Arboriculture & Urban Forestry 2012. 38(5): 214–228

Soil Quality Attributes as Indicators of Urban Tree Performance

Bryant C. Scharenbroch and Michelle Catania

Abstract. Soil quality assessments are needed to improve a professional's ability to manage urban soils and trees. This research was conducted to identify which soil properties are most useful for relating information on urban tree performance. In total, 48 soil properties were measured at 84 sites from five urban landscapes in the western suburbs of Chicago, Illinois, U.S. Key physical, chemical, and biological properties to be included in a minimum data set (MDS) for assessing urban soil quality were identified using statistical approaches and practical considerations. The MDS included: texture, bulk density, wet-aggregate stability, pH, electrical conductivity, soil organic matter (SOM), and particulate organic matter. The MDS was used to establish an urban soil quality index (USQI). The MDS and USQI were highly correlated with tree size attributes of height, trunk diameter, crown area, and age. Correlations between the MDS and USQI with trunk diameter growth rate, height growth rate, foliar N, and chlorophyll content were often significant, but less strong. Among the MDS parameters, SOM, pH, and texture appear to be the most informative measures for soil quality relating to urban tree performance. Soil quality and tree performance increased logarithmically following site disturbance, with a plateau after 50 years.

Key Words. Minimum Data Set; Organic Matter; pH, Texture; Tree Growth; Urban Site Index.

Soil quality is defined as the capacity of soil to function (Karlen et al. 1997). Some important soil functions include: water and solute flow and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of toxic materials, and maintenance of biodiversity and habitat (Larson and Pierce 1994; Doran et al. 1996). The term soil quality also refers to the effects of human use and management on these soil functions (Doran and Jones 1996; Seybold et al. 1999).

As a consequence of anthropogenic influences and management practices, the quality of urban soils is commonly impaired. Urban soils often have high bulk densities and low porosities, poor soil structure, altered water status and redoximorphic features, elevated pH and salinity, environmental contaminants, reduced organic matter contents, and altered microbial populations (e.g., Short et al. 1986; Craul 1999; Scharenbroch et al. 2005; Scheyer and Hipple 2005; Pouyat et al. 2007). Degraded soil conditions constrain urban tree growth and health (Craul 1992; Watson and Neely 1994; Neely and Watson 1998; Watson et al. 2008). Assessment and improvement of urban soil quality is imperative for the establishment, growth, and longevity of urban trees.

Urban tree performance (e.g., establishment, growth, longevity) is influenced by interactions of edaphic, genetic, climatic, and anthropogenic factors (Kozlowski 1971a; Kozlowski 1971b; Harris et al. 1999). Foresters commonly express the quality of the site in terms of site index or the average height of dominant trees at age 50. Techniques for estimating site quality have emphasized analysis of soil properties because site quality within moderately broad geographic areas appear to be controlled more by soil characteristics than by climatic factors (Colie and Schumacher 1953). Soil quality indicators are commonly used to predict or assess forest stand productivity (Burger and Kelting 1999; Woolery et al. 2002). To date, no such approaches have been developed for urban trees and soils.

Indices of forest soil quality are most useful if they incorporate soil physical, chemical, and biological properties, and are sensitive to management-induced changes, easily measured, inexpensive, relevant across sites and over time, and adaptable for specific ecosystems (Schoenholtz et al. 2000). Soil physical properties, especially those with direct impact on soil moisture, have been shown to have large impacts on tree growth (e.g., Zahner and Stage 1966; Schoenholtz et al. 2000; Woolery et al. 2002; Galvez et al. 2004; de Castilho et al. 2006). The importance of soil chemical properties to tree growth is represented by the voluminous literature showing the stimulating effects of fertilizers on growth of trees (e.g., Himelick et al. 1965; Schoenholtz et al. 2000; Udawatta and Henderson 2003; Galvez et al. 2004; Hamel et al. 2004). Soil biological factors influence both soil tilth and fertility (Knoepp et al. 2000), and need be considered for their impacts on urban tree growth.

Minimum data sets (MDS) of soil parameters and methods to use for assessing soil quality have been identified (e.g., Arshad and Coen 1992; Doran and Parkin 1994). These indicators should: correlate well with ecosystem processes, integrate soil properties and processes, be accessible to many users, be sensitive to management and climate, and when possible, be components of existing databases (Doran and Parkin 1994). Minimum data sets should include soil physical, chemical, and biological properties (Gregorich et al. 1994). Relatively easy to perform and cheap field diagnostic techniques are preferred to expensive laboratory measurements (Halvorson et al. 1996).

Assessment of soil quality requires evaluation of the current state of an indicator in comparison with known or desired values (Karlen et al. 1997; Burger and Kelting 1999). However, established norms for urban soil properties that accurately reflect a soil's inherent productive or environmental filtering potential do not exist. Currently, it is very difficult to evaluate urban soil quality as related to soil function criteria. Multivariate statistical approaches such as principal component analyses (PCA) provide non-subjective means to extract and weight information in complex univariate data sets and are appropriate first steps towards soil quality assessments (Halvorson et al. 1995; Wander and Bollero 1999).

In this study, physical, chemical, and biological properties contributing to urban soil quality were evaluated in relation to tree performance. The specific objectives were to 1) sample 84 plots in five locations in the western suburban area of Chicago, Illinois, U.S.; 2) characterize soils (17 physical, 17 chemical, and 14 biological responses) and trees (9 performance responses); 3) establish MDS and an urban soil quality index (USQI) for assessing urban soil quality; 4) test the MDS and USQI for predicting urban tree performance; and 5) discuss the mechanism(s) driving soil quality and tree performance in these urban landscapes.

MATERIALS AND METHODS

Site Description

Sampling occurred at four residential homeowner's associations (sites): Arboretum Estates in Glen Ellyn, IL; Baker Hill in Glen Ellyn, IL; River Oaks in Warrenville, IL; and Stonebridge in Aurora, IL; and at The Morton Arboretum in Lisle, IL; all located approximately 20 km west of Chicago, IL (Appendix 1). The four residential homeowner associations were selected from a larger group based on similarities in human impacts, soil management, topography, parent material, and age. Surveys of all trees in roadside planting strips were performed at each of the four homeowner's associations. Street trees were located in the space between the sidewalk and the road. In a few plots without sidewalks or with sidewalks up to road, street trees were in the front yard within 10 m of the street. On each site, approximately 25% of the street tree population was sampled. The major species representing each site were identified and at least nine and up to 26 trees per species were then randomly selected from that population for sampling. The Morton Arboretum was included as a fifth site to provide information on older, less-disturbed urban landscapes of similar parent material, topography, and management. Twelve arboretum trees were randomly selected from the collections list to match *Fraxinus* and *Quercus* genera found in the homeowner's associations.

Soils at the residential locations are classified as urban land, built up areas and deep, gently rolling to nearly level, moderately to poorly drained soils that have clayey subsoil and formed in glacial till (Mapes 1979). Typical native soils in these areas and at the arboretum include forest (e.g., Markham series) to prairie (e.g., Ashkum series) soils. The Markham series are fine, illitic, mesic Mollic Oxyaquic Hapludalfs, consisting of very deep, moderately well drained soils on Wisconsin, U.S., till plains formed in thin layers of loess or silty material and in the underlying silty clay loam till. Ashkum series are fine, mixed, superactive, mesic Typic Endoaquolls, consisting of very deep, poorly drained soils on till plains formed in colluvial sediments and in the underlying silty clay loam till. Mean annual precipitation is about 890 mm, and mean annual air temperature is about 10°C (Mapes 1979).

Soil management and human impacts at the residential sites were attained from interviews with managers from each homeowner's association. All sites were developed in a similar fashion, which is typical of the region. At site development, topsoil (c.a., 0 to 25 cm) was removed, and the subsoil was graded and compacted to standard densities to support the infrastructure (c.a., 1.5 to 1.7 Mg m^{-3}). Nominal depths (3 to 6 cm) of topsoil were replaced on the sites after construction. The ages of urban landscapes were inferred from manager interviews and tree cores from the sites. Site disturbance at the arboretum was relatively minimal and trees were planted in soils that were not truncated, buried, graded, or compacted. Tree planting and care on all sites was performed by qualified arborists. Tree fertilization and irrigation was performed according to standards and best management practices during the tree establishment period (two to three years). Tree fertilization was not performed on any of the trees in the three years leading up to sampling. Granular NPK fertilizer was applied annually in the spring, following manufacturer's label, to turf areas in the residential associations, but not in the arboretum. No trees received irrigation, herbicides, or pesticides in any of the sites, including the arboretum trees, over at least the past five years. Trees in all sites were pruned as needed to develop ideal form and remove dead wood, typically at three- to five-year pruning cycles. Tree ages ranged from 5- to 86-years-old, trunk diameters from 7 to 80 cm, and heights from 4 to 27 m (Appendix 1).

At each individual tree plot the following was measured and recorded: address, GPS coordinates, slope, aspect, distance to nearest building, distance to nearest hardspace, estimation of plantable space, and the percent of that space covered by cement, tar, rock, mulch, grass, and herbaceous/shrub plants (Appendix 1). In estimating plantable space, it was assumed that tree roots were able to grow beneath sidewalks, but researchers did not extend this beyond buildings, driveways, and roads. Maximum plantable space was set at 3,848 m^2 (35 m radius), which is approximately 10 times the maximum canopy surface area.

Soil Assessment

The eighty-four plots were sampled between July and August in 2010. All soil sampling was performed at random locations under the tree drip line. Many of the field assessments of soil quality were adapted from Doran's soil test kit procedure (Sarrantonio et al. 1996) and the field book for describing and sampling soils (Schoeneberger et al. 2002). Given the uncertainty and heterogeneity of urban soils, the study includes a wide and exhaustive range of soil properties from which a small subset is selected for relating tree performance. Certain soil properties are known to be highly variable (e.g., moisture and temperature) or influenced by other soil properties (e.g., penetration resistance); however, these properties were included in the initial characterization given reoccurrence in the literature to assess to soil quality, ease of measurement, and potential ability to correlate with more time-consuming or expensive soil assessments.

Soil physical observations were performed on a 25 cm × 25 cm × 20 cm deep excavation on each plot. Soil color (hue, value, and chroma) was determined using Munsell soil color charts on wet and air dried soils. Color determinations were made by three individuals per soil and means were calculated. Soil structure type (platy-massive = 0, angular blocky = 1, subangular blocky = 2, granular = 3), structure grade (structureless = 0, weak = 1, moderate = 2, strong = 3), and structure size (very fine = 0, fine = 1, medium = 2, coarse = 3) were described and scored. Numbers of fine (1 to 2 mm diameter) plant roots were estimated at ten, one cm^2 points. Coarse (2 to 10 mm in diameter) roots were estimated at four faces, each 100 cm^2. The areas of redoximorphic concentrations and depletions were estimated on the exposed profile face.

The soil from the 25 cm × 25 cm × 20 cm hole was sorted for earthworms. A hot mustard powder solution (50 g L^{-1}) was poured in the excavated hole to extract deeper earthworms (Lawrence and Bowers 2002). The number of adult and juvenile earthworms was tallied for each excavation, and reported as individuals m^{-3}. Earthworms were stored on ice in a cooler in petri dishes with damp towels and returned to the laboratory. Earthworms were identified using a dissecting microscope and dichotomous key for the Great Lakes, U.S., region (Hale 2010). For each plot, adult earthworm biomass (ash-free dry mass) was determined for each species (Hale et al. 2004). *Lumbricus terrestris* was the only species encountered in the earthworm sampling.

Three penetration resistance profiles (0 to 45 cm) were measured per plot using a cone penetrometer (FieldScout SC 900 Soil Penetrometer, Spectrum Technologies, Inc., Plainfield, IL, U.S.). Mean penetration resistance over the 0 to 20 cm depth was calculated. The root restriction depth was calculated by computing the mean penetration resistance profiles for each plot and then identifying the depth at which penetration resistance exceeded 2.3 MPa. According to Day and Bassuk (1994), the critical soil strength above which woody plant root elongation is restricted is in the vicinity of 2.3 MPa, depending on soil type and plant species.

Infiltration rate was measured at two locations per plot using a double-ring infiltrometer (Turf-Tec International, Tallahassee, Florida, U.S.). Sample locations were pre-saturated with 1 L of water. Infiltration rates were measured twice at each sample point and means computed. Volumetric water content of the 0 to 20 cm depth was measured at ten points per plot using a time-domain reflectrometry probe (Field-Scout TDR 300 Soil Moisture Meter, Spectrum Technologies, Inc., Plainfield, Illinois, U.S.). Soil temperature was measured by inserting a 10 cm thermocouple thermometer into the soil (Fluke 52 K/J Thermometer, Everett, Washington, U.S.).

Bulk density (ρ_b) was measured on undisturbed soil core samples (70 mm wide × 70 mm deep) collected from each plot. Only samples that completely filled the entire core volume were used. The core samples were kept shaded and on ice for transport to the lab. Soil was sieved, homogenized, and dried in an oven for 48 hours at 105°C. Material (roots, rock, etc.) greater than 2 mm was removed, and its volume and oven-dry weight determined for bulk density corrections for non-soil material.

Ten, 2.5 cm wide × 20 cm deep cores were taken from random plot locations for soil characterization in the laboratory. A uniform sampling depth of 20 cm was adopted since this depth is likely to include mainly the A horizon across all sample plots. The ten soil cores were composited per plot and kept shaded and on ice in a cooler for transport to the lab. In the laboratory, soil sub-samples were weighed, dried for 24 hours at 105°C, and reweighed to calculate gravimetric soil moisture (Topp et al. 2008). Sand, silt, and clay (%) were calculated using the modified pipette method of Kettler et al. (2001). Stability of aggregates (1 to 2 mm) was measured by oscillation of the sample through a height of 37 mm height, 29 times per minute for ten minutes in water (Angers et al. 2008). The oven-dry weight of water-stable aggregates (WAS) per total oven-dry soil was expressed as a percentage.

Soil pH and electrical conductivity (EC) in dS cm^{-1} were measured in 1:1 (soil:deionized) water pastes (Model Orion 5-Star, Thermo Fisher Scientific Inc., Waltham, Massachusetts, U.S.). Total C and N (%) were determined by automated dry combustion analyzer (Elementar Vario EL III CHNOS, Elementar, Hanau, Germany). Loss on ignition at 360°C for six hours was used to determine the soil organic matter (SOM) (Nelson and Sommers 1996). Soil sub-samples were extracted with 1 M NH_4OAc (pH 7.0) and mg kg^{-1} of potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were determined with atomic adsorption spectroscopy (Model A5000, Perkin Elmer Inc., Waltham, MA, U.S.) (Schollenberger and Simon 1945). The sum of these exchangeable bases was expressed as effective cation exchange capacity (eCEC) (Sumner and Miller 1996). Sodium adsorption ratio was computed as the milliequivalent weight of Na divided by the square root of the milliequivalent weight of Ca and Mg divided by two. Soil phosphorus (P) was determined with the Olsen extraction and extracts were analyzed colorimetrically at 882 nm on a spectrophotometer (Model UV mini 1240, Shimadzu Inc., Kyoto, Japan) (Olsen and Sommers 1982). Soils were extracted with 0.5 M K_2SO_4 and NH_4^+ measured using a modified indophenol blue method for microplate analyses at absorbance readings of 650 nm (Model ELx 800, Biotek Instruments Inc., Winooski, Vermont, U.S.) (Sims et al. 1995). With Devarda's alloy, NO_3^- was reduced to NH_4^+, which was then quantified using Sims et al. (1995). Dissolved organic N was reduced to NH_4^+ with persulfate and Devarda's alloy and also measured following Sims et al. (1995). Inorganic N was the sum of extracted $NH_4^+$and NO_3^-.

Particulate organic matter (POM) was measured after shaking 25 g subsamples for 15 hours with sodium hexametaphosphate $(NaPO_3)_6$ and then collecting litter organic matter on a 2000 µm sieve, coarse POM on a 250 µm sieve, and fine POM on a 53 µm sieve (Gregorich and Beare 2008). Loss on ignition at 360°C for six hours was used to determine the OM content of the litter SOM, fine POM, and coarse POM fractions (Nelson and Sommers 1996). The soil fumigation-extraction method (Brookes et al. 1985) was used to determine microbial biomass N in mg kg^{-1}. Soil subsamples were fumigated with ethanol-free chloroform for five days and extracted with 0.5 M K_2SO_4. Microbial biomass N was the difference in dissolved organic N between the fumigated and unfumigated baseline samples, using an extraction efficiency factor of $_kEN = 0.54$ (Joergensen and Mueller 1996). Nitrogen mineralization and microbial respiration were measured using 20-day soil incubations in the dark, at 25°C and with soils adjusted to 60% water-filled-pore space. Carbon dioxide in 0.25 M NaOH traps was precipitated with $BaCl_2$, followed by 0.25 M HCl (standardized) titration to a phenolphthalein endpoint (Parkin et al. 1996), expressed as soil respiration (mg CO_2 kg^{-1} d^{-1}). Concentrations of NH_4^+ and NO_3^- in incubated soils were determined colorimetrically as previously described (Sims et al. 1995). Nitrogen mineralization was determined by subtracting inorganic N (NH_4^+ and NO_3^-) in base extracts from the extracts of the incubated soils divided by the incubation period (mg

NH_4^+/NO_3^- kg^{-1} d^{-1}). Microbial biomass C (MBC) was calculated from microbial biomass N values, assuming 8/1 microbial C/N (Inubushi et al. 1991), and used to calculate two microbial efficiency indices. The metabolic quotient (qCO_2) mg CO_2 evolved h^{-1} g^{-1} / mg MBC g^{-1} and the ratio of MBC to soil C (MBC/TOC).

Tree Performance

Tree age (years) was determined by collecting increment cores (one per tree at 1 m from ground) with a tree increment borer. Increment cores were mounted on grooved wood blocks, sanded using progressively finer sandpaper to help distinguish rings, and analyzed using a Velmex stage micrometer and a Metronics Quick-Chek 1000 (Heidenhain, Schaumburg, Illinois, U.S.). The program Measure J2X v4.2 (VoorTech Consulting, Holderness, New Hampshire, U.S.) was used to record annual ring-widths to the nearest 0.001 mm. The mean diameter growth rate (mm yr^{-1}) was computed as the mean annual increment growth throughout the tree's lifespan. Tree height (m) was measured using a Suunto clinometer (Suunto, Ogden, Utah, U.S.). Tree height growth rate was tree height divided by tree age (m yr^{-1}). Tree trunk diameter (cm) was measured at 1.38 m with a Lufkin diameter tape (Lufkin, Lufkin, Texas, U.S.). The short and long diameters of the crown were measured from the trunk to dripline, with crown area (CA) (m^2) = crown width long * crown width short * π / 400 (Uzoh and Ritchie 1996).

Leaf chlorophyll content (leaf greenness) was measured on ten random leaves per tree using a SPAD-502 Plus Chlorophyll meter (Konica Minolta, Tokyo, Japan). After measurement the ten leaves were collected and composited per tree, stored on ice, ground with a mortar and pestle in the laboratory, and analyzed for total N (%) by automated dry combustion (Elementar Vario EL III CHNOS, Elementar, Hanau, Germany). A qualitative tree condition index (TCI) value was calculated based on Webster (1979). The TCI was a summation of trunk, crown, root, structure, growth, pest, and life expectancy factors (Table 1).

Statistical Analyses

Statistical analyses were conducted using SAS JMP 7.0 software (SAS Institute Inc., Cary, North Carolina, U.S.). Data distributions were checked for normality using the Shapiro-Wilk W test. All soil responses aside from clay, WAS, ρ_b, water content, NH_4^+, dissolved organic N, Mg, and microbial biomass N, required data transformations or non-parametric tests. Variables were grouped into physical, chemical, and biological categories. Multivariate statistical analysis was conducted in two steps as suggested by Hatcher and Stepanski (1996). Multivariate analysis of variance (MANOVA) was used to detect significant location effects on at least one physical, chemical, or biological variable assessed. After meeting the criteria, analysis of variance (ANOVA) of individual parameters was run on all parameters. The obtained F statistic was used to test the null hypothesis of no location effect. Those variables for which the F statistic was significant ($P \leq 0.05$) and variance was low (CV ≤ 60) (Hatcher and Stepanski 1996), were retained for further analyses. Treatment mean separations were interpreted using Tukey-Kramer's HSD test to protect for the overall error rate.

Other studies have found principal component analyses (PCA) to be practical and effective tools in selection of appropriate soil quality indicators for predicting plant performance (Maddonni et al. 1999; Brejda et al. 2000a; Brejda et al. 2000b; Shukla et al. 2006; Rodrigues de Lima et al. 2008; Bautista-Cruz et al. 2011). Retained parameters from the ANOVA were used in PCA for fur-

Table 1. Trunk, crown, root, structure, growth, pest, and life expectancy factors comprising the urban tree condition index. Tree condition index is the summation of the seven scores. Adapted from Webster (1979).

Factor	Score				
	5	4	3	2	1
Trunk	Sound and solid throughout	Minor damage	Early decay signs	Extensive decay, hollowness, cambium damage	Same as two, but cross-section is a half circle
Crown	Dense, evenly balanced crown	Dense, slightly unbalanced crown	Thin or severely imbalanced crown	Thin and slightly imbalanced crown	Thin and severe imbalanced crown
Root	Three or more visible and evenly balanced root flares (<2 cm deep)	Three or more visible and slightly unbalanced root flares (<2 cm deep)	Less than three visible or severely unbalanced root flares (<2 cm deep)	No visible root flares and structural roots (2 to 15 cm deep)	Structural roots (>15 cm deep)
Structure	No major limbs missing, broken, or dead; no narrow crotches; good radial distribution	Narrow crotch on a major limb	One of major limbs is dead or broken	Two or three major limbs with narrow crotches and one broken or dead major limb	Two or three major limbs with narrow crotches and broken or dead major limbs
Growth	>15 cm annual twig elongation	10 to 15 cm annual twig elongation	5 to 10 cm annual twig elongation	2 to 5 cm annual twig elongation	<2 cm annual twig elongation
Pest	No insect or disease problems	Minor insect or disease problems	Minor insect and disease problems	Serious disease or insect problems (e.g., canker, wilt, bark beetles, wood borers)	Serious disease and insect problems (e.g., canker, wilt, bark beetles, wood borers)
Life expectancy	>50 years	30 to 50 years	20 to 30 years	10 to 20 years	<10 years

ther screening. Eigenvalues are the amount of variance explained by each factor. Factors with eigenvalues greater than one were retained for interpretation, because factors with eigenvalues less than one explained less variance than individual soil attributes (Kaiser 1960). The retained factors were subjected to varimax rotation, which redistributes the variance of significant factors to maximize the relationship between interdependent soil variables. All meaningful loadings (i.e., >0.40) were included in the interpretation of the PCA. Principal components that explained more than 5% of the total variance were considered significant. PCA was also used to identify single values for an USQI and also to synthesize tree attributes. Multivariate regression was used to identify relationships in the data sets. Step-wise regression modeling with mixed direction and probability to enter or leave at $P \leq 0.05$ was used to develop predictive models among soil and tree properties.

RESULTS AND DISCUSSION

Establishing the MDS for Assessing Urban Soil Quality

Using ANOVA, PCA, and regression analyses the data were screened to identify soil parameters to include in the MDS for assessing urban soil quality. The ANOVA revealed the general location effects on individual soil parameters. The PCA identified which variables differed most and which were most informative and unique. Regression analyses detected redundancy among the soil properties, and were used to select the practical and informative measures in the final MDS.

The results from the ANOVA analyses are summarized in Table 2. Location effects were evident for many factors. Sixteen parameters were excluded from further consideration because they failed to meet the screening criteria ($P < 0.05$ for location effect and CV < 60%). Thirty-two parameters met the criteria and were retained for further screening.

The relative significance of the data set parameters was assessed using PCA of the 32 retained variables from the ANOVA (Table 3). There were five significant principal components (PC) that explained 65% of the variance. The first PC explained 26% of the total variance, contrasted ρ_b, and was positively related to measures of SOM. The seven parameters with significant positive loading on PC1were: SOM, total N, total C, fine POM, total POM, K, and WAS (Table 3). Bulk density was a significant negative loading on PC1. Higher PC1 scores appear to relate increases in soil quality. Principal component 2 explained 16% of the total variance and included five positive significant variables: Ca, pH, eCEC, EC, and C/N (Table 3). Higher PC2 scores show relative decreases in soil quality. Significant PC3, PC4, and PC5 loadings explained 10%, 7%, and 6% of the total variance (Table 2). Higher PC3, PC4, and PC5 scores were interpreted as increases in soil quality. The PC3 scores were positively loaded with root restriction depth, and negatively loaded with water content, penetration resistance, and chroma. The PC4 scores were positively loaded with microbial biomass N, MBC/TOC, and silt and negatively loaded with sand. Microbial respiration was a positive, and the qCO_2 was a negative loading on PC5.

The 24 soil properties (listed in order of importance) passing the ANOVA and PCA screening included: SOM, N, C, fine POM, total POM, K, ρ_b, WAS, Ca, pH, eCEC, EC, C/N, gravimetric soil moisture, volumetric water content, penetration resistance, root restriction depth, microbial biomass N, MBC/TOC, silt, sand, clay, respiration, and qCO_2. Further screening with regression analyses were used to identify redundancy among the 24 remaining soil parameters (Table 4). In the following section, justification is provided for reducing these 24 parameters to the nine MDS parameters of: sand, silt, clay, ρ_b, WAS, pH, EC, SOM, and POM.

Measures of organic matter (SOM, C, N, and C/N) were heavily weighted in the PCA. These responses had relatively low CV values and high R2 values for the ANOVA site differences. Higher SOM, C, and N contents indicate increases in soil quality (Doran and Parkin 1994; Knoepp et al. 2000). Increased C/N ratios indicate lower decomposition rates and relatively lower N mineralization potentials (Bengtsson et al. 2003). Loss on ignition is the least costly of these analyses and was significantly correlated with the other responses (C = 1.57 + 0.0329 * SOM, $R^2 = 0.43$, $P < 0.0001$), (N = -0.0458 + 0.00479 * SOM, $R^2 = 0.86$, $P < 0.0001$), (C/N = 24.0 – 0.147 * SOM + 24.0, $R^2 = 0.42$, $P < 0.0001$), and color (SOM = 114 – 14.1 * dry value, $R^2 = 0.24$, $P < 0.0001$) (Table 4). Overestimation errors may occur with loss on ignition for soils with high clay contents and carbonate materials (Nelson and Sommers 1996). Soil C, N, or C/N ratio are more costly, but often preferred to loss on ignition due to greater accuracy. Measurements of C, N, C/N ratio, and SOM relate similar information, and any one of these measurements may be suitable. Loss on ignition was chosen in the MDS due to its lower cost of analysis.

Particulate organic matter appears to be a sensitive indicator for assessing urban soil quality. Particulate organic matter is positively related to nutrient supply and soil physical condition (Wander et al. 1994; Six et al. 2000; Scharenbroch and Lloyd 2006). Particulate organic matter was identified as the primary indicator of soil quality for assessing the impact of tillage in Illinois, U.S. (Wander and Bollero 1999). The ANOVA showed strong location effects for POM, and POM was a highly weighted variable in the PCA. In this data set, POM was significantly correlated with 27 of 48 total parameters (7 of 17 physical responses, 15 of 17 chemical responses, and 5 of 14 biological responses) (data not shown). Indices of microbial respiration, microbial biomass, and N mineralization are good estimates of potential nutrient availability, gross microbial functioning, and soil quality (Knoepp et al. 2000). Particulate organic matter was significantly correlated with these measures (microbial biomass N = 87.4 + 14.1 * POM, $R^2 = 0.26$, $P < 0.0001$), (soil respiration = 53.0 + 6.85 * POM, $R^2 = 0.05$, $P = 0.0328$), and (N mineralization = 1.18 + 0.184 * POM, $R^2 = 0.13$, $P = 0.0010$) (Table 4). The POM assessment requires substantially less time, money, and expertise to measure compared to those microbial assessments. These findings suggest POM as a necessary inclusion in a MDS to assess urban soil quality.

Soil pH influences many soil properties and is often included in assessments of soil quality (Schoenholtz et al. 2000). Higher soil pH values (>8.0) are associated with decreases in soil quality (Gale et al. 1991). Acidity is also known to inhibit biological activity, so the relationship with soil reaction and tree growth is likely not linear. Soil pH was heavily weighted in the PCA. Location effects were largely significant and variation was low for pH. Soil pH is relatively easy to measure and cost of analysis is cheap. For all of these reasons soil pH should be included in a MDS to assess urban soil quality.

Increased Na and EC indicate greater salinity and are interpreted as deleterious to soil quality (Doran and Parkin 1994; Karlen and Stott 1994). Increases in exchangeable bases can

Table 2. Analysis of variance (ANOVA)[z,y] for physical, chemical, and biological soil properties[x] in 84 plots in western suburban Chicago, IL.

	The Morton Arboretum	Arboretum Estates	Stone-bridge	River Oaks	Baker Hill	CV	R^2	*P*-value
Physical parameters								
Structure type	1.92ab	2.20a	2.08a	1.70ab	1.29b	43.9	0.21	0.0008
Structure grade[y]	1.83	2.00	2.02	2.00	1.72	31.5	0.05	0.3977
Structure size[y]	1.58a	0.70b	1.48a	1.20ab	0.72b	72.9	0.22	0.0007
Value	3.71ab	3.33b	3.70ab	4.00a	3.84a	11.5	0.17	0.0044
Chroma	1.54a	1.00b	1.15b	1.55a	1.45a	28.7	0.27	<0.0001
Redox (%)[y]	19.25ab	3.00b	24.08a	26.00a	13.19ab	105.6	0.16	0.0092
Root restriction depth (cm)	35.00a	36.54a	22.76b	17.53b	20.70b	36.3	0.55	<0.0001
Penetration resistance (kPa)	1813.02ab	1083.82b	1421.06b	2174.74a	2072.87a	42.9	0.26	<0.0001
Sand (%)	18.00a	11.59c	10.96c	13.22bc	15.05b	27.6	0.43	<0.0001
Silt (%)	37.51a	24.66bc	38.07a	33.17ab	20.81c	35.4	0.52	<0.0001
Clay (%)	44.49c	63.75a	50.98bc	53.61b	64.14a	18.6	0.52	<0.0001
WAS (%)	83.84a	84.30a	71.95b	68.14b	71.25b	14.6	0.29	0.0002
ρ_b (Mg m^{-3})	1.11b	1.05b	1.18b	1.10b	1.32a	13.1	0.40	<0.0001
Infiltration rate (mm hr^{-1})[y]	2.88a	1.14b	1.37b	1.42b	1.32b	66.4	0.29	<0.0001
Gravimetric soil moisture (%)	21.35c	31.30a	24.89b	16.35d	20.53c	23.3	0.61	<0.0001
Volumetric water content (%)	30.58b	51.35a	47.29a	32.40b	44.76a	26.4	0.39	<0.0001
Temperature (°C)[y]	16.9d	17.0d	23.0b	19.9c	24.5a	73.6	0.74	<0.0001
Chemical parameters								
pH	7.11d	7.78c	8.03b	8.12ab	8.23a	5.4	0.75	<0.0001
EC (dS m^{-1})	69.56c	113.76b	139.38b	125.52b	161.28a	30.3	0.57	<0.0001
Ca (mg kg^{-1})	866.45b	1226.95a	1122.34a	1145.84a	1190.42a	15.1	0.43	<0.0001
Mg (mg kg^{-1})	641.03c	753.68ab	797.62a	751.10ab	670.84bc	14.7	0.33	<0.0001
K (mg kg^{-1})	196.45a	199.28a	172.79ab	140.016bc	131.63c	27.8	0.36	0.0002
Na (mg kg^{-1})[y]	10.08c	64.41abc	99.56ab	58.57bc	123.52a	81.8	0.31	<0.0001
eCEC ($cmol_{(+)}$ kg^{-1})	10.15b	13.13a	13.05a	12.52a	12.35a	11.2	0.48	<0.0001
Sodium absorption ratio[y]	0.06c	0.36bc	0.56ab	0.33bc	0.71a	83.1	0.30	<0.0001
P (mg kg^{-1})[y]	18.11a	10.55ab	9.95b	8.91ab	7.18b	84.5	0.17	0.0107
NH_4^+ (mg kg^{-1})	1.89b	4.30a	3.82a	3.17ab	4.64a	52.8	0.21	0.0009
NO_3^- (mg kg^{-1})[y]	19.20	12.12	14.09	17.46	12.94	50.6	0.11	0.0637
Inorg. N (mg NH_4^+/NO_3^- kg^{-1})[y]	21.09a	16.42b	17.91b	20.62ab	17.58b	41.1	0.04	0.4882
DON (mg kg^{-1})	29.58a	24.90ab	19.43b	31.56a	19.68b	43.9	0.22	0.0004
N (%)	0.33a	0.31a	0.25b	0.24bc	0.19c	25.9	0.56	<0.0001
C (%)	3.85a	3.98a	3.60ab	3.97a	3.19b	17.5	0.25	0.0001
SOM (%)	7.55a	7.59a	6.22b	5.85bc	5.07c	20.4	0.59	<0.0001
C/N	11.62d	13.36cd	14.52bc	16.55ab	16.76a	19.2	0.41	<0.0001
Biological parameters								
Litter OM (g kg^{-1})[y]	0.62	1.19	1.40	0.69	1.13	101.90	0.07	0.1183
Coarse POM (g kg^{-1})[y]	3.03	3.15	3.21	2.68	2.84	34.3	0.04	0.5414
Fine POM (g kg^{-1})	6.13a	5.67a	5.83a	6.00a	3.95b	31.2	0.32	<0.0001
Total POM (g kg^{-1})	9.16a	8.82ab	9.04a	8.69ab	6.79b	29.3	0.18	0.0053
RES (mg CO_2 kg^{-1} d^{-1})	87.70ab	60.65b	100.20ab	123.47a	77.13ab	54.3	0.14	0.0014
MBN (mg kg^{-1})	152.74ab	167.11ab	190.72a	175.40a	132.31b	27.9	0.28	<0.0001
N min. (mg NH_4^+/NO_3^- kg^{-1} d^{-1})	2.40ab	1.63c	2.32ab	2.56a	1.92bc	40.0	0.12	0.0027
qCO_2	3.21ab	1.92b	2.81ab	3.82a	3.15a	55.9	0.09	0.0083
MBC/TOC	3.18b	3.37b	4.25a	3.69ab	3.38b	26.7	0.18	0.0006
EW (# 0.0125 m^{-3})[y]	2.17ab	2.60a	0.80bc	0.00c	0.52c	180.6	0.21	0.0009
EW biomass (mg 0.0125 m^{-3})[y]	131.92a	118.22ab	39.80bc	0.00c	61.94abc	187.7	0.11	0.0448
Fine roots (# cm^{-2})	1.33b	1.48ab	1.39b	1.30b	1.94a	49.8	0.12	0.0374
Coarse roots (# cm^{-2})[y]	3.08	3.14	3.20	2.60	2.74	69.4	0.01	0.9028
Total roots (# cm^{-2})[y]	4.42	4.62	4.59	3.90	4.68	49.6	0.01	0.9179

[z] Values within rows not followed by the same letter are significantly different at the 0.05 probability level using Tukey's HSD test.
[y] Parameters that were highly variable (CV > 60%) and not significantly affected by location ($P > 0.05$) were dropped from further consideration in principal component analyses.
[x] Wet-aggregate stability (WAS), bulk density (ρ_b), electrical conductivity (EC), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), effective cation exchange capacity (eCEC), sodium adsorption ratio (SAR), Olsen phosphorus (P), ammonia (NH_4^+), nitrate (NO_3^-), dissolved organic N (DON), nitrogen (N), carbon (C), soil organic matter (SOM), particulate organic matter (POM), microbial respiration (RES), microbial biomass N (MBN), N mineralization (Nmin), metabolic quotient (qCO_2) in 10^{-3}, and microbial biomass C / total organic C (MBC/TOC) in 10^{-2} and earthworms (EW).

indicate greater nutrient availability and retention, but are also associated with higher soil pH values (Doran and Parkin 1994). The eCEC is a value that corresponds to total CEC, but only represents the base contribution (i.e., sum of exchangeable bases). Measures of soil salinity and exchangeable bases were heavily weighted in the PCA and site differences were apparent with the ANOVA. Significant relationships were detected for EC and these other measures (Na = -59.4 + 1.10 * EC, R^2 = 0.40, $P < 0.0001$), (Ca = 802 + 2.43 * EC, R^2 = 0.33, $P < 0.0001$), (K = 206 – 0.332 * EC, R^2 = 0.09, $P = 0.0065$), (sodium adsorption ratio = -0.349 + 0.00631 * EC, R^2 = 0.40, $P < 0.0001$), and (eCEC = 10.3 + 0.0153 * EC, R^2 = 0.19, $P <$

Table 3. Principal component scores based on 32 variables[zyx]. Data from 84 plots in western suburban Chicago, IL.

	Principal component PC1	PC2	PC3	PC4	PC5
Eigenvalue	8.23	5.10	3.26	2.40	2.53
Proportion	25.71	15.93	10.19	7.49	6.04
Cumulative proportion	25.71	41.64	51.83	59.32	65.36
	Scores of five rotated eigenvectors				
SOM (%)	0.90[y]	-0.27	0.25	0.12	-0.09
N (%)	0.89[y]	-0.34	0.22	0.05	-0.07
C (%)	0.80[y]	0.22	0.15	-0.09	0.18
Fine POM (g kg^{-1})	0.74[y]	-0.08	-0.07	0.40	0.21
Total POM (g kg^{-1})	0.70[y]	0.00	-0.12	0.40	0.15
K (mg kg^{-1})	0.55[y]	-0.27	0.42	0.10	0.07
WAS (%)	0.53[y]	-0.33	0.01	-0.02	-0.33
DON (mg kg^{-1})	0.46	-0.22	-0.14	-0.09	0.20
Mg (mg kg^{-1})	0.42	0.37	0.15	0.34	-0.20
Root restriction depth (cm)	0.37	-0.37	0.59[y]	-0.19	-0.19
Structure type	0.36	-0.04	0.49	0.22	-0.02
MBN (mg kg^{-1})	0.35	0.15	0.12	0.77[y]	0.00
Silt (%)	0.29	-0.39	-0.01	0.66[y]	0.32
Nmin. (mg NH_4^+ and NO_3^- kg^{-1} d^{-1})	0.24	-0.15	-0.25	0.24	0.44
eCEC ($cmol_{(+)}$ kg^{-1})	0.22	0.82[y]	0.28	0.14	-0.16
GSM (%)	0.12	0.02	-0.83[y]	0.18	-0.28
NH_4^+ (mg kg^{-1})	0.11	0.43	-0.44	0.14	-0.22
Sand (%)	0.09	-0.18	-0.25	-0.54[y]	0.06
RES (mg CO_2 kg^{-1} d^{-1})	0.08	0.06	-0.06	0.16	0.82[y]
Ca (mg kg^{-1})	-0.01	0.84[y]	0.23	-0.19	0.00
VF/F roots (# cm^{-2})	-0.05	0.16	-0.01	-0.24	-0.04
qCO_2	-0.05	-0.02	-0.12	-0.24	-0.79[y]
PR (kPa)	-0.07	-0.06	-0.87[y]	-0.06	-0.07
MBC/TOC	-0.17	0.00	0.01	0.87[y]	-0.09
Chroma	-0.25	-0.35	-0.47	-0.06	0.15
EC (dS m^{-1})	-0.31	0.72[y]	-0.13	0.04	0.01
Clay (%)	-0.33	0.49	0.10	-0.50[y]	-0.36
VWC (%)	-0.37	0.36	-0.71[y]	0.09	-0.21
C/N	-0.44	0.63[y]	-0.10	-0.25	0.26
pH	-0.45	0.83[y]	-0.02	0.01	0.06
Value	-0.47	-0.10	-0.36	0.13	0.20
ρ_b (Mg m^{-3})	-0.55[y]	0.12	-0.39	-0.16	-0.38

[z] Only principal components with eigenvalues >1 and that explain >5% of the total variance were retained.
[y] Parameters with significant loadings on the within column principal component.
[x] Wet-aggregate stability (WAS), dissolved organic N (DON), microbial biomass N (MBN), N mineralization (Nmin), microbial respiration (RES), bulk density (ρ_b), electrical conductivity (EC), calcium (Ca), magnesium (Mg), potassium (K), effective cation exchange capacity (eCEC), gravimetric soil moisture (GSM), ammonia (NH_4^+), nitrogen (N), carbon (C), soil organic matter (SOM), particulate organic matter (POM), metabolic quotient (qCO_2) in 10^{-3} (mg CO_2 kg^{-1} d^{-1} / mg MBC g^{-1}), penetration resistance (PR), microbial biomass C / total organic C (MBC/TOC) in 10^{-2}, very fine and fine roots (VF/F).

0.0001) (Table 4). Conductivity measurements are relatively easy and have lower costs compared to measurements of exchangeable bases. Consequently, EC is the preferred inclusion in the MDS to assess urban soil quality. Exchangeable Na, Ca, Mg, and K can also be included in the MDS, but these parameters are secondary inclusions given their potential redundancy, greater costs, and need for laboratory instrumentation.

Soil texture is often included in other MDS for assessing soil quality (Doran and Parkin 1994). Loam-textured soils are preferable for plants compared to soils with higher proportions of clay or sand (Larson and Pierce 1994). Clay contents are relatively high in these urban soils, so greater amounts of silt and sand indicate higher soil quality. Location effects were significant and variation was low for percentages of sand, silt, and clay. Percentages of sand and silt were heavily weighted in PCA. For these reasons, soil texture is included in the MDS for assessing urban soil quality.

Soil compaction is a major problem in urban soils (Gregory et al. 2006). Soil quality decreases with increasing ρ_b and penetration resistance (Doran and Parkin 1994; Larson and Pierce 1994). Soil ρ_b and penetration resistance were highly loaded in the PCA, and the ANOVA showed strong site effects for these measurements. Comparisons of penetration resistance across sites and time-frames are susceptible to interferences associated with soil texture and moisture content. Soil ρ_b measurements involve field collection and minimal laboratory work (Larson and Pierce 1994) and do not have inherent spatial or temporal bias. For these reasons, ρ_b is suggested as a primary inclusion in the MDS for assessing urban soil quality. Soil penetration resistance was significantly correlated with ρ_b (ρ_b = 1.05 + 0.0000789 * penetration resistance, R^2 = 0.19, P = 0.0004) (Table 4). Soil penetration resistance may be included, but given its inaccuracies, it is only recommended as a secondary inclusion.

Wet-aggregate stability (WAS) increases with tilth and is suggested as a necessary parameter in a soil quality MDS (Arshad and Coen 1992). Aggregate stability was heavily weighted in the overall PCA, and strong location effects were detected for WAS in the ANOVA. Aggregate stability is a measure that integrates physical, chemical, and biological properties. Aggregate stability was correlated with 21 of 48 total parameters (5 of 17

Table 4. Multivariate regression and r-values with 24 soil parameters[z] passing ANOVA and PCA screening for urban soil MDS. Data from 84 plots in western suburban Chicago, IL.

	Sand	Silt	Clay	GSM	VWC	ρ_b	RRD	PR	WAS	pH	EC	Ca	K	eCEC	C	N	C/N	SOM	fPOM	POM	MBN	MB/TOC	RES	qCO_2
Sand	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Silt	-0.25	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clay	-0.11	-0.94	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
GSM	-0.34	0.01	0.11	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VWC	-0.35	-0.31	0.44	0.70	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
ρb	0.13	-0.36	0.32	-0.35	0.02	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
RRD	-0.07	0.00	0.02	0.64	0.58	-0.28	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PR	0.17	-0.05	0.00	-0.77	-0.62	0.38	-0.81	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WAS	0.00	0.15	-0.16	0.14	-0.19	-0.21	-0.06	0.03	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
pH	-0.10	-0.38	0.43	-0.10	0.40	0.36	-0.02	0.01	-0.49	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-
EC	-0.13	-0.33	0.38	-0.08	0.31	0.34	0.01	0.07	-0.36	0.70	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca	-0.13	-0.41	0.47	0.17	0.43	0.11	0.10	-0.19	-0.27	0.72	0.57	1.00	-	-	-	-	-	-	-	-	-	-	-	-
K	-0.25	0.38	-0.30	0.34	-0.04	-0.45	0.19	-0.32	0.44	-0.48	-0.29	-0.10	1.00	-	-	-	-	-	-	-	-	-	-	-
eCEC	-0.31	-0.15	0.27	0.29	0.41	-0.07	0.10	-0.24	-0.09	0.61	0.44	0.73	0.05	1.00	-	-	-	-	-	-	-	-	-	-
C	0.11	0.17	-0.21	0.12	-0.20	-0.52	0.06	-0.24	0.25	-0.19	-0.15	0.28	0.45	0.31	1.00	-	-	-	-	-	-	-	-	-
N	0.06	0.36	-0.39	0.31	-0.26	-0.54	0.10	-0.22	0.55	-0.69	-0.53	-0.24	0.66	0.00	0.70	1.00	-	-	-	-	-	-	-	-
C/N	0.11	-0.41	0.38	-0.28	0.19	0.27	-0.04	0.03	-0.54	0.71	0.55	0.61	-0.44	0.24	-0.01	-0.70	1.00	-	-	-	-	-	-	-
SOM	-0.01	0.37	-0.38	0.38	-0.21	-0.62	0.08	-0.23	0.56	-0.64	-0.51	-0.17	0.67	0.07	0.66	0.93	-0.64	1.00	-	-	-	-	-	-
fPOM	-0.07	0.51	-0.50	0.09	-0.30	-0.50	-0.06	-0.11	0.25	-0.39	-0.28	-0.16	0.39	0.03	0.59	0.64	-0.39	0.68	1.00	-	-	-	-	-
POM	-0.08	0.45	-0.44	0.08	-0.25	-0.41	-0.07	-0.07	0.30	-0.32	-0.18	-0.10	0.36	0.04	0.54	0.55	-0.30	0.62	0.94	1.00	-	-	-	-
MBN	-0.26	0.46	-0.38	0.27	0.04	-0.36	0.11	-0.19	0.15	-0.03	0.00	0.03	0.23	0.28	0.39	0.36	-0.17	0.41	0.51	0.50	1.00	-	-	-
MB/TOC	-0.34	0.37	-0.25	0.16	0.14	-0.06	0.07	-0.01	-0.02	0.09	0.09	-0.17	-0.06	0.09	-0.25	-0.09	-0.17	-0.01	0.16	0.17	0.78	1.00	-	-
RES	-0.03	0.26	-0.26	-0.24	-0.21	-0.35	-0.15	0.06	-0.07	0.05	0.02	-0.08	0.08	-0.03	0.13	0.01	0.07	0.02	0.23	0.20	0.21	0.18	1.00	-
qCO_2	0.06	0.03	-0.05	-0.33	-0.21	-0.15	-0.20	0.15	-0.12	0.02	-0.02	-0.07	-0.01	-0.17	-0.03	-0.11	0.11	-0.13	0.01	-0.02	-0.27	-0.23	0.85	1.00

[z] Sand (%), silt (%), clay (%), gravimetric soil moisture (GSM) (%), volumetric water content (VWC) (%), bulk density (ρ_b) (Mg m^{-3}), root restriction depth (RRD) (cm), penetration resistance (PR) (kPa), wet-aggregate stability (WAS) (%), electrical conductivity (EC) (dS m^{-1}), calcium (Ca) (mg kg^{-1}), potassium (K) (mg kg^{-1}), effective cation exchange capacity (eCEC) (cmol kg^{-1}), nitrogen (N) (%), carbon (C) (%), soil organic matter (SOM) (%), fine and total particulate organic matter (fPOM and POM) (%), microbial biomass N (MBN) (mg kg^{-1}), microbial biomass C / total organic C (MB/TOC), microbial respiration (mg kg^{-1} d^{-1}), metabolic quotient (qCO_2).

physical responses, 10 of 17 chemical responses, and 6 of 14 biological responses) (data not shown). It is a low-cost measure that can be performed in the field with minimal equipment requirements, thus WAS is included in the MDS for urban soil quality.

Both gravimetric and volumetric soil moisture contents revealed significant location effects with the ANOVA, but soil moisture was weakly loaded in the PCA. Soil water changes rapidly, and repeated measurements are often needed to make inference on soil quality. Furthermore, information on both water content and tension is needed to provide accurate assessments of plant available water status. Soil water content appears too elusive and not practical enough to be included in the MDS.

Compared to other studies (Wander and Bollero 1999; Brejda et al. 2000a; Brejda et al. 2000b), researchers did not detect just one soil property with the greatest potential for relating soil quality. Similar to other studies, the MDS included physical, chemical, and biological soil properties (Shukla et al. 2006; Rodrigues et al. 2008). The MDS in this research included seven soil properties: three physical (texture, ρ_b, and WAS), two chemical (pH and EC), and two biological (SOM and POM).

Establishing an Urban Soil Quality Index

A PCA was performed with the MDS soil properties to create an urban soil quality index (USQI) (Table 5). The first principal component explained 44% of the MDS soil parameters and was mostly highly loaded by SOM and pH, followed by WAS, POM, ρ_b, and EC. The second and third components explained an additional 16% and 13% of the MDS variance and were loaded by soil texture (clay, silt, and sand). The first PC explained most variance, and these values were selected for use as the USQI scores.

Evaluating the MDS Parameters and USQI for Predicting Urban Tree Performance

A PCA was performed on the nine tree response parameters to identify which variables were most important in explaining variance of the measured tree responses (Table 6). The first principal component explained 50% of the tree performance variation and was positively loaded by tree size parameters (age, trunk diameter, tree height, and crown area), and to a lesser degree, leaf N content. The second principal component explained an additional 20% and was related to tree growth parameters (trunk diameter growth rate and height growth rate). The principal components derived from tree responses (PC1 ≈ tree size) and (PC2 ≈ tree growth) were assessed in relation to the soil properties identified in the MDS and the USQI (Table 7).

The majority of the individual soil MDS parameters were well correlated to the tree response parameters (Table 7). Significant correlations were detected for silt (7 of 9), clay (8 of 9), WAS (7 of 9), ρ_b (6 of 9), pH (9 of 9), EC (6 of 9), SOM (6 of 9), and POM (5 of 9) with the individual tree response parameters. Soil pH (5 of 9), EC (5 of 9), clay (4 of 9), SOM (4 of 9), POM (4 of 9), and silt (3 of 9) were highly correlated (r-values > 0.4 and $P < 0.0001$) with many of the tree response parameters. Soil pH, clay, EC, and SOM were well correlated with PC1 ≈ tree size variable and explained 54, 32, 32, and 29% of its variance, respectively. The second principal component relating to tree growth was only correlated with WAS. The USQI values (loaded by SOM and pH) were significantly correlated with all tree responses aside from the tree condition index. Step-wise regression produced significant models for all tree response parameters, including PC1 ≈ tree size and PC2 ≈ tree growth (Table 7). Soil parameters that appeared most often in the step-wise models were SOM, pH, and texture (clay and silt). Relationships between the tree responses and the USQI and also the step-wise models were tighter than for the individual MDS parameters, suggesting multiple parameters are better predictors of urban tree performance compared to any single soil measurement.

These analyses suggest that SOM, pH, and texture are capable and most useful in explaining urban tree performance attributes. To date, no available studies have assessed urban soil quality in relation to tree performance, so it is not possible to relate these findings to an existing knowledge base. Similar approaches to this study have examined soil quality in relation to land use or agricultural plant performance. Most of these studies report SOM or C (Brejda et al. 2000a; Brejda et al. 2000b; Shukla et al. 2006; Rodrigues de Lima et al. 2008; Bautista-Cruz et al. 2011) as primary indicators of soil quality. Some of these studies also report pH and texture (Shukla et al. 2006; Bautista-Cruz et al. 2011) along with other properties (e.g., available water, porosity, bulk density, aggregate

Table 5. Principal component scores from nine soil MDS parameters[zyx]. Data from 84 plots in western suburban Chicago, IL.

	Principal component PC1 ≈ OM, pH	PC2 ≈ texture	PC3 ≈ texture
Eigenvalue	3.97	1.42	1.15
Proportion	44.18	15.78	12.83
Cumulative proportion	44.18	59.96	72.79
	Scores of three rotated eigenvectors		
SOM (%)	0.86[y]	-0.24	-0.16
WAS (%)	0.76[y]	0.07	-0.01
POM (%)	0.56[y]	-0.42	-0.37
Silt (%)	0.16	-0.94[y]	-0.18
Sand (%)	-0.03	0.03	0.83[y]
Clay (%)	-0.18	0.96[y]	-0.12
ρ_b (Mg m^{-3})	-0.57[y]	0.28	0.36
EC (dS m^{-1})	-0.68[y]	0.28	-0.37
pH	-0.78[y]	0.30	-0.26

[z] Only principal components (PC) with eigenvalues >1 and that explain >5% of the total variance were retained.
[y] Parameters with significant loadings on the within column principal component.
[x] PCA performed on only nine MDS parameters to establish urban soil quality gradient.

stability, earthworms, and micronutrients) to be important secondary inclusions to indicate differences in soil quality. Despite differences in parent material, climate, organisms, relief, time, and human influences, the MDS derived for these urban soils appears to be similar to MDS from other systems.

Table 6. Principal component scores based on nine tree response variables.[z,y] Data from 84 trees in western suburban Chicago, IL.

	Principal component PC1 ≈ size	PC2 ≈ growth
Eigenvalue	4.60	1.82
Proportion	50.09	20.25
Cumulative proportion	50.09	70.34
	Scores of two rotated eigenvectors	
Age (yr)	0.96[y]	-0.04
Trunk diameter (cm)	0.89[y]	0.38
Height (m)	0.85[y]	0.37
Crown area (m^2)	0.80[y]	0.47
Leaf N (%)	0.65[y]	0.07
Tree condition index[x]	0.26	0.59[y]
Leaf chlorophyll (SPAD)	0.19	0.67[y]
Trunk diameter growth rate (mm yr^{-1})	0.08	0.84[y]
Tree height growth rate (m yr^{-1})	-0.57[y]	0.38

[z] Only principal components (PC) with eigenvalues >1 and that explain >5% of the total variance were retained.
[y] Identifies parameters with significant loadings on the within column principal component.
[x] Tree condition index is a qualitative score of seven factor scores of growth, structure, pest, trunk, crown, root, and life.

Urban Tree Size, Soil Quality, and Landscape Age

Tree size increased with urban landscape age and also across the urban soil quality gradient (Figure 1). It is reasonable to expect tree size to increase with age and also improved soil quality with time; however, this study was unable to distinguish if either of these two mechanisms were more important. Urban soil quality is linked with urban landscape age (Figure 1). The authors propose two mechanisms for the increase in soil quality with time: 1) advances in construction equipment and compaction technology increasing the soil impact on more recently developed sites, and 2) biogeochemical processes increasing soil quality with time.

Major advances in earthmoving and soil compaction equipment in the last century include the standardization of the internal combustion engine, the sheep's foot roller (c.a., 1920s), and the vibratory compactor (c.a., 1960s) (Harris 2006). It is likely that the progression in construction technology over the past century has influenced the extent and degree of urban site disturbance and impact on soil quality. However, the significant linear relationship with soil quality and age of site disturbance in the most recently disturbed sites (within the last 30 years) (USQI = -5.66 + 0.318 * age; R^2 = 0.43, P < 0.0001) (data not shown) suggests that technological advances may not play the only role in explaining the observations.

Time is one of the five soil formation factors (Jenny 1945). There are many biogeochemical processes that may increase soil quality over time (Buol et al. 2003). The predominant examples relevant to urban soils include: littering (organic accumulation on soil surface), desalinization (removal of soluble salts), dealkalization (removal of sodium carbonate), lessivage (migration of mineral particles from A to B horizons), pedoturbation (biological or physical churning of soil materials), decomposition (breakdown of mineral and organic materials), synthesis (formation of new mineral and organic species), humification (transformation of raw organic materials to humus), mineralization (release of oxide solids through organic matter decomposition), and loosening (increase in void volumes through biological and physical processes or by leaching). A number of processes may also contribute to decreases in urban soil quality with time: salinization (accumulation of soluble salts), alkalization (accumulation of sodium carbonate), and hardening (decrease in void volume by collapse, compaction, and in-filling).

Others studies have found improvements in urban soil quality with landscape age. An urban soil study in the U.S. Pacific Northwest by Scharenbroch et al. (2005) found increased SOM contents, increased nutrient availability, increased biological activity, increased microbial efficiency, and decreased bulk density with urban landscape age. Smetak et al. (2007) found greater earthworm biomass and abundances in older urban soils compared to younger ones. Beyer et al. (1995) report increased SOM and microbial efficiencies with landscape age in urban soils in Kiel, Germany. Studies in non-urban systems confirm these studies showing soil recovery after site disturbance progresses via organic matter accumulations, increases in microbial activity and nutrient availability (e.g., Pastor et al. 1987; Zak et al. 1990; Diquelou et al. 1999).

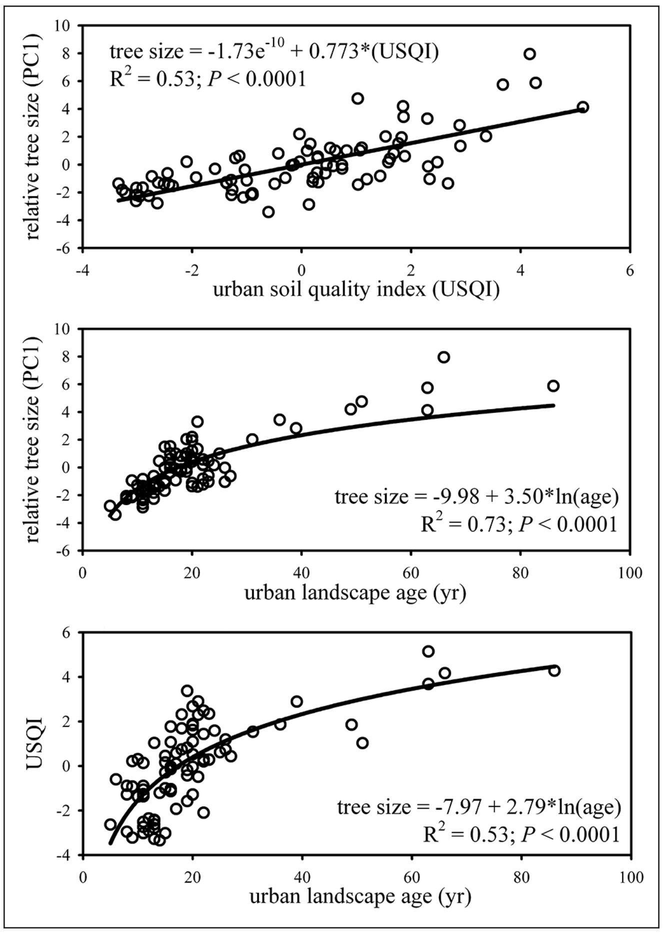

Figure 1. Relative tree size, urban soil quality index, and urban landscape age for 84 plots in western suburban Chicago, IL,U.S.

Table 7. Correlations (r-values) between the urban soil MDS parameters[z], urban soil quality index, individual tree responses, and principal components derived from nine tree response variables. Data from 84 plots in western suburban Chicago, IL.

Tree response	Individual MDS parameters									Step-wise models		USQI (PC1 ≈ OM, pH)
	Sand (%)	Silt (%)	Clay (%)	WAS (%)	ρ_b (Mg m^{-3})	pH	EC (dS m^{-1})	SOM (%)	POM (%)	r-value	Parameters	
Age (yr)	0.12	0.38**	-0.44***	0.40**	-0.36**	-0.71***	-0.52***	0.53***	0.47***	0.75***	pH, POM	0.78***
Trunk diameter (cm)	0.07	0.54***	-0.58***	0.36**	-0.39**	-0.72***	-0.56***	0.54***	0.42***	0.78***	Clay, pH, POM	0.77***
Height (m)	0.10	0.46***	-0.51***	0.29**	-0.32**	-0.68***	-0.53***	0.51***	0.45***	0.73***	Clay, pH, POM	0.75***
Crown area (m2)	0.10	0.46***	-0.51***	0.24*	-0.36**	-0.61***	-0.50***	0.54***	0.43***	0.70***	Clay, WAS, pH, SOM	0.65***
Trunk diameter growth rate (mm yr^{-1})	-0.14	0.41**	-0.37**	0.03	-0.22*	-0.23*	-0.30**	0.21	0.09	0.46***	WAS, SOM	0.41***
Height growth rate (m yr^{-1})	0.01	-0.11	0.11	-0.33**	0.23*	0.34**	0.17	-0.38**	-0.25*	-0.41**	Silt, EC, POM	-0.35**
Leaf chlorophyll (SPAD)	-0.09	0.34**	-0.32**	0.24*	-0.09	-0.23*	-0.09	0.21	0.27*	0.40***	Silt, WAS	0.32**
Leaf N (%)	0.39**	0.16	-0.30**	0.24*	-0.11	-0.63***	-0.51***	0.35**	0.05	0.73***	Sand, pH, POM	0.42***
Tree condition index	0.04	0.30**	-0.32**	-0.17	-0.01	-0.24*	-0.14	0.01	0.11	0.48**	Clay, WAS, pH, SOM	0.18
PC1 ≈ tree size	0.12	0.51***	-0.57***	0.32**	-0.36**	-0.73***	-0.57***	0.53***	0.43***	0.79***	Clay, pH, POM	0.73***
PC2 ≈ tree growth	-0.15	0.16	-0.11	-0.23*	0.10	0.20	0.10	-0.19	-0.10	0.36*	Silt, WAS, pH	0.31*

[z] Wet-aggregate stability (WAS), bulk density (ρ_b), electrical conductivity (EC), nitrogen (N), soil organic matter (SOM), and particulate organic matter (POM), minimum data set (MDS), urban soil quality index (USQI), and principal component (PC). Step-wise models are created from nine MDS soil parameters. One asterisk (*) is $P < 0.05$, two asterisks (**) is $P < 0.01$, and three asterisks (***) is $P < 0.0001$.

Soil recovery following disturbance may be delayed initially, but there is a tendency for the soil to rapidly increase after 10 to 20 years, often in association with woody vegetation establishment and differentiation of the A horizon (Zak et al. 1990; Diquelou et al. 1999). Rates of A horizon formation are variable and range from 10 year cm^{-1} in an Oregon, U.S., Mollisol soil (Forcella 1978); 12 year cm^{-1} in an Iowa, U.S., Mollisol soil (Simonson 1959); to 38 year cm^{-1} in a Wisconsin, U.S., Alfisol soil (Nielson and Hole 1964). The results of the current study demonstrate linear improvements in urban soil quality in urban landscapes that are <30-years-old, with a potential progression towards a flattening of this curve near 100 years. Scharenbroch et al. (2005) supports this finding of an approximate urban soil recovery time of >50 to 100 years.

CONCLUSION

The urban soil quality MDS for predicting urban tree performance included texture, ρ_b, WAS, pH, EC, POM, and total SOM. The authors suspect the MDS developed from these urban soils in western Chicago, IL, will be applicable to other urban soils. The MDS includes physical, chemical, and biological properties. The MDS includes parameters commonly included in standard soil assessments and other MDS databases (e.g., SOM and pH). The MDS includes soil properties that are responsive to soil management practices and disturbances at local scales (e.g., POM, WAS, and ρ_b). The MDS includes relatively permanent soil properties that are used in soil classification at global scales (e.g., texture and EC). A model for assessing urban soil quality for trees must be accurate, conceptually simple, cheap, and easy to apply. The proposed MDS meets these criteria and provides a framework for further testing. Future research should apply this MDS and test its predictive ability for tree performance in other urban systems. In order to expand to other urban areas climate (mean annual precipitation and temperature, degree days, etc.), parent material and site factors (e.g., proximity to infrastructure and plantable space) may also need to be considered. However, adding complexity to the MDS to improve accuracy must be balanced with practical considerations of taking those additional measurements.

Acknowledgments. The authors gratefully acknowledge financial support from the Tree Research & Education Endowment Fund John Z. Duling grant and The Morton Arboretum Endowment. We thank The Morton Arboretum Soil Science laboratory volunteers: Mark McKinney, Marlene Hahn, Kathy Davidson, and other volunteers for their assistance. Special thanks to the residents and homeowners associations and (their managers): Arboretum Estates Townhomes in Glen Ellyn, IL, (Lisa Cherry); Baker Hill in Glen Ellyn, IL, (Peggy Drescher and Daniel Richardt); River Oaks in Warrenville, IL (Ruth Brackmann); and Stonebridge Country Club in Aurora, IL (Roy Logan). We thank Edith Makra and Beth Corrigan for their assistance in working with the homeowners' associations.

TREE FUND
Tree Research & Education Endowment Fund

LITERATURE CITED

Angers, D.A., M.S. Bullock, and G.R. Mehuys. 2008. Aggregate stability to water. In: M.R. Carter and E.G. Gregorich (Eds.). Soil sampling and methods of analysis. Canadian Society of Soil Science. CRC Press, Boca Raton, Florida, U.S. pp. 811–820.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture 7:12–16.

Bautista-Cruz, A., F. De Leon-Gonzalez, R. Carrillo-Gonzalez, and C. Robles. 2011. Identification of soil quality indicators for maguey mezcalero (*Agave angustifolia* Haw.) plantations in southern Mexico. African Journal of Agricultural Research 6:4795–4799.

Bengtsson, G., P. Bengtson, and K.F. Mansson. 2003. Gross nitrogen mineralization-, immobilization-, and nitrification rates as a function of soil C/N ratio and microbial activity. Soil Biology and Biochemistry 35:143–154.

Beyer, L., H.-P. Blume, D.C. Elsner, and A. Willnow. 1995. Soil organic matter composition and microbial activity in urban soils. Science Total Environment 168:267–278.

Brejda, J.J., D.L. Karlen, J.L. Smith, and D.L. Allen. 2000b. Identification of regional soil quality factors and indicators: II. Northern Mississippi loess hills and Palouse prairie. Soil Science Society American Journal. 64:2125–2135.

Brejda, J.J., T.B. Moorman, D.L. Karlen, and T.H. Dao. 2000a. Identification of regional soil quality factors and indicators: I. Central and southern high plains. Soil Science Society American Journal 64:2115–2124.

Brookes, P.C., A. Landman, G. Pruden, and D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology and Biochemistry 17:837–842.

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel. 2003. Soil genesis and classification. Iowa State University Press, Ames, Iowa, U.S.

Burger, J.A., and D.L. Kelting. 1999. Using soil quality indicators to assess forest stand management. Forest Ecology and Management 122:155–166.

Collie, T.S., and F.X. Schumacher. 1953. Relation of soil properties to site index of loblolly and shortleaf pines in the Piedmont region of the Carolinas, Georgia, and Alabama. Journal of Forestry 51:739–744.

Craul, P.J. 1992. Urban soil in landscape design. John Wiley & Sons, New York, U.S.

Craul, P.J. 1999. Urban Soils: Applications and Practices. John Wiley & Sons, New York, U.S..

Day, S.D., and N.L. Bassuk. 1994. A review of the effects of soil compaction and amelioration treatments on landscape trees. Journal of Arboriculture 20:9–17.

de Castilho, C.V., W.E. Magnusson, R.N.O. de Araujo, R.C.C. Luizao, F.J. Luizao, A.P. Lima, and N. Higuchi. 2006. Variation in aboveground tree live biomass in a central Amazonian forest: effects of soil and topography. Forest Ecology and Management 234:85–96.

Diquelou, S., F. Rozeand, A.J. Francez. 1999. Changes in microbial biomass and activity during old field successions in Brittany, France. Pedobiologia 43:470–479.

Doran, J. W., and T.B. Parkin. 1994. Defining and assessing soil quality. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart. (Eds.). Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication no. 35, Madison, WI. pp. 3–21.

Doran, J.W., and A.J. Jones. 1996. Methods for Assessing Soil Quality. Soil Science Society of America Special Publication no. 49. Madison, Wisconsin, U.S.

Doran, J.W., M. Sarrantonio, and M.A. Liebig. 1996. Soil health and sustainability. Advances in Agronomy 56:1–54.

Forcella, F. 1978. Ants on a Holocene mudflow in the Coast Range of Oregon. Soil Survey Horizons 18:3–8.

Gale, M.R., D.F. Grigal, and R.B. Harding. 1991. Soil productivity index: predictions of site quality for white spruce plantations. Soil Science Society of America Journal 55:1701–1708.

Galvez, M., M.A. Parra, and C. Navarro. 2004. Relating tree vigour to the soil and landscape characteristics of an olive orchard in a marly area of southern Spain. Scientia Horticulturae 101:291–303.

Gregorich, E.G., and M.H. Beare. 2008. Physically uncomplexed organic matter. In: M.R. Carter and E.G. Gregorich (Eds.). Soil Sampling and Methods of Analysis. Second Edition. Canadian Society of Soil Science. CRC Press, Boca Raton, Florida, U.S. pp. 607–635.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Canadian Journal of Soil Science 74:367–385.

Gregory, J.H., M.D. Duke, P.H. Jones, and G.L. Miller. 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation 61:117–124.

Hale, C.M. 2010. Key to exotic earthworm species common in the Great Lakes region. Great Lakes Worm Watch. University of Minnesota. Duluth, Minnesota, U.S.

Hale, C.M., L.E. Frelich, and P.B. Reich. 2004. Allometric equations for estimation of ash-free dry mass from length measurements for selected European earthworm species (*Lumbricidae*) in the western Great Lakes region. American Midland Naturalist 15:179–185.

Halvorson, J.J., J.L. Smith, and R.I. Papendick. 1995. Integration of multiple soil parameters to evaluate soil quality: A field example. Biology and Fertility Soils 21:207–214.

Halvorson, J.J., J.L. Smith, and R.I. Papendick. 1996. Integration of multiple soil parameters to evaluate soil quality: a field example. Biology and Fertility of Soils 21:207–214.

Hamel, B., N. Belanger, and D. Pare. 2004. Productivity of black spruce and Jack pine stands in Quebec as related to climate, site biological features and soil properties. Forest Ecology and Management 191:239–251.

Harris, R.W., J.R. Clark, and N.P. Matheny. 1999. Arboriculture: Integrated management of landscape trees, shrubs, and vines. 3rd Edition. Prentice Hall, New Jersey.

Harris, S. 2006. A century of equipment. Roads and Bridges 44:1–3.

Hatcher, L., and E.J. Stepanski 1996. A step by step approach to using the SAS system for univariate and multivariate statistics. SAS Institute. Cary, North Carolina, U.S.

Himelick, E.B., D. Neely, and W.R. Crowley, Jr. 1965. Experimental field studies on shade tree fertilization. Illinois Natural History Survey Division Biology Notes 53.

Inubushi, K., P.C. Brookes, and D.S. Jenkinson. 1991. Soil microbial biomass C, N and ninhydrin-N in aerobic and anaerobic soils measured by the fumigation-extraction method. Soil Biology and Biochemistry 23:737–741.

Jenny, H. 1945. Factors of soil formation: a system of quantitative pedology. Dover Publications, Mineola, New York, U.S.

Joergensen, R.G., and T. Mueller. 1996. The fumigation-extraction method to estimate soil microbial biomass: Calibration of the kEN value. Soil Biology and Biochemistry 28:33–37.

Kaiser, H.F. 1960. The application of electronic computers to factor analysis. Educational Psychological Measurement 29:141–151.

Karlen, D.L., and D.E. Stott. 1994. A framework for evaluating physical and chemical indicators of soil quality. In: J.W. Doran (Ed.) Defining soil quality for a sustainable environment. Soil Science Society of America, no. 35. Madison, Wisconsin, U.S. pp. 53–72.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Science Society of America Journal 61:4–10.

Kettler, T.A., J.W. Doran, and T.L. Gilbert. 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Science Society American Journal 65:849–852.

Knoepp, J.D., Coleman, D.C., Crossley, D.A., and J.S. Clark. 2000. Biological indices of soil quality: An ecosystem case study of their use. Forest Ecology and Management 138:357–368.

Kozlowski, T.T. 1971a. Growth and development of trees. Volume I: Seed germination, ontogeny, and shoot growth. Academic Press, New York, U.S.

Kozlowski, T.T. 1971b. Growth and development of trees. Volume II: Cambial growth, root growth, and reproductive growth. Academic Press, New York, U.S.

Larson, W. E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. In: J.W. Doran, D.C. Coleman, D.F. Bezdicek, and B.A. Stewart. (Eds.). Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication no. 35. Madison, Wisconsin, U.S. pp. 37–51.

Lawrence, A.P., and M.A. Bowers. 2002. A test of the "hot" mustard extraction method of sampling earthworms. Soil Biology and Biochemistry 34:549–552.

Maddonni, G.A., S. Urricariet, C.M. Ghersa, and R.S. Lavado. 1999. Assessing soil quality in the rolling Pampa, using soil properties and maize characteristics. Agronomy Journal 91:280–287.

Mapes, D.R. 1979. Soil survey of DuPage and part of Cook counties, Illinois. U.S. Department of Agriculture, Soil Conservation Service and Illinois Agricultural Experiment Station, Urbana, IL.

Neely, D., and G.W. Watson. (Eds.). 1998. Landscape Below Ground II. Proceedings of the International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture. Champaign, Illinois, U.S.

Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. In: D.L. Sparks (Eds.). Methods of Soil Analysis. Part 3. Chemical Methods. Soil Science Society of America. Madison, Wisconsin, U.S. pp. 961–1010.

Nielsen, G.A., and F.D. Hole. 1964. Earthworms and the development of coprogenous A1 horizons in forest soils of Wisconsin. Soil Science Society of America Proceedings 28:426–430.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. In: A.L. Page et al. (Eds.). Methods of Soil Analysis Part 2. Soil Science Society of America. Madison, Wisconsin, U.S. pp. 403–430.

Parkin, T.B., J.W. Doran, and E. Franco-Viscaino. 1996. Field and laboratory tests of soil respiration. Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: J.W. Doran and A.J. Jones (Eds.). Methods for Assessing Soil Quality. Soil Science Society of America, no. 49. Madison, Wisconsin, U.S. pp. 231–246.

Pastor, J., M.A. Stillwell, and D. Tilman. 1987. Nitrogen mineralisation and nitrification in four Minnesota old fields. Oecologia 71:481–485.

Pouyat, R.V., I.D. Yesilonis, J. Russell-Anelli, and N.K. Neerchal. 2007. Soil chemical and physical properties that differentiate urban land-use and cover types. Soil Science Society American Journal 71: 1010–1019.

Rodrigues de Lima, A.C., W. Hoogmoed, and L. Brussaard. 2008. Soil quality assessment in rice production systems: establishing a minimum data set. Journal of Environmental Quality 37:623–630.

Sarrantonio, M., J.W. Doran, and M.A. Liebig. 1996. On-farm assessment of soil quality and health. In: J.W. Doran and A.J. Jones (Eds.). Methods for assessing soil quality. Soil Science Society of America Journal. Madison, Wisconsin, U.S.

Scharenbroch, B.C., and J.E. Lloyd. 2006. Particulate organic matter and soil nitrogen availability in urban landscapes. Arboriculture & Urban Forestry 32:180–191.

Scharenbroch, B.C., J.E. Lloyd, and J.L. Johnson-Maynard. 2005. Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49:283–296.

Scheyer, J.M., and K.W. Hipple. 2005. Urban Soil Primer. United States Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schoeneberger, P.J., D.A. Wysocki, E.C. Benham, and W.D. Broderson (Eds.). 2002. Field book for describing and sampling soils. Natural Resources Conservation Service. National Soil Survey Center. Lincoln, Nebraska, U.S.

Schoenholtz, S.H., H. Van Miegroet, and J.A. Burger. 2000. A review of chemical and physical properties as indicators of forest soil quality: Challenges and opportunities. Forest Ecology and Management 138:335–356.

Schollenberger, C.J., and R.H. Simon. 1945. Determination of exchange capacity and exchangeable bases in soils - ammonium acetate method. Soil Science 59:13–24.

Seybold, C.A., J.E. Herrick, and J.J. Brejda. 1999. Soil resilience: a fundamental component of soil quality. Soil Science 164:224–234.

Short, J.R., D.S. Fanning, J.E. Foss, and J.C. Patterson. 1986. Soils of the Mall in Washington, D.C.: I. Statistical summary of properties. Soil Science Society of America Journal 50:699–705.

Shukla, M.K., R. Lal, and M. Ebinger. 2006. Determining soil quality indicators by factor analysis. Soil and Tillage Research 87:194–204.

Simonson, R.W. 1959. Outline of a generalized theory of soil genesis. Soil Science Society of America Proceedings 23:152–156.

Sims, G.K., T.R. Ellsworth, and R.L. Mulvaney. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. Communications Soil Science Plant Analysis 26:303–316.

Six, J., E.T. Elliot, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-till agriculture. Soil Biology and Biochemistry 32:2099–2103.

Smetak K., J.L. Johnson-Maynard, and J.E. Lloyd. 2007. Earthworm population density and diversity in different-aged urban systems. Applied Soil Ecology 37:161–168

Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. In: D.L. Sparks (Ed.). Methods of soil analysis, Part 3. Chemical methods. Soil Science Society of America, no. 5. Madison, Wisconsin, U.S.

Topp, G.C., G.W. Parkin, and T.P.A. Ferre. 2008 Soil water content. In Carter, M.R. and E.G. Gregorich (Eds.). Soil sampling and methods of analysis. Canadian Society of Soil Science. CRC Press, Boca Raton, Florida, U.S. pp. 939–962.

Udawatta, R.P., and G.S. Henderson. 2003. Root distribution relationships to soil properties in Missouri oak stands: a productivity index approach. Soil Science Society American Journal 67:1869–1878.

Uzoh, F.C.C., and M.W. Ritchie. 1996. Crown area equations for 13 species of trees and shrubs in northern California and southwestern Oregon. United States Department of Agriculture. Forest Service. Pacific Northwest Research Station. PSW-RP-227-Web 1996.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Science Society of America Journal 63: 961–971.

Wander, M.M., S.J. Traina, R.B. Stinner, and S.E. Peters. 1994. The effects of organic and conventional management on biologically-active soil organic matter pools. Soil Science Society of America Journal 58:1130–1139.

Watson, G.W., and D. Neely (Eds.). 1994. The Landscape Below Ground I. Proceedings of the International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture. Savoy, Illinois, U.S.

Watson, G.W., L. Costello, B.C. Schaernbroch, and E. Gilman (Eds.). 2008. The Landscape Below Ground III: Proceedings of the International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture. Champaign, Illinois, U.S.

Webster, B.L. 1979. Guide to judging the condition of a shade tree. Journal of Arboriculture 4:247–249.

Woolery, M.E., K.R. Olson, J.O. Dawson, and G. Bollero. 2002. Using soil properties to predict forest productivity in southern Illinois. Journal of Soil and Water Conservation 57:37–45.

Zahner, R., and A.R. Stage. 1966. A procedure for calculating daily moisture stress and its utility in regressions of tree growth on weather. Ecology 47:64–74.

Zak, D.R., D.F. Grigal, S. Gleeson, and D. Tilman. 1990. Carbon and nitrogen cycling during old-field succession: constraints on plant and microbial biomass. Biogeochemistry 11:111–129.

Bryant C. Scharenbroch (corresponding author)
Research Department
The Morton Arboretum
4100 Illinois Route 53
Lisle, Illinois 60532-1293, U.S.
bscharenbroch@mortonarb.org

Michelle Catania
Research Department
The Morton Arboretum
4100 Illinois Route 53
Lisle, Illinois 60532-1293, U.S.

Résumé. Des évaluations de la qualité du sol sont nécessaires afin d'améliorer la capacité des professionnels à gérer les sols et les arbres urbains. Cette recherche a été menée pour identifier quelles sont les propriétés de sol qui sont les plus utiles afin d'obtenir des informations adéquates sur la performance d'un arbre urbain. Au total, 48 propriétés de sol ont été mesurées dans 84 sites répartis au sein de cinq aménagements localisés dans la banlieue Ouest de Chicago en Illinois aux États-Unis. Les propriétés physiques, chimiques et biologiques clés à être incluses dans un ensemble minimal de données pour évaluer la qualité d'un sol urbain ont été identifiées au moyen d'approches statistiques et de considérations pratiques. Cet ensemble minimal de données incluait: la texture, la densité, la stabilité de l'agrégat mouillé, le pH, la conductivité électrique, la quantité en matière organique du sol et la substance de la matière organique. L'ensemble minimal de données a été employé pour établir un index de qualité des sols. L'ensemble minimal de données ainsi que l'index de qualité des sols ont été fortement corrélés avec les attributs des arbres que sont la hauteur, le diamètre du tronc, la largeur de la couronne et l'âge. Les corrélations entre l'ensemble minimal de données et l'index de qualité des sols par rapport au taux de croissance en diamètre du tronc, le taux de croissance en hauteur, le contenu foliaire en azote et le contenu en chlorophylle étaient aussi significatives, mais avec un degré moins fort. Parmi les paramètres de l'ensemble minimal de données, la quantité en matière organique, le pH et la texture apparaissent être les mesures les plus instructives sur la qualité des sols en relation avec la performance de l'arbre. La qualité du sol et la performance d'un arbre s'accroissent à rythme logarithmique après la perturbation d'un site, avec un plateau après 50 ans.

Zusammenfassung. Die Untersuchungen von Bodenqualität sind erforderlich, um die Fähigkeiten der Verantwortlichen zum Management urbaner Böden und Bäume zu verbessern. Diese Studie wurde durchgeführt, um herauszubekommen, welche Bodenverhältnisse für die Erhebung von Informationen zur Straßenbaum-Performance am geeignetsten sind. Insgesamt wurden 48 Bedingungen an 84 Standorten aus fünf urbanen Landschaften in der westlichen Vorstadt von Chicago, Illinois, USA, gemessen. Die physikalischen, chemischen und biologischen Schlüsselbedingungen, die in ein Minimum-Data-Set (MDS) zur Untersuchung der urbanen Bodenqualität eingeschlossen sein müssen, wurden mittel statistischer Ansätze und praktischen Überlegungen identifiziert. Das MDS beinhaltet: Textur, Körperdichte, Stabilität des feuchten Aggregats, pH, elektrische Leitfähigkeit, organische Masse des Boden (SOM) und partikuläre organische Masse. Das MDS wurde verwendet, um einen urbanen Bodenqualitätsindex (USQI) zu etablieren. Das MDS und der USQI wurden hoch korreliert mit den Attributen der Höhe, Stammdurchmesser, Kronenfläche und Alter. Korrelationen zwischen MDS und USQI mit der Stammzuwachsrate, Höhenwachstumsrate, Blattstickstoffgehalt und Chlorophyllanteil waren oft signifikant aber weniger stark. Unter den MDS-Parametern schienen SOM, pH, und Textur am meisten informativ für die Messung von Bodenqualität in Bezug auf die urbane Baum-Performance. Die Bodenqualität und Baum-Performance stieg logarithmisch nach einer Standortstörung, mit einer Plateaubildung nach 50 Jahren.

Resumen. Las evaluaciones de calidad de suelos son necesarias para mejorar la capacidad de un profesional para administrar árboles y suelos urbanos. Esta investigación se realizó para identificar qué propiedades del suelo son más útiles para dar información sobre el rendimiento del árbol urbano. En total, se midieron 48 propiedades del suelo en 84 sitios de cinco paisajes urbanos en los suburbios occidentales del occidente de Chicago, Illinois, Estados Unidos. Se identificaron propiedades químico-físicas y propiedades biológicas que deben incluirse en un conjunto mínimo de datos (MDS) para evaluar la calidad del suelo urbano utilizando métodos estadísticos y consideraciones prácticas. El MDS incluyó: textura, densidad aparente, estabilidad de agregados húmedos, pH, conductividad eléctrica, materia orgánica del suelo (SOM) y materia orgánica particulada. El MDS se utilizó para establecer un índice de calidad de suelo urbano (USQI). El MDS y USQI estuvieron altamente correlacionados con atributos de tamaño de árbol como altura, diámetro del tronco, cobertura y edad. Correlaciones entre el MDS y USQI con la tasa de crecimiento del diámetro del tronco, tasa de crecimiento de altura, N foliar y contenido de clorofila, a menudo, fueron significantes, pero menos fuertes. Entre los parámetros MDS y SOM, pH y textura parecen ser las medidas más informativas para la calidad del suelo relacionados con el rendimiento del árbol urbano. Calidad del suelo y rendimiento del árbol incrementaron logarítmicamente, luego de la alteración del sitio con una terraza después de 50 años.