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RESEARCH ARTICLE

Heterogeneity in soil chemistry relates to urbanization while soil homogeneity relates to plant invasion in small temperate deciduous forests

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Abstract
Context Soil heterogeneity versus homogeneity patterns are observed within and across urban landscapes at multiple scales. To fully evaluate human-mediated influences on soil properties and processes, we need to understand spatial patterns and variation in soil characteristics within a single ecosystem patch type (e.g., forests) in and near cities.
Objectives Our research objectives were to: (1) identify soil characteristics important in driving variation in soil chemistry *within* urban forests, and (2) examine whether urbanization and invasion gradients were related to variation in soil chemistry *within* these forests.
Methods We measured soil chemical properties within 36 forests across the U.S. mid-Atlantic. The forests are spatially distributed across an urbanization gradient and comprise a gradient of non-native plant invasion.
Results Urbanization was related to more variation in soil chemistry, whereas plant invasion was related to less variation in soil chemistry *within* our forests. Soil Ca and Mg concentrations increase with plant invasion yet are less variable *within* invaded forests most likely due to invasive plants taking up and concentrating these elements. Soil pH, Ca, Mg, Zn, and Cu increase in forests surrounded by greater urbanization, however, these elements are more variable *within* urban forests likely due to edge effects altering element deposition.
Conclusions Our results demonstrate that while urbanization and invasion can increase soil chemical concentrations, they differentially alter variation in soil chemistry *within* urban forests. Plant invasion and urban environmental conditions need separate consideration in future conceptual models of urban ecological theory since non-native invasive plants influence soil chemistry independent of other urban factors.

Keywords Plant invasion · Soil heterogeneity · Soil homogeneity · Temperate deciduous forest · Urban forests · Urban soils

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Introduction

Humans have altered the environment at local, regional, and global scales, and this is especially apparent within and across urban environments (Pouyat et al. 2015, 2017). Ecological understanding of patterns and processes in, of, and for cities is important for creating healthy, resilient cities (Grimm et al. 2000; Childers et al. 2015). The concept of ecological convergence (Pouyat et al. 2003) has been applied to plant composition (Wheeler et al. 2017; Pearse et al. 2018) and soils (Pouyat et al. 2015; Herrmann et al. 2020; Trammell et al. 2020a) as well as microclimate (Hall et al. 2016) in urban ecosystems to explain how human preferences, behaviors, site disturbance, and management (Polsky et al. 2014) drive similarity or homogeneity in ecosystem structure and function at continental and global scales. Research on soil chemistry in residential yards (e.g., Raciti et al. 2011; Yesilonis et al. 2016), remnant and rejuvenated forests (e.g., Pouyat et al. 1995; Trammell et al. 2021), and urban parks (e.g., Setälä et al. 2016) advanced understanding of how land-use legacies, management, and shifts in plant communities influence spatial and temporal complexity in soil chemistry at local to regional scales. Focusing research on patch-scale patterns in soil heterogeneity (i.e., greater variation) versus homogeneity (i.e., less variation) and the potential drivers of soil variation will further our understanding of how anthropogenic versus natural factors influence soil properties and processes in urban landscapes.

Soil physical, chemical, and biological properties are influenced by human activities associated with urbanization. Altered abiotic environmental conditions, such as the urban heat island (e.g., Oke 1973; Bonan 2002), elevated nutrient and metal deposition (e.g., Lovett et al. 2000; Rao et al. 2014; Decina et al. 2019), and greater atmospheric carbon dioxide (CO_2) concentrations (e.g., Idso et al. 1998, 2001), differentially influence soil properties due to interactions, site legacies, or human management. For instance, elevated atmospheric CO_2 concentrations have the potential to enhance primary production (Ziska et al. 2003; Smith et al. 2019) and increase subsequent organic matter inputs to soil and soil carbon (C) sequestration (Trammell et al. 2017a). However, removal of aboveground biomass in turf grass ecosystems (e.g., mowing) reduces OM inputs to soil and overall soil C sequestration (Bandaranayake et al. 2003; Trammell et al. 2017b). Similarly, elevated metal deposition (e.g., transportation) in combination with site legacies effects patterns in soil chemistry in forests embedded within cities (Trammell et al. 2011). Previous research on soil characteristics across cities found spatial patterns in soils based on different ecosystem patch types (i.e., land use and land cover; Boeckx et al. 2006; Pouyat et al. 2007) and based upon management practices within similar ecosystem patches across cities (i.e., turf grass ecosystems; Pouyat et al. 2015). However, to further evaluate human-mediated influences on soil properties and processes, we need to understand spatial patterns and variation in soil characteristics within a single ecosystem patch type within cities (i.e., patch scale).

In addition to abiotic environmental changes in cities, shifts in species composition can influence soil properties and processes, especially invasion by non-native plants and/or soil organisms (e.g., Barrico et al. 2018; Ward et al. 2020). Non-native invasive plants can alter soil pH, calcium and nitrogen concentrations, soil organic matter, and C content as well as shift soil ecosystem processes, such as organic matter decay, nitrogen mineralization, and carbon sequestration (Liao et al. 2008; Ehrenfeld 2010; Trammell et al. 2012, 2021). Similarly, non-native invasive earthworms influence organic matter decay and soil N mineralization rates in urban forests (Pouyat et al. 1997; Zhu and Carreiro 2004; Chang et al. 2016, 2017, 2018). While there is ample evidence of the influence of invasive species on soil properties and processes in invaded compared to uninvaded forests (e.g., Ehrenfeld 2010; Peltzer et al. 2010; Vilá 2011), there is little understanding on how invasive species may drive patterns of soil variation *within* forests. A question remains as to whether invasive plants colonize soils that have altered soil properties or whether invasive plants drive changes in soil biogeochemistry. Research on differences in foliar chemistry and decay rates between invasive and native plant species (Ashton et al. 2005; Trammell et al. 2012) suggests invasive plants alter soil biogeochemistry. Similarly, differences in soil Ca and N concentrations as well as soil N mineralization in soils directly beneath an invasive plant compared to adjacent soil supports the importance of invasive plants in driving soil chemistry patterns (e.g., Kourtev et al. 1999; Leicht-Young et al. 2009). Studying the influence of non-native invasive plants and urban environmental conditions simultaneously on soil characteristics can inform whether invasive plants are more adapted to altered environments (e.g., greater cation concentrations) or whether invasive plants drive changes in soil conditions. Patterns in soil chemistry variation *within* an urban ecosystem patch can help elucidate the significance of invasive plants influencing soil biogeochemistry.

Soil functions, such as nutrient retention and C sequestration, depend on underlying soil physical, biological, and chemical conditions that can vary across urban habitat types (Pouyat et al. 2015) due to urbanization and plant invasion. At the same time, urban soil properties converge within similar landscape patch types (e.g., residential yards) across continental and global scales (Pouyat et al. 2015; Trammell et al. 2020a). While previous research has documented how human activities can drive similarity in soil chemistry between managed versus native ecosystems at coarse spatial scales, more research is needed to identify fine-scale patterns in soil properties within ecosystem patch types in cities. Depending on the scale of observation, urban soils differentially respond to soil forming factors across space and time (Pouyat et al. 2010; Yesilonis et al. 2016). Studying variation in soil properties and drivers of soil heterogeneity or homogeneity within urban ecosystems (i.e., patch scale) can elucidate how anthropogenic drivers influence soil biogeochemistry in urban landscapes.

The overarching goal of this study was to assess soil spatial homogeneity/heterogeneity *within* urban forests in the mid-Atlantic region of the eastern United States. We addressed the following research objectives: (1) to identify soil characteristics important in driving variation in soil chemistry *within* urban forests, and (2) to examine whether urbanization and invasion gradients were related to variation in soil chemistry *within* these forests. We measured soil chemical properties within 36 forests across northern Delaware and southeastern Pennsylvania (i.e., Philadelphia MSA). The forests are spatially distributed across an urbanization gradient (i.e., surrounding % impervious surface area) and a gradient of non-native plant invasion (i.e., total number of invasive plants), yet the abundance of invasive plants has no relationship to surrounding urbanization (Trammell et al. 2020b). Therefore, we utilize our urbanization and invasion gradients to assess relationships between human-derived abiotic and biotic gradients of change with variation in soil properties.

At each sampling location *within* the forests, we measured soil chemical characteristics (e.g., pH, organic matter, nutrient, and metal concentrations) as well as plant (i.e., ground, vertical, and canopy plant cover) and forest (i.e., distance to forest edge and nearest road) structural characteristics. We expect greater soil nutrients (i.e., P, K, S) and metals (i.e., Zn, Cu) closer to the forest canopy edge in our forest sites (Weathers et al. 2001; Trammell et al. 2011). However, we expect greater pH and Ca concentrations at soil sampling locations with greater total non-native invasive plants (Trammell et al. 2021). Based upon previous research that found convergence in urban soil characteristics at continental scales (Herrmann et al. 2020; Trammell et al. 2020a), it is reasonable to expect sites with greater urbanization surrounding the forest patch to have lower *within* site variation in soil chemistry due to widespread deposition inputs of nutrients and metals (Lovett et al. 2000) and/or adjacent management activities (Polsky et al. 2014). Alternatively, complexity in forest patch shape (i.e., edge) and site legacies may contribute to greater variation in forest sites with more surrounding urbanization. Similarly, non-native plant invasion may increase soil variation due to greater non-native plant abundance on forest edges or decrease soil variation since non-native invasive plants have consistently been shown to alter soil biogeochemistry (Liao et al. 2008; Ehrenfeld 2010; Trammell et al. 2012).

Methods

Study area

Our long-term urban forest ecology study, the FRAME (FoRests Among Managed Ecosystems, http://sites.udel.edu/frame/), is in the mid-Atlantic region of the U.S. eastern seaboard. Centuries of deforestation after colonization, followed by afforestation of abandoned post-agricultural land (e.g., Whitney and DeCant 2003; Flinn and Vellend 2005), created a mosaic of forest patches within this megalopolis. Our forest sites traverse an urbanization gradient extending from Newark, DE (population = 31,454 people, density = 1403 people km^{-2}) to Philadelphia, PA (population = 1,526,006 people, density = 4405 people km^{-2}; US Census Bureau 2010) and enable long-term study that addresses questions related a wide range of urbanization impacts across spatial scales. The forests within this mid-Atlantic urban area span Coastal Plain and Piedmont geologic regions.

To randomly select forest sites, we used a Generalized Random Tesselation Stratified (GRTS) design, a method well-suited for long-term monitoring programs in patchy landscapes (Comiskey et al. 2009; Lookingbill et al. 2012). Forests were excluded if owned by private individuals to ensure long-term establishment and study, thus, forests are located on municipal, local, or state park lands as well as University of Delaware property. All forest sites are separated by roads and at least 250 m apart, except for two forests that are 150 m apart yet are separated by a four-lane divided highway. We randomly positioned a 25 m × 25 m grid along the edge of each forest and using a stratified random approach along every other line on the grid. We established ten to fifteen grid points for long-term observation *within* each forest patch.

Urban and plant invasion gradients

The forests in our study span a wide range in urbanization surrounding the forest sites (i.e., 0% to almost 50% impervious surface within 1000-m of the forest edge) as well as high variability in non-native plant invasion within the forests (i.e., 0–279 stems of invasive plants per sampling location). Since we found no statistically significant relationship between urbanization and invasion (Trammell et al. 2020b), we can assess urbanization and plant invasion influences on soil chemistry separately (Trammell et al. 2021). The urbanization gradient is represented by the % impervious surface area within 1000-m surrounding the forest patches. The ISA metric was selected based on a multivariate principal component analysis (PCA) conducted on multiple landscape metrics (e.g., ISA, population density, number of buildings). The metrics associated with urbanization (e.g., high population) correlated strongly and comprised the first principal component (PC1), and ISA was the most important variable driving variation on PC1 (Trammell et al. 2020b). Therefore, ISA serves as our proxy for the urbanization gradient and is comparable among many published studies. The invasion gradient is comprised of the total number of non-native invasive plants within the forest patches (Trammell et al. 2020b). Since forest patch size, forest patch edge:interior ratios, and year since the forest canopy closed relate to our urbanization and invasion gradients (Trammell et al. 2020b, 2021), we analyzed *within* site variation in soil chemistry with these forest characteristics to enhance the interpretation of our findings.

Plant and forest structural characteristics

Six plot-scale plant and forest structural characteristics were measured as possible explanatory variables for the observed patterns in soil chemistry *within* forest sites. To assess urbanization influences on soil chemistry within each forest site, we measured the distance from each sampling location within the forest (n = 10–15) to the forest canopy edge (m) and to the nearest road (m) using Geographic Information Systems (ArcGIS 10.8.1). The vegetation structure (e.g., plant density) was measured at each sampling location to determine the influence of plant structural characteristics and non-native plant invasion on soil chemistry. In each plot, we conducted the following plant measurements: (1) total count of all non-native invasive woody plants with a height ≥ 1 m in a 2.5-m radius circular plot around the sampling location (i.e., non-native stems), (2) total vegetation ground cover at 5% increments within the 2.5-m circular plot (i.e., ground cover), (3) vertical canopy density in four cardinal directions 15-m from the sampling location using a Nudds board (Nudds 1977; i.e., vertical structure), and (4) plant canopy cover using a forest densiometer in four cardinal directions 2.5-m from the sampling location.

Soil sample collection and analyses

Within all forest sites (n = 36 forests), soils were collected at each sampling location (n = 10–15 points) during the peak growing season. Prior to soil collection, loose leaf litter was removed from the soil surface. We collected two pooled soil cores (2-cm diameter) from the top 12–15 cm of mineral soil. Soil samples were analyzed for soil chemical properties important in plant (e.g., growth) and soil (e.g., decay) function. All soil samples were analyzed for pH, soil organic matter (SOM), and elemental concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, S, and Al) at the University of Delaware Soil Testing Lab (https://www.udel.edu/academics/colleges/canr/cooperative-extension/environmental-stewardship/soil-testing/). A 1:1 soil (15 g) to deionized water (15 ml) solution was mixed for 30 min to measure soil pH. SOM was analyzed using the loss-on-ignition method (500 °C for

6 h). The Mehlich-III extraction method was used to extract soil elements and analyzed on an ICP-OES (Thermo Iris Intrepid II XSP Duo View ICP). The extraction technique was selected to capture variability in soil elements deposited to urban forest soil and influenced by plant/forest structure rather than nutrients or metals associated with mineral soil weathering and/or underlying parent material.

Statistical analysis

All data analyses were conducted in R (Version 4.0.3; R Core Team 2020). All tests for significance are reported at the $\alpha = 0.05$ critical value, and in a few cases the $\alpha = 0.10$ critical values are reported as marginally significant to identify potential trends in the data.

To determine which soil chemical characteristics *within* our forests explain the most variation in soil chemistry, we conducted principal components analysis (PCA) using a correlation matrix with the prcomp function in R. The soil characteristics used in this analysis were soil pH, SOM, and elemental concentrations (P, K, Ca, Mg, Mn, Zn, Cu, Fe, S, Al). We report soil patterns for the first four principal components based upon the proportion of variance explained by each component and the scree plot using the print and summary pca functions in R. The soil characteristics most strongly loaded on each principal component were evaluated using the factor loadings and Pearson correlation analysis in R. To determine which plant and forest structural characteristics (distance to forest canopy edge, distance to the nearest road, ground plant cover, vertical plant density, canopy cover, and the total number of non-native invasive plant stems at each soil sampling location) most strongly correlate with the principal components, we conducted Pearson correlation analysis using the rcorr function in the Hmisc package (Harrell 2019). In addition, to determine correlations between plant and forest structural characteristics, we conducted Pearson correlation analysis (rcorr function, Hmisc package; Harrell 2019).

To determine variation in soil characteristics at two spatial scales, we calculated the coefficient of variation (CV) for each soil characteristics *across* all the forests ($n = 36$) and *within* each forest site. The *within* site variability in soil characteristics was determined by calculating the CV across the 10–15 sampling subplots within each forest. CV is a useful statistical measure to determine variation in soil variables since the variation is normalized by the mean. Lower CV values suggest more similarity in soil characteristics (i.e., homogeneity) and higher CV values suggest less similarity (i.e., heterogeneity). To aim for parsimony in our analysis and reduce potential Type I inflation errors from multiple comparisons, we analyzed soil characteristics important in driving variation in soil chemistry *within* forest sites from the PCA analysis (i.e., selected 8 variables for comparisons). We used bivariate linear regression analysis to determine whether urbanization, invasion, forest patch size, forest patch E:I, and year the forest patch canopy closed significantly explained patterns of soil chemistry variation *within* forests.

Results

Soil characteristics within forests

The total variation explained by the first four axes was 69.4%. The first principal component explained 32.7% of the variation (Fig. 1a). The soil characteristics that load the strongest on PC1 were soil pH ($R = -0.89$), Ca ($R = -0.90$), and Mg ($R = -0.84$; Fig. 1c). Soils with greater soil pH, Ca, and Mg had more non-native invasive plants ($R = -0.25$) and greater ground ($R = -0.29$) and vertical ($R = -0.39$) plant cover ($p < 0.001$), but lower canopy cover ($R = 0.17$, $p = 0.001$). The second principal component explained 15.4% of the variation across soil sampling locations (Fig. 1a), and among all the soil characteristics Zn ($R = 0.75$) and Cu ($R = 0.72$) load most strongly on this axis (Fig. 1c). Soils with greater Zn and Cu concentrations were closer to the forest canopy edge ($R = -0.20$, $p < 0.001$) and roads ($R = -0.11$, $p = 0.02$).

The third principal component explained 11.2% of the variation (Fig. 1b), and OM content ($R = 0.63$) and Al concentrations ($R = -0.73$) load the strongest on this axis (Fig. 1b). Soils with higher OM content and lower Al concentrations were further from the forest canopy edge ($R = 0.19$, $p < 0.001$). The fourth principal component explained 10.1% of the variation (Fig. 1b), and OM content ($R = -0.60$) and P concentrations ($R = -0.65$) load most strongly on this axis (Fig. 1d). Soils with greater OM and P concentrations

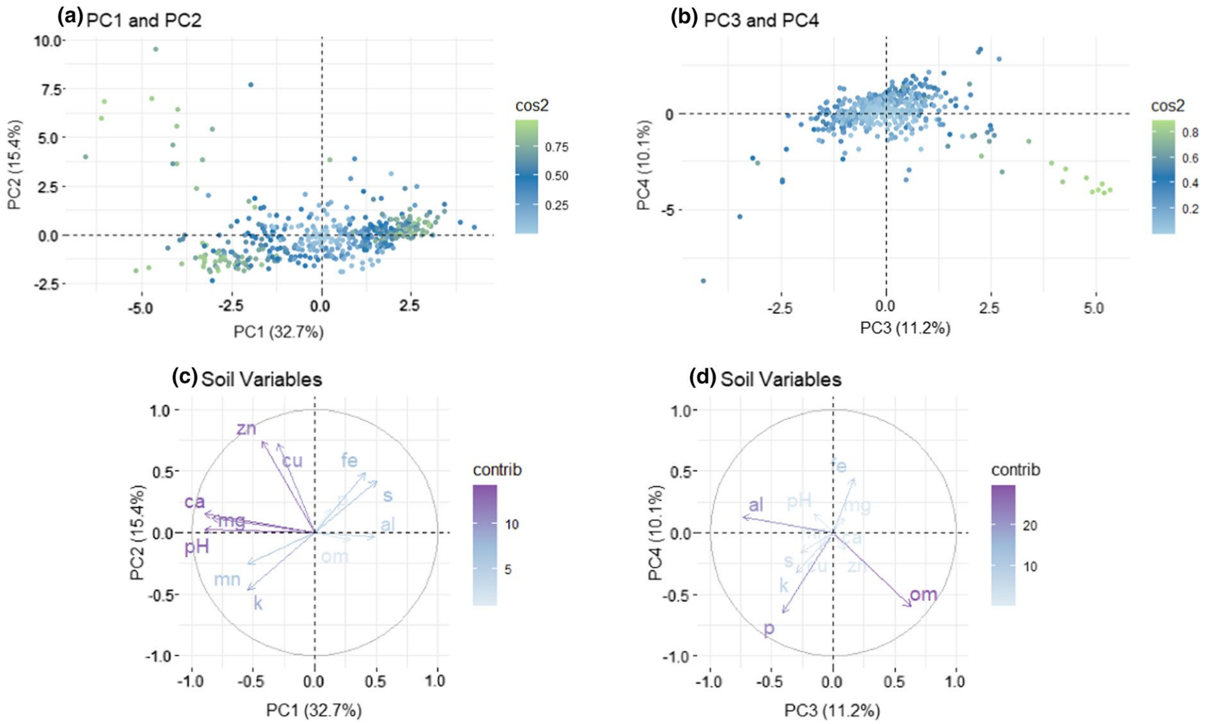

Fig. 1 Soil characteristics within 36 forest sites, each point represents one forest sampling location which are color coded based on correlations with principal components (**a**, **b**). The soil variables that most strongly loaded with (**c**) PC1 were Ca (−), pH (−), and Mg (−) and with PC2 were Zn (+) and Cu (+). The variables most strongly loaded with (**d**) PC3 were OM (+) and Al (−) and with PC4 were OM (−) and P (−)

were further from the forest canopy edge ($R = -0.13$, $p < 0.01$).

Correlations between plant and forest structural characteristics

The distance to the forest canopy edge was positively correlated with the distance to the nearest road ($R = 0.31$, $p < 0.001$). Variables associated with potential urban impacts (i.e., distance to canopy edge and nearest road) correlated with vegetation structural characteristics within the forest sites. The distance to the forest canopy edge positively correlated with the canopy cover ($R = 0.25$) and negatively correlated with the abundance of invasive plants ($R = -0.17$), ground cover ($R = -0.18$), and vertical cover ($R = -0.22$, $p < 0.001$). The distance to the nearest road negatively correlated with the vertical plant cover ($R = -0.18$, $p < 0.001$).

The abundance of non-native invasive plants was positively correlated with ground ($R = 0.39$, $p < 0.001$) and vertical ($R = 0.49$, $p < 0.001$) plant cover and negatively correlated with the overstory canopy cover ($R = -0.29$, $p < 0.001$). The ground and vertical plant cover were positively correlated ($R = 0.41$), whereas the overstory canopy cover was negatively correlated to the ground ($R = -0.42$) and vertical ($R = -0.22$) plant cover ($p < 0.001$).

Variation in soil characteristics

Across the 36 forest sites, the *within* forest site coefficient of variation (CV) in soil characteristics ranged from a minimum of 4.6 (pH) to a maximum of 226.3 (Zn; Table 1). For all soil characteristics except soil organic matter (SOM), the CV *across* the 36 forest sites was in between the minimum and maximum *within* site CV values. Overall, the variation in soil characteristics is greater *within* than *across* forests for most of the forest sites.

Abiotic and biotic factors influenced the variation in soil characteristics *within* forest sites. The

Table 1 Coefficient of variation (CV) for soil chemical properties *across* the 36 forest sites, and the minimum, median, and maximum *within* forest site CV in soil characteristics

Soil characteristic	CV *across* forests	*Within* forest site CV		
		Minimum	Median	Maximum
pH	12.2	4.6	11.1	19.3
SOM	89.7	16.5	37.5	74.4
P	47.2	17.8	45.8	193.4
K	42.5	14.0	36.2	64.4
Ca	48.8	18.3	51.9	133.5
Mg	46.1	17.5	45.8	113.1
Mn	51.7	29.5	51.4	98.8
Zn	95.0	25.0	52.8	226.3
Cu	58.0	12.9	37.1	189.0
Fe	42.6	17.8	33.9	64.5
S	32.8	18.5	30.3	105.2
Al	18.1	9.7	21.0	51.2

within forest CV in soil pH ($r^2 = 0.34$, $p < 0.001$), Mg ($r^2 = 0.12$, $p = 0.04$), Zn ($r^2 = 0.26$, $p = 0.002$), and Cu ($r^2 = 0.27$, $p = 0.001$) significantly increased as the urban intensity surrounding the forest increased, and there was a trend for greater soil Ca variation ($r^2 = 0.08$, $p = 0.09$) in forests surrounded by more urban development (Fig. 2). Similarly, the *within* forest CV in soil pH ($r^2 = 0.11$, $p = 0.05$), Zn ($r^2 = 0.21$, $p < 0.01$), and Cu ($r^2 = 0.10$, $p = 0.05$) increased as the size of the forest decreased, and there was a trend for greater *within* forest CV in soil Ca ($r^2 = 0.10$, $p = 0.07$; SM Fig. 1).

Conversely, there was a trend for lower *within* forest CV in soil Ca ($r^2 = 0.08$, $p = 0.10$), Mg ($r^2 = 0.08$, $p = 0.10$), and Al ($r^2 = 0.09$, $p = 0.08$) in forests invaded by non-native plants (Fig. 3). With increasing forest shape complexity (edge:interior) we found greater *within* forest CV in soil pH ($r^2 = 0.15$, $p = 0.02$) and Zn ($r^2 = 0.12$, $p = 0.04$) and a trend for greater CV in soil Ca ($r^2 = 0.09$, $p = 0.07$), yet lower *within* forest CV in soil Al ($r^2 = 0.17$, $p = 0.04$; SM Fig. 2). Furthermore, *within* forest CV in soil Al ($r^2 = 0.13$, $p = 0.03$) decreased in forests with more recent canopy closure (SM Fig. 3).

Discussion

Soil chemical properties associated with human-mediated environmental change, such as pH, Ca, Zn, and OM, varied within our forest sites (Table 1, Fig. 1). Forests surrounded by greater urbanization had more variation in soil chemistry (Fig. 2) suggesting deposition and site legacies that alter soil chemistry are highly variable within urban forests. Alternatively, increasing abundance of non-native invasive plants within our forests related to decreasing variation in soil chemistry demonstrating that forests dominated by invasive plants experience homogenizing effects on soils (Fig. 3). Vegetation and forest structural characteristics associated with urbanization and non-native plant invasion can provide insight into potential mechanisms driving soil heterogeneity versus homogeneity within urban forests.

Soil heterogeneity in urban forests

Our research demonstrated more variation in soil chemistry in forests surrounded by more intense urbanization suggesting current and legacy human-driven chemical inputs that are highly variable across urban landscapes influence *within* site variation. While heterogeneity in soil chemistry is expected across the urban matrix and to relate strongly to land-cover and/or land-use type (Pouyat et al. 2010), evidence of more variation in soil chemistry *within* forests emphasizes the importance of direct human management in controlling convergence of soil chemistry observed in previous research at continental and global scales (Pouyat et al. 2015; Trammell et al. 2020a). Urban forest patches are an unmanaged land-use type within urban landscapes, and, thus, reflect indirect anthropogenic influences on soil structure and function (Pouyat and Trammell 2019). To our knowledge, this is the first study to provide empirical evidence of highly variable human influences *within* urban forest patches, which is not unexpected, yet important to document. It is valuable to highlight that our scale of research differs from studies that demonstrate concepts of urban homogenization or convergence, which are focused on the comparison of developed landscapes in relation to the native ecosystems replaced by urban development (Pouyat et al. 2003; Groffman et al. 2014). The novelty of our work is the documentation of the influence of urbanization driving heterogeneity *within* ecosystem or patch types (i.e., urban forest patches) across the urban matrix. Large scale observations (i.e., continental, global) encompass large environmental differences associated

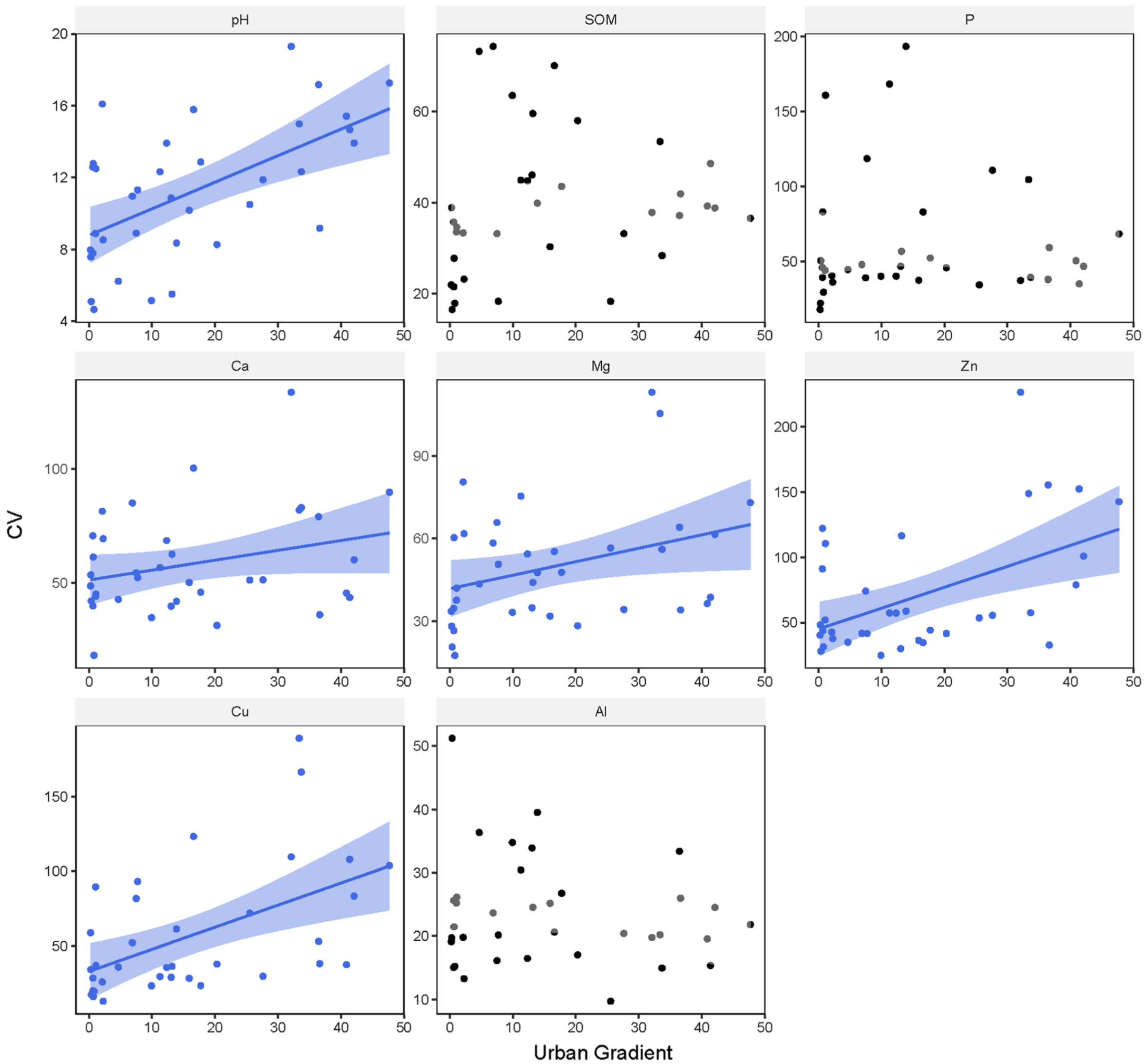

Fig. 2 The relationship between the coefficient of variation in soil chemical properties and the urban gradient (% impervious surface surrounding each forest plot). Significant positive relationships are shown in blue

with ecosystem type and/or soil parent material, whereas regional scale studies have less variation in underlying ecosystem structure. Across this metropolitan region (Philadelphia—Newark, DE), soil parent material was not a driver of patterns in soil characteristics (Trammell et al. 2021) further supporting the importance of anthropogenic influences driving variation in urban forest soils at patch scales.

Across all our sites, forests surrounded by greater urbanization intensity (i.e., impervious surface area) are also smaller in total area and have greater shape complexity (i.e., edge:interior ratios [E:I]; Trammell et al. 2021). Smaller forests with greater E:I and surrounded by more urbanization had greater variation in soil pH, Ca, Zn, and Cu (Fig. 2, SM Figs. 1, 2), yet forests with greater urbanization also had greater variation in soil Mg (Fig. 2). Thus, the potential mechanisms driving heterogeneity in soil chemistry differs between soil elements. Soil elements that have greater concentrations and variation related to distance to forest canopy edge and/or forest patch sizes and E:I are likely influenced by deposition inputs

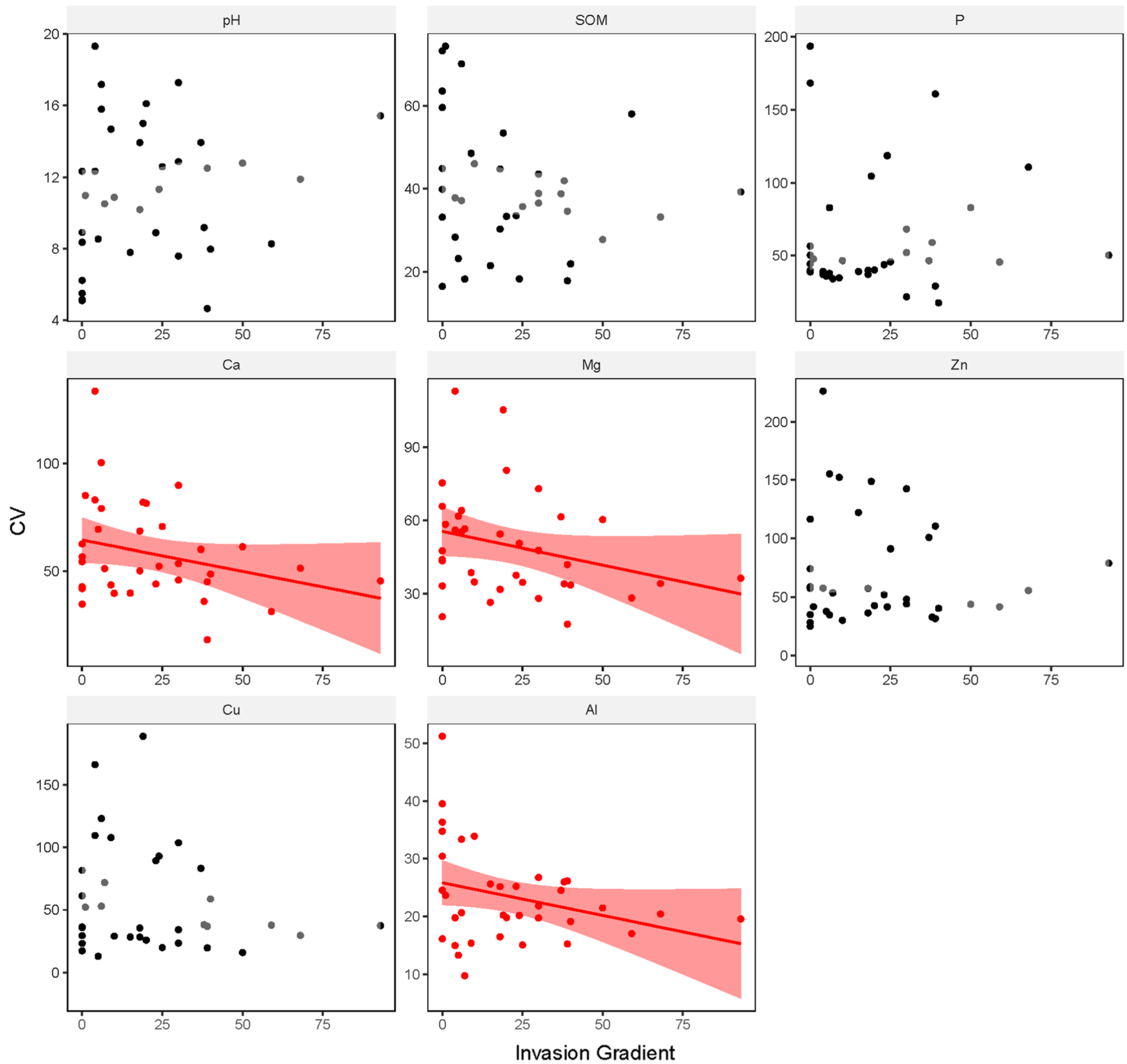

Fig. 3 The relationship between the coefficient of variation in soil chemical properties and the invasion gradient (# non-native invasive stems forest^{-1}). Significant negative relationships are shown in red

from anthropogenic activities along forest edges. Various factors associated urban development and activities can increase (e.g., cation deposition from construction or liming activities; Lovett et al. 2000) soil pH and Ca concentrations driving deposition to forest edges. Similarly, Zn and Cu deposition varies with traffic volume (Pouyat et al. 2007; Trammell et al. 2011) resulting in variable concentrations in forests embedded across urban landscapes. Alternatively, increased variation in soil Mg with increasing urbanization may be due to within site legacies more than current deposition since the forest size and shape had no relationship with variation in soil Mg. Forest location across the urbanization matrix as well as the forest edge and total size influence heterogeneity in soil chemistry in these urban forests.

Structural plant characteristics (e.g., canopy cover) in our forests related to factors that influence urbanization impacts on these forests (e.g., distance to roads). While it is not unexpected that the forest canopy cover would increase with increasing distance to the forest edge and roads or that the vertical and ground plant cover would increase closer to the forest edge, this can provide additional insight to how plant cover can influence elemental deposition to urban forests. Dense vertical plant structure on forest edges can increase pollutant capture and deposition to the soil (Weathers et al. 2001) and, thus, may facilitate Ca, Zn, and Cu deposition along forest edges in the more urbanized forest sites contributing to the observed variation. While urbanization and invasion have no relationship at the site-scale across our forests (Trammell et al. 2020b), more non-native invasive plants at the forest edges contributes to the plant density that may increase pollutant capture at the edge. Furthermore, human use of urban and suburban forests can alter forest edge conditions (Matlack 1993) impacting the plant community composition along the edge. Our results provide evidence that forest and plant structure influences soil chemistry patterns that contribute to soil heterogeneity. Further research on determining the causal links between plant and forest structure with soil chemistry, as well as the potential impacts on nutrient cycling in these forests, will further our understanding of how urbanization influences biogeochemical cycles in urban ecosystems.

Soil homogeneity in urban forests

The presence of non-native invasive plants in the forest understory related to less variation in soil chemistry *within* our forest sites (Fig. 3). In addition to plant invasion, the time since canopy closure, a proxy for forest age, was related to decreasing variation in soil chemistry in our forests (SM Fig. 3). Previous research in these forests demonstrated a negative relationship between non-native invasive plants and the age of the forest patch (i.e., younger forests had more plant invasion; Trammell et al. 2020b). Thus, it is difficult to separate the influence of current plant invasion from the legacy of previous land use on soil chemistry. However, only one of the soil elements that converged in relation to invasive plants was also related to decreasing forest age. Soil Al concentrations decreased in variation in younger forests (SM Fig. 3). This suggests that land use legacies due to previous agricultural practices, increasing non-native invasive plants, or the combination led to similar concentrations in Al across our forests.

Soil Ca and Mg concentrations decreased in variation with increasing plant invasion in our forests (Fig. 2). Previous research has shown increases in soil Ca concentrations within greater plant invasion at the site-level (Gavilán et al. 2016; Trammell et al. 2020a, b). We found increasing soil Ca and Mg concentrations with increasing total invasive plants at individual sampling locations across our forests (i.e., *within* site variation). While soil cations can be variable within a forest site (Table 1), soil Ca and Mg concentrations increase with plant invasion at fine scales. However, the variation in soil Ca and Mg concentrations decrease with increasing plant invasion (Fig. 3), which provides support that invasive plants may drive changes in soil biogeochemical cycling. Invaded sites have been shown to have increased concentrations in soil Ca and Mg (Leicht-Young et al. 2009), and some researchers have attributed increased soil Mg and other soil nutrients in invaded sites to plant invaders spreading into nutrient-rich landscapes (Howard et al. 2004). While this is a plausible explanation for increased Ca and Mg with increasing invasion in our forest sites, the decrease in Ca and Mg variation with invasion, yet not with time since canopy closure, suggests invasive plants may concentrate these cations in the soil underneath their canopies altering and homogenizing soil cation concentrations. Future research in our forests will analyze locations with increasing, decreasing, and stable invasive plant abundance over time with changes in soil Ca and Mg concentrations over time to assess whether these plants are contributing to concentrating these elements in the soil.

Our forest sites with greater plant invasion and younger forest canopies were also characterized by greater vertical and ground plant cover. Forests invaded by understory woody plants, especially shrub species, have altered vertical structure as demonstrated by altered foliar biomass distribution and light conditions (Luken et al. 1997; Trammell and Carreiro 2011). Probable explanations for increased cations under invasive plants are increased cation uptake that concentrates in foliar tissue and/or invasive plant canopies intercepting urban deposition/dust which is redistributed to the forest soil after senescence. Research utilizing stable Ca isotopes as tracers (Nielsen et al. 2012), manipulated experimentation, and/or change over time studies on plant-soil interactions could elucidate mechanisms driving similarity in soil chemistry below invasive plants, and further decipher whether invasive plants colonize sites with altered soil chemistry or whether these plants indeed drive altered soil biogeochemistry.

Conclusion

Small temperate deciduous forests embedded across developed landscapes experience a multitude of factors driving patterns in soil chemistry. The soil cations that increase in concentration with increasing plant invasion are more similar within forests most likely due to the dominating presence of invasive plants that concentrate and homogenize soil chemistry. Alternatively, soil nutrients and metals that increase in small forests with high edge:interior ratios surrounded by greater urbanization pressures diverge in soil chemistry probably due to edge effects and forest size altering deposition of elements within forest sites. Our results demonstrate that while urbanization and invasion can increase concentrations of soil nutrients and metals, they differentially alter variation in soil chemistry within forest sites. Since non-native invasive plants influence soil chemistry independent of other urban factors, plant invasion and urban environmental conditions need to be distinguished in future conceptual models of urban ecological theory. Insight on the magnitude and distribution of soil chemical properties within forests exposed to abiotic and biotic human-mediated drivers of ecological change is necessary for furthering our knowledge on soil biogeochemical cycles that control nutrient retention and carbon sequestration in forests.

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References

Ashton IW, Hyatt LA, Howe KM, Gurevitch J, Lerdau MT (2005) Invasive species accelerate decomposition and litter nitrogen loss in a mixed deciduous forest. Ecol Appl 15(4):1263–1272

Bandaranayake W, Qian YL, Parton WJ, Ojima DS, Follett RF (2003) Estimation of soil organic carbon changes in turfgrass systems using the CENTURY model. Agro J 95(3):558–563. https://doi.org/10.2134/agronj2003.5580

Barrico L, Castro H, Coutinho AP, Gonçalves MT, Freitas H, Castro P (2018) Plant and microbial diversity in urban forests and public gardens: insights for cities' sustainable development. Urban For Urban Green 29:19–27

Boeckx P, Van Meirvenne M, Raulo F, Van Cleemput O (2006) Spatial patterns of $\delta^{13}C$ and $\delta^{15}N$ in the urban topsoil of Gent, Belgium. Org Geochem 37:1383–1393

Bonan GB (2002) Ecological climatology. Concepts and applications. Cambridge University Press, Cambridge

Chang CH, Snyder BA, Szlavecz K (2016) Asian pheretimoid earthworms in North America north of Mexico: an illustrated key to the genera Amynthas, Metaphire, Pithemera, and Polypheretima (Clitellata: Megascolecidae). Zootaxa 4179:495–529

Chang CH, Szlavecz K, Buyer JS (2017) *Amynthas agrestis* invasion increases microbial biomass in Mid-Atlantic deciduous forests. Soil Biol Biochem 114:189–199

Chang CH, Johnston MR, Görres JH, Dávalos A, McHugh D, Szlavecz K (2018) Co-invasion of three Asian earthworms, *Metaphire hilgendorfi*, *Amynthas agrestis* and *Amynthas tokioensis* in the USA. Biol Invasions 20:843–848

Childers D, Cadenasso ML, Grove JM, Marshall V, McGrath B, Pickett STA (2015) An ecology *for* cities: a transformational nexus of design and ecology to advance climate change resilience and urban sustainability. Sustainability 7(4):3774–3791

Comiskey J, Schmit JP, Sanders S, Campbell P, Mitchell B (2009) Forest vegetation monitoring in eastern parks. Park Sci 26:76–80

Decina SM, Hutyra LR, Templer PH (2019) Hotspots of nitrogen deposition in the world's urban areas: a global data synthesis. Front Ecol Environ 18(2):92–100

Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. Annu Rev Ecol Evol Syst 41:59–80

Flinn KM, Vellend M (2005) Recovery of forest plant communities in post-agricultural landscapes. Front Ecol Environ 3(5):243–250

Gavilán RG, Sánchez-Mata D, Gaudencio M, Gutiérrez-Girón A, Vilches B (2016) Impact of the non-indigenous shrub species *Spartium junceum* (Fabaceae) on native vegetation in Central Spain. J Plant Ecol 9(2):132–143

Grimm NB, Grove JM, Pickett STA, Redman CL (2000) Integrated approaches to long-term studies of urban ecological systems. BioScience 50(7):571–584

Groffman PM, Cavender-Bares J, Bettez ND, Grove JM, Hall SJ, Heffernan JB, Hobbie SE, Larson KL, Morse JL, Neill C, Nelson K, O'Neil-Dunne J, Ogden L, Pataki DE, Polsky C, Roy Chowdhury R, Steele M (2014) Ecological homogenization of urban USA. Front Ecol Environ 12:74–81

Hall SJ, Learned J, Ruddell B, Larson KL, Cavender-Bares J, Bettez N, Groffman PM, Grove JM, Heffernan JB, Hobbie SE, Morse JL, Neill C, Nelson KC, O'Neil-Dunne J, Ogden L, Pataki DE, Pearse WD, Polsky C, Roy Chowdhury R, Steele M, Trammell TLE (2016) Convergence of microclimate in residential landscapes across diverse cities in the United States. Landsc Ecol 31(1):101–117

Harrell FE Jr, Dupont C, et al (2019) Hmisc: Harrell Miscellaneous. R package version 4.3-0.Available at: https://CRAN.R-project.org/package=Hmisc

Herrmann DL, Schifman LA, Shuster WD (2020) Urbanization drives convergence in soil profile texture and carbon content. Environ Res Lett 15:114001

Howard TG, Gurevitch J, Hyatt L, Carreiro M, Lerdau M (2004) Forest invasibility in communities in southeastern New York. Biol Invasions 6:393–410

Idso CD, Idso SB, Balling RC Jr (1998) The urban CO_2 dome in Phoenix, Arizona, USA. Phys Geogr 19:95–108

Idso CD, Idso SB, Balling RC Jr (2001) An intensive two-week study of an urban CO_2 dome in Phoenix, Arizona, USA. Atmos Enivron 35:995–1000

Kourtev S, Huang WZ, Ehrenfeld JG (1999) Differences in earthworm densities and nitrogen dynamics in soils under exotic and native plant species. Biol Invasions 1:237–245

Leicht-Young SA, O'Donnell H, Latimer AM, Silander JA Jr (2009) Effects of an invasive plant species, *Celastrus orbiculatus*, on soil composition and processes. Am Midl Nat 161:219–231

Liao C, Peng R, Luo Y, Zhou X, Wu X, Fang C, Chen J, Li B (2008) Altered ecosystem carbon and nitrogen cycles by plant invasion: a meta-analysis. New Phytol 177:706–714

Lookingbill T, Schmit JP, Carter SL (2012) GRTS and graphs: monitoring natural resources in urban landscapes. In: Gitzen RA, Millspaugh JJ, Cooper AB, Licht DS (eds) Design and analysis of long-term ecological monitoring studies. Cambridge University Press, Cambridge, pp 361–380

Lovett GM, Traynor MM, Pouyat RV, Carreiro MM, Zhu W, Baxter JW (2000) Atmospheric deposition to oak forests along an urban-rural gradient. Environ Sci Tech 34:4294–4300

Luken JO, Kuddes LM, Tholemeier TC (1997) Response of understory species to gap formation and soil disturbance in *Lonicera maackii* thickets. Restor Ecol 5(3):229–235

Matlack GR (1993) Sociological edge effects: spatial distribution of human impact in suburban forest fragments. Environ Manag 17(6):829–835

Nielsen LC, Druhan JL, Yang W, Brown ST, DePaolo DJ (2012) Calcium isotopes as tracers of biogeochemical processes. In: Baskaran M (ed) Handbook of environmental isotope geochemistry. Advances in isotope geochemistry. Springer, Berlin, Heidelberg

Nudds TD (1977) Quantifying the vegetative structure of wildlife cover. Wildlife Soc Bull 5(3):113–117

Oke TR (1973) City size and the urban heat island. Atmos Environ 7:769–779

Pearse WD, Cavender-Bares J, Hobbie SE, Avolio ML, Bettez N, Chowdhury RR, Darling LE, Groffman PM, Grove JM, Hall SJ, Heffernan JB, Learned J, Neill C, Nelson KC, Pataki DE, Ruddell BL, Steele MK, Trammell TLE (2018) Homogenization of plant diversity, composition, and structure in North American urban yards. Ecosphere 9(2):e02105

Peltzer DA, Allen RB, Lovett GM, Whitehead D, Wardle DA (2010) Effects of biological invasions on forest carbon sequestration. Glob Change Biol 16:732–746

Polsky C, Grove JM, Knudson C, Groffman PM, Bettez N, Cavender-Bares J, Hall SJ, Heffernan JB, Hobbie SE, Larson KL, Morse JL, Neill C, Nelson KC, Ogden LA, O'Neil-Dunne J, Pataki DE, Roy Chowdhury R, Steele MK (2014) Assessing the homogenization of urban land management with an application to US residential lawn care. PNAS 111:4432–4437

Pouyat RV, Trammell TLE (2019) Climate change and urban forest soils. In: Busse M, Dumroese D, Morris D, Giardina C (eds) Developments in soil science vol 36. Global change and forest soils: demands and adaptions of a finite natural resource. Elsevier, New York, pp 189–211

Pouyat RV, McDonnell MJ, Pickett STA (1995) Soil characteristics of oak stands along an urban-rural land-use gradient. J Environ Qual 24:516–526

Pouyat RV, McDonnell MJ, Pickett STA (1997) Litter decomposition and nitrogen mineralization in oak stands along an urban-rural land use gradient. Urban Ecosyst 1:117-131

Pouyat RV, Groffman PM, Yesilonis I, Hernandez L (2003) Soil carbon pools and fluxes in urban ecosystems. In: Kimble JM, Heath LS, Birdsey RA, Lal R (eds) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton, pp 347–362

Pouyat RV, Yesilonis ID, Russell-Anelli J, Neerchal NK (2007) Soil chemical and physical properties that differentiate urban land-use and cover types. Soil Sci Soc Am J 71(3):1010–1019

Pouyat RV, Szlavecz K, Yesilonis ID, Groffman PM, Schwarz K (2010) Chemical, physical, and biological characteristics of urban soils. In: Aitkenhead-Peterson J, Volder A (eds) Urban Ecosystem Ecology, Agronomy Monograph 55, pp 119–152

Pouyat RV, Yesilonis ID, Dombos M, Szlavecz K, Setälä H, Cilliers S, Hornung E, Kotze J, Yarwood S (2015) A global comparison of surface soil characteristics across five cities: a test of the ecosystem convergence hypothesis. Soil Sci 180:136–145

Pouyat RV, Setälä H, Szlavecz K, Yesilonis ID, Cilliers S, Hornung E, Yarwood S, Kotze DJ, Whitlow T (2017) Introducing GLUSEEN: a new open access and experimental network in urban soil ecology. J Urban Ecol. https://doi.org/10.1093/jue/jux002

R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rao P, Hutyra LR, Raciti SM, Templer PH (2014) Atmospheric nitrogen inputs and losses along an urbanization gradient from Boston to Harvard Forest, MA. Biogeochemistry 121:229–245

Raciti SM, Groffman PM, Jenkins JC, Pouyat RV, Fahey TJ, Pickett STA, Cadenasso ML (2011) Nitrate production and availability in residential soils. Ecol Appl 21:2357–2366

Setälä H, Francini G, Allen JA, Hui N, Jumpponen A, Kotze DJ (2016) Vegetation type and age drive changes in soil properties, nitrogen, and carbon sequestration in urban parks under cold climate. Front Ecol Evol 4:93

Smith IA, Dearborn VK, Hutyra LR (2019) Live fast, die young: accelerated growth, mortality, and turnover in street trees. PLoS ONE 14(5):e0215846

Trammell TLE, Carreiro MM (2011) Vegetation composition and structure of woody plant communities along urban interstate corridors in Louisville, KY, USA. Urban Ecosyst 14:501–524

Trammell TLE, Schneid BP, Carreiro MM (2011) Forest soils adjacent to urban interstates: soil physical and chemical properties, heavy metals, disturbance legacies, and relationships with woody vegetation. Urban Ecosyst 14:525–552

Trammell TLE, Ralston HA, Scroggins SA, Carreiro MM (2012) Foliar production and decomposition rates in urban forests invaded by the exotic invasive shrub, *Lonicera maackii*. Biol Invasions 14(3):529–545

Trammell TLE, Day S, Pouyat RV, Rosier C, Scharenbroch B, Yesilonis I (2017a) Drivers of urban soil carbon dynamics. In: Lal R, Stewart BA (eds) Urban soils: advances in soil science. Taylor and Francis Publishing, Boca Raton, pp 93–120

Trammell TLE, Pouyat RV, Carreiro MM, Yesilonis I (2017b) Drivers of soil and tree carbon dynamics in urban residential lawns: a modeling approach. Ecol Appl 27(3):991–1000

Trammell TLE, Pataki DE, Pouyat RV, Rosier C, Avolio ML, Bettez N, Cavender-Bares J, Groffman PM, Grove J, Hall SJ, Heffernan J, Hobbie SE, Larson KL, Morse JL, Neill C, Nelson KC, O'Neil-Dunne J, Polsky C, Roy-Chowdhury R, Steele M, Wheeler MM (2020a) Urban soil carbon and nitrogen converge at a continental scale. Ecol Monogr. https://doi.org/10.1002/ecm.1401

Trammell TLE, D'Amico V, Avolio ML, Mitchell JC, Moore E (2020b) Temperate deciduous forests embedded across developed landscapes: younger forests harbour invasive plants and urban forests maintain native plants. J Ecol 108(6):2366–2375

Trammell TLE, Pouyat RV, D'Amico V III (2021) Soil chemical properties in forest patches across multiple spatiotemporal scales in mid-Atlantic U.S. metropolitan areas. Urban Ecosyst. https://doi.org/10.1007/s11252-021-01096-5

US Census Bureau (2010) The United States Census Bureau. American Fact Finder. Available https://www.census.gov/

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species communities and ecosystems. Ecol Lett 14(7):702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

Ward EB, Pregitzer CC, Kuebbing SE, Bradford M (2020) Invasive lianas are drivers of and passengers to altered soil nutrient availability in urban forests. Biol Invasion 22(3):935–955

Weathers KC, Cadenasso ML, Pickett STA (2001) Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. Conserv Biol 15(6):1506–1514

Wheeler MM, Neill C, Groffman PM, Avolio ML, Bettez N, Cavender-Bares J, Chowdhury RR, Darling L, Grove JM, Hall SJ, Heffernan JB, Hobbie SE, Larson KL, Morse JL, Nelson KC, Ogden LA, O'Neil-Dunne J, Pataki DE, Polsky C, Steele M, Trammell TLE (2017) Continental-scale homogenization of residential lawn plant communities. Landsc Urban Plan 165:54–63

Whitney GG, DeCant JP (2003) Physical and historical determinants of the pre- and post-settlement forests of northwestern Pennsylvania. Can J For Res 33:1683–1697

Yesilonis ID, Pouyat RV, Russell-Anneli J (2016) The effect of landscape cover on surface soils in a residential suburban neighborhood in Baltimore, Maryland. Urban Ecosyst 19:115–129

Zhu W-X, Carreiro MM (2004) Temporal and spatial variations in nitrogen transformations in deciduous forest ecosystems along an urban–rural gradient. Soil Biol Biochem 36:267–278

Ziska LH, Gebhard DE, Frenz DA, Faulkner S, Singer BD, Straka JG (2003) Cities as harbingers of climate change: common ragweed, urbanization, and public health. J Allergy Clin Immunol 111(2):290–295