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Data proxies for assessment of urban soil suitability to support green infrastructure

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Abstract: Use of urban green infrastructure (GI) such as rain gardens, wetlands, and cisterns is a management option to provide ecosystem services such as stormwater detention, community green space, and pollinator habitat in urban core areas. It would be beneficial to efficiently and inexpensively characterize land parcels for GI suitability. We hypothesize that the capability of urban soils to support green infrastructure might be adequately characterized by extant site land cover rather than comparatively expensive and slow soil sampling and testing. As a pilot study, we directly characterized soil taxonomic, physical, and chemical characteristics and measured the percentage of vegetated, bare, and paved land cover for perimeters and interiors of 62 vacant lots and city parks located in Cleveland, Ohio, United States. All vacant lots and park areas were vegetated to some extent, and we were able to relate surface vegetation to several soil properties. Our results indicate that vegetation is correlated to sandiness, drainage capability, and basic metrics of nutrient availability for these sites, and that it might be possible with a group of such studies to identify a minimum suite of observations necessary to characterize urban lots in any city for GI suitability.

Keywords: green infrastructure—land cover—soil quality—stormwater management—urban ecosystems

Due to legacy blight (Gordon 2003) and the US foreclosure crisis (Leitsinger 2011), some major US cities have begun systematically clearing vacated residential properties (vacant lots). These parcels of vacant land represent a type of voluntary green infrastructure (GI), which we define as a plant-soil system that can attenuate runoff to urban sewers, and provide other ecosystem services such as reducing soil erosion, improving aesthetics, mitigating heat island effects, and providing habitat for urban wildlife. Spontaneous, unplanned urban GI encompasses, and is often indicated by, volunteer vegetation or turf seeded in after land disturbance to reduce soil erosion. The effectiveness of such urban GI is expected to be mediated by biogeochemical and physical qualities of urban soils, much as crop productivity is mediated by the quality of agricultural soils (Wander and Drinkwater 2000; Arshad and Martin 2002; Smagin et al. 2006; Schindelbeck et al. 2008).

It would be beneficial to have an inexpensive and reliable method available to predict what parcels of urban land would be the best candidates for voluntary GI, or that would require the least expenditures to perform satisfactorily as GI sites. Such a method would ideally also have some utility in quantifying the amount of potential runoff mitigation on a site-specific basis. An applicable conceptual framework for this idea has already been developed for agricultural soils, termed soil quality. The concept of agricultural soil quality was developed as an attempt to synthesize soil biogeochemical and physical characteristics so as to better understand how to sustain productivity in managed agroecosystems (Doran and Parkin 1994; Wander and Drinkwater 2000). The concept of agricultural soil quality has led to considerable efforts to develop a consensus of what overall soil condition can best support soil functions (Wander and Drinkwater 2000; Schindlebeck et al. 2008) and develop a minimal soil-factor spanning dataset (MSD) necessary to characterize agricultural soil quality, thereby facilitating optimal management. A suggested MSD can include physical (texture, bulk density, infiltration rate, and depth of rooting), chemical (pH, conductivity, nitrogen [N], phosphorus [P], potassium [K], and organic matter), and biological (soil respiration, potentially mineralizable N, and microbial biomass) parameters (Doran and Parkin 1994).

With wholesale shifts in urban land mass to vacant property (Goodman 2005), we must have a conceptual lens through which planning and management of urban soils can be focused, and thereby maximize their utility. Recent urban soil research (Jim 1998; Lorenz and Kandeler 2005; Smagin et al. 2006; Vrščaj et al. 2008; and Scalenghe and Marsan 2009) collectively suggests development of an MSD for quantifying management impacts on urban soil quality. Both Smagin et al. (2006) and Schindelbeck et al. (2008) connect the importance of soils conditions to supporting healthy vegetation and view tillage, traffic, vegetative cover, and organic or inorganic nutrient transformations as important influences of soil quality for both rural and urban areas.

Much of the soil quality literature compares measurements with preestablished ranges in parameters to judge if a soil possesses a certain capacity to function. Some authors (Arshad and Martin 2002) argue, however, that ranges are not universally applicable and should instead be linked to specific vegetation-environmental conditions. Working across an urban-rural gradient near Baltimore, Maryland, Pouyat et al. (2007) screened soil physicochemical measurements and found that separation between forest cover from other land uses was best correlated to K, P, and soil bulk density and that the extent of turf cover was best related to soil pH. Dobbs et al. (2011) quantified the value of urban

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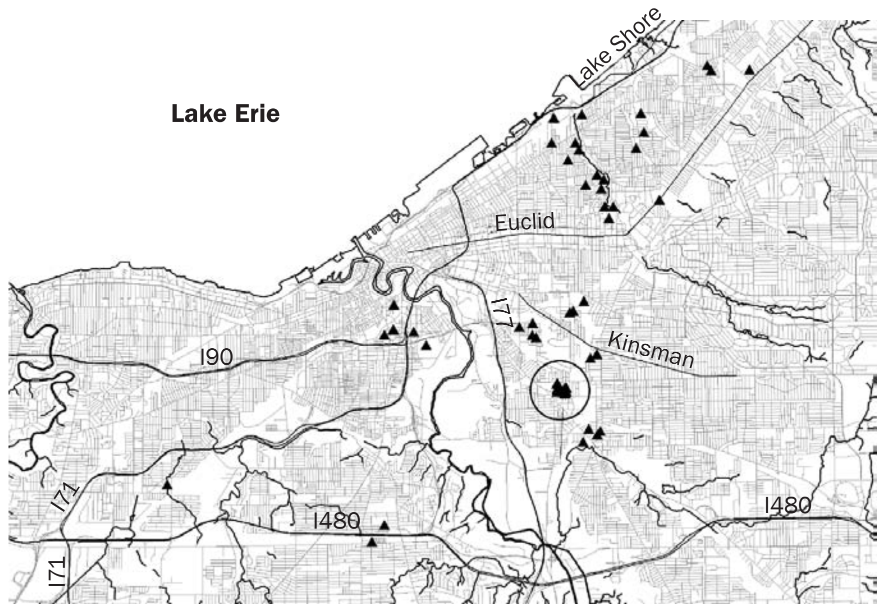
forests in Gainesville, Florida, for different ecosystem services, including drainage. The best indicators were tree cover, soil pH, and soil organic matter which were influenced by land use and time since urbanization, but not property value or household income. On the other hand, measurements of infiltration rate (which is related to soil structure) and redistribution of soil moisture—both key soil functions for sustaining plant growth as well as providing stormwater volume management—are not well characterized in current agricultural MSD parameter sets or in urban soils. Additional studies are therefore needed to adequately characterize the suitability of urban soils for GI. These studies should include taxonomic and basic physical and chemical analyses to better characterize the capacity of urban soils to support vegetation, and should characterize surface and shallow subsurface hydrology to better understand the extant and potential role of urban soil in stormwater management and GI.

In this study we apply the concept of soil quality to urban environments and limit our definition of urban soil quality to only attributes pertinent to the capacity of a soil to support vegetation as a proxy for potential success of GI. We screen a large number of putative descriptors of physical, hydrologic, and chemical soil qualities, and evaluate these by both their relationships with extant vegetation (i.e., existing green infrastructure) and their utility as potential members of an MSD for urban soils. The principle objective of this study was to determine if there were useful predictors for suitability to voluntary GI within the observed ranges of the variables measured. We therefore generated pairwise linear and rank correlation matrices for the ensemble of variables, then developed partials of the matrix and assessed these for spurious and interacting relationships, and also looked for clusters of "redundant" soil variables that shared similar relationships with surface vegetation characteristics. We then use these groupings to summarize the relationship between vegetation and soil conditions and to suggest construction of an MSD for assessing the utility of urban soils for GI. Additional studies of a similar nature in other locales would be necessary to define the inference space for these relationships, and thereby their generalizability.

Figure 1
Map of Cleveland, Ohio, vacant land and park parcels sampled in 2010 and 2011. The study sites are indicated by black triangles.



Materials and Methods

Site Selection. We evaluated vacant residential parcels within the boundary of the Northeast Ohio Regional Sewer District (NEORSD) combined sewer service area (figure 1). There were 60 vacant parcels available for study, all owned by either the city or county land bank corporations and proximal to relatively low volume (<60 ML [or million liters] y^{-1}), high frequency (>5 activations per year) combined sanitary and stormwater sewer conveyances. Forty-two vacant lot and park parcels were sampled in July of 2010, and 21 vacant lots were sampled in July of 2011.

Field Investigations. Vacant property assessment was performed as described in Shuster et al. (2011). A set of coordinates were determined in the center of each site with a handheld global positioning system unit (Garmin Rino 520, Kansas City, Kansas). Each site and its immediate vicinity were sketched, salient features were recorded, and photographs of site interiors and perimeters were taken from the front and rear of each property. Interior and perimeter site land use was recorded as visually estimated percentages of areal coverage by pavement, bare soil, turf, weeds, shrubs, and trees. The percent canopy in the north, south, east, and west directions was measured with a spherical densitometer.

The prevalence of buried debris at each site was estimated using the average refusal of a length of ~2 cm diameter steel reinforcing bar driven with a 0.3 m (1 ft) free fall of a hand-held 2.3 kg (5 lb) hammer. Refusal was defined as 30 blows per 0.01 m (0.03 ft) advance. The number of blows to reach refusal or a maximum depth of 0.66 m (2.2 ft) depth was recorded for seven equidistant points along two transects spanning between opposite corners of the sites. Percent refusal was calculated by dividing the number of sites sampled registering refusal by the total number of points sampled and multiplying by 100. The average depth to refusal was calculated for the subset of sampling points where refusal was encountered.

Hydraulic conductivity at the surface was assessed with tension infiltrometers run at a suction head of 2 cm (0.8 in) (measuring matrix rather than macropore flow), run in two replications in each of native and fill locations, and $K_{sat, matrix}$ was estimated according to manufacturer recommended methods (Mini Disk Infiltrometer User's Manual, Decagon Devices, Pullman, Washington).

Soil borings were advanced at each site using a truck-mounted Geoprobe 5400 (Geoprobe Systems, Salina, Kansas). Each boring was continuously sampled using a 6 cm (2.4 in) diameter carbon-steel split spoon lined with a clear acetate tube and driven in 1.3 m (4.3 ft) increments. At each residential vacant lot site, two soil borings were advanced in a relatively undisturbed section in the former backyard (native), and one boring was advanced within the footprint of former dwelling (fill). Core samples were inspected in the field to locate the shallowest hydraulically-restrictive soil transition, which was identified as a change to a finer-textured soil material, a perched water table, and gleyic coloration as morphologic cues. Soils were described and sampled according to USDA Natural Resourse Conservation Service (NRCS) Soil Survey standards from the National Soil Survey Handbook (USDA NRCS 2010b) and the Soil Survey Manual (USDA NRCS 1993), and classified per Keys to Soil Taxonomy (USDA NRCS 2010a). All borings were advanced to approximately 4 m (13.1 ft) unless refusal or saturated soils were encountered at a shallower depth. The second boring in each subarea (i.e., native or fill) was advanced to the depth of the first hydraulically-restrictive soil (HR) as identified using the samples from the other borings. The saturated hydraulic conductivity of the HR soil was measured with a compact constant head permeameter (CCHP) (Ksat, Inc., Raleigh, North Carolina). Per Amoozegar (1989), the water flux data collected from the CCHP was used to calculate K_{sat} with

$$K_{sat} = AQ, \tag{1}$$

where K_{sat} is the estimated subsurface hydraulic conductivity ($K_{sat, HR}$), A is a constant based on the radius and head of water in the borehole, and Q is the steady-state rate of water flow into the borehole.

Laboratory Analyses. Soil samples from the surface and first subsurface hydraulically restrictive horizon were analyzed for physical and chemical characteristics. Particle size analysis was conducted using the pipette method (Gee and Bauder 1986) with hydrogen peroxide treatments to remove organic matter (no other treatments were necessary). Soil pH was measured using a Ross combination glass electrode (Thermo Fisher Scientific; Beverly, Massachusetts) with a 1:1 suspension in deionized water (Eckert and Sims 1995). Available calcium (Ca), copper (Cu), magnesium (Mg), P, K, sulfur (S), and zinc (Zn) were measured using the Mehlich 3 extraction with inductively coupled plasma atomic emission spectroscopy (Varian 730-EOS; Agilent Corp., Santa Barbara, California), (Wolf and Beegle 1995) with cation exchange capacity subsequently calculated by summation (Ross 1995). Dry combustion methods were used to determine total C (Nelson and Sommers 1996) and N (Bremner 1996) with a CE Instrument (Wigan UK) EA1110 CHNS-O analyzer.

Statistical Analysis. Approximately 7% to 10% percent of data were missing from various fields in the final dataset. This was predominantly due to limited access to certain parts of a site for the requisite amount of time required to complete a measurement, but also due to insufficient amount of soil to supply all analytic procedures. To facilitate standard statistical analyses, the missing data were imputed to have minimal effect on the cross-variable covariance matrix, with the imputed values being similar to variable means. Data were pooled where necessary to reflect site-level conditions, and each variable was rank-transformed. The imputations were performed on the Statistical Analysis System (version 9.3; SAS Institute, Research Triangle Park, North Carolina).

The data were analyzed using commercially available add-ons for Microsoft Excel (ver. 10; Microsoft; Redmond, Washington) augmented with macros written in Visual Basic to facilitate data handling and tabulation. Nominal (nonnumeric) data as well as numeric data were included in the statistical analyses, with nominal data treated as classes and ordinal data treated as ranks. Pearson and Spearman correlations were computed for all pairings of numeric variables. Nonnegative linear correlation for pairings of numeric and nominal variables was estimated from the square root of a one way analysis of variance test (ANOVA) adjusted r^2. Nonnegative linear correlation for pairings of nominal variables was estimated using contingency tables, because existing statistics for pair-wise comparison of nominal variables that we are aware of (e.g., Cramer's V) generally require use of additional information such as expected values, or are relatively complex to calculate. We constructed a two-way contingency table for each pairing, including one row for each extant level of the first variable and one column for each extant level of the second variable. We populated the cells of the table with the number of occurrences of each class-level pairing across the two variables, and reduced the value of each nonzero table cell by one. A grand sum of squares was calculated by summing the squares of these values, and then we calculated partial sums of squares for each variable by summing across the opposite dimension of the table prior to squaring and final summation. An r^2 was estimated by dividing the grand mean by the square root of the product of two partial sums of squares. The square root of the r^2 was used as our measure of correlation between the two nominal variables.

A screening test of significance for each pair-wise correlation was conducted using a t-test on Fisher-transformed correlations. We used an alpha of 0.05, adjusted using a Bonferroni correction for all possible comparisons, and that controlled the probability of Type I errors at the expense of an elevated probability of Type II errors.

Principal component analysis (PCA) was performed on the cross-variable rank correlation matrix via singular value decomposition to extract nonredundant information in the dataset and to quantify relationships of each of the observed variables to these latent variables. No rotation was performed. The number of underlying or latent factors in the data set that related to one or more of the land cover types was estimated using a scree plot of the singular value decomposition eigenvalues. The loading vectors of variables were then commensurately reduced in dimension, and correlations between the trimmed loading vectors were used to cluster their parent variables into groups based on which latent factors they characterized (Zha et al. 2002; Ding and He 2004; Drineas et al. 2004). A minimum correlation cutoff for inclusion in loading vector calculations was used to separate the clusters. A search of cutoffs in 0.1 increments indicated that the global optimal cutoff for cluster separation of land classes (turf, herbaceous, shrubbery, tree, bare, paved, and mown) occurred at 0.8, but the maximum amount of congruence between land cover and descriptor variable clusters existed at a local optimum at 0.5.

The magnitudes of the factor loading vectors were used to rank the utility of each variable within its group, based on the presumption that higher overall loadings corresponded to better characterization of the latent factor(s) underlying the MSD. Thus, a reader could use the results of this study to choose the best of whatever preexisting data are available to them from each group, and to choose which additional variables to measure, to characterize the suitability for GI of any urban soils they are interested in. The best subset would be comprised of at least one variable that characterized each latent factor, preferably with the largest magnitude within its group.

Variable	n	Permeability (k)	Maximum	Minimum	Mean	se
Parcel Conditions (interior)						
Turf (%)	118	—	95	0	49.9	2.84
Herbaceous (%)	118	—	95	0	30.1	2.43
Shrub (%)	118	—	30	0	2.8	0.51
Tree (%)	118	—	30	0	5.2	0.63
Bare (%)	118	—	80	0	10.3	1.35
Paved (%)	118	—	10	0	1.5	0.24
Mown (class)	118	binary	—	—	—	—
Parcel Conditions (perimeter)						
Turf (%)	118	—	95	0	17.8	2.44
Herbaceous (%)	118	—	70	0	11.5	1.48
Shrub (%)	118	—	50	0	13.2	1.03
Tree (%)	118	—	35	4	017.3	3.01
Bare (%)	118	—	20	0	0.7	0.26
Paved (%)	118	—	85	0	42.0	2.44
Mown (class)	116	binary	—	—	—	—

Table 1
Land cover.

Results and Discussion

Site Conditions. In the case of the Cleveland vacant lots, diverse land coverage may be a product of a wide variety of niches for plant colonization (Jim 1998; Godefroid et al. 2007). Some proportion of volunteer vegetation, as well as bare or paved areas, was present at all sites. Grass seed was spread after buildings were razed. No other intentional plantings were done, and no previous plantings were removed other than any incidentally destroyed during razing. Not surprisingly, management of vegetation with mowing was positively correlated with percent turf cover and negatively correlated with all other cover types. Herbaceous plants were concentrated at the margins of disturbance from razing, and in site areas with cracks where there was the pavement or incomplete demolition, rather than only invading turf. Shrub cover was likely to coexist with herbaceous and tree cover, though quite logically not in mown site areas. Shrubs observed appeared to be volunteers rather than obviously planted ornamentals.

The predominant interior cover on the sites were turf and herbaceous, and perimeter areas were mostly paved or bare, with the distinction between these often gradational due to mixtures of undemolished patches of pavement and bare fill (table 1). Interior turf cover was positively correlated with perimeter turf cover. The strongest correlation by far was a negative one between interior turf and interior herbaceous material (table 2). This is consistent with an antagonistic relationship between turf and weeds, although field observations indicated that weeds were often clustered in pavement cracks and at the edges of disturbed areas. There were also weaker, but still negative relationships between interior turf cover with interior shrub, tree, and paved covers. This is consistent with a competitive relationship of turf with other vegetative covers, and with domination of sites by either large proportions of turf or pavement.

In contrast with the apparently antagonistic relationships between interior turf and other covers, interior herbaceous cover was positively albeit weakly correlated with shrub and paved cover. It is possible that some or all of these correlations are spurious, the result of turf cover dominating a closed system (fixed proportional area of 100%). Nonetheless, these relationships are consistent with early-succession weeds and shrubs conjointly colonizing sites. Tree cover was generally sparse, possibly due to their later succession status, so the lack of their inclusion in the suite of herbaceous relationships could be due to lack of representation in the dataset. At the parcel perimeter turf cover was positively correlated with bare areas, apparently due to interspersion of turf and bare areas due to incomplete establishment of postrazing seeding. Perimeter turf cover was negatively correlated with herbaceous, shrub, tree, and pavement cover. Similar to site interiors, domination of these areas by turf would predict antagonistic relationships with other covers.

Shading from the cardinal directions was often present (table 3). Significant relationships between site covers and shade were more frequent at site perimeters than within site interiors (table 4), most frequent on northern exposures, and least frequent on southern exposures. On razed sites shade comes predominantly from buildings and trees on adjacent sites, and trees at the site perimeter. Shade was positively correlated with pavement and tree cover. Shade was usually negatively correlated with herbaceous cover, possibly due to a predominance of shade intolerant rather than tolerant herbaceous species, or more effective competition in the shade by C3-metabolism grass seed mixes typical of the area. These relationships were biased due to ongoing maintenance of complete turf coverage in park parcels, and ten vacant lot sites from our 2011 sampling that were highly-managed under a uniform turf cover.

Soil Physical Characteristics. Our measurement of refusal frequency at the ground surface indicated prevalent shallow-buried debris (average of 70%) (table 3). The percentage of "rock" fragments in the surface soil, including anthropogenic materials such as brick and block, was positively correlated with both shrub and bare cover and negatively correlated with pavement (table 4). Rock fragments were more prevalent in disturbed areas, and undisturbed lawns established prior to demolition appeared to be less frequently invaded by volunteer vegetation than disturbed areas reseeded after building razing. Rock fragment percentages in the deeper soil HR horizons, generally below the depth of demolition disturbances, surprisingly exhibited significant yet different relationships with land covers; they were positively correlated with turf, herbaceous, and shrub covers, yet negatively correlated with bare areas, pavement, and trees (table 5). Also, all of the respective partial correlations (not shown) were significant with the exception of perimeter trees, indicating that the relationships were not likely to be spurious. We have no satisfactory explanation for these relationships.

Based on grain size distributions (table 3), surface soils were classified as sandy loam to silt loam, and HR soils varied from coarse sand to silty-clay loam. The percentage sand in surface and HR soils was negatively correlated with turf and tree cover, but positively correlated with herbaceous cover, perhaps indicating better adaptation of weeds to sandier, presumably drier and possibly less fertile soils. Silts and clays (fines) generally showed correlations to vegetation opposite those for

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Table 2
Land cover rank correlations. The entry "ns" indicates a correlation indicated to be insignificant by a pairwise Fisher test.

	Pavement		Bare		Tree		Shrub		Herbaceous		Turf		Mown	
Variable	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter
Pavement														
Site	—	ns	ns	ns	ns	ns	ns	0.23	0.51	0.24	−0.39	−0.18	ns	ns
Perimeter	—	—	0.38	−0.33	ns	ns	ns	ns	ns	−0.44	−0.19	−0.48	ns	ns
Bare														
Site	—	—	—	ns	ns	ns	ns	−0.20	ns	ns	−0.28	ns	ns	ns
Perimeter	—	—	—	—	ns	ns	ns	−0.16	ns	ns	ns	0.16	ns	ns
Tree														
Site	—	—	—	—	—	0.27	0.23	ns	ns	ns	−0.19	ns	ns	ns
Perimeter	—	—	—	—	—	—	0.22	ns	0.30	ns	−0.38	−0.34	−0.20	ns
Shrub														
Site	—	—	—	—	—	—	—	0.22	0.26	0.16	−0.33	−0.29	−0.29	ns
Perimeter	—	—	—	—	—	—	—	—	0.30	ns	ns	−0.34	−0.48	ns
Herbaceous														
Site	—	—	—	—	—	—	—	—	—	0.27	−0.81	−0.48	−0.39	ns
Perimeter	—	—	—	—	—	—	—	—	—	—	−0.22	ns	−0.21	ns
Turf														
Site	—	—	—	—	—	—	—	—	—	—	—	0.46	0.39	ns
Perimeter	—	—	—	—	—	—	—	—	—	—	—	—	0.25	ns
Mown														
Site	—	—	—	—	—	—	—	—	—	—	—	—	—	ns
Perimeter	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 3
Site and soil physical characteristics (class-variables excluded).

Variable	*n*	Maximum	Minimum	Mean	se
North shade (%)	115	100	0	24.2	2.73
South shade (%)	115	96	0	28.6	2.81
East shade (%)	115	100	0	22.3	2.74
West shade (%)	115	98	0	28	3.09
Surface soil					
Sand (%)	118	90	10	55	1.5
Silt (%)	118	58	7	29	1
Clay (%)	118	32	2	12	0.5
Rock fragment (%)	118	40	0	19	1
Other fragment (%)	107	50	5	24	1
Frequency of refusal (%)	63	1	0	0.7	0.02
Average depth of refusal (cm)	882	31	2	12.6	0.59
K_{sat}, tension infiltrometer (TI) (cm h^{-1})	118	10.58	0.03	1.70	0.16
K_{sat}, std TI measures (cm h^{-1})	118	6.62	0	0.88	0.10
HR soil					
Sand (%)	118	92	1	50	2.2
Silt (%)	118	68	7	32	1.4
Clay (%)	118	44	1	13	0.9
Rock fragment (%)	118	100	0	22	2.1
Other fragment (%)	62	100	2	24	2.4
K_{sat} compact constant head permeameter (CCHP) (cm h^{-1})	118	126.51	0	5.76	1.39
Depth of CCHP measurement (cm)	118	184.00	55	98.40	3.04
Time to CCHP equilibrium (min)	118	120.00	2.50	29.90	1.91

Table 4
Land cover rank correlations with site and surficial soil characteristics. The entry "ns" indicates a correlation indicated to be insignificant by a pairwise Fisher test.

	Pavement		Bare		Tree		Shrub		Herbaceous		Turf		Mown	
Variable	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter
North shade	ns	0.18	ns	ns	0.27	0.21	0.19	−0.21	0.19	ns	−0.24	ns	ns	ns
South shade	ns	ns	ns	ns	ns	0.17	ns	−0.24	ns	ns	ns	ns	0.22	ns
East shade	ns	0.29	0.18	ns	0.27	0.20	ns	−0.19	ns	ns	ns	ns	ns	ns
West shade	ns	0.28	ns	ns	ns	ns	ns	−0.19	ns	−0.16	0.16	ns	ns	ns
Native or fill	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Horizon	ns	0.16	ns	0.38	ns	ns	0.18	0.40	ns	0.36	ns	0.25	0.26	ns
Series	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Classification	0.27	0.28	0.28	ns	ns	0.28	ns	0.24	0.24	ns	0.25	0.16	ns	ns
Texture	ns	0.26	ns	ns	ns	0.16	0.17	ns	0.24	0.22	0.23	0.30	ns	ns
Color	ns	0.31	ns	0.25	0.16	ns	0.26	ns	ns	0.30	0.19	0.25	0.39	ns
Redox color	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Sand (%)	ns	0.32	ns	−0.21	ns	ns	ns	ns	0.19	ns	−0.16	−0.27	ns	ns
Silt (%)	ns	ns	ns	ns	ns	ns	ns	0.33	ns	0.24	ns	ns	−0.33	ns
Clay (%)	ns	ns	ns	ns	ns	ns	ns	0.21	ns	0.16	ns	ns	−0.24	ns
Rock fragment	−0.27	ns	0.18	ns	ns	ns	0.15	ns	ns	ns	ns	ns	ns	ns
Other fragment	ns	ns	ns	ns	ns	−0.21	ns	0.17	ns	ns	ns	ns	ns	ns
Type fragment	0.54	ns	ns	ns	ns	ns	0.47	0.59	ns	ns	ns	ns	0.26	ns
Fragment	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.18	ns	ns	ns	ns
Frequency of refusal	ns	−0.17	ns	0.19	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Average depth of refusal	ns	ns	−0.23	ns	ns	ns	0.24	ns	ns	−0.20	ns	ns	−0.24	ns
K_{sat}, tension infiltrometer (TI)	0.20	0.19	ns	ns	ns	ns	ns	ns	0.18	ns	−0.16	−0.33	0.17	ns
K_{sat}, std TI measures	0.20	0.16	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

sand, consistent with lower fertility and less moisture retention capacity in sandy soils.

Surface K_{unsat} measurements (mean 1.8 cm h^{-1} [0.71 in hr^{-1}]) were negatively correlated with both site and perimeter turf coverage, and positively correlated with both site and perimeter paved cover and site herbaceous cover (table 4). The mean drainage rate in the subsurface soil ($K_{sat,\,HR}$) was positively correlated with site mowing practices and negatively correlated with perimeter shrub and herbaceous cover (table 5). The K_{unsat} measurements indicated the presence of matrix flow at a surprisingly high average infiltration rate. This was in spite of the predominance of slaked soil surfaces in vacant lots. These sealed surfaces were left by erosion of fines that may have led to the subsequent sealing of the surface, preventing seed germination or otherwise mitigating against turf cover. Surface soils with a larger percentage of rock fragments (demolition debris) or frequent rates of refusal may have decreased soil depth and otherwise impeded plant root growth (Jim 1998). Subsoil drainage was affected by the typically great extent to which anthropogenic fill was used to backfill excavated areas, creating the artifact of freer drainage. This may have created perennially-droughty root zones, which would have discriminated against deeper-rooted perennial shrubs and herbaceous vegetation.

The perimeter areas, however, were apparently undisturbed by demolition activities. Due to the assumed absence of fill in subsurface of these areas, and rather deep native soil horizons, it is no surprise that they would be vegetated with deep-rooted shrub and herbaceous species. The negative correlation between land covers with $K_{sat,HR}$ (a proxy for drainage) in perimeter areas may be an indication that plants therein will thrive and succeed, compared to plants attempting to establish in disturbed areas with discontinuous soil horizons that also contain rubble and debris.

Soil Chemistry and Nutrients. Both surface and subsurface HR soil pH (table 6) were negatively correlated with turf cover, site mowing, and bare areas but positively correlated with perimeter pavement and shrubs, and site herbaceous cover (tables 7 and 8). Cation exchange capacity averaged a relatively fertile 15.7 ± 0.3 (se) in surface soil and 11.7 ± 0.5 (se) meq 100 g^{-1} in HR horizon soil (table 6) and was negatively correlated with onsite turf, mowing, and perimeter bare patches, but positively correlated with site and perimeter herbaceous cover and perimeter shrubs. Soil reaction may have been elevated in the proximity of paved concrete areas (table 6), which would predict the success of turf in the more alkaline soil, and mowing might be associated with further intentional maintenance (e.g., liming, deicing). Calcium ions were relatively predominant in overall base saturation, with the Ca ion accounting for 76% and 68% of the exchange complex for surface and HR soils, respectively. Jim (1998) suggests that dissolution of buried concrete, drywall, and plaster debris regulated the soil solution balance amongst base-forming Ca and Mg ions and the soil acidifying influence of S-containing compounds; and soluble calcium chloride deicing salts are another potential source. Vacant lots are furthermore a close analog to the unlined construction and demolition landfills studied by Weber et al. (2002). The leachate collected from these landfills was concentrated with calcium and sulfate ions, a direct outcome of the dissolution of gypsum wallboard material.

The relationships between both surface and HR horizon nutrients and land cover are positive for shrub and herbaceous cover, and absent for the other covers (tables 6 through

Table 5

Land cover rank correlations with hydraulically restrictive soil characteristics. The entry “ns” indicates a correlation indicated to be insignificant by a pairwise Fisher test.

	Pavement		Bare		Tree		Shrub		Herbaceous		Turf		Mown	
Variable	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter
Horizon	ns	0.36	ns	ns	0.47	ns	ns	0.25	ns	0.19	ns	ns	ns	ns
Parent	0.19	0.18	0.39	0.30	0.36	0.35	ns	0.25	0.23	0.26	ns	0.22	0.33	ns
Texture	ns	0.23	ns	0.34	0.23	0.26	0.40	ns	0.21	ns	0.23	0.23	ns	ns
Color	ns	0.53	ns	ns	0.26	ns	ns	0.39	ns	0.29	ns	ns	0.23	ns
Redox color	ns	ns	0.32	ns	ns	ns	ns	ns	0.93	ns	0.67	ns	1.00	ns
Sand (%)	ns	0.16	−0.18	ns	−0.25	ns	ns	ns	ns	ns	ns	−0.19	ns	ns
Silt (%)	ns	ns	0.21	−0.16	0.23	ns	ns	0.20	ns	0.20	−0.16	ns	−0.20	ns
Clay (%)	ns	ns	0.18	ns	0.26	ns	ns	ns	ns	0.19	−0.15	ns	ns	ns
Rock fragment	ns	−0.35	−0.27	ns	ns	−0.24	ns	0.36	ns	0.16	0.25	0.21	ns	ns
Other fragment	ns	ns	ns	ns	ns	−0.30	ns	ns	ns	ns	ns	ns	ns	ns
Type fragment	0.30	ns	0.45	0.73	ns	ns	ns	ns	0.48	ns	0.61	ns	ns	ns
Fragment	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Drainage	ns	ns	ns	ns	ns	0.18	ns	ns	ns	ns	0.20	ns	ns	ns
K time to equilibrium	−0.20	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 6

Soil chemistry and nutrients.

	Surface soil					Hydraulically restrictive soil				
Variable	*n*	Maximum	Minimum	Mean	se	*n*	Maximum	Minimum	Mean	se
pH	118	8.6	5.28	7.23	0.0817	18	9.1	4.8	7.01	0.105
Cation exchange capacity (meq 100 g^{-1} soil)	118	23.2	6.5	15.7	0.324	118	31.5	2.78	11.7	0.528
Total carbon (%, weight basis)	118	9.69	0.46	3.65	0.178	118	10.6	0.056	1.23	0.139
Zinc (mg kg^{-1} soil)	118	311	2.5	49.4	4.54	118	1,230	0.6	40.3	14.2
Copper (mg kg^{-1} soil)	118	218	1.9	16.8	2.42	118	228	0.9	6.97	1.95
Sulfur (mg kg^{-1} soil)	118	1,337	8.9	81.7	17.1	118	2,958	4.6	114	27.8
Total nitrogen (mg kg^{-1} soil	118	0.658	0.039	0.176	0.00842	118	0.312	0.008	0.0619	0.0039
Phosphorus (mg kg^{-1} soil)	118	758	3	91.8	9.66	118	165	1	24.1	2.44
Potassium (K) (mg kg^{-1} soil)	118	486	50	140	6.33	118	221	16	70.7	3.52
Magnesium (Mg) (mg kg^{-1} soil)	118	919	94	298	11.2	118	1,932	42	282	20.1
Calcium (Ca) (mg kg^{-1} soil)	118	9,739	1,256	3,620	105	118	24,620	441	2,590	217
Acidity	118	6.3	0	0.374	0.0983	118	11.1	0	0.822	0.161
Base saturation, K (%)	118	8	0.9	2.28	0.108	118	4.5	0.4	1.67	0.0703
Base saturation, Mg (%)	118	33	6.6	15.1	0.386	118	51.1	4.5	19.1	0.587
Base saturation, Ca (%)	118	89	53.1	76.5	0.89	118	94.4	22.7	68.1	1.43

8). There is no clear, cross-cutting mechanism that would comprehensively explain the correlations of minor nutrients to cover type, other than lower disturbance in perimeter areas allowing accumulation and leaching of ions to the shallowest, hydraulically restrictive soil (i.e., HR horizon).

Total carbon (TC) was positively correlated to site tree and perimeter herbaceous cover, and TC in the HR horizon was positively correlated with perimeter herbaceous and shrub cover, and negatively correlated to perimeter tree and pavement cover (table 7). The patterning of TC relationships with land cover in our study is unclear. Since soil pH tended toward the alkaline in both horizons sampled (table 6), however, total carbon (C) measurements accounted for organic and inorganic C sources. Correlations are largely with the less-disturbed perimeter land covers. Soil C content appeared to be related to tree and herbaceous cover, indicating enhanced C storage at parcels with higher percentage of perennial vegetation. This may also indicate, however, that the amount of TC is related to differences in disturbance history among site and perimeter areas. There were considerable mass percentage nonsoil fragments (table 6) identified as recalcitrant organic C (e.g., wood) or anthropogenic C sources as ash, slag, cotton or woolen textiles, bituminous materials, and plastic materials. Our soil taxonomic data identified a broad range of types of carbonaceous materials as buried fragments (wood, petroleum products, ash, etc.). This may indicate that our TC measures

Table 7

Site cover rank correlations with surface soil chemistry and nutrients. The entry "ns" indicates a correlation indicated to be insignificant by a pairwise Fisher test.

	Pavement		Bare		Tree		Shrub		Herbaceous		Turf		Mown	
Variable	**Site**	**Perimeter**	**Site**	**Perimeter**	**Site**	**Perimeter**	**Site**	**Perimeter**	**Site**	**Perimeter**	**Site**	**Perimeter**	**Site**	**Perimeter**
Chemistry														
pH	ns	0.22	ns	−0.30	ns	ns	ns	0.24	0.28	ns	−0.24	−0.30	−0.22	ns
Acidity	ns	−0.15	ns	0.24	ns	ns	ns	−0.26	−0.29	−0.18	0.17	0.27	0.18	ns
Base saturation														
Potassium	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.15	ns
Magnesium	ns	ns	−0.17	ns	ns	−0.17	ns	0.26	0.21	ns	ns	ns	−0.20	ns
Calcium	ns	0.18	ns	−0.27	ns	0.27	ns	0.18	0.26	0.16	−0.16	−0.30	ns	ns
Cation exchange ns capacity	ns	ns	−0.16	ns	ns	ns	0.21	0.20	0.19	−0.21	ns	−0.21	ns	
Nutrients														
Total carbon	ns	ns	ns	ns	0.18	ns	ns	ns	ns	0.23	ns	ns	ns	ns
Total nitrogen	ns	ns	ns	ns	0.16	ns	ns	ns	ns	0.17	ns	ns	ns	ns
Phosphorus	ns	0.15	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.16	ns
Potassium	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.16	ns	ns	ns	ns
Calcium	ns	ns	ns	−0.21	ns	ns	ns	ns	0.22	ns	ns	ns	ns	ns
Copper	ns	ns	ns	ns	ns	−0.16	ns	ns	ns	0.18	ns	ns	ns	ns
Magnesium	ns	ns	ns	ns	ns	−0.23	ns	0.29	0.18	0.23	ns	ns	−0.22	ns
Sulfur	ns	−0.27	ns	0.22	ns	−0.40	ns	ns	ns	ns	ns	0.30	ns	ns
Zinc	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

represent a much broader range of C sources, which can vary widely as actual organic matter composed of humified substances, wood, coal, bituminous substances, legacy leakage from heating oil tanks, and other anthropogenic C molecules (Lorenz et al. 2005).

There were some relationships between surface cover and soil metals. Surface soil mass concentration of Cu was positively correlated with perimeter herbaceous cover and negatively correlated with perimeter tree cover (table 7). Surface Zn was not correlated with any of the land cover classes. Subsurface, hydraulically restricted layer soil concentration of Cu was negatively correlated with bare site and perimeter pavement cover, and positively correlated with perimeter shrub cover (table 8). The mass concentration of Zn in HR soil was positively correlated with site turf cover, perimeter mowing, and perimeter bare areas; and negatively correlated with bare site and herbaceous, perimeter pavement cover. Overall, the Cu and Zn present in surface soil may have affected perimeter land cover only—where we assume disturbance is limited, and potential for accumulation large—and were much less than that observed by either Schindlebeck et al. (2008) or Pouyat et al. (2007) in urban sites located in Baltimore, Maryland. We could not find in the literature a basis for comparison with HR soils. The absence of a consistent pattern in the relationships between metals and land cover suggest deposition as a driver for soil Cu concentration. Copper inputs may have been elevated due to long-term use of Cu-based fungicides for past residential horticultural activities (Meuser et al. 2011) or the presence of Cu-treated lumber in construction debris. From the standpoint of promoting vegetation in vacant lots, the maximum soil concentrations of Cu and Zn in surface and HR soils were not limiting as a nutrient, or available in quantities that would be toxic (table 6).

Clustering of Land Covers and Measured Variables. We retained the top ten latent factors from the PCA of pairwise correlations between soil variables and surface covers, based on a scree plot of eigenvalues. We reasoned that the most useful soil variables should have both high total loadings on these factors and high correlations to the surface covers. We therefore used the magnitude of the loading vector for each variable, ||PCA||, and the vector-sum of the correlations of each variable to land cover classes, ||CC||, to characterize their predictive utilities (table 9 and figure 2).

Land cover types had the highest ||CC||, followed by site descriptors, soil chemistry, nutrients, and physical characteristics. Consistent with this, the ||PCA|| were stronger for land cover types, site descriptors, and soil chemistry, but were less well defined for soil nutrients and physical characteristics. It should not be surprising that land covers would have strong interrelationships, as they were characterized as proportions summing to unity. Perimeter cover may be a good indicator of overall relationships with the ensemble of measured variables, possibly because it was consistently free of disturbance.

Further interpretation is afforded by understanding the ecophysiology of plant growth. Plant growth is an integrator of growth-controlling environmental factors. Furthermore, about 70% to 90% of plant roots are usually located within the top 20 to 30 cm (65.6 to 98.4 in) of soil, with deeper roots scavenging for water rather than both water and nutrients. With this understanding, it appears that soil nutrients and physical soil characteristics were not factors that limited growth, though soil chemistry and site descriptors such as available light or soil mechanical resistance to root perfusion, were apparently related to limitation on vegetative coverage. The ||CC|| for the soil variables were generally equivalent between surface and HR soils, except for soil chemistry, for which correlations involving vegetation were more frequent with surficial soils rel-

Table 8

Site cover rank correlations with hydraulically restrictive soil chemistry and nutrients. The entry "ns" indicates a correlation indicated to be insignificant by a pairwise Fisher test.

	Pavement		Bare		Tree		Shrub		Herbaceous		Turf		Mown	
Variable	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter	Site	Perimeter
Chemistry														
pH	ns	0.24	0.25	ns	ns	ns	ns	ns	0.18	ns	−0.22	−0.24	−0.20	ns
Acidity	ns	ns	ns	0.19	ns	ns	ns	ns	−0.16	ns	ns	0.16	ns	ns
Base saturation														
Potassium	ns	ns	ns	−0.18	ns	ns	ns	ns	0.16	ns	ns	ns	0.26	ns
Magnesium	ns	ns	−0.19	−0.16	ns	ns	ns	0.28	0.20	ns	ns	ns	ns	ns
Calcium	ns	0.24	0.21	−0.19	ns	ns	ns	ns	0.19	ns	−0.23	−0.24	−0.20	ns
Cation exchange capacity	ns	ns	0.19	ns	ns	−0.17	ns	0.25	ns	0.22	ns	ns	−0.22	ns
Nutrients														
Total carbon	ns	−0.15	ns	ns	ns	−0.19	ns	0.20	ns	0.17	ns	ns	ns	ns
Total nitrogen	ns	ns	0.17	ns	0.21	ns	0.16	0.25	ns	0.22	ns	ns	−0.16	ns
Phosphorus	ns	ns	−0.29	ns	−0.19	ns	ns	ns	ns	ns	ns	ns	ns	ns
Potassium	ns	ns	ns	ns	0.18	ns	ns	0.27	ns	0.20	ns	ns	ns	ns
Calcium	ns	ns	0.28	ns	ns	0.21	ns	ns	ns	ns	ns	ns	ns	ns
Copper	ns	−0.24	−0.29	ns	ns	ns	ns	0.16	ns	ns	ns	ns	ns	ns
Magnesium	ns	ns	ns	ns	ns	−0.19	ns	0.27	ns	0.22	ns	ns	ns	ns
Sulfur	ns	ns	ns	0.18	ns	−0.18	ns	ns	ns	ns	ns	ns	ns	ns
Zinc	ns	−0.28	−0.23	0.24	ns	ns	ns	ns	−0.19	ns	0.25	ns	ns	ns

ative to HR soils. This may be due to the typically decreasing prevalence of roots with increasing depth, and scavenging for nutrients in the uppermost soils where they are usually most available. There was also a relatively strong correlation between percent site interior tree cover and shade (table 4 and ||CC|| in table 9), indicating that the shade (a site-level descriptor) may be a useful variable for predicting the type and extent of vacant lot vegetative cover.

The best clusterings are based on paired correlations of PCA loading vectors for each of the variables. Five clusters were identified based on the cutoff of 0.5 (table 9). The relationship between variables and individual land cover types appeared to be stronger for perimeter land covers than site interior land covers. A large proportion of the descriptor variables fell in PCA cluster 1, and particularly for surface and HR soil physical characteristics and soil nutrient groupings. Cluster 1 was associated with land covers including onsite trees, shrubs, and weeds. Cluster 2 contained only double-ring infiltrometer K_{sat}, for which there were no relationships to land cover, and was therefore of no value. Cluster 3 indicated that site interior herbaceous (weeds) were related to frequency of refusal (a proxy for soil strength, and amount of buried debris), and soil pH at both depths. The relationship to soil pH in the HR soil is probably spurious, occurring due to the similarity of the pH between sampled depths. Cluster 4 contains bare site interiors only, and was therefore of no value. Cluster 5 was associated with site interior and perimeter covers of pavement and turf, site interior mowing, and site perimeter bareness and trees, all associated with both surface and HR descriptors of percentage of sand, acidity, base saturation components of K and Ca, and P; southern shade; and surficial refusal and depth of HR-CCHP borehole hydraulic conductivity.

From a statistical standpoint, the efficiency of clustering relationships was optimized by keeping the number of "best" clusters limited to the number of land cover categories. Shrub and herbaceous areas (cluster 1) were separated from pavement, turf, mowing, and some bare areas (cluster 5). Likewise, cluster 1 was heavily represented in both surface and HR soil physical characteristics and nutrients, while cluster 5 was represented by probe resistance (refusal), sand content, permeability, K and Ca base saturation, and P. Broadly, our results seem to indicate that paved and lawn areas were associated with better-drained sandy soils that were relatively high in K and Ca base saturation, and P, while (deeper-rooted) shrubs and weeds apparently integrated across the whole of soil descriptors and thus this land cover would have potentially less discriminatory value. If the observed variables do not exhibit appreciable range of variation relative to plant requirements in any study locale, then there is a significant likelihood that our analytical methods might fail to identify important members of an MSD. Also, a limited range of variation within selected variables, within a given study area, might result in inability to separate variables into sensible groupings due to confounding of unmeasured, underlying factors.

In order to proceed toward a soil management and utilization goal, the concept of soil quality becomes operative when the desired soil functions are clearly stated. Note that in the work of Schindelbeck et al. (2008) and Vrščaj et al. (2008), the former did not provide data sampling distributions against which normative judgments of soil quality were made, and the latter left choice of measurements flexible, yet largely undefined. A change in higher expectations for urban soil functions motivates greater consideration for managing these distinctive soils. The gap between urban vacant lot soils as they are, and the management inputs that they would need to reach full potential is largely an open-ended question. A holistic approach to vacant lot management through green infrastructure would include building soil organic matter, to increase soil tilth and fertility (Jim 1998; Smagin et al. 2006) and protect soils from degradation (Abiven et al. 2009), which may be carried out with agroecosystem management techniques (e.g., intentional cover cropping). Over the course of this admittedly longer-term process, the lot would be expected to demonstrate improved infiltration rates (as higher K_{unsat}) and capacity over time, along with an enhanced ability to sustainably support vegetation as green infrastructure. When it comes to the implementation of green infrastructure, many cities and municipalities circumvent correcting the management gap of urban soils by simply replacing them with engineered soils.

Summary and Conclusions

We adapted a traditional approach to soil quality characterization, with emphasis on soil physical and chemical characteristics to determine if there were common or unique physical and chemical characteristics of vacant lots that support a certain type and extent of vegetative cover. We have shown that urban soils are generally supportive of opportunistic plant communities, and that the extant combinations of soil physical and chemical properties make this possible. Our results emphasize the potential of soils in perimeter land cover to support volunteer vegetation, which are the least disturbed in comparison to the residential footprint of the site area. Due to the effects of incomplete demolition, it was difficult to separate bare and paved land cover, as they were often intermixed. Although we found that all vacant lots and park areas were vegetated to some extent, the amount of degraded vacant space in bare or paved area signifies opportunity and potential for revegetation.

The foregoing analysis may be applicable to highlighting the utility of existing data in the assessment of urban soil quality, formalizing planning and management actions to restore or support soil functions required for vegetation and stormwater infiltration capacity, and in particular, clarify steps to repurpose vacant lots for provision of ecosystem services. Additional studies will be needed to better define the relevant groupings of variables necessary for inclusion in an MSD because it is unlikely that the full range of any particular variable would be expressed globally and by assessment of a single locale. Thus, variables or groups of variables might appear unimportant in any particular study simply because they do not fall appreciably outside the optimal range for plant growth or because they are not a growth-limiting factor. Additional studies will be needed to better determine the inference space, both within and between cities, for the use of readily obtainable information such as land cover to serve as proxy data for indirect characterization of urban soil quality.

Table 9

Principal component analysis (PCA) cluster membership, vector magnitudes of loadings on top ten PCA factors (||PCA||), and vector-sums of correlations to land covers (||CC||). Clusters are shown for minimum correlation cutoffs of 0.5.

Variable group	Cluster	||PCA||	||CC||
Group 1: Greenery classifications			
Pavement site	5	1.60	2.07
Perimeter	5	1.91	1.97
Bare site	4	1.80	1.84
Perimeter	5	1.67	1.91
Tree site	1	1.57	2.12
Perimeter	5	1.79	2.07
Shrub site	1	1.55	2.39
Perimeter	1	2.10	2.10
Herbaceous site	3	2.18	2.21
Perimeter	1	1.75	2.14
Turf site	5	2.20	1.85
Perimeter	5	2.00	1.82
Mown site	5	2.02	1.76
Perimeter	0	—	—
Group 2: Site variables			
North shade	1	1.79	2.10
South shade	5	1.71	1.75
East shade	1	1.67	1.93
West shade	1	1.40	1.93
Frequency of refusal	3	1.66	1.89
Average depth of refusal	5	1.57	1.79
Depth of compact constant head permeameter measurement	5	2.23	1.78
Group 3: Surficial soil physical characteristics			
Native or fill	1	0.67	0.53
Horizon	1	1.70	0.74
Classification	1	2.28	0.49
Texture	1	2.17	0.57
Color	1	2.24	0.69
Redox color		—	—
Sand (%)	5	2.79	1.41
Silt (%)	0	3.16	1.50
Clay (%)	1	2.84	1.35
Rock fragment	1	1.85	1.19
Other fragment	1	1.99	1.22
Type fragment	1	2.37	0.97
Fragment	1	2.04	1.50
Ksat, tension infiltrometer (TI)	5	1.86	1.40
Ksat, std TI measures	1	1.68	1.08

Continued

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Table 9 Continued

Variable group	Cluster	||PCA||	||CC||
Group 4: Surficial soil chemistry			
pH	3	2.01	1.68
Acidity	5	2.29	1.51
Base Saturation			
K	5	1.74	1.06
Mg	1	2.12	1.65
Ca	5	1.74	1.81
Cation exchange capacity CEC	1	2.44	1.47
Group 5: Surficial soil nutrients			
Total carbon	1	1.28	1.20
Total nitrogen	1	1.76	1.01
Phosphorus	5	2.53	0.77
Potassium	1	1.65	1.25
Calcium	1	1.97	1.30
Copper	1	1.80	1.19
Magnesium	1	3.08	1.49
Sulfur	1	1.90	1.43
Zinc	1	2.18	0.83
Group 6: Subsurface soil physical characteristics			
Horizon	1	1.65	0.86
Parent	1	2.68	0.70
Texture	1	2.47	0.71
Color	1	2.18	0.79
Redox color	1	3.62	0.71
Sand (%)	5	2.82	1.11
Silt (%)	1	3.04	1.58
Clay (%)	1	3.07	1.54
Rock fragment	1	2.32	1.54
Other fragment	1	1.58	0.85
Type fragment	1	2.45	0.68
Fragment	1	1.42	0.67
Drainage	1	1.56	0.52
K time to equilibrium.	1	1.58	1.20
Group 7: Subsurface soil chemistry			
pH	3	2.37	1.47
Acidity	5	2.00	1.45
Base Saturation			
K	5	1.60	1.48
Mg	1	1.74	1.66
Ca	5	2.17	1.46
Cation exchange capacity	1	3.06	1.42
Group 8: Subsurface soil nutrients			
Total carbon	1	2.37	1.05
Total nitrogen	1	2.49	1.50
Phosphorus	5	1.85	0.98
Potassium	1	2.41	1.48
Calcium	1	2.00	1.32
Copper	1	1.90	1.22
Magnesium	1	3.04	1.42
Sulfur	1	2.05	1.23
Zinc	1	2.13	1.25

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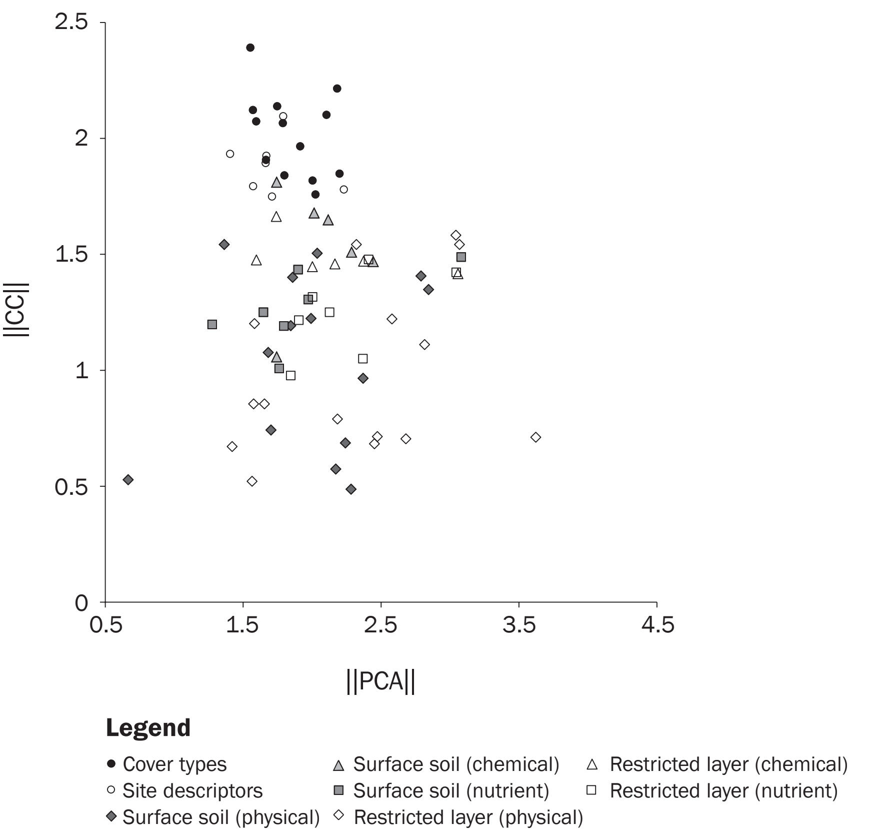
Figure 2
Magnitudes of the principal component analysis (PCA) loading vectors, ||PCA||, versus magnitudes of correlation vectors with land cover classes, ||CC||, for each variable.



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