THE INFLUENCE OF ABIOTIC FACTORS ON STREET TREE CONDITION AND MORTALITY IN A COMMERCIAL-RETAIL STREETSCAPE

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ABSTRACT

Successfully growing trees in highly-urbanized areas, such as downtown commercial-retail districts, is challenging. As part of a streetscape revitalization project, initiated in 2010, 133 London Planetrees (*Platanus x acerifolia*) were planted in structural soil cells along the downtown, commercial district of Bloor Street in Toronto, Canada. After most trees experienced severe decline, with many dying, all trees were removed and replaced in 2015. This research reports on an investigation of multiple abiotic factors that may have contributed to the decline and mortality of the Bloor Street trees. We collected cross-sectional data on soil texture, soil compaction, soil chemistry, built-environment characteristics (e.g., proximity to road intersections, pit or bed planter), and sunlight availability, and historic data on tree condition and mortality, and analyzed them with multivariate statistical techniques (e.g., correlation, MANOVA, contingent and ANOVA tests) to investigate the potential for relationships to tree mortality (mortality rate of 46.6% before removal) and tree condition. Results indicate that trees that were alive and demonstrated better structural and foliar condition before removal in 2015 had significantly lower levels of soil salinity and alkalinity, sunlight exposure, and signs of physical damage, suggesting co-occurring and cumulative impact of these variables on tree performance. Modification to streetscape design can ameliorate tree decline in the long-term, while education targeted at raising awareness about de-icing salt application and irrigation practices will lessen tree stressors immediately.

KEYWORDS:

urban soils, de-icing salts; sunlight availability; structural soil cell; London Planetree

INTRODUCTION

North-American cities are setting goals to increase the number of trees in urban spaces (e.g., City of Toronto 2012), particularly in downtown commercial areas, where trees can increase the aesthetic appeal of streets, enhance retail activity (Wolf 2005), and provide environmental benefits, such as moderating ambient heat (Greene and Millward 2017). Growing trees in these areas, however, is a significant technical challenge, as they frequently face high rates of decline and mortality (Jim 1997). Incorporating trees in these spaces usually necessitates the adoption of techniques that can improve soil quality and water availability conducive to tree-root development (Bassuk and Whitlow 1987). Underground structural elements, such as structural soil cells, have the capacity to significantly improve growing conditions for trees (Grabosky et al. 2001; Day et al. 2010, Bartens et al. 2010; Brockbank and Slater 2016). Structural soil cells, an underground framework that contains prescribed soil conditions, are designed to support tree growth and provide a system of passive irrigation to the trees, while also collecting, absorbing, and infiltrating surface water runoff (Page et al. 2015).

Structural soil cells were installed along Bloor Street, located in a downtown shopping district in Toronto, Canada, and notably one of the most important commercial retail streets in the country. This tree installation was part of a multi-million-dollar street-revitalization project finalized in 2011, which had the goal of improving tree-growing habitat to maximize survivorship and enhance growth, thus ensuring a consistent flow of aesthetic and environmental benefits. Despite significant consideration for tree growing conditions, and substantial investment in underground soil infrastructure, many of the 133 trees originally planted fared poorly or died. Eventually, all the trees, living and deceased, were removed in 2015 and replaced.

At present, arboricultural science contains insufficient clues that could explain why so many street trees declined so rapidly at the Bloor Street location. Soil cell technology is growing in popularity and projects that involve structural soil cells to grow trees in urban areas are generally viewed in a positive light (e.g., Page et al. 2015; Brockbank and Slater 2016). However, to date, there are no investigations into factors contributing to tree decline and mortality under the conditions of commercial-retail streetscapes revitalized with structural soil cells.

Moreover, although it is well known that trees growing close to roadsides and highly urbanized streets suffer disproportionally from high levels of mortality (Hodge and Boswell 1993; Nowak et al. 2004; Roman and Scatena 2011), most research on urban tree growth, condition, and mortality, is carried out at broad spatial scales, such as at the scale of an entire city. Tree performance at small spatial scales (streetscapes), and in commercial-retail settings is usually not assessed in depth (Steenberg et al. 2017). Therefore, it is unclear how trees planted in commercial-retail spaces perform given changing soil, microclimatic, and built environment conditions. Extrapolating from existing research would not be enough to explain precisely what variables may be contributing, as well as potentially interacting, to influence tree performance in specific urban planting sites, such as along Bloor Street.

This study seeks to fill some of these research gaps by reporting on an investigation of the abiotic factors that have influenced tree mortality and condition along Toronto's Bloor Street. To contextualize the environment of the Bloor Street trees and determine the point of departure for our examination, we review the factors that influence tree performance in highly-urbanized streetscapes below. We then provide more details about this research study.

Abiotic Factors Influencing Tree Performance in Urban Areas

The most important abiotic factors influencing tree performance in urban areas include: soil conditions; environmental conditions, such as micro-climate and air pollution; physical characteristics of the built environment (e.g., streetscape morphology); and tree maintenance practices (Steenberg et al. 2017).

Soil provides the rooting medium and essential nutrients for above-ground growth of trees (Trowbridge and Bassuk 2004). However, soils found in highly urbanized streetscapes are generally not conducive to optimal tree growth (Bassuk and Whitlow 1987). Some of the most important reasons for this include: 1) lack of soil volume available for adequate root growth (Lindsey and Bassuk 1991); 2) low soil nutrient and organic matter content (Cekstere and Osvalde 2013); 3) soil compaction, which hinders root development and water availability (Day et al. 2010); 4) elevated soil salinity (Czerniawska-Kusza et al. 2004), which causes osmotic stress to trees and is frequently manifest in leaf chlorosis (Munns and Tester 2008); 5) high soil alkalinity, which can influence nutrient availability (Gałuszka et al. 2011); and 6) either poor drainage or low soil water-holding capacity (Nielsen et al. 2007). Frequently, many of these conditions are coexistent in urban streetscapes and collectively influence tree growth, condition and mortality.

Urban areas often have elevated summer temperatures due to the urban heat island effect (Souch and Grimmond 2006). Because of this, cold-adapted tree species may not perform as expected in certain cities that would otherwise be characterized as having a northern climate (Yang 2009). Similarly, elevated temperature in conjunction with minimal precipitation can exacerbate plant water stress (Nielsen et al. 2007; Gillner et al. 2013a). Finally, although not usually a significant influence on tree decline, air pollution, such as tropospheric ozone, can cause some damage to tree leaves and reduce biomass production. However, this effect is species dependent (Xu et al. 2015).

The urban built environment can also be a source of stress for trees. The geometry and density of buildings and other urban structures affect both the irradiation essential for photosynthesis and plant growth, and the urban microclimate (Oke et al. 1989). This can further exacerbate the negative influence of urban microclimatic conditions on trees, reviewed above. Although some trees can adapt to the low light environment of urban areas (Harris and Bassuk 1993), a decreased exposure to sunlight hours can significantly affect urban tree growth in urban canyons (e.g., a streetscape flanked by multi-story buildings) (Jutras et al. 2010).

Moreover, urban trees are also regularly exposed to contact with humans, including vandalism, and improper handling and maintenance at the time of planting or pruning, all of which can negatively and disproportionately affect street trees because of their proximity to sidewalks and roads highly-trafficked by humans (Nowak et al. 2004). Decision-making processes during design projects, such as nursery stock selection, the timing of tree planting, the use of watering bags for newly planted trees, the presence of metal gratings in the planting pit, among other factors, can also be major contributors to street tree condition and propensity for survival (Lu et al. 2010; Jutras et al. 2010).

The consequences to street trees of these urban conditions include: failure to establish (i.e., point at which trees start to grow again after transplantation; Sherman et al. 2016); and, retarded growth rates (Jutras et al. 2010). An annual slowing of tree growth can be a precursor to mortality (Gillner et al. 2013b). Downtown commercial urban areas present some of the most challenging conditions for trees to establish and grow (Roman and Scatena 2011). It has been reported that, in North American cities, trees growing along commercial-retail streetscapes survive for between 5 and 20 years, a considerably abbreviated existence providing that many tree species can live for 75 years, or more, in good conditions (Nowak et al. 2004). Short-lived trees not only provide fewer benefits, but ultimately cost more to maintain and replace, thus straining municipal budgets and never manifesting their true potentials when considering aesthetic and ecological benefits (Roman et al., 2013).

This Study

Bloor Street is a major east-west thoroughfare in Toronto. The area between Church Street and Avenue Road is one of the most commercially important urban spaces in Canada, housing high-profile retail businesses. This section of Bloor Street went through a period of revitalization finishing in 2011, when the streetscape was redesigned to include structural soil cells for planting trees. 133 London planetrees (*Platanus x acerifolia*) were planted in 2010 to 2011 in a combination of raised flowerbed and at-grade pit planters interconnected by the soil cells. London planetrees were chosen by the design team. This species is usually chosen because it is tolerant of urban growing conditions, including soil compaction and drought (Gilman and Watson 1994; Sherman et al. 2016). After five years, many of the trees manifested signs of severe canopy decline. Consequently, all the trees were removed, including both dead and living trees, in a re-planting effort from May to June of 2015.

The aim of our study was to explain why the 133 London planetrees planted along Bloor from 2010-2015 performed so poorly. Our objectives were to: 1) collect and analyze environmental and ecological data describing the Bloor Street trees; and 2) identify which factors contributed the most to tree performance, explained by tree mortality and condition patterns. The focus of the study was to explain tree mortality patterns in a commercial-retail space revitalized with structural soil cells, rather than a comparative study of tree performance with and without structural soil cells. This study allowed us to dig deeper into other characteristics that may contribute cumulatively to tree performance in these spaces. We believe the results of this study will help guide future soil-cell research and refinement of tree-planting projects along downtown streetscapes.

MATERIALS & METHODS

Site Description

Toronto, a city located on the northwestern shore of Lake Ontario, is the provincial capital of Ontario and the largest city in Canada (Statistics Canada 2011). The city has a mean annual rainfall precipitation, based on a normal of a 30-year span (1981–2010), of 831.1 mm, and a mean annual snow cover accumulation of 121.5 cm. The annual mean daily maximum and minimum temperatures are 12.9°C and 5.9°C, respectively, and the extreme maximum and minimum temperatures are 40.6°C and -32.8°C, respectively. The annual average number of hours of sunshine in Toronto is 2066.3, and there is an average of 170 degree-days above 10°C (Environment Canada 2014). The city is located in the 7a plant hardiness zone (NRC 2016) and its soils, where not highly altered by anthropogenic processes, are representative of the Lawrence river soil system, characterized by silt clay soils from glacial and fluvial deposits.

Data Collection

Since tree decline and failure are usually the cumulative effect of several stressors over time (Trowbridge and Bassuk 2004), this study considered as many different physical, design, and maintenance factors as possible to understand the causes driving tree mortality and decline along Bloor Street. Abiotic factors were the focus of the study because the trees showed no visual signs of being affected by pests and/or diseases before being removed, and all the trees were the same species. Soil samples, built environment details, and tree performance metrics were collected as trees were being replaced throughout the removal operations (May-June of 2015), as explained below.

Soil samples were collected from the two different types of planters (flower bed or “beds” and ground-level pit, or “pits”) at between 30 and 40 cm away from the tree trunk and at a depth of between 15 and 30 cm. Additional soil samples were collected from a distance of between 50 to 75 cm away from the tree trunk at a depth of between 15 to 30 cm. Soil samples were frozen and stored before texture and chemical analysis was conducted. Soil compaction was measured on-site using a FieldScout SC-900 Soil Compaction Meter at two distances from the tree trunk, between 20 and 30cm and between 65 and 75 cm. Compaction measurement profiless were taken from the soil surface to 45 cm deep at 2.5 cm intervals. These values were averaged into 3 groupings: 0-15 cm; 15-30 cm; and 30-45 cm. Compaction was only measured in pit planters, given that ornamental plants in the bed planters prohibited acquisition of accurate compaction meter measurements.

Information was recorded on the type of planter (beds/pits), planter location (north or south side of the street), distance of planting site to the nearest street intersection, and the type of intersection (major or minor street intersection; determined through analysis of the City of Toronto Roads Dataset in ArcGIS 2016, v.10.4.1). While the trees were being removed, data were collected on tree mortality (alive/dead before removal), diameter at breast height (DBH), and damage, for which a binomial yes/no measure of whether the tree had appreciable torn limbs, trunk scars, missing canopy, pruning scars, cracks, and peeling bark before removal in 2015, was used. Historical data on the condition of each tree were captured using a qualitative assessment based on scale of 0 to 3, where 0 = dead; 1 = poor; 2 = fair; and 3 = good. These data were collected using three sources: (1) contractual reports based on summer field surveys by a registered arborist covering the pre-removal period 2011 – 2014; (2) close-range digital images from Google StreetView, an efficient way to survey street trees and up to 90% agreeable with field survey data (Berland and Lange 2017); and, (3) a 2014 summer street tree survey, available digitally from the City of Toronto.

Since light availability in urban canyons (i.e., high-density urban streetscapes) can influence tree growth (Jutras et al. 2010), data were collected on the hours of exposure to sunlight received at each tree-planting site. The 3D building dataset (i.e., 3D Massing) of the City of Toronto was used in Sun Shadow Volume tool included in the Visibility Toolset ArcGIS 3D Analyst extension (2016, v.10.4.1) to model the shadow patterns for each building in proximity to the planting sites.

March 21 (Spring Equinox) and June 21 (Summer Solstice) were selected for shadow modeling. These days represent the lower and upper range (minimum and maximum) of light availability for the growing season for trees. Light availability was modelled differently for each day, including from 9:00AM to 6:00PM for March 20, and from 7:00AM to 7:00PM for June 21. The modelling timeframe was offset by 1.5 hours after and before sunrise and sunset times, given that the sun is low in the horizon at these times and may not cast shadow on the planting sites.

Daily shadow patterns at the study site were estimated at 4 metres above the ground surface, as this area better approximates the light availability at the tree canopy. The site had minimal elevation variability (<1m). Shadow hours were converted to sunlight hours by using the following equation in the Raster Calculator tool within ArcGIS's Map Algebra Toolset: sunlight hours = total hours of sunlight modelled for the given day – hours of shadow.

The number of sunlight hours for each planting location was determined by taking the average of a circle with a radius of 1.5m circle centered on each planting location, where this zone represented the approximate area of the tree canopy. Sunlight range (maximum value of either March 20 or June 21, minus minimum value of either March 20 or June 21) and average sunlight (Light in March 20 minus Light in June 21, divided by 2) were later calculated from the values of light availability for the two dates to accurately describe the variation of light availability. The four measures of light availability, including sunlight for March 20, sunlight for June 21, sunlight range, and sunlight average, were used in subsequent analyses.

Finally, the intention of this study was to account for the effect of climatic influences on tree condition, such as drought and prolonged heat/cold events, or weather influences, such as storm events. While we sourced temperature and precipitation records from the closest Environment Canada weather station, and analyzed these with the yearly tree-condition ratings, this analysis was inconclusive. For this reason, we do not include analytical procedures or results from these analyses.

Subsampling & Laboratory Analysis

In-depth soil analyses were conducted on a subsample (n = 57) of all collected soil at the site; this sample represented 43% of all tree growing locations. Since the sample collection procedure did not cover all bed planters, the subsample included all available soil samples from bed planters (17 total) and a representative, randomly selected subsample (40 total) of soil from pit planters. The subsample of pit planters was determined by stratifying trees at the site into five groups of approximately equal number of pit plantings (mean = 17, SD = 2.6) in close proximity to one another, and using the RAND function in Microsoft Excel to randomly select eight samples from each respective group.

Frozen soil samples of the selected subsample were sent to Agri-Food Laboratories Inc., which meets all requirements of the Standards Council of Canada, for a full soil analysis, including texture (% of sand, clay, and silt), organic matter (% of total), pH, electrical conductivity (EC) (in dS/m) (done with the solid paste method at a standard solubility ratio of 1:1; see Rhoades, 1996; Thomas, 1996), and concentration of Calcium (Ca), Magnesium (Mg), and Sodium (Na) (in ppm) (done with mass spectrometry).

Data Analysis

The main purpose of the analysis was to investigate the effect of abiotic influences on the patterns of tree mortality and condition, measured by two factors: (1) tree condition ratings (dead/poor/fair/good); and (2) mortality status in 2015 (dead/alive). To achieve a more comprehensive analysis, the role of additional factors, including planter type (beds/pits), planting location (north/south side of the street), proximity to and type of road intersections (major/minor) and presence of tree damage (yes/no for all measures) was also examined. Although historical tree-condition ratings were collected for every year from 2011 to 2014 using the sources of data described above, only the City of Toronto dataset from 2014, which provided the most recent assessment of tree condition, was useful in the analysis given the cross-sectional nature of most other variables. As mentioned above, although temperature and precipitation records were collected, these data could not be analyzed effectively in a way that could be paired with the other temporal data, the yearly tree condition ratings. Therefore, we do not report on these analytical procedures. Therefore, we do not report on these analytical procedures.

A combination of multivariate statistical techniques was used to identify the variables that were related to the patterns of tree mortality and condition along Bloor Street. Correlation analysis, one-way multivariate analysis of variance (MANOVA), and contingency analysis were used, as they are useful to explore patterns in multivariate datasets (Hair et al. 2010). Correlation analysis was used to explore the association between continuous variable pairs (e.g., Na and Ca concentrations), and correlation coefficients (e.g., Pearson's *r*, non-parametric rank-order Spearman's Rho) were calculated to evaluate the magnitude of the association. MANOVA was used to explore the differences of the variance amongst groupings of data (e.g., variability of Ca concentrations between bed and pit planters) (Huberty and Olejnik 2006).

Contingency analysis was employed to explore the differences in proportions between discrete variables (e.g., tree condition ratings between bed and pit planters), using contingency coefficients (e.g., Pearson's $\chi 2$) to determine if there was a difference (Jutras et al. 2010). The magnitude of this difference was then measured using Phi (φ) and Cramer's measures, for both binomial and multinomial factors, respectively. Given the limited availability of data for some variables, correlation, MANOVA, and contingency analyses were applied either to the subsample ($n = 57$), or the full dataset ($n = 133$), depending on available data. Modelling techniques, such as logistic regression, were tested but later discarded due to small sample size and inconclusive results. All data in these analyses were tested for normality with the Shapiro-

Wilk's and Kolmogorov–Smirnov tests, and for homogeneity of variance with the Levene's Median test.

Follow-up univariate ANOVAs, *t*-tests, and non-parametric Mann-Whitney tests were performed on the continuous variables that were identified as significant in MANOVA. Comparison of means between groups in multinomial variables (i.e. tree condition) was performed by the Tukey's HSD post-hoc and non-parametric Kruskal-Wallis tests. Given the limited availability of data for some variables, these tests were performed either on the full (n = 133) or the subsampled (n = 57) datasets. All statistical analyses were carried out using a 95% confidence level (critical *p*-value <0.05) in R (v. 3.3.2) and IBM SPSS (v. 23) software. Only significant results are reported.

RESULTS

The 133 trees were planted in soils of a sandy-clay-loam texture (averaging: sand = 65%, silt = 14%, clay = 21%, by weight). The soil in the pit planters had moderate levels of compaction, never exceeding 2 MPa. The distance from the planting locations to the nearest intersection ranged between 6.2 and 129 m (mean = 54.3 m, SE = 2.9), with 45 trees located in closest proximity to a major intersection, and 88 to a minor one. There were 71 alive and 62 dead trees at the time of removal in 2015 (i.e., over four years, a mortality rate of 46.6%), where 64.5% of the dead trees were assessed as already dead in 2014. The majority (79%) of trees removed in 2015 displayed some form of human-caused damage. Soil at the site had generally high pH (mean = 8.2, SE = 0.1) and elevated Na (mean = 685.3 ppm, SE = 72.6), but a low EC content (mean = 0.61dS/m; SE = 0.04). Finally, the site displayed variable sunlight availability, receiving more sunlight hours in the Summer solstice (mean = 5.3 hr, SE = 0.2) compared to the Spring equinox (mean = 1.6 hr, SE = 0.1). The growing season range of sunlight per site varied between 0 and 8 hours (mean = 3.7 hr, SE = 0.2), and averaged seasonally between 0.5 and 7 hours (mean = 3.4 hr, SE = 0.1).

Analyses indicated that there were strong or moderate correlations between some soil indicators and tree metrics, particularly between Na, EC, and Mg; and Ca, pH, and DBH (Table 1). There were statistically significant differences in the distribution of dead and alive trees and tree condition and tree damage, with a moderate or strong association (φ or Cramer measure >0.2; Table 2). However, there were no differences between mortality and type of planter (Tables 2). The variations in Mg, Na, EC, and DBH were statistically significant according to tree mortality (Table 3) and tree condition patterns (Table 4), as were variations in Mg, Na, pH, and EC in bed and pit planters (Table 5). Finally, there were statistically significant differences in the way sunlight was distributed across tree planters on the north and south sides of the street (Table 6). As noted before, the temporal analyses between yearly tree-condition ratings and climatic data were inconclusive and are not reported.

Table 1: Results from the correlation analysis of tree and soil characteristics of the Bloor Street trees, in Toronto, Canada, indicating correlation coefficients, with significant values in bold (analysis performed on subsample, n=57)

Variable	*Correlation Coefficient*					
	Mg	*Na*	*Ca*	*pH* [1]	*EC*	*DBH*
Ca	0.18	-0.15	n.a.	**0.49**	0.08	**0.38**
DBH	**0.29**	**-0.45**	**0.38**	0.08	**-0.32**	n.a.
EC	**-0.58**	**0.78**	0.08	0.05	n.a.	**-0.32**
Mg	n.a.	**-0.63**	0.18	**-0.27**	**-0.58**	**0.29**
Na	**-0.63**	n.a.	-0.15	**0.31**	**0.78**	**-0.45**
pH [1]	**-0.27**	**0.31**	**0.49**	n.a.	0.05	0.08

1. Coefficients refer to Spearman's Rho, since the variable is not normally distributed (i.e. Shapiro-Wilk's and Kolmogorov–Smirnov tests p-value = < 0.05)

Table 2: Results from contingency analysis between selected tree-habitat characteristics and tree mortality patterns of the Bloor Street trees, in Toronto, Canada, with significant values in bold (analysis performed on full dataset, n=133)

Variable	*Measure*	*Frequency of counts (alive / dead)*	*Contingency Analysis*		
			χ^2	*p-value*	*Strength of association* [1]
Type of Planter	Beds	39.4 / 30.6	1.120	0.29	0.92
	Pits	60.6 / 69.4			
Location of Planter	North of Street	35.3 / 61.3	9.029	**0.003**	-0.26
	South of Street	64.8 / 38.7			
Tree Condition 2014	Dead	1.4 / 64.5	72.57	**<0.001**	0.74
	Poor	12.9 / 5.6			
	Fair	26.8 / 9.7			
	Good	66.2 / 12.9			
Tree Damage and Signs of Stress	Trees with cracks	33.8 / 83.3	31.60	**<0.001**	0.49
	Trees with bark peel	21.1 / 43.5	7.701	**0.006**	0.24

1. All values refer to the Phi (ϕ) measure, except Tree Condition 2014, which refers to Cramer's measure

Table 3: Results from the multi- and uni-variate means analyses between selected tree-habitat characteristics and tree mortality patterns (alive/dead) of the Bloor Street trees, in Toronto, Canada, with significant values in bold (analyses performed on subsample, n=57, except otherwise indicated)

Variable	*Mean of Rating (± standard error)*		*MANOVA*		*Means Analysis (p-values)*		
	Alive	*Dead*	*F*	*P-value*	*One-way ANOVA*	*Two-tailed t-test*	*Mann-Whitney Test*
Ca (ppm)	3343.34 (± 170.22)	2845.50 (±219.07)	3.31	0.074	0.074	0.079	0.058
DBH (cm)	9.91 (± 0.25)	8.46 (± 0.29)	4.75	**0.034**	**< 0.001** [2]	**< 0.001** [2]	**0.002** [2]
EC (dS/m)	0.49 (± 0.05)	0.69 (± 0.07)	5.66	**0.021**	**0.021** [1]	**0.017**	**0.032**
Mg (ppm)	187.57 (± 10.40)	160.34 (± 12.65)	4.21	**0.045**	0.101	**< 0.001**	**0.031**
Na (ppm)	570.87 (± 71.31)	847.40 (± 138.91)	4.63	**0.036**	**0.015** [1]	**< 0.001**	0.112
pH	8.23 (± 0.14)	8.13 (± 0.13)	0.26	0.61	0.61	0.59	0.73

1. Significant for Levene's test, $p < 0.05$
2. Analysis performed on full dataset (n = 133)

Table 4: Results from the multi- and uni-variate means analyses between selected tree-habitat characteristics and tree condition patterns (dead/poor/fair/good) of the Bloor Street trees, in Toronto, Canada, with significant values in bold (analyses performed on subsample, n=57, except otherwise indicated)

Variable	*Mean of Rating (± standard error)*				*MANOVA*		*Means Analysis (p-value)*	
	Dead (0)	*Poor (1)*	*Fair (2)*	*Good (3)*	*F*	*P-Value*	*One-way ANOVA*	*Kruskal-Wallis Test*
Ca (ppm)	2802.96 (± 273.86)	4161.53 (± 332.38)	2989.55 (± 350.53)	3173.23 (± 187.27)	2.32	0.085	0.085	0.086
EC (dS/m)	0.85 (± 0.09)	0.39 (± 0.07)	0.51 (± 0.15)	0.47 (± 0.03)	6.79	**0.001**	**0.023** [2]	**0.006**
DBH (cm)	8.06 (± 0.41)	10.50 (± 0.47)	9.48 (± 0.45)	9.72 (± 0.25)	3.85	**0.015**	**0.002** [1]	**< 0.001** [1]
Mg (ppm)	149.04 (± 17.04)	206.19 (± 26.55)	170.67 (± 13.56)	186.46 (± 11.54)	1.34	0.271	0.179	**0.035**
Na (ppm)	1135.05 (± 165.48)	233.03 (± 77.47)	665.42 (± 191.45)	541.11 (± 74.47)	6.01	**0.001**	**0.001**	**0.001**
pH	8.27 (± 0.15)	8.84 (± 0.22)	8.18 (± 0.34)	8.07 (± 0.14)	1.37	0.26	0.26	0.22
Sunlight Average (hr)	4.02 (± 0.28)	3.95 (± 0.49)	4.01 (± 0.35)	2.62 (± 0.16)	8.62	**< 0.001**	**< 0.001** [1]	**< 0.001** [1]
Sunlight in March 21 (hr)	1.92 (± 0.26)	1.37 (± 0.40)	1.89 (± 0.32)	1.18 (± 0.19)	1.69	0.178	0.082 [1]	**0.040** [1]
Sunlight Range (hr)	4.21 (± 0.32)	5.11 (± 0.48)	4.35 (± 0.46)	2.89 (± 0.22)	8.53	**< 0.001**	**< 0.001** [1]	**< 0.001** [1]

1. Analysis performed on full dataset (n = 133)
2. Significant for Levene's test, p < 0.05

Table 5: Results from the multi- and uni-variate means analyses between selected tree-habitat characteristics and type of tree planter (bed/pit) of the Bloor Street trees, in Toronto, Canada, with significant values in bold (analyses performed on subsample, n=57, except otherwise indicated)

Variable	*Mean of Rating (± margin of error)* [1 2]		*MANOVA*		*Means Analysis (p-value)*		
	Beds	*Pits*	*F*	*P-Value*	*One-way ANOVA*	*Two-tailed t-test*	*Mann-Whitney Test*
Ca (ppm)	3156.35 (± 227.79)	3129.45 (± 171.73)	0.0078	0.93	0.93	0.93	0.77
EC (dS/m)	0.37 (± 0.03)	0.64 (± 0.05)	9.85	**0.003**	**0.003** [2]	**0.003**	**0.002**
Mg (ppm)	209.32 (± 9.42)	162.61 (± 10.18)	5.15	**0.008**	**0.008**	**0.008**	**< 0.001**
Na (ppm)	214.64 (± 36.13)	880.46 (± 84.64)	22.58	**< 0.001**	**< 0.001** [2]	**< 0.001**	**< 0.001**
pH	7.81 (± 0.14)	8.34 (± 0.12)	6.36	**0.015**	**0.015**	**0.015**	**0.012**
Sunlight in June 21 (hr)	5.92 (± 0.34)	4.97 (± 0.24)	5.22	**0.023**	**0.023** [1]	**0.023** [1]	**0.026** [1]

1. Analysis performed on full dataset (n = 133)
2. Significant for Levene's test, p < 0.05

Table 6: Results from the multi- and uni-variate means analyses between selected tree-habitat characteristics and street side (North/South) of the Bloor Street trees, in Toronto, Canada, with significant values in bold (analyses performed on subsample, n=57, except otherwise indicated)

Variable	*Mean of Rating (± margin of error)*		*MANOVA*		*Means Analysis (p-value)* [1]		
	North	*South*	*F*	*P-Value*	*One-way ANOVA*	*Two-tailed t-test*	*Mann-Whitney Test*
Sunlight Average (hr)	4.82 (± 0.13)	2.19 (± 0.13)	208.72	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Sunlight in March 21 (hr)	2.40(± 0.19)	0.79 (± 0.14)	45.46	**< 0.001**	**< 0.001** [2]	**< 0.001**	**< 0.001**
Sunlight in June 21 (hr)	4.46 (± 0.24)	6.07 (± 0.29)	18.57	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Sunlight Range (hr)	4.82 (± 0.236)	2.83 (± 0.20)	41.06	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**

1. Analysis performed on full dataset (n = 133)
2. Significant for Levene's test, p < 0.05

DISCUSSION

Implications of Findings

The results of this study have revealed some important relationships between abiotic variables and their association with tree decline and mortality patterns in a commercial-retail streetscape located in a northern climate. Factors affecting tree decline and mortality were determined to be multi-faceted, co-occurring, and likely cumulative. Drivers of tree decline were found to be elevated soil salinity and alkalinity, characteristics of the planting sites, as well as human and/or climate-induced physical damage to tree bark and canopy. The authors speculate that exposure to excessive solar radiation could have also contributed to heat stress and soil moisture loss (especially in the rooting zone), additionally aggravating the growing conditions for these trees.

The levels of EC and Na found in the Bloor Street soils were above the suggested thresholds of 0.16 dS/m and 260 ppm, respectively, concentrations beyond which negative effects are expected to manifest in compromised tree condition (Byron and Barker 2002; Czerniawska-Kusza et al. 2004). However, the comparison between our study results and the thresholds suggested by previous studies, particularly in terms of the significant relationship between soil salinity and tree condition, must be interpreted with caution given that some laboratory soil analyses and tree species vary. Although urban soils generally display elevated EC and Na levels, these are rarely ever found above 1.5 dS/m and 1500 ppm, respectively (Craul 1999). The most probable source of these salts is winter de-icing agents (Cekstere et al. 2008; Cunningham et al. 2008); this has been corroborated by recent reports on urban tree health in Canadian cities (Equiza et al. 2017). The commercial area around Bloor Street is an area with very low tolerance to ice on the sidewalks, thus the intense use of de-icing agents.

In our study, trees that were dead, trees that displayed poor canopy condition, and trees that were planted in pits, had soil conditions with a significantly higher levels of Na and EC than other trees (Tables 3, 4 and 5). The presence of salt ions may have caused osmotic and ionic stress to the trees, dehydrating plant tissue, impairing photosynthesis, and accelerating leaf senescence (Munns and Tester 2008). Although it could be argued that the choice of tree species for this stretch of commercial-retail street was poor, given that London planetrees have a low to moderate salinity tolerance (Gilman and Watson 1994; Morton Arboretum 2017), it is unclear if another tree species would perform differently in this environment, as in many situations de-icing salts accumulate long-term, and the high soil salinity caused by this accumulation negatively affects tree condition regardless of species (Equiza et al. 2017).

But de-icing salts alone do not explain the patterns of tree mortality on Bloor Street. Ultimately, some of the trees that were still alive before removal had high soil concentrations for Na and EC (Table 4). The characteristics of the planting sites, such as type of planter, may have exacerbated tree decline and mortality for at least some of the 133 trees. Although the type of planter was not significantly associated with mortality rates (Table 2), soil within pit planters had significantly higher levels of salts (Table 5). These planters may have been more susceptible to salt influx, as is commonly the case with street-level planters (Hootman et al. 1994). Although soil compaction can influence salt accumulation (Grabosky et al. 2001), our analysis did not see this relationship directly, as compaction remained below the suggested threshold of between 2.0 and 2.6 MPa (Day and Bassuk 1994; Day et al. 2010; Millward et al. 2011).

In addition, soil alkalinity along Bloor Street was generally higher than the recommended pH 6.5 for growing trees in urban areas (Jim 1997; Trowbridge and Bassuk 2004), especially in pit planters (Table 5). The associations between pH and Na, Mg, and Ca seen in our data (Table 1) corroborate previous reports on how elevated salt concentrations and pH result in conditions amenable to leaching of soil nutrients, a known stressor of plant health (Gałuszka et al. 2011; Kargar et al. 2015; Eimers et al. 2015). However, given the lower concentration of Mg in pit planters, compared to bed planters (Table 5), Mg concentrations could have been replenished by the application of fertilisers to the flowers in the bed planters. Despite the strong associations this study found between soil chemical variables and tree condition, more research is needed on the interactions among nutrients, salinity, and pH, in urban soils, and their collective and cumulative effects on urban tree performance.

Our analysis identified sunlight availability as an important factor influencing tree mortality patterns. Lack of available sunlight has been suggested as a possible cause for poor tree performance (Jutras et al. 2010). In our study, trees that were in better condition had more available direct sunlight at the beginning of the growing season, but lower seasonal variation (Table 4). Another important association of this factor is inferred indirectly. Since the north side of Bloor Street received more direct sunlight compared to the south side (Table 6), and this side displayed higher rates of tree mortality (Table 2), it is suggested that too much sunlight may have affected tree health at the North side through heat stress and soil moisture loss. Since elevated soil temperatures in the rooting zone can damage existing roots, and inhibit root growth (Gillner et al. 2013a), we speculate that these conditions may have exacerbated soil moisture loss through evaporation and influence tree mortality and condition patterns.

Finally, trees with more physical damage (e.g., broken branches, trunk scars, missing bark) displayed higher rates of mortality along Bloor Street (Table 2). This is consistent with the literature on tree condition in urban areas (Nowak et al. 2004; Lu et al. 2010). Nonetheless, some of this physical damage to tree limbs and bark may have resulted from weather conditions or storm events between 2011 and 2015, since bark peel is a common manifestation of heat stress in trees, and ice damage causes broken branches (Trowbridge and Bassuk 2004). However, we were not able to quantify actual physical damage to trees resulting from meteorological conditions, as weather data were not compatible with our analysis.

Limitations

There are several limitations to this study, the most important of which was our inability to process the collected climatic data so it could provide strong analytical insight. This is due to the temporal variability of these data and requirement for microclimate-scale monitoring data in dense urban environments. Nonetheless, we recognize that this is an important factor that deserves future exploration. Toronto, the location of the Bloor Street trees, is at the northern edge of London Planetrees' suggested range (GBIF, 2017). Therefore, climatic conditions that could not be analyzed in this study may have also contributed to tree decline and mortality. Regardless, these conditions would have co-occurred and cumulatively impacted tree mortality and decline along with the other factors described above.

The associations between trees with larger DBH values and less mortality, better condition, and lower salinity levels (Tables 1, 3, and 4), are not conclusive. This is because the historical data collected on the Bloor Street trees (see above) at this point did not provide enough information about tree replacements and replanting (e.g., which trees were replaced; when where they replaced; and what size of tree was planted initially and as a replacement), which is necessary to provide baseline conditions for a more adequate evaluation of tree performance. Tree-size at the time of planting could have influenced a tree's capacity to adapt to the growing conditions at Bloor Street. A further examination of this issue is warranted.

Other limitations include the fact that soil analyses only provided a cross-sectional snapshot in time of the soil conditions, and these conditions will vary seasonally and from year to year. Salt concentration in soils is influenced by de-icing salt application protocol in relation to weather patterns, maintenance regulations specific to a property close to a tree planting site, as well as salt flushing rates, which were not considered in our analysis. Also, we recognize that leaf analysis may be necessary for an adequate examination of salt impact on trees, and that leaf damage may have been both a potential cause of decline and mortality as it could be a result of this process along Bloor Street. Finally, while the relatively small sample size of some variables was analytically restrictive, our multimodal analysis, based on a variety of simple but sound multivariate statistics, did allow for a deeper examination of a greater number of factors characterizing the Bloor Street environment.

CONCLUSION

Our investigation of the Bloor Street trees has highlighted several important ways in which abiotic factors can influence tree condition and mortality in highly-urbanized settings, such as in downtown commercial-retail streetscapes. These factors include soil salinity and alkalinity; built environment characteristics (e.g., planter type, such as pit or bed); sunlight exposure; and, physical damage to trees. Importantly, we show that tree performance in these settings cannot be explained solely by the influence of one variable, but rather by the co-occurring interaction among several variables with a likelihood of cumulative influence.

Structural soil cells are useful for providing soil volume and quality necessary to support the growth of trees along commercial-retail streetscapes. Their presence along Bloor Street allowed for us to investigate an urban growing environment for trees that controlled for soil volume and several soil quality characteristics at the time of tree planting. Nonetheless, investigating the movement of salts in structural soil cell installations, and investigating the mechanisms for restricting de-icing salt access to, and accumulation within, these cells, are useful topics for future research. This is instrumental for developing strategies to reduce the negative impacts of salts on trees growing in these cells. Finally, with climate change increasing the incidence of extreme weather events, such as ice storms and freeze-thaw cycles (Chiotti and Lavende 2008), the application of de-icing salts could increase in the future and challenge urban-tree performance in areas with low tolerance for ice accumulation, such as commercial-retail streetscapes.

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