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Towards an Improved Rapid Urban Site Index

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Abstract. Background: An urban site index is an approach for identifying site quality for optimal matching of urban tree tolerances to site conditions and for determining the efficacy of soil management actions. The Rapid Urban Site Index (RUSI) was previously developed and found to significantly relate to urban tree performance. However, the RUSI needs further testing to verify its accuracy in other urban tree populations. Furthermore, calibration of the RUSI with parameter weighting and additional parameters might also improve its accuracy. Methods: The objectives of this study are to: (1) evaluate the RUSI in 3 Wisconsin cities; (2) evaluate RUSI parameter weighting models to improve its accuracy; and (3) examine the addition of a labile organic matter indicator to the RUSI for detection of a soil management action. Results: The RUSI was found to significantly correlate to urban tree metrics in 3 Wisconsin cities ($r = 0.29$ to 0.31; $n = 90$). Parameter weighting increased significant correlation values between urban tree metrics and the RUSI model ($r = 0.24$ to 0.37; $n = 90$). The Solvita® soil respiration test detected differences in soils from a biosolids application ($P = 0.0275$), and its addition to the RUSI model improved significant correlation values to urban tree metrics ($r = 0.27$ to 0.38; $n = 90$). Conclusions: This research demonstrates effective approaches for RUSI refinement. These findings show the RUSI to be a valid approach for urban site assessment and demonstrate how the RUSI can be tailored and refined for use in specific urban tree populations.

Keywords. Site Assessment; Soil Quality; Urban Soils; Urban Tree Growth; Urban Tree Health.

INTRODUCTION

Urban Site Assessments

Urban sites and soils are variable and influence tree species selection and performance. An urban site index helps arborists and urban foresters characterize this heterogeneity to increase species diversity of urban forests (Scharenbroch et al. 2017). Urban tree species have a range of site condition tolerances (Sjöman and Nielsen 2010). By planting trees with a low site condition tolerance on high-quality sites, new tree species may be successfully introduced to the urban environment. Trees with high site condition tolerance can then be planted on low-quality sites to maintain and improve forest canopy. An accurate and field-based site index may allow arborists and urban foresters to increase the health and benefit of urban forests.

An urban site index would also aid in the management of urban soils for individual tree performance. Due to the often degraded nature of urban soils, amendments have been found to enhance urban tree performance (e.g., Scharenbroch and Watson 2014). Industry standards recommend, but do not require, soil testing before and after performing management actions to monitor their necessity and impact (American National Standards Institute 2018). Current urban site assessments are limited in their ability to measure the efficacy of soil management actions (Scharenbroch and Watson 2014). Improving these assessments will allow for improved urban tree site management.

Rapid Urban Site Index

Recent efforts to create an urban site index include the Ohio urban site index (Siewert and Miller 2011), the soil quality minimum data set (Scharenbroch and Catania 2012), and the Rapid Urban Site Index (RUSI) (Scharenbroch et al. 2017). The RUSI was based on these previous urban and several nonurban site indices. The RUSI consists of 5 factors and 15 parameters. Factors include climate, urban, soil physical, soil chemical, and soil biological. Climate parameters include precipitation (PPT), growing degree days (GDD), and exposure (EXP). Urban parameters include traffic (TRA), infrastructure (INF), and surface (SUR). Soil physical parameters include texture (TEX), structure (STR), and penetration (PEN). Soil chemical parameters include pH, electrical conductivity (EC), and organic matter (SOM). Soil biological parameters include estimated rooting area (ERA), depth of the A-horizon (HOR), and wet aggregate stability (WAS). Each parameter is measured and scored from 0 to 3 using scoring functions which are described in the Appendix. After development, the RUSI was tested in 7 cities to determine its ability to predict urban tree performance. Initial testing was performed in Boston, MA, USA; Chicago, IL, USA; Cleveland, OH, USA; Springfield, MA, USA; Toledo, OH, USA; Ithaca, NY, USA; and New York City, NY, USA (Scharenbroch et al. 2017). This research showed a significant correlation between the RUSI and urban tree performance across all cities and species tested ($P < 0.0001$; R^2 values of 0.18 to 0.40).

Initial RUSI testing showed the need for refinement to other urban tree populations, parameter weighting, and inclusion of dynamic parameters that would respond to soil management. To date the RUSI has only been tested in a limited number of cities and with a few urban tree species. Research is needed to test the RUSI model's applicability in other cities and tree species.

The current RUSI assigns equal weights for all 15 parameters, but initial testing identified several parameters which appeared to be better predictors of urban tree performance. These parameters include those associated with soil volume and compaction, such as estimated rooting area (ERA), structure (STR), and wet aggregate stability (WAS). This importance was expected, as many urban tree health issues are due to limited soil volume and compaction (Jim 1998). Soil quality indices often utilize unequal parameter importance with weighting schemes (Andrews et al. 2002). In this approach, parameter weights are assigned based on available data, literature, and expert knowledge (Karlen et al. 2003).

Labile organic matter is a portion of total soil organic matter (SOM) that is readily available for decomposition by soil organisms. Consequently, it is proposed as an ideal indicator of dynamic soil properties, such as nutrient availability, and has been found to be responsive to soil management actions (Sharifi et al. 2008; van der Heijden et al. 2008). A variety of methods exist for determining labile organic matter including direct measures of organic matter pools (Marriott and Wander 2006) or microbial activity (Zou et al. 2005). Particulate organic matter (POM) is a measure of the low-density, sand-sized organic matter (Cambardella and Elliott 1992). Permanganate oxidizable carbon (POXC) is labile organic matter measured with a chemical reaction (Tirol-Padre and Ladha 2004). Total microbial biomass carbon (MBC) and nitrogen (MBN) are the total carbon (C) or nitrogen (N) contained in the microbial biomass pool and are measured with fumigation and extraction. Indirect measurements of labile organic matter include quantifying microbial respiration defined as the CO_2 production of microbial communities within a soil sample that is placed in a sealed container (Alvarez and Alvarez 2000). These CO_2 levels are often measured by observing a color change in chemical indicators. The inclusion of a more sensitive soil biological indicator may increase accuracy of the RUSI, allowing it to be used to assess soil management actions.

Objectives

This study investigated 3 knowledge gaps in the current RUSI. First, does the RUSI correlate to urban tree performance in other urban tree populations? Second, can customizing the RUSI with parameter weighting increase its correlation to tree growth and health? Third, is the RUSI sensitive to soil management actions and does the addition of a labile organic matter parameter increase this sensitivity? To address these knowledge gaps 3 specific hypotheses were developed: (1) the RUSI will significantly correlate to tree performance in 3 Wisconsin cities; (2) adjusting the parameter weighting will improve the correlation between RUSI and tree performance; (3) the addition of a labile organic matter parameter will increase the RUSI correlation to urban tree performance.

METHODS AND MATERIALS

Description of Study Cities and Plots

This research was conducted in Stevens Point, Green Bay, and Milwaukee, WI, USA. These cities were chosen due to funding available for travel to conduct the research, the cities' willingness to participate, and the presence of accurate planting and tree inventories. Full descriptions and data on human and tree populations, climate, and native soils are provided in the Appendix. Thirty sample plots were randomly selected in each city from planting data and tree inventories. A target tree age of 5 to 12 years old was selected to avoid trees that might still be under transplant stress. The most common species planted in this age cohort in all 3 cities was *Tilia* spp. and thus was chosen as the tree species for this experiment. Sample plots were defined as a single tree and the surrounding 9.3-m^2 circular or rectangular planting area. In Stevens Point and Green Bay, 15 plots were rectangular shaped between the street and the sidewalk, with the other 15 plots circular shaped (not bound by a sidewalk). In Milwaukee, all of the study sites were rectangular shaped between the street and sidewalk.

Field Assessments

Urban tree performance was assessed by a single primary investigator using urban tree growth and health metrics (Table 1). Tree performance evaluations were done independently of the site assessments to limit bias. The urban tree health metrics included tree condition (TC), tree condition index (TCI), and urban tree health (UTH), as used by Scharenbroch et al. (2017). Tree health was also assessed by measuring leaf chlorophyll contents of 12 leaves per tree using a SPAD meter (SPAD-502, Konica Minolta, Tokyo, Japan). These 12 leaves were collected on 4 sides of the tree from equally distributed branch tips throughout the bottom, middle, and top of the crown. Growth metrics included total tree height measured with a height pole and diameter at breast height, which was measured at 1.37 m and marked to ensure accurate follow-up readings. Crown volume was calculated by measuring the crown radius in each of the 4 cardinal directions and then calculated using the equations presented in Moser et al. (2015).

Table 1. Mean (n = 90), standard deviations (SD), minimum values, and maximum values for tree diameter (DIA), tree height (HT), tree crown volume (CV), leaf greenness (SPAD), tree condition (TC), tree condition index (TCI), and urban tree health (UTH).

Property	Mean	SD	Minimum	Maximum
DIA (cm)	12.6	3.88	5.48	21.8
HT (cm)	624.0	148.0	328.0	1,002.0
CV (m^3)	55.7	42.9	4.39	211.0
SPAD	38.4	6.86	20.5	57.1
TC	2.19	0.34	1.5	3.0
TCI	67.0	8.57	44.4	83.3
UTH	88.5	8.48	48.0	100.0

Site quality was assessed by a single primary investigator at each sample plot using the RUSI in the spring and fall of 2017 (Table 2). The RUSI uses climatic, urban, soil physical, soil chemical, and soil biological factors to provide an index (0 to 100) of urban site quality (Scharenbroch et al. 2017). Embedded in each of these main factors are 3 parameters. Individual parameters were assessed in the field and scored on a 0 to 3 scale using the scoring functions described in Scharenbroch et al. (2017). Observed scores were summed, divided by the maximum possible score, and then multiplied by 100 to compute the RUSI score.

Soil Collection, Treatment, and Analyses

During each site visit, 20 soil cores 2.5 cm wide by 15 cm deep were randomly collected throughout each sample plot. Cores were composited by plot, placed in individually labeled plastic bags, and kept on ice in

Table 2. Mean (n = 90), standard deviations (SD), minimum values, and maximum values for scores of precipitation (PPT), growing degree days (GDD), exposure (EXP), traffic (TRA), infrastructure (INF), surface (SUR), estimated rooting area (ERA), penetration (PEN), A-horizon (HOR), texture (TEX), structure (STR), wet aggregate stability (WAS), soil organic matter (SOM), electrical conductivity (EC), pH, and Rapid Urban Site Index (RUSI).

Property	Mean	SD	Minimum	Maximum
PPT	1.69	0.51	1.00	3.00
GDD	1.34	0.47	1.00	2.00
EXP	2.77	0.45	1.00	3.00
TRA	2.86	0.49	0.00	3.00
INF	0.72	0.45	0.00	1.00
SUR	1.89	0.40	1.00	3.00
ERA	2.31	0.73	0.00	3.00
PEN	1.63	0.84	0.00	3.00
HOR	2.42	0.51	1.00	3.00
TEX	2.46	0.58	1.00	3.00
STR	2.19	0.57	0.50	3.00
WAS	2.42	0.54	1.00	3.00
SOM	2.65	0.48	2.00	3.00
EC	1.12	0.79	0.00	3.00
pH	1.93	0.27	1.00	3.00
RUSI	67.6	5.47	51.1	81.1

a cooler until being transported to the laboratory where they were then stored at 5 °C until analyses were performed.

Immediately after the first soil sampling, a top dressing of organic biosolids (Milorganite, Milwaukee, WI, USA) was applied by hand at 3 rates. Biosolids are high in carbon, nutrients, microbes, and microbial activity, and thus have been found to stimulate the biological communities and increase decomposition and nutrient mineralization (Sullivan et al. 2006). Application rates based on nitrogen (N) content were chosen in accordance with industry standards on urban tree fertilization (American National Standards Institute 2018). Ten sites per city received the maximum rate of 2.92 kg N 100 m^{-2}, ten sites received the standard rate of 1.46 kg N 100 m^{-2}, and the remaining ten sites received no soil amendment and served as the control.

In the laboratory, each soil sample was sieved through a 6-mm screen for homogenization and removal of coarse material. Soil particle-size analysis was performed using the hydrometer method (Gee and Or 2002) to verify the field assessment of soil texture. The total soil organic matter (SOM) was determined using the loss on ignition method at 360 °C for 6 hours (Nelson and Sommers 1996). The particulate organic matter (POM) was determined following particle size fractionation (Gregorich et al. 2006). Potassium permanganate oxidizable carbon (POXC) was determined colorimetrically (Weil et al. 2003). Potentially mineralizable carbon (PMC) was measured as the amount of CO_2 in 0.25-M NaOH traps following a 7-day soil incubation, which was then titrated to a phenolphthalein endpoint using 0.25 N HCl (Parkin et al. 1997). Soil respiration was determined using the Solvita® gel system (Solvita, Woodsend Laboratories, Augusta, ME, USA) which incubates a color gel paddle in a container with a field moist soil sample for 24 hours, after which the paddle color indicates the quantity of CO_2 present (Haney et al. 2008). Microbial biomass carbon and nitrogen were determined using a chloroform fumigation and extraction (Vance et al. 1987), using efficiency factors of $k_N = 0.54$ (Joergensen and Mueller 1996) and $k_C = 0.45$ (Beck et al. 1997). After fumigation, samples were extracted using 0.5 M K_2SO_4 and analyzed for microbial biomass nitrogen and carbon on a PerkinElmer C:N analyzer (PerkinElmer Inc., Waltham, MA, USA). The labile organic matter parameters tested in this study attempt to assess soil biological condition by measuring the microbial biomass (MBC and MBN), microbial activity (PMC and SOLV), or the microbial substrate (SOM, POM, or POXC).

Statistical Analyses

Statistical tests were conducted using SAS JMP 13.2.1 software (SAS Institute Inc., Cary, NC, USA) with significance determined at a 95% confidence level.

To answer the first research question, Pearson product-moment correlation analyses were conducted with the RUSI model and the tree metrics. The R-correlation and P-value statistics were used to evaluate the strength and significance of the correlations.

To answer the second research question, parameter weighting was applied (Table 3). For each model, all weights summed to one. Weights were developed using the data collected during the second sampling period and were tested on data collected during the

Table 3. Property weights for RUSI, weighted RUSI (RUSIw), and organic weighted RUSI (RUSIow) models. Precipitation (PPT), growing degree days (GDD), exposure (EXP), traffic (TRA), infrastructure (INF), surface (SUR), estimated rooting area (ERA), penetration (PEN), A-horizon (HOR), texture (TEX), structure (STR), wet aggregate stability (WAS), soil organic matter (SOM), electrical conductivity (EC), pH, and Solvita® (Solvita, Woodsend Laboratories, Augusta, ME, USA) soil respiration (SOLV).

Property	RUSI	RUSIw	RUSIow
PPT	0.066	0.000	0.000
GDD	0.066	0.000	0.000
EXP	0.066	0.043	0.038
TRA	0.066	0.043	0.038
INF	0.066	0.043	0.038
SUR	0.066	0.087	0.077
ERA	0.066	0.087	0.077
PEN	0.066	0.087	0.077
HOR	0.066	0.130	0.115
TEX	0.066	0.130	0.115
STR	0.066	0.130	0.115
WAS	0.066	0.087	0.077
SOM	0.066	0.043	0.038
EC	0.066	0.043	0.038
pH	0.066	0.043	0.038
SOLV	n/a	n/a	0.115
Total	1.00	1.00	1.00

Table 4. Potential limitation to tree health and growth for each of the RUSI parameters. The lower the rank, the more limiting that parameter was expected to be for tree growth and health based on expert opinions and professional experiences of the primary investigators. Precipitation (PPT), growing degree days (GDD), exposure (EXP), traffic (TRA), infrastructure (INF), surface (SUR), estimated rooting area (ERA), penetration (PEN), A-horizon (HOR), texture (TEX), structure (STR), wet aggregate stability (WAS), soil organic matter (SOM), electrical conductivity (EC), and pH.

Property	Rank
PPT	15
GDD	14
EXP	12
TRA	13
INF	10
SUR	11
ERA	4
PEN	3
HOR	5
TEX	1
STR	2
WAS	6
SOM	7
EC	8
pH	9

first sampling period. The weighted RUSI models were compared to the nonweighted RUSI model, which had an equal weight distribution for the 15 parameters.

Parameter weights for the weighted RUSI (RUSIw) were assigned based on limiting factor rank, relative correlation strengths to tree metrics, and data distributions. The 15 parameters were ranked 1 to 15 based on their potential limitation for tree health and growth (Table 4). Parameters that were expected to be more limiting received a lower rank. The *R*-correlation values for the 15 RUSI parameters and each tree metric were determined (Table 5). Data distributions were examined to determine the mean, standard deviation, minimum, and maximum scores for each of the RUSI parameters (Table 2). Four weighting tiers (and weights) were established: none (0.00), low (0.04), moderate (0.09), and high (0.13). Parameters in the high tier were expected to be limiting, had relatively high correlation to tree metrics, and had relatively wide data distributions. Parameters in the none tier were not expected to be limiting, had relatively low correlation values, and had narrow data distributions. Parameters in the low and moderate tiers fell in between those extremes for these 3 weighting criteria.

For the third research question, analysis of variance (ANOVA) with Tukey-Kramer Honestly Significant Difference (HSD) testing was used to examine the responses of labile organic parameters (SOM, POM, POXC, PMC, SOLV, MBC, and MBN) as a result of the soil amendment (biosolids) application. Labile organic matter measurements were determined on soils from the spring and fall collections. Percent changes in each of the parameters were computed for each plot. The ANOVA analyses were conducted on data from the fall sampling and the percent change data for each parameter. The labile organic matter parameter that most significantly responded to treatments was included in the RUSI model as a 16th parameter for the organic weighted RUSI model (RUSIow). The RUSIow model with the labile organic matter parameter was then tested for correlation with urban tree condition metrics using the previously described methods.

RESULTS AND DISCUSSION

RUSI Significantly Correlates with Urban Tree Health in Wisconsin

Across all 3 Wisconsin cities, RUSI scores significantly ($P \leq 0.05$) correlated with tree condition ($R = 0.32$), tree condition index ($R = 0.29$), and urban tree health ($R = 0.29$)(Figure 1). The RUSI scores were not significantly correlated with leaf greenness (SPAD), diameter, height, or crown volume. These results confirm findings of the original RUSI study (Scharenbroch et al. 2017) and again suggest that the model is a better predictor of tree health, not growth.

Correlation strength between RUSI scores and urban tree health metrics tended to be weaker than in the previous study (Scharenbroch et al. 2017). The observed tree performance and site quality ranges were narrower in this study (RUSI scores = 51.0 to 81.1) compared to the initial study (RUSI scores = 30.0 to 82.2). This reduced variability truncates the data distribution and may have led to a reduction in the strength of correlation. The limited geographic extent of the current study resulted in a decreased range of climate factors. Initial study sites occurred in 4 states with mean annual temperatures ranging from 6.7 to

Table 5. Pearson *R*-correlation values (*n* = 90) of tree diameter (DIA), tree height (HT), tree crown volume (CV), leaf greenness (SPAD), tree condition (TC), tree condition index (TCI), and urban tree health (UTH) with RUSI scores for precipitation (PPT), growing degree days (GDD), exposure (EXP), traffic (TRA), infrastructure (INF), surface (SUR), estimated rooting area (ERA), penetration (PEN), A-horizon (HOR), texture (TEX), structure (STR), wet aggregate stability (WAS), soil organic matter (SOM), electrical conductivity (EC), and pH.

RUSI	DIA	HT	CV	SPAD	TC	TCI	UTH
PPT	–0.13	0.14	–0.04	–0.38*	0.05	–0.01	–0.11
GDD	0.06	0.12	0.08	–0.03	0.05	0.02	–0.09
EXP	–0.08	–0.27*	–0.23*	0.09	–0.01	–0.03	–0.01
TRA	–0.01	–0.02	–0.07	0.02	–0.02	0.12	0.04
INF	–0.02	–0.15*	–0.08	0.09	0.10	0.14	0.19*
SUR	–0.04	–0.06	–0.05	0.19*	0.14	0.17*	0.15*
ERA	0.11	–0.06	–0.01	0.16*	0.11	0.02	0.17*
PEN	–0.03	0.08	0.09	–0.15*	0.22*	0.23*	0.19*
HOR	0.12	0.24*	0.29*	0.04	0.18*	0.24*	0.19*
TEX	0.13	0.02	0.16*	0.28*	0.07	0.15*	0.25
STR	0.19*	0.26*	0.31*	0.29*	0.25*	0.21*	0.22*
WAS	0.24*	0.19*	0.18*	0.42*	0.08	0.00	–0.02
SOM	–0.07	0.10	0.07	–0.04	0.06	0.10	0.14
EC	0.15*	0.09	0.09	0.37*	0.01	–0.09	–0.08
pH	0.02	0.00	–0.05	0.13	0.02	–0.03	0.01

*$P \leq 0.05$

12.9 °C (US Climate Data 2018), mean annual precipitations ranging from 830 to 1,219 mm yr^{-1} (US Climate Data 2018), and growing degree days ranging from 2,808 to 3,948 (Growing Degree Days 2014). Sites in this study occurred in a single state with mean annual temperatures ranging from 6.7 to 8.8 °C (US Climate Data 2018), mean annual precipitations ranging from 830 to 876 mm yr^{-1} (US Climate Data 2018), and growing degree days ranging from 2,378 to 2,696 (Growing Degree Days 2014). The observed decrease in the variability of climate factors related to the limited geographic extent of this study may have reduced the RUSI models' ability to predict tree performance.

Weighting RUSI Parameters Improves Correlation to Urban Tree Health

Parameter weighting improved correlation to urban tree condition. The weighted RUSI model (RUSIw) improved the correlation to all urban tree health and growth assessments compared to the nonweighted model (RUSI)(Figure 1). The RUSIw was also significantly correlated with leaf color, which was not the case for the nonweighted RUSI model.

The RUSIw model applies the greatest weights to the depth of the A-horizon, soil texture, and soil structure. Surface condition, estimated rooting area, and penetration resistance were assigned the next greatest weights in the RUSIw model. The RUSIw applies no weight to the precipitation and growing degree days scores. The weighting in the RUSIw was developed based on limiting factor rank, relative correlation strengths to tree metrics, and data distributions. An urban tree manager will likely have a reasonable understanding of the limiting factors for the trees they are managing. They can, and should, utilize that information to assign greater weights to those parameters that are likely driving site quality differences. Furthermore, some of the RUSI parameters may not be important for separating site quality differences for a particular population of urban trees. This was the case for the current study in which all trees were in a similar climate with similar precipitation and growing degree days. Consequently, the parameter weighting removed those parameters from the RUSI model by assigning a 0.000 weight.

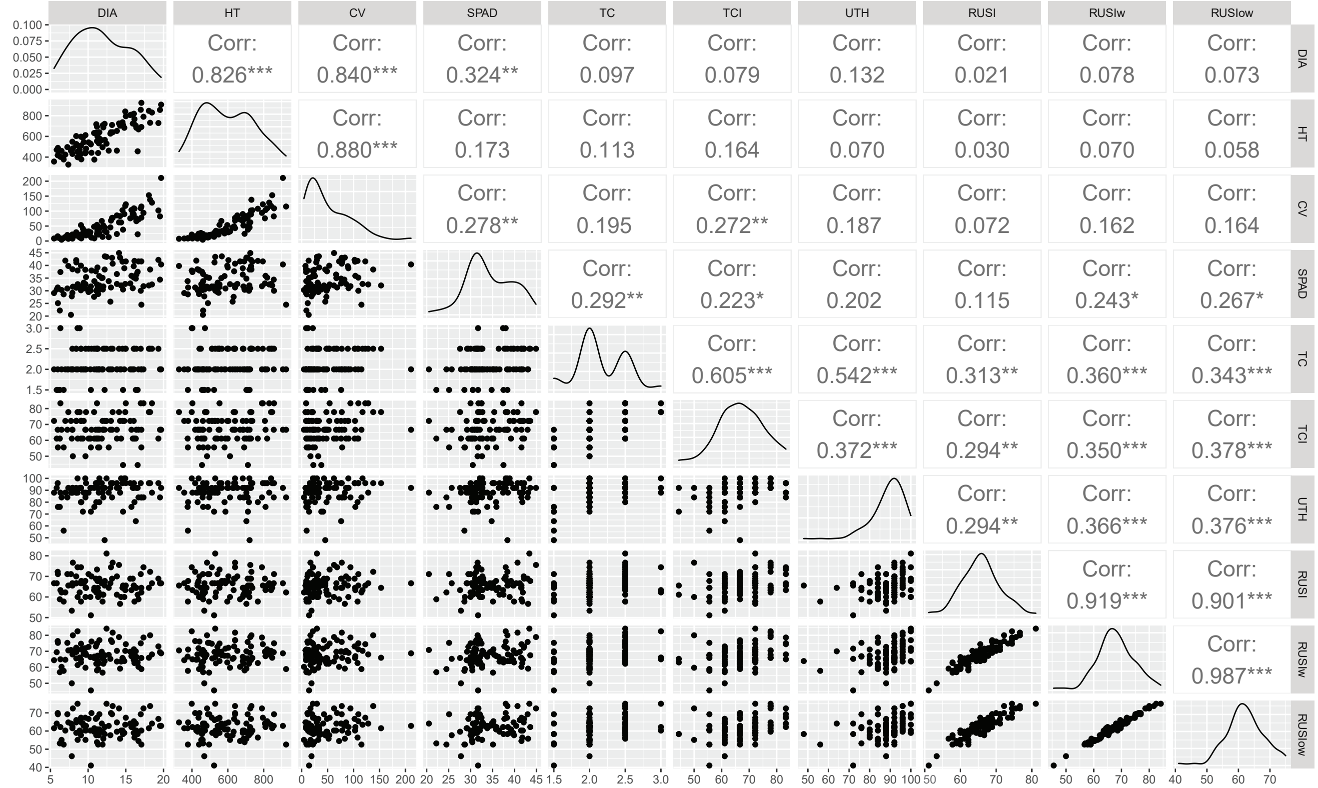

Figure 1. Matrix of scatterplots (black dots), data distributions (solid lines), and Pearson *R*-correlation values (Corr:) among tree diameter (DIA), tree height (HT), tree crown volume (CV), leaf greenness (SPAD), tree condition (TC), tree condition index (TCI), urban tree health (UTH), RUSI, weighted RUSI (RUSIw), and organic weighted RUSI (RUSIow) models. *$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

Adding a Labile OM Parameter Improves RUSI's Sensitivity to Soil Management

The Solvita® (SOLV) respiration test was significantly greater with the high (33.9 mg kg^{-1} d^{-1}) biosolids application rate compared to the null (32.4 mg kg^{-1} d^{-1}) (Table 6). The SOLV responses for the low biosolids application rate were between the high and null although not significantly different from either (Table 6). Significant differences for the other 6 labile organic matter parameters were not detected among the treatments. It is unclear why significant differences were not detected with these other labile organic matter measurements. The standard errors appear relatively high for these measurements compared to SOLV, possibly suggesting that site variability may have masked treatment differences.

The Solvita® test appears to be the most accurate and most practical measurement for detecting response to soil management—in this case, biosolids amendment. All of the other labile organic matter measurements (MBC, MBN, SOM, PMC, POM, and POXC) involve laboratory analyses that are beyond the capabilities of typical urban foresters and arborists. Conversely, the Solvita® test is practical and can easily be utilized and interpreted by an urban tree manager without the need for expensive laboratory testing. Materials to conduct the Solvita® test can be purchased for approximately $10 (US dollars) per sample, and the test is conducted over a 24-hour period.

An organic weighted model (RUSIow) was created by adding SOLV as a 16th parameter and weighting it in the tier of greatest importance (Table 3). Improvements in correlation strength to urban tree health metrics were found with the RUSIow compared to the original RUSI model. Slight improvements in correlation strength to urban tree health were also observed for RUSIow compared to the RUSIw model. This finding was expected because the existing RUSI parameters and tree responses are likely not dynamic enough to respond to a soil amendment over the course of several months. The addition of the

Table 6. Mean (*n* = 30) and standard error of the mean (SE) for total soil organic matter (SOM), particulate organic matter (POM), potassium permanganate oxidizable carbon (POXC), potentially mineralizable carbon (PMC), Solvita® (Solvita, Woodsend Laboratories, Augusta, ME, USA) soil respiration (SOLV), microbial biomass carbon (MBC), and microbial biomass nitrogen (MBN).

Property	Null[a]		Low[a]		High[a]		*P*-value
	Mean	SE	Mean	SE	Mean	SE	
SOM (%)	6.9	0.6	7.2	0.6	7.4	0.7	0.9012
POM (%)	1.4	0.1	1.6	0.1	1.5	0.1	0.6372
POXC (mg/kg)	1,020	54.9	850	57.5	991	53.5	0.0793
PMC (mg/kg/d)	77.4	7.6	91.6	5.5	86.3	7.3	0.3492
SOLV (mg/kg/d)	32.4b	0.5	33.8ab	0.4	33.9a	0.4	0.0275*
MBC (mg/kg)	39.5	3.7	45.9	5.8	48.3	4.4	0.4167
MBN (mg/kg)	8.6	0.7	9.9	1.4	8.9	0.8	0.6717

[a] Data is from the fall sampling period. Treatments are high, low, and no biosolids application (null). The *P*-values for the analysis of variance (ANOVA) are given. Letters identify Tukey-Kramer Honestly Significant Difference (HSD) mean separations with unique letters identifying significant differences.
*$P \leq 0.05$

dynamic labile organic matter parameter that is more sensitive to a soil amendment did appear to provide an early indication of potential site quality improvements leading to improved tree growth and health.

CONCLUSION

This study showed that the RUSI can be used in Wisconsin to relate urban site conditions and urban tree performance. The study also demonstrated the value of parameter weighting to improve the RUSI model. Lastly, the study identified a labile organic matter parameter that might be used to make the RUSI model more dynamic and detect soil management.

It is important to recognize that the RUSI model was developed as an approach, not a "one-size-fits-all" model. The approach allows for sensible and meaningful tailoring of RUSI to specific site conditions and urban tree populations. The RUSI approach involves understanding the site conditions affecting an urban tree population, tailoring an assessment to those conditions, assessing those conditions, and then evaluating the results for management. The results from the current study demonstrate the value of parameter weighting, adding or removing parameters, and using labile organic matter for improving the RUSI model for more accurate site assessments for urban trees.

It is also important to recognize that nonsite factors also influence the health and growth of urban trees. Understanding site conditions is important for urban tree management, but other factors (e.g., nursery practices, pruning) also impact urban tree condition. Significant but relatively low correlations between RUSI scores and urban tree condition parameters in this study provide evidence for this statement.

Urban forests, soils, and sites are diverse. Our understanding for assessing those conditions, and then evaluating the results, is evolving. Future work on the RUSI model should be directed at tailoring and testing the RUSI model in more urban tree populations, soils, and site conditions. The corresponding author of the current study has begun working with individual urban forest managers to develop tailored RUSI models for specific cities. Data from these case studies will be critical for improving the RUSI model and further demonstration of how it can be practically applied. If interested in participating in this effort, please contact the corresponding author.

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Résumé. Contexte: L’indice de site urbain est une approche permettant d’identifier la qualité d’un site donné pour une adaptation optimale des tolérances des arbres urbains aux conditions de ce site et pour déterminer l’efficacité des actions de gestion du sol. Le Rapid Urban Site Index (RUSI) a été développé antérieurement et s’est avéré avoir un lien significatif avec la performance des arbres urbains. Cependant, le RUSI doit faire l’objet de davantage de tests afin de vérifier son exactitude pour d’autres populations d’arbres urbains. En outre, la calibration du RUSI avec une pondération des paramètres de base et des paramètres supplémentaires pourrait également améliorer sa précision. Méthodes: Les objectifs de cette étude sont: (1) d’évaluer le RUSI dans 3 villes du Wisconsin; (2) d’évaluer les modèles de pondération des paramètres du RUSI pour améliorer sa précision; et (3) d’examiner l’ajout d’un indicateur de manière organique labile au RUSI pour l’identification d’une action de gestion des sols. Résultats: La corrélation entre le RUSI et les mesures des arbres urbains s’est avérée significative pour les 3 villes ($r = 0.29$ à 0.31; $n = 90$). La pondération des paramètres a augmenté les valeurs de corrélation significatives entre les paramètres des arbre urbains et le modèle RUSI ($r = 0.24$ à 0.37; $n = 90$). Le test de respiration du sol Solvita® a détecté des différences dans les sols provenant d’une application de biosolides ($P = 0.0275$) et son ajout au modèle RUSI a amélioré les valeurs de corrélation significatives avec les paramètres des arbres urbains ($r = 0.27$ à 0.38; $n = 90$). Conclusions: Cette recherche présente des approches efficaces pour le raffinement du RUSI. Ces résultats montrent que le RUSI est une approche valide pour l’évaluation des sites urbains et indiquent comment le RUSI peut être adapté et affiné pour une utilisation avec des populations d’arbres spécifiques.

Zusammenfassung. Hintergrund: Ein Standortindex für Stadtbäume ist ein Hilfsmittel zur Ermittlung der Standortqualität, mit dem die Toleranzen von Stadtbäumen optimal an Standortbedingungen angepasst werden können und mit dem sich die Wirksamkeit von Bodenpflegemaßnahmen bestimmen lässt. Der Rapid Urban Site Index (RUSI) wurde früher entwickelt und es wurde festgestellt, dass er in signifikantem Zusammenhang mit der Leistung von Stadtbäumen steht. Der RUSI muss jedoch weiter getestet werden, um seine Genauigkeit bei anderen städtischen Baumbeständen zu überprüfen. Darüber hinaus könnte eine Kalibrierung des RUSI mit Parametergewichtung und zusätzlichen Parametern seine Genauigkeit verbessern. Methoden: Die Ziele dieser Studie sind: (1) Evaluierung des RUSI in drei Städten in Wisconsin; (2) Evaluierung von Modellen zur Gewichtung von RUSI-Parametern, um die Genauigkeit zu verbessern; und (3) Untersuchung der Hinzufügung eines Indikators für labile organische Substanz zum RUSI, um eine Bodenbewirtschaftungsmaßnahme zu erkennen. Ergebnisse: Es wurde festgestellt, dass der RUSI in 3 Städten in Wisconsin signifikant mit den Metriken für Stadtbäume korreliert ($r = 0{,}29$ bis 0,31; $n = 90$). Die Parametergewichtung erhöhte die signifikanten Korrelationswerte zwischen städtischen Baumkennzahlen und dem RUSI-Modell ($r = 0{,}24$ bis 0,37; $n = 90$). Der Solvita®-Bodenatmungstest ermittelte Unterschiede in Böden nach einer Klärschlammaustragung ($P = 0{,}0275$), und seine Ergänzung des RUSI-Modells verbesserte die signifikanten Korrelationswerte zu den Metriken für Stadtbäume ($r = 0{,}27$ bis 0,38; $n = 90$). Schlussfolgerungen: Diese Forschung zeigt effektive Ansätze für die RUSI-Verfeinerung.

Die Ergebnisse zeigen, dass der RUSI ein valider Ansatz für die Bewertung von städtischen Standorten ist und wie der RUSI für die Verwendung in spezifischen städtischen Baumbeständen angepasst und verfeinert werden kann.

Resumen. Antecedentes: Un índice de sitio urbano es un enfoque para identificar la calidad del sitio para una coincidencia óptima de las tolerancias de los árboles urbanos con las condiciones del sitio y para determinar la eficacia de las acciones de manejo del suelo. El Índice Rápido de Sitio Urbano (RUSI) se desarrolló previamente y se encontró que se relacionaba significativamente con el rendimiento de los árboles urbanos. Sin embargo, el RUSI necesita más pruebas para verificar su precisión en otras poblaciones de árboles urbanos. Además, la calibración del RUSI con ponderación de parámetros y parámetros adicionales también podría mejorar su precisión. Métodos: Los objetivos de este estudio son: (1) evaluar el RUSI en 3 ciudades de Wisconsin; (2) evaluar los modelos de ponderación de parámetros RUSI para mejorar su precisión; y (3) examinar la adición de un indicador de materia orgánica inestable al RUSI para la detección de una acción de manejo del suelo. Resultados: Se encontró que el RUSI se correlaciona significativamente con las métricas de árboles urbanos en 3 ciudades de Wisconsin (r = 0,29 a 0,31; n = 90). La ponderación de los parámetros aumentó significativamente los valores de correlación entre las métricas de árboles urbanos y el modelo RUSI (r = 0,24 a 0,37; n = 90). La prueba de respiración del suelo Solvita® detectó diferencias en los suelos de una aplicación de biosólidos (P = 0,0275) y su adición al modelo RUSI mejoró los valores de correlación significativa con las métricas de árboles urbanos (r = 0,27 a 0,38; n = 90). Conclusiones: Esta investigación demuestra enfoques efectivos para el refinamiento de RUSI. Estos hallazgos muestran que el RUSI es un enfoque válido para la evaluación del sitio urbano y demuestran cómo el RUSI se puede adaptar y refinar para su uso en poblaciones específicas de árboles urbanos.

Appendix.

DESCRIPTION OF STUDY AREAS

Stevens Point, WI, USA (44.523483, −89.574814) has a total population of 26,670 people (US Census Bureau 2017) with an elevation of 331.9 m, average precipitation of 83.0 cm, and an average temperature of 6.7 °C. Native soils in Stevens Point are described as a Plainfield-Friendship association, which is moderate to excessively well-drained and formed in deep sandy glacial deposits (USDA NRCS 1978). Stevens Point has approximately 7,230 city trees distributed among 47 species, with dominant genera of *Acer* (25%), *Fraxinus* (15%), *Malus* (7%), *Tilia* (6%), and *Pinus* (6%)(Davey Resource Group 2010).

Green Bay, WI, USA (44.513287, −88.01326) has a total population of 104,779 people (US Census Bureau 2017) with an elevation of 177.0 m, average precipitation of 74.9 cm, and an average temperature of 6.7 °C. The native soils in Green Bay are described as an Oshkosh-Manawa association. These soils are well-drained to somewhat poorly drained with sand and loamy subsoil (USDA NRCS 1974). Green Bay has approximately 35,000 city trees, with dominant genera of *Acer* (31%), *Fraxinus* (21%), *Tilia* (19%), and *Gleditsia* (9%)(Freberg 2016).

Milwaukee, WI, USA (43.04181, −87.90684) has a total population of 599,164 people (US Census Bureau 2017) with an elevation of 188.0 m, average precipitation of 87.4 cm, and an average temperature of 8.7 °C. The native soils in Milwaukee are described as an Ozaukee-Marley-Mequon association. These soils are well-drained to somewhat poorly drained with clay subsoils (USDA NRCS 1971). Milwaukee's total tree population is approximately 3,377,000 trees, with dominant genera of *Rhamnus* (23%), *Acer* (20%), *Fraxinus* (17%), *Ulmus* (6%), and *Gleditsia* (6%)(i-Tree 2008). It should be noted that native soils in all 3 cities have been significantly altered by urbanization.

TREE PERFORMANCE METRICS

Qualitative tree health was assessed using 3 metrics: tree condition (TC), tree condition index (TCI), and urban tree health (UTH). Equations and scoring functions for these metrics are as follows.

Tree condition (TC) scores were calculated following Scharenbroch et al. 2017 (Equation S1; Table S1). This method is a quick assessment of the relative growth and signs/symptoms of stress. It provides a 0 to 3 rating based on an ocular estimation of the presence of leaves and their condition, bark condition, and growth rate. The tree condition is considered dead when more than one-half of the crown is dead and bark is sloughing off. Trees are in poor condition when less than half of the crown is dead and there are signs of severely stunted growth. Trees are in fair condition if they have reduced growth, minor dieback, and/or are chlorotic. Trees are in good condition when there are no signs of stress present and exhibit high growth rates.

Equation S1. Tree condition (TC) = n

Table S1. Parameters and scoring function for the tree condition (TC) model.

TC	Score
Dead (> 1/2 of the crown dead, sloughing bark)	0
Poor (< 1/2 of the crown dead, growth severely stunted)	1
Fair (reduced growth, chlorotic, minor dieback)	2
Good (no stress present, high growth rates)	3

Tree condition index (TCI) scores were calculated using the modified Webster (1979) method first used by Scharenbroch and Catania (2012)(Equation S2; Table S2). This method provides a rating on a 1 to 5 scale on the tree's trunk, crown, and roots. The trunk factor rates how sound the tree is and the presence of damage or decay and its extent. Crown is the tree's canopy density and balance or evenness. The roots factor is the presence of proper rooting habits represented by a large, evenly spaced structural root flare.

Equation S2. Tree condition index (TCI) = $(\sum n/3n) \times 100$

Table S2. Parameters and scoring function for the tree condition index (TCI) model. Adapted from Webster (1979).

TCI	5	4	3	2	1
Trunk	Sound and solid throughout	Minor damage	Early decay signs	Extensive decay, hollowness, cambium damage	Same as 2, 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 severely imbalanced crown
Roots	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 3 visible or severely unbalanced root flares (< 2 cm deep)	No visible root flares and structural roots (2 cm to 15 cm deep)	Structural roots (> 15 cm deep)

Urban tree health (UTH) scores were calculated following the methods developed by Jerry Bond (2012)(Equation S3; Table S3). This method provides a 0 to 5 scale rating the tree's live crown ratio, opacity, vitality, growth, and quality. The live crown ratio is the percent live crown height to the total live tree height. Opacity is the percent of light visibly blocked by branches, foliage, and reproductive structures of the actual live crown. Vitality is the percent of the upper crown that is free from recent mortality. Growth is the 3-year average terminal shoot extension on 3 random branches with the same sun exposure that have not been pruned or damaged. Quality measures the percent of the upper crown that is free from necrotic, chlorotic, or undersized foliage.

Equation S3. Urban tree health (UTH) = $(\sum n/5n) \times 100$

Table S3. Parameters and scoring function for the urban tree health (UTH) model. Adapted from Bond (2012).

UTH	0	1	2	3	4	5
Crown ratio	No live crown	1% to 20%	21% to 40%	41% to 60%	61% to 80%	81% to 100%
Opacity	No live crown	1% to 20%	21% to 40%	41% to 60%	61% to 80%	81% to 100%
Vitality	No live crown	1% to 20%	21% to 40%	41% to 60%	61% to 80%	81% to 100%
Growth	No live crown	< 5 cm	5 to 10 cm	10 to 15 cm	15 to 20 cm	> 20 cm
Quality	No live crown	1% to 20%	21% to 40%	41% to 60%	61% to 80%	81% to 100%

RAPID URBAN SITE INDEX

Rapid Urban Site Index (RUSI) scores were calculated following Scharenbroch et al. (2017)(Equation S4; Table S4). A description of each of the 15 RUSI parameters is as follows.

The climate factors of the RUSI model include precipitation (PPT), growing degree days (GDD), and exposure (EXP). For PPT and GDD scores, it is suggested to use the most recent, practical, and accurate local data available. The PPT score was calculated using data acquired from US Climate Data (2014). If irrigation was present on the site, then the PPT score was increased one point to a maximum score of 3. The GDD score is a measure of heat accumulation. The GDD units are calculated by mean daily temperature (maximum plus minimum divided by 2) minus base temperature (10 °C). The GDD units are summed for the year for annual GDD. The Growing Degree Days smartphone application was used to determine the GDD score for each location (Growing Degree Days 2014). The start date was 2016 January 01 and the end date was 2016 December 31 and the GDD50 was selected as the base temperature. The free application returns the GDD for the most recent 2 years, and a mean of this value was used to score GDD. The EXP score was assessed in the field based on the number of faces of the tree that were exposed to full sun.

The urban factors in the RUSI model are traffic (TRA), infrastructure (INF), and surface (SUR). The TRA score was based on the number of lanes and amount of parking available on the street. More lanes and less parking indicate more traffic, likely faster-moving automobiles, and more of an “urban” impact (e.g., road salts, recent soil disturbance) on the site. The INF score was based on the distance to the nearest hard-space or building from the main stem of the tree. The SUR score was based on the type of ground covering for the majority (greater than 50%) of the rooting area for the tree.

Soil physical factors include texture (TEX), structure (STR), and penetration (PEN). Texture reflects the relative particle size distribution and is determined by the feel method. Structure is the shape of the soil aggregates present. Methods for assessing soil texture by the feel method and structure shape are described in Schoeneberger et al. (2012) and Scharenbroch and Watson (2014). Penetration was assessed by recording the depth and ease that the core sampler went into the soil when collecting samples.

The soil chemical factors were pH, electrical conductivity (EC), and soil organic matter (SOM). Soil pH and EC were measured on homogenized subsamples at each site using a handheld combination pH/EC meter. For this research, the Oakton PCTestr 35 (OAKTON Instruments, Vernon Hills, IL, USA) was used. Soil organic matter was estimated using the Color Chart for Estimating Organic Matter in Mineral Soils of Illinois (Alexander 1971).

The soil biological factors were estimated rooting area (ERA), depth of the A-horizon or topsoil (HOR), and wet aggregate stability (WAS). Estimated rooting area was an evaluation of the surface permeable space for root growth. The ERA score was increased by 1 to a maximum of 3 if a breakout area of at least 50 m^2 was present within 2 m of the tree. The HOR was the depth of the A-horizon or topsoil via visual inspection. The A-horizon was distinguished by darker color, a more well-developed structure, and a greater abundance of fine roots compared to the underlying horizon. Wet aggregate stability is an estimate of the strength of the aggregates to resist degradation (Nimmo and Perkins 2002). A modified field method was used to assess WAS. A total of 5 aggregates 2 to 5 mm in diameter were placed on a 1-mm screen. The aggregates were soaked in water for 30 seconds. After 30 seconds the screen was agitated (i.e., a vigorous swirl) for another 30 seconds. The number and amount of aggregates left after the soak and swirl were volumetrically estimated and scored.

Equation S4. Rapid Urban Site Index (RUSI) = $(\sum s/3n) \times 100$

Table S4. Parameters and scoring functions for the Rapid Urban Site Index (RUSI) model. Precipitation = PPT; growing degree days = GDD; exposure = EXP; traffic = TRA; infrastructure = INF; surface = SUR; texture = TEX; structure = STR; penetration = PEN; A-horizon = HOR; estimated rooting area = ERA; wet aggregate stability = WAS; soil organic matter = SOM; electrical conductivity = EC; sand = S; sandy clay = SC; silt = SI; sandy loam = SL; clay = C; loam = L; clay loam = CL; loamy sand = LS; sandy clay loam = SCL; silty clay = SIC; silt loam = SIL; silty clay loam = SICL; coarse fragment (>2 mm in diameter) = CF; massive = M; single-grained = SG; platy = PL; angular blocky = ABK; subangular blocky = SBK; granular = GR.

RUSI	Units	0	1	2	3
PPT[a]	mm yr^{-1}	< 500	500 to 750	751 to 1,000	> 1,000
GDD	d	< 1,000	1,001 to 2,500	2,501 to 4,000	> 4,000
EXP	#	0	1 to 2	3 to 4	5
TRA	n/a	> 4 lanes	2 to 4; no parking	2 to 4; parking	< 2 lanes
INF	m	< 1	1 to 5	6 to 10	> 10
SUR	n/a	nonpermeable or bare	patchy vegetation	thick vegetation	organic mulch
TEX	n/a	no soil; CF > 75%	S, SI, C; CF = 50% to 75%	LS, SCL, SICL, CL, SC, SIC; CF = 25% to 49%	SL, SIL, L; CF < 25%
STR	n/a	M, SG, PL	ABK	SBK	GR
PEN	cm	< 5	5 to 20	20 with max effort	20 with min effort

Table S4. continued

RUSI	Units	0	1	2	3
HOR	cm	< 1	1 to 5	6 to 15	> 15
ERA[b]	m^2	< 5	5 to 25	26 to 50	> 50
WAS	%	no aggregates	< 50% post soak	< 50% post swirl	> 50% post swirl
SOM	IL SOM chart	gray	chip 1	chip 2 to 3	chip 4 to 5
EC	$\mu S\ cm^{-1}$	< 50 or > 3,000	50 to 100 or 2,001 to 3,000	101 to 300 or 1,001 to 2,000	301 to 1,000
pH	n/a	< 4 or > 9	4 to 4.9 or 8.1 to 9	5 to 5.9 or 6.6 to 8	6 to 6.5

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[a] Add 1 to the PPT if irrigation is present within 3 m of the tree.

[b] Add 1 to the ERA score if a breakout zone of at least 50 m^2 is present within 2 m of the main stem of the tree.

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