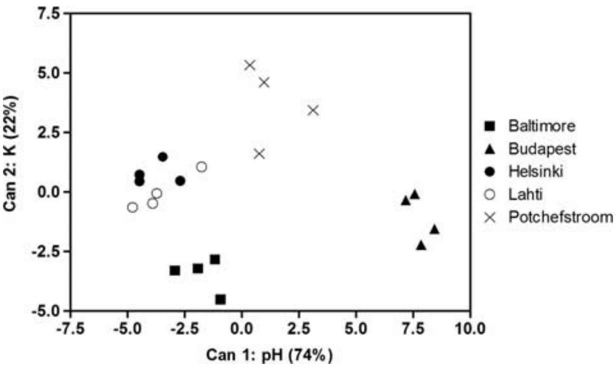

FIG. 4. Scatterplot of first and second canonical variates (Can) of a CDA procedure using five soil variables to discriminate plots by city (Baltimore, Budapest, Helsinki, Lahti, and Potchefstroom). The first canonical variate was correlated to pH (74% of variation) and the second to K (22% of variation).

Comparison Across Cities: CDA

The five cities were significantly differentiated by the five soil variables used in the CDA (MANOVA, $P < 0.001$). The CDA showed that the first (CAN1) and second (CAN2) canonical variates accounted for 74% and 22% of the variation, respectively, for a total of 96%—a very high percentage. Positive coefficients for CAN1 were related to high pH (Fig. 4). CAN1 largely separated Budapest, and to a lesser degree Potchefstroom, from the other cities, with the Budapest sites corresponding to positive coefficient values or higher pH values. CAN2 was related to K and appeared to separate Potchefstroom (high concentrations) and Baltimore (low concentrations) from the Finnish cities and Budapest (intermediate concentrations). As with the PCA showing symbols of city sites, we interpret the distribution of cities along the CAN1 and CAN2 axes to local factors, which in this case is most likely due to parent material (a native soil-forming factor) and its effect on pH.

Comparison Across Soil Habitat Types: CDA

The four soil habitat types were significantly differentiated in the CDA (MANOVA, $P < 0.0183$). The CDA showed that CAN1 and CAN2 accounted for 89% and 10% of the variation, respectively, for a total of 99%—as with the city CDA—a very high percentage. Positive coefficients for CAN1 were related to high pH and P and low OC and TN (Fig. 5). CAN1 largely separated the REF and REM sites from the RUD and TUR sites, with the RUD and TUR sites corresponding to positive coefficient values, or higher pH and P, and lower OC and TN. CAN2 explained only 10% of the variation and appeared to be heavily influenced by a TUR site that had very high P concentrations. We interpret the distribution of soil habitat types along the CAN1 axis to anthropogenic factors such as disturbance and management, which are reflected in the RUD and TUR sites, respectively. Moreover, three characteristics that were largely associated with CAN1—OC, TN, and pH—also exhibited a convergence in the CV plots (Fig. 2).

DISCUSSION

The overall objective of this study was to compare, as a proof of concept, surface soil characteristics of moderately managed TUR, highly disturbed or RUD soils, REM or undisturbed parcels, and a REF or native soil habitat type within and among five metropolitan areas. At a global scale, we expected soil characteristics to differentially converge across the cities by urban soil habitat type, with those cities situated in biomes with more limiting climatic conditions (Helsinki and Lahti in Finland and Potchefstroom in South Africa; Table 1) exhibiting the most convergence, while at the same time revealing the greatest dissimilarity among soil habitat types within the city's metropolitan area. Moreover, we expected soil characteristics that are strongly influenced by climatic factors (OC and TN) to exhibit the greatest differences.

Comparisons Within Cities

Cities with the most limiting environments for biological activity are the Finnish cities located in the boreal-hemiboreal and Potchefstroom in the semiarid biomes, respectively (Table 1). Therefore, we expected to observe the greatest dissimilarities among soil habitat types for OC and TN in these cities, which was the case for Helsinki and Lahti but not Potchefstroom (Table 2). In fact, in the PCA scatterplot using symbols for individual cities, the Finnish cities exhibited the widest spread of points on the PC1 axis, which was correlated with OC and TN (Fig. 3A).

Unexpectedly, however, Potchefstroom had the greatest differences among soil habitat types for K and P concentrations, primarily due to the TUR and to a lesser degree RUD sites, which had up to 5-fold higher concentrations relative to the other soil habitat types in that city's metropolitan area (Table 2). Both K and P are commonly included in TUR fertilizer supplements, which could explain these differences; however, it is not clear if the higher concentrations in the TUR and RUD sites can be attributed to fertilizer additions, which were not measured, or to a local factor such as parent material (diabase intrusions) in the Potchefstroom metropolitan area.

Soil pH is affected by several soil-forming factors including parent material, soil age, climate, and plant-soil interactions, but also anthropogenic factors such as additions of lime, nitrogen fertilizer (Barak et al., 1997), and calcium associated with urban environments (Pouyat et al., 2007a). Therefore, both anthropogenic and native soil-forming factors may be influencing soil pH levels across the cities and soil habitat types included in this study. The fact that for four of the five cities pH was significantly higher in the soil habitat types dominated by anthropogenic factors (TUR and RUD) versus native soil-forming factors (REF and REM) suggests pH is at least partly an urban effect (Table 2). Potchefstroom had a similar trend, but it was not statistically significant. These results suggest that urban environments have a significant impact on soil pH even when local factors such as parent material rich in calcium carbonate are present, for example, the Rendzina soils in Budapest. Several studies have shown that urban soils, especially

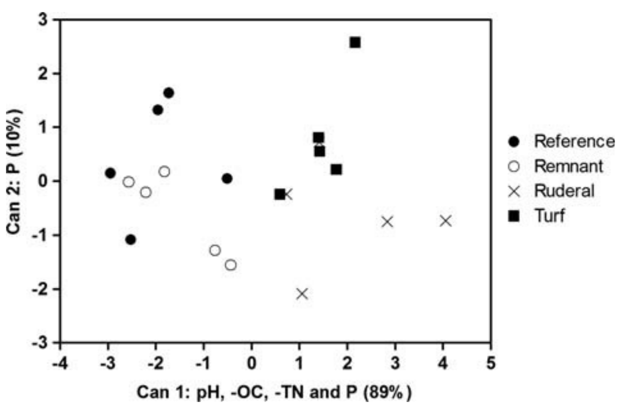

FIG. 5. Scatterplot of first and second canonical variates (Can) of a CDA procedure using five soil variables to discriminate plots by soil habitat type. The first canonical variate was correlated to pH, −OC, −TN, and P (89% of variation) and the second to P (10% of variation).

those disturbed or heavily managed, are typically high in pH (e.g., see Craul and Klein, 1980; Jim, 1993; Hagan et al., 2012; Kuoppamäki et al., 2014), which in turn has been associated with materials used in infrastructure and buildings that are high in calcium, such as concrete (Pouyat et al., 2007a).

Comparisons Among Cities

In the global comparison of cities, we expected the soil characteristics most associated with biogenic factors (OC and TN) to exhibit the greatest convergence among biomes, whereas P and K would not converge. Furthermore, soil pH can be affected by both biogenic and physicochemical factors, and thus, it was unclear how this measure would compare across biomes and soil habitat types. Inspection of the CV for each soil variable suggests two types of responses: those soil characteristics that converged, or became more similar in the soil habitat types dominated by anthropogenic factors, and those characteristics that actually "diverged" became less similar (Fig. 2). In the first case, as expected, OC and TN converged, whereas in the second case K and P actually diverged or exhibited greater differences in the soil habitat types influenced by anthropogenic factors. Moreover, pH showed a similar but smaller convergence than OC and TN (Fig. 2A). The relationships in the CV for OC, TN, and pH across all soil habitat types were supported by the PCA. In particular, the PC1 (OC, N, −pH) and PC2 (K and P) scatterplot shows that REM and REF soil habitat types exhibited a much wider spread in sites than the RUD and TUR sites (Fig. 3B).

These results suggest that anthropogenic factors have a strong impact on soil characteristics associated with biogenic processes, with convergence being the net result. In the cities Helsinki and Lahti, located in a biome with soils high in OC and TN (REF, REM), there is a large net loss of C and N in soil types dominated by anthropogenic factors (RUD, TUR). In Baltimore and Budapest, a similar and significant relationship occurred; however, the difference between native (REF) and anthropogenic (RUD, TUR) soil types was orders of magnitude less than in the cities in the boreal biome (Table 2). By contrast, in Potchefstroom, the TUR soil type had higher OC and TN than in the REF soil type, which for the semiarid biome was expected because native soils in these regions have inherently low OC and TN concentrations (Mucina and Rutherford, 2006).

Given the limitations of this study design, we can only speculate as to why a strong convergence occurred in the Finnish cities and relatively weak or lack of convergence demonstrated in the other cities for OC and TN. First, the inclusion of a very thick Oa horizon in the samples taken in Helsinki and Lahti REF and REM sites would partially explain this result. Second, it is apparent that soil disturbance, especially the magnitude necessary for a RUD soil to form, results in a major loss of carbon and nitrogen from soils (Table 2, Fig. 5). Consequently, soils having naturally high OC and TN have more to lose and thus exhibit the greatest differences between REF and RUD soil habitat types. For example, Pouyat et al. (2007b) using topographic changes reported by McGuire (2004) calculated that up to 10 kg C m^{-2} to a 1-m depth (or, 2.7×10^4 kg C for the entire 2,600-m^2 construction site) is potentially disturbed or removed as top soil in the construction of a housing development in the metropolitan area of Baltimore. This compared with highly disturbed areas in the region having soil carbon densities as low as 1.5 kg C m^{-2} to a 1-m depth (Pouyat et al., 2010). Moreover, many studies have measured the loss of C from soil as a result of anthropogenic disturbance such as in the cultivation of agricultural soils (reviewed by Lal, 2010). The mechanism for losses of C and presumably N from soil disturbance is due to the destruction of soil structure and the subsequent loss of protected OC from the predisturbed native soil (Elliott, 1986). On the other hand, any anthropogenic factor (e.g., fertilization, irrigation, or atmospheric deposition of nitrogen) that disproportionately increases NPP to the rate of decomposition is likely to result in an increase in OC and TN (e.g., see Hope et al., 2005, Zhu et al., 2006), which in part may have caused higher OC and TN in the TUR than in the RUD soil habitat types found for all the cities (Table 2).

The divergence in K and P was unexpected. Our expectation was that soil properties affected strongly by local factors such as parent material would interact with anthropogenic factors, which in a global comparison of urban and native soil habitat types would increase the complexity of the resulting patterns. Nevertheless, both K and P are included in many TUR fertilizers and thus could, especially for P, build up in the TUR soil habitat types (Bennett et al., 2004; Yesilonis et al., in press). Under these circumstances, a convergence would be expected, if the management effect was uniform across all parcels within a soil habitat type. Nonetheless, our results suggest a divergence in K and P, which is best explained by a nonuniform effect of an anthropogenic factor occurring within a soil habitat type. For example, studies have shown that the addition of water or fertilizer to TUR systems can vary significantly from one parcel to another within a metropolitan area (Law et al., 2004; Hope et al., 2005; Polsky et al., 2014).

Not all variables were disproportionately affected by anthropogenic factors. For example, soil pH weighted most strongly in discriminating cities by biome. In particular, Budapest and Potchefstroom were separated from the other cities on the CAN1 axis (pH), whereas the CAN2 axis (K concentrations) discriminated Baltimore, Potchefstroom, and the Finnish cities (Fig. 4). The resultant scatterplot shows a tight clustering of sites by city, suggesting that local or native soil-forming factors, such as parent material, have a significant effect on soil pH and K (Fig. 4). By contrast, CAN1 (pH, OC, and TN) discriminated native soils from anthropogenic soils in the comparison of soil habitat types, suggesting an anthropogenic or urban effect (Fig. 5).

CONCLUSIONS

The methods and study design reported in this article are part of a "proof of concept" for comparing soil abiotic and biotic characteristics in the GLUSEEN network. The comparison of soils among and within five cities across four distinct biomes suggests that anthropogenic, and to a lesser degree native, soil-forming factors interact and have a significant effect on soils found in urban landscapes. Specifically, soil characteristics (OC and TN) closely associated with biogenic processes and at the same time highly effected by management exhibited a convergence across soil habitat types, whereas characteristics (K and P) closely associated with local pedogenic factors, such as parent material, did not converge but actually diverged across all soil habitat types. The convergence of OC and TN and the divergence of K and P are best explained as a management effect occurring within a soil habitat type and city. For OC and TN, management appears to be more uniform within soil habitat types than for K and P. In comparison, soil pH was a result of the interaction of both anthropogenic (e.g., calcium carbonate from building materials) and native soil factors, such as differences in parent material across biomes.

These results partially support the urban ecosystem convergence hypothesis in that a convergence occurred for soil characteristics that are dominated by anthropogenic factors, which included characteristics limited by climate (OC, TN) and to a lesser degree parent material (pH). By contrast, the divergence of K and P suggests a revision of the hypothesis is warranted. Specifically, the hypothesis should account for variations that may occur in management within soil types in a metropolitan area; that is, the anthropogenic factor is not uniform and will vary depending on the soil characteristic being compared. In addition, the typology of soil habitat types categorized from a matrix of management and disturbance appeared to work well in conducting multiple scale comparisons of urban soil properties. In particular, having an REF and REM soil to compare against soil habitat types dominated by anthropogenic or urban factors made it possible to assess urban land use changes on soil characteristics at local and global scales. Moreover, the matrix of six soil habitat types provided the flexibility to create a sampling design (for this study, we used four of the six options) across a diversity of urbanized landscapes that exists in a worldwide network such as GLUSEEN.

ACKNOWLEDGMENTS

The authors thank M. Bernard, A. Dec, E. Draskovits, S. Mishra, S. Molnar, E. Powell, and Z. Toth for their efforts in support of this study. C. O'Dea, W. Zipperer, and two anonymous reviewers made helpful comments to the manuscript.

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