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PRACTICAL ARTICLE

Fine-scale soil heterogeneity at an urban site: implications for forest restoration

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Soils within a forested park in New York City, NY, USA, were sampled to evaluate spatial variation in pH on a disturbed forest restoration site, and compare soil physicochemical parameters (pH, texture, moisture, organic matter [OM], plant available Mg, Ca, Mn, Al, Fe, K, Na, P, Cu, and Zn) between the restoration site and an intact forest. The divergence of soil parameters between sites suggests that forest clearing on the restoration site initiated the erosion of fine particles and altered soil chemistry. Within the restoration site, the spatial pattern, and correlation with base-cations, suggests that localized impacts from the built environment drive fine-scale pH variation with implications for nutrient availability and native plant establishment. The majority of our site was found to be unsuitable for native species adapted to acidic soils. However, sampling points spaced less than 10 m apart can capture the pH variation and allow for the identification of acidic soil patches.

Key words: digital soil mapping, soil pH, soil sampling, urban forest

Implications for Practice

- Sites with complex land-use histories may have variation in soil properties that is not attributable to obvious landscape features. Sampling such sites at multiple points and analyzing the points separately can identify extreme conditions. This point data can be used to develop precision soil maps to inform restoration design.
- Remnant forest soils can be substantially impacted by the surrounding urban environment. In particular, vegetation disturbance, erosion, and high levels of base-cations can drive soil conditions unfavorable for native tree re-establishment.

Introduction

There is a growing demand for natural areas to mitigate the impacts of urbanization and improve the quality of life in cities (Pickett et al. 2011; Elmqvist et al. 2015). In New York City, this has included planting forests on disturbed lands with complex land-use histories (Bounds et al. 2014). Re-establishing forests on degraded urban lands provides an opportunity to adapt restoration design to novel conditions. In New York City, forests planted on human-altered and transported soils (including dredge spoils and coal-ash dump sites) experience an extreme range of conditions that affect plant growth and establishment (Pregitzer et al. 2016). Even remnant natural soils show increased hydrophobicity, elevated levels of contaminants, high bulk density, altered nutrient cycling, and a high prevalence of artifacts due to urbanization (Pouyat et al. 1995, 2007, 2010).

The distribution and intensity of these impacts can be difficult to predict. Soil pH, for example, can be dramatically increased or lowered, expanding the natural range of soil conditions and altering spatial heterogeneity. The urban soil mosaic can be composed of hierarchically nested patches, with soil properties affected by urbanization differently across scales (Pouyat et al. 2010). While environmental heterogeneity is a primary driver of the maintenance of biodiversity and the distribution of species (Tilman 1982; Wilson 2000), not all measurable environmental variation has ecological relevance. To generate ecological heterogeneity, environmental variation must exist on a scale that interacts with the ecological unit under consideration (Allen & Hoekstra 1991; Pickett et al. 2000). Soil heterogeneity is common across forests and has the potential to affect species composition and ecosystem-level processes (Brandt et al. 2013; Warring et al. 2015); however, there has been little study of spatial heterogeneity within urban forest soils, particularly at scales relevant to the establishment of individual trees.

Author contributions: JS, PG, RAH designed the study; JS collected and processed soil samples; RAH analyzed samples; MD, JS performed statistical analysis: JS performed geostatistical analysis; all authors wrote the manuscript.

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In this study, we compared soil physicochemical parameters between a disturbed restoration site and an intact forested site in Highbridge Park in New York City, USA. Within the restoration site, intensive grid sampling was performed to characterize the spatial variability of a suite of soil physicochemical parameters and to map the distribution of soil pH using geostatistical approaches. We hypothesized that: (1) Soil heterogeneity is greater on the restoration site than the forested site. (2) Soil physicochemical parameters (pH, texture, moisture, organic matter [OM], plant available Mg, Ca, Mn, Al, Fe, K, Na, P, Cu, and Zn) differ between the restoration and forested site. (3) Within the restoration site, the spatial variation in pH is large enough to influence microsite planting design.

Methods

Study Site

Approximately 56 ha in area, Highbridge Park (40.8538°N, 73.9257°W) is mostly woodland; with a network of paved paths and lawns, gardens, and built amenities along the periphery. The park was formed by merging a variety of parcels, from 1876 to the 1960s (New York City DPR 2019) including Revolutionary Era fortifications and a sprawling amusement park, which burned in 1914. Once open vistas have returned to successional forest or invasive-dominated vineland. In other areas, the steep slopes limited farming and development, preventing the removal of the historic oak-hickory forests (Natural Resources Group 2005).

The study area is a 3.2 ha section of the park located on east-facing slopes. We compared a 1.2 ha forest restoration site with 2 ha of intact, oak-dominated forest. Both sites have a similar aspect and topography, and are interspersed with small streams. The average slope of the restoration site is 29% while the forested site is 25%. Our review of aerial photos and maps from 1924 to the present indicate that the forested site was continuously wooded, while the restoration site was mostly devoid of vegetation in 1924 and 1951, with vegetation re-establishing at an unknown time between 1951 and 1996 (New York City 2021). We do not know when the restoration site was first cleared or how the land was used prior to the establishment of the park. Both sites have a history of dumping and a similar proximity to the built environment; however, at the time of restoration, the restoration site had a greater volume of dumped construction debris and automobile parts. Prior to this study, the restoration site was dominated by a dense network of vines and invasive vegetation covering the debris (Fig. 1), a condition characteristic of disturbed forests in New York City parks (Bounds et al. 2014). During restoration, some surface debris was removed. The soil on both sites is classified as Rock Outcrop-Hollis-Chatfield Complex, a shallow sandy glacial till, which is extremely to moderately acidic in the mineral horizons, with a pH of 3.5–6 (Soil Survey Staff 2017).

Soil Sampling and Analysis

Between June and August of 2017, 263 soil samples were collected from the study sites. After removing any surface organic material, soil was sampled to a depth of 20 cm with a 3.0 cm diameter coring device. When the soil depth was less than 20 cm, soil was sampled to bedrock. On the restoration site, intensive sampling (3 m grid) was conducted on a 60 by 51 m area. Both sites were sampled every 9 m on transects. On the restoration site, a 180 m transect approximately bisects the slope, with two perpendicular transects. On the forested site, a 189 m transect bisects the slope, with two perpendicular transects. This nested design (Fig. 2) was intended to capture fine-scale pH variation independent of obvious landscape features and place it in context of larger-scale variation of multiple soil parameters. Sub-meter accuracy GPS data were collected for all sample points. Samples were air dried, ground, and sieved using a 2 mm screen. Only pH values were obtained for the samples collected from the 3 m grid. Samples every 9 m were analyzed for pH, sand, clay, soil moisture, organic matter (OM), Mg, Ca, Mn, Al, Fe, K, Na, P, Cu, and Zn; only this data was used to compare sites.

Figure 1. The restoration site prior to preparation for planting.

Samples were analyzed for pH in 1:2 (V/V) Soil:0.01 M $CaCl_2$ suspension (Robarge & Fernandez 1987), organic matter content (OM) (g_{OM} /g_{soil}) was estimated by loss-on-ignition, and soil texture (g/g) was determined using the hydrometer method (Day 1965). Plant available elements were extracted with modified Morgan's solution (NH_4OAC, pH 4.8) (McIntosh 1969) followed by analysis with inductively coupled plasma spectroscopy. Soil moisture (g_{water}/g_{soil}) was determined by drying at 105°C for 24 hours.

Statistical Analysis

Statistical analysis and graphical outputs were done in R version 3.3.2 software (R Core Team 2014). *Ade4* (Dray & Dufour 2007) and *FactoMineR* (Husson et al. 2007) packages were used

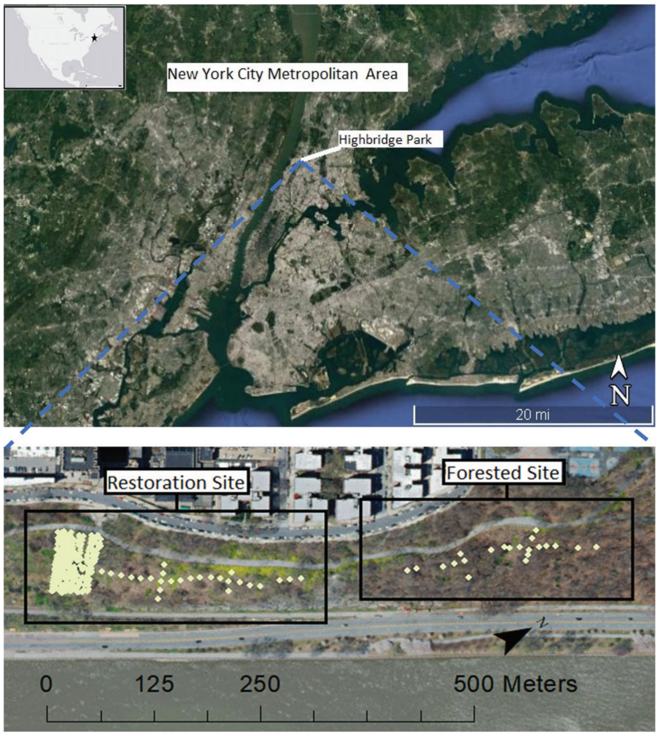

Figure 2. Location of research site and map of soil sample locations.

for normalized principal components analysis (PCA) to examine relationships between the multiple soil parameters measured in this study (pH, sand, clay, soil moisture, OM, Mg, Ca, Mn, AL, Fe, K, Na, P, Cu, and Zn) and how these relationships differ between the restoration and forested sites. Medians and coefficients of variation (CV) were calculated for parameters for both sites. Medians were compared between sites with a Kruskal–Wallis rank test. The correlations between soil parameters (pH, sand, clay, soil moisture, OM, Mg, Ca, Mn, Al, Fe, K, Na, P, Cu, and Zn) and elevation were evaluated with Spearman's rank correlation coefficient. Correlations between variables and site differences were considered significant when the p value was ≤0.05.

The effect of site (forested or restoration) on the observed variability was evaluated with a Monte Carlo analysis (999 permutations) of the between-groups inertia percentage with a "randtest" function. The criterion used in this test is the ratio of the between-class inertia to the total inertia. The simulated p value and the observed criterion were obtained by displaying the rtbetsite object (Thioulouse et al. 2018).

Geostatistical Analysis and Digital Soil Mapping

Data from the 3 m sample grid were used for geostatistical analysis conducted in ArcMap 10.7.1 to determine the average size of pH patches, and to interpolate between sample points to create maps of soil pH. An empirical semivariogram was generated by plotting semivariance against distance between sample points and fitted with a stable model (ESRI 2001). The fitted semivariogram has a range of 19.62 m, the distance at which sample

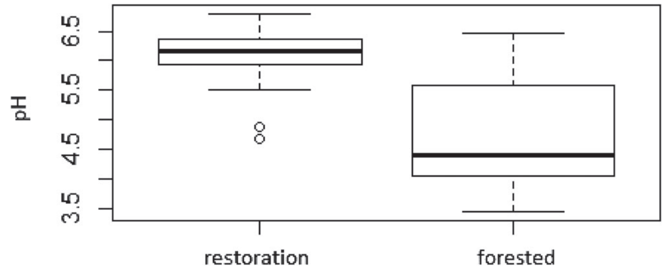

Figure 3. Boxplot comparing pH on restoration sites to forested sites ($p < 0.0001$), the middle bar is the median, the box extends from 25% to 75% quartile, and horizontal bars show minimum and maximum values.

values are no longer spatially autocorrelated (Robertson 1984). The semivariogram was used to generate a prediction of values at unsampled locations with ordinary kriging (Trangmar et al. 1985), which produces the best-unbiased estimates of soil properties at unsampled locations (Panday et al. 2018). This interpolation was used to develop an equal interval map of pH on the restoration site.

Results

The median values of pH, %sand, Ma, Ca, Al, Fe, K, P, and Ca were all significantly different between sites. Moisture, %clay, OM, Na, and Zn showed no significant differences. The restoration site had a higher median percent sand (49.6%) than the forested site (45.47%). The median pH value of the restoration site was 6.17, greater than the forested site, pH 4.4 (Fig. 3). The CV was lower on the restoration site for all soil parameters tested except %sand, moisture, and Al. The medians of all available macronutrients tested (Ca, Mn, K, and P) were higher on the restoration site than the forested site.

The first two axes of the PCA performed on the soil parameters explained 57% of the total variance (Table S1, Fig. 4). The first PCA axis, which explained 36% of the total variance, was negatively correlated (in decreasing order) with Ca, Mn, soil moisture, pH, OM, P, and clay ($|r| > 0.60$). The second PCA axis explained 21% of the total variance and was strongly correlated with OM, pH, and sand ($|r| > 0.60$) and to a lower degree with Cu, Al, Fe, clay, soil moisture, Zn, and Mg (Table S1). Sand, pH, and Mg were positively correlated to the second PCA axis whereas OM, Cu, Al, Fe, clay, soil moisture, and Zn were negatively correlated to the second PCA. Calcium had the highest correlation to the first axis ($r = -0.87$) followed by Mn ($r = -0.77$), Na ($r = -0.65$), OM ($r = -0.65$), clay ($r = -0.65$), and pH ($r = -0.63$). The difference between restoration and forested sites was highly significant ($p = 0.001$, Monte Carlo test). The restoration and forested sites were primarily distinguished by Ca, Mn, Na, Al, and pH on the first axis ($p < 0.0001$, $R^2 = 0.14$) and by OM and pH on the second axis ($p < 0.0001$, $R^2 = 0.26$) (Fig. 3b, Table S1).

Several variables, including pH, Na, Ca, and Mn, were negatively correlated with elevation across the site. Calcium, Mg, Mn, and % sand were positively correlated with pH, while Al

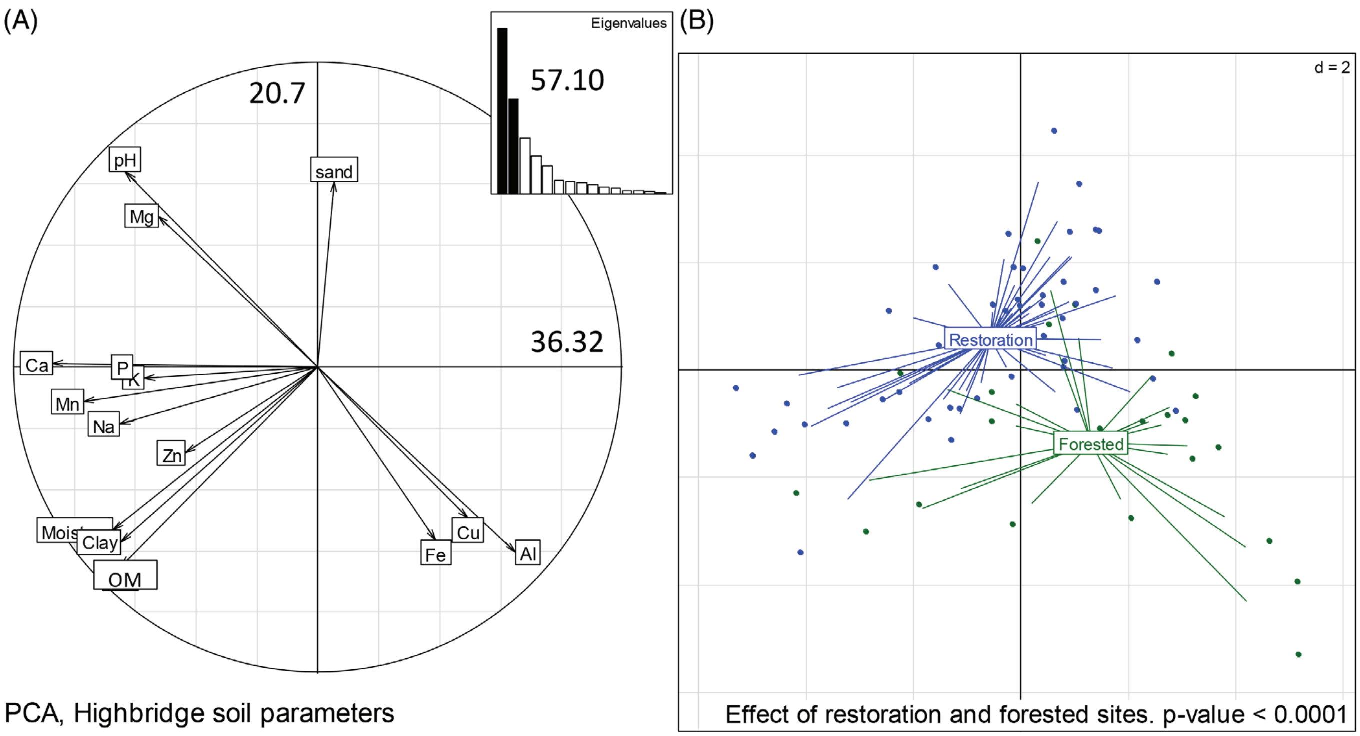

Figure 4. Principal components analysis (PCA) showing the influence of restoration and forested sites on soil parameters: pH, sand%, clay%, soil moisture ratio (moisture) %, organic matter (OM) %, Mg, Ca, Mn, Al, Fe, K, Na, P, Cu, and Zn.

Table 1. Comparison of soil parameters between restoration and forested sites. Significant difference 1 between medians in bold (*p* value <0.05).

Restoration Site (n = *50*)					*Forested Site* (n = *22*)			
Soil parameter	*Range*	*Median*	*SD*	*cv (%)*	*Range*	*Median*	*SD*	*cv (%)*
pH	**4.7–6.8**	**6.2**	**0.43**	**7**	**3.4–6.5**	**4.4**	**0.96**	**2**
Sand %	**34–75**	**50**	**0.07**	**14**	**32–54**	**45**	**0 .05**	**12**
Clay %	12–27	19	0.03	17	13–32	18	0.04	23
Moisture g /g	0.0113–0.119	0.0262	0.02	67	0.0165–0.0897	0.0294	0.02	50
OM g/g	3–29	10	0.1	51	4–28	9	0.06	54
Mg mg/kg	**124–2,348**	**537**	**427**	**62**	**29–921**	**282**	**307**	**78**
Ca mg/kg	**1,211–20,523**	**4,660**	**3,711**	**66**	**290–7,876**	**1,959**	**2,450**	**83**
Mn mg/kg	**27–221**	**95**	**47**	**47**	**18–351**	**60**	**86**	**100**
Al mg/kg	**8–215**	**20**	**35**	**122**	**20–711**	**163.5**	**203**	**9**
Fe mg/kg	**4–102**	**10**	**17**	**107**	**6–217**	**19.5**	**49**	**126**
K mg/kg	**85–590**	**537**	**113**	**62**	**53–643**	**158**	**133**	**66**
Na mg/kg	13–670	28	167	148	11–697	29	176	187
P mg/kg	**9–255**	**70.5**	**57**	**69**	**3–197**	**24**	**44**	**118**
Cu mg/kg	**1-4**	**1**	**0.9**	**57**	**1–7**	**2**	**1.6**	**60**
Zn mg/kg	5-147	37	26	26	6–80	29.5	22	72

and Fe were negatively correlated with pH. Percent clay was higher on the forested site (Table 1) and had a strong positive correlation with OM and soil moisture ratio.

The kriging of pH on the sample grid had a root-mean-square error of 0.357 and a range of 19.62 m. The resulting map (Fig. 5) suggests that elevated pH patches in the restoration site may be driven by historic land use and dumped construction debris, although the high levels of Ca may also originate from beyond the study site and appear to be interacting with elevation and site hydrology.

Discussion

Heterogeneity Between Sites

Discussions of urban heterogeneity often assume that ecological variables, including soil properties, tend to be more homogeneous

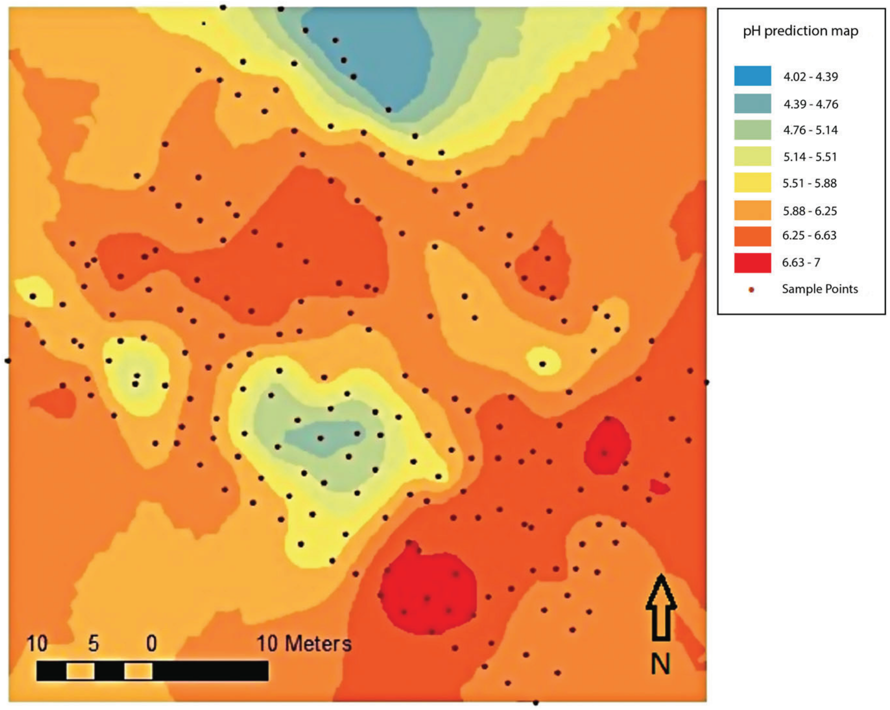

Figure 5. Equal interval pH prediction map.

within urban parcels (Pouyat et al. 2007). However, soil heterogeneity within parcels can be increased by urbanization, with strong gradients (hot spots) resulting from the legacy of historic land uses (Schwarz et al. 2012). Our first hypothesis, that the land- use history of the restoration site would increase soil heterogeneity, was not supported. The restoration site demonstrated a general homogenization of soil properties (as measured by CV) in comparison to the forested site. These results highlight the importance of forest vegetation to the maintenance of soil heterogeneity and support the generalization that anthropogenic disturbance creates ecological homogeneity (Trammell et al. 2020).

Soil Properties Between Sites

Our second hypothesis, that the soil properties differed between sites, was supported for most soil properties. This broad divergence in soil properties demonstrates the limitations of relying on contemporary land use, or coarse grain soil maps for restoration. Though multiple factors likely drive the variation between sites, the difference in soil textures suggests that forest clearing triggered the erosion of silt, initiating a different trajectory on the restoration site. Medians for all macronutrients were significantly higher on the restoration site. The high percentage of clay and reduced soil volume in the remaining soils may contribute to high nutrient levels. Soil pH on the restoration site was higher than would be predicted based on the description of the soil series, pH 4.5–6.1 (Soil Survey Staff NRCS 2017) or earlier studies across an urban–rural gradient in oak forest stands on comparable soils in the region, pH 4.2–4.5 (Pouyat et al. 1995). There has been recent recognition that urbanization can lead to marked increases in soil pH (Pouyat et al. 2015) due to the influence of construction debris (Jim 1998; Pouyat et al. 2007), liming of residential lawns (Yesilonis et al. 2016), or dumping of ash, bones, and other waste (Asabere et al. 2018). Trees growing on urban soils with elevated pH may face nutrient imbalances including Fe deficiency leading to chlorosis (Korcak 1987). The higher nutrient availability and pH of the restoration site may favor invasive vegetation (Daehler 2003; Ward et al. 2020). The higher pH, nutrient levels, and associated invasive vegetation may be characteristic of forest slopes that are cleared within a heavily developed urban matrix.

Fine-Scale pH Heterogeneity and Restoration Design

We found a pH greater than 6 at 67% of the gridded sample points and expect that plants adapted to acidic soils will face challenges establishing on most of the restoration site. Within the restoration site, our map indicated areas that would be suitable for vegetation adapted to acidic conditions. Previous fine-scale studies of pH have found large variations on the scale of individual trees in non-urban forests (Zinke 1962). In a 50-year-old New York State forest plantation, pH varied more under individual trees than between plots of different species; however, the pH range, sampled on a 1.5 m scale, was between 3 and 4 (Riha et al. 1986), a substantially smaller range than at our study site (4.7–6.8). The semivariogram range determined by geostatistical analysis (about 20 m) represents an average patch size for pH on the restoration site. At this patch size, newly planted containerized trees may be unable to effectively “forage” beyond their “patch.” These results suggest that localized, functionally homogeneous soil patches are critical for microsite design.

Although the range of our semivariogram may not be typical for comparable sites, it can provide preliminary guidance for sampling urban soils. Kerry and Olver (2004) recommend sampling soils at an interval of just under half the range of a typical semivariogram to map the variation of soil properties. At our site, sampling points closer than 10 m would capture the pH variation and allow for the identification of areas suitable for native species adapted to acidic soils. These areas would not be revealed by composite sampling which could yield average values unsuitable for many target native species. While resources may not allow sampling at this intensity, it may be useful for urban restoration practitioners to increase the number of samples collected from restoration sites and analyze them separately. Patches of elevated pH could be treated with targeted application of soil amendments, a strategy comparable to the use of digital soil mapping in precision agriculture (McBratney & Pringle 1999). Alternately, species selection could be adjusted to suit pH hot spots.

By characterizing the heterogeneity within a remnant forest soil in New York City's urban core, where the built environment and mature forests have interacted since northern Manhattan completed the transition from an agricultural to an urban matrix in the 1930s, we can better understand the interaction of traditional soil-forming factors with urbanization. Forest soils in dense urban centers that have been previously cleared and have a history of interaction with surrounding built environments will have different properties than forests that established prior to urbanization and may exhibit increased pH and nutrient availability favoring invasive plants. Specific instances of dumping and other land use legacies may be remediated; however, the general trend of base-cation transport from the built environment is likely to be a long-term urban soil-forming factor. Conservation goals could be supported by the increased use of calcareous communities as references for urban forest restoration. In general, detailed soil mapping could facilitate the maintenance of vegetation with narrow edaphic requirements in the urban landscape. Additional properties of the patch structure of urban soils may also prove to be a source of ecological heterogeneity if incorporated into restoration design.

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Supporting Information

The following information may be found in the online version of this article:

Table S1: Soil measured variables contributing significantly to the first three axes
Table S2: Spearman correlations between soil parameters
Figure S1: pH semivariogram

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