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The Effects of Residential Street Tree Spacing and Crown Interactions on Crown Dimensions and Canopy Cover

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Abstract. Urban trees provide people with a range of ecosystem services. Trees planted along streets have been a large focus of urban forest research and practice, and municipalities invest significant resources in their survival. However, the optimal spacing of street trees is not addressed in the scientific literature, and existing municipal street tree spacing standards are highly variable and poorly enforced. In this study, we examine variability in crown shape and size for street trees to test for possible interaction effects at closer spacings. We measured variability in crown diameters both parallel and perpendicular to street tree rows to test whether changes in crown dimensions can be explained by interaction effects with neighbouring trees, and whether crown interactions lead to a reduction in total crown projection area (i.e., canopy cover). We measured the crown dimensions and diameter at breast height of 1,338 street trees in Halifax, Canada. We used two-way analysis of variance to test whether crown shape and crown projection area were affected by crown interactions and spacing. We found that the effect of narrower spacing and interactions (i.e., crowns touching/overlapping) among trees translated to crowns extending away from the direction of interaction. We also found that these changing crown dimensions were associated with increases in canopy cover. Urban forest ecosystems are a vital resource for the increasingly urban population. There is a need for empirical research on spacing standards and practices that investigate their influence on the supply of ecosystem services, such as stormwater retention, air pollution removal, and cooling.

Keywords. Canopy Cover; Competition; Ecosystem Services; Spacing; Street Trees; Tree Planting.

INTRODUCTION

Trees and forest patches in the urban landscape provide people with a wide range of ecosystem services, including air pollution mitigation, heat island amelioration, stormwater retention, and energy benefits for buildings (Boyd and Banzhaf 2007; Fisher et al. 2009; Duinker et al. 2015). Trees in the city also assist in adaptation to climate change (Gill et al. 2007). Trees planted along city streets within the public right of way (i.e., street trees) have been a large focus of urban forest research and practice and provide high levels of benefits given their close proximity to built infrastructure (Steenberg et al. 2017). These include attracting consumers to commercial streets and improving road surface longevity (McPherson and Muchnick 2005; Duinker et al. 2015). Street trees also face higher rates of stress and disturbance compared to many other sites (Jutras et al. 2010; Lu et al. 2010; Ordóñez et al. 2018). Perhaps most importantly, street trees comprise the majority of trees owned by municipalities and directly managed by municipal urban forest practitioners. Municipalities therefore have a considerable investment in ensuring their survival and performance in terms of ecosystem service delivery.

A key issue that is not addressed in the scientific literature is the optimal spacing of street trees. In other words, what distance between planted street trees would maximize the delivery of ecosystem services while balancing the costs of management and possible negative effects of competition? Many studies on urban tree allometry suggest that their findings could be useful for urban planners in determining growing space requirements (Pretzsch et al. 2015;

Dahlhausen et al. 2016; Monteiro et al. 2016). However, the studies do not specifically address the issue of competition and spacing in street plantings, nor provide subsequent recommendation on spacing standards. Indeed, the focus is often on the space requirements of trees based on crown dimensions (Pretzsch et al. 2015), not changes in crown dimensions at different spacings. There is a plethora of municipal standards and guidelines for street tree spacing. For example, Vancouver, British Columbia (Canada) and Visalia, California (USA) have spacing standards based on tree size, which are 6 m to 10 m for medium trees and 9 m to 14 m for large trees (City of Visalia 2005; City of Vancouver 2012). However, street trees are typically planted at considerable distances apart, much further than municipal standards might demand, which results in increased leaf area and reduced aboveground biomass of individual trees (Nowak et al. 2008), but lower overall leaf area and canopy cover on a given street. For example, Aryal (2017) found that the average street tree spacing in Halifax, Canada was over 15 m (in some neighbourhoods, over 20 m). The street tree density in several studied streetscapes in California was found to be lower than 50 trees/km and has declined nearly 30% since 1988 (McPherson et al. 2016).

Arguably, there are two issues at play: (1) based on the very limited empirical evidence available, it seems that street tree spacing is typically exceeding recommended standards, leading to fewer overall trees and lower canopy and ecosystem services; and (2) there is no published evidence that any of these highly variable street tree spacing standards and guidelines are based on empirical research on street tree performance and costs, though our assumption around this issue is certainly a source of uncertainty in this study that warrants future research (e.g., interviews with municipal practitioners that have standards in place). Regarding the first issue, several factors might explain existing street tree spacing patterns. First, street trees are expensive to plant, as the balled-and-burlapped nursery stock costs over $400 to install in Halifax (J. Simmons, personal communication, 2018 February 2). Second, it is often necessary to space street trees at certain distances away from existing infrastructure, such as driveways, hydrants, signage, underground pipes and wires, street lights, and utility poles (The City of Winnipeg 2009; Miller et al. 2015). Third and paramount, a main driver of street tree planting and management is their aesthetic value, which is based on fully developed crowns unaffected by competition with neighbouring trees (Miller et al. 2015; Aryal 2017).

If spacing guidelines and practices are to consider street trees not only as amenities, but also as ecosystem service providers, then a reconsideration of spacing standards is necessary, as is compliance with these standards in municipal street tree plantings. Many of the ecosystem services provided by street trees are positively associated with the amount of tree foliage (Nowak et al. 2008). Over the long term, the amount of tree foliage per unit area of city street is highly dependent on the number of trees. Our theory is that increasing the density of street plantings has the potential to achieve higher levels of ecosystem service supply, especially when the trees are young. However, there is also the potential for adverse impacts due to competition and costs, which are discussed later in this paper. It stands to reason that, at a minimum, improving planting practice to conform to established street tree spacing guidelines is needed, while conducting research on spacing guidelines to optimize ecosystem service supply would be valuable.

With regard to increasing street tree density to improve urban forest benefits, it is important to consider trade-offs in planting costs (i.e., cost versus size of the stock), but also trade-offs in reduced tree performance due to biological competition between trees. With regard to crown architecture, research has primarily focused on commercial forests and silviculture, in particular on young trees, saplings, and seedlings, to examine the competitive effects on individual tree growth and tree crown structure (Weiner 1982; Canham et al. 2004; Coates et al. 2009; Thorpe et al. 2010). To be applicable to street trees and optimal street tree spacing, there is a need for research that investigates competitive effects on trees growing only in linear rows, with competition occurring with no more than two neighbouring trees.

In this study, we examine variability in crown shape and size for street trees in Halifax, Canada, to test for possible interaction effects of street tree spacing. Specific research objectives include: (1) to measure variability in crown diameters both parallel and perpendicular to street tree rows; (2) to test whether differences in crown dimensions can be explained by interaction effects with neighbouring trees; and (3) to measure if any existing differences in crown dimensions associated with crown interactions lead to a reduction in total crown projection area (i.e., canopy cover), or more generally, to study the effects of tree competition on the total canopy cover.

Our hypothesis, based on existing empirical research in Halifax (Aryal 2017), is that under increased levels of competition in rows at closer spacings, street trees will respond with crowns that extend perpendicular to tree rows. If these changing crown dimensions correspond to no statistically significant change in canopy cover—or even increases in canopy cover—it would suggest that street tree standards could integrate closer spacing without reducing the overall supply of ecosystem services. While the study does not provide guidance on optimal distances for new street tree standards, it does begin to address a current gap in the interface between research and practice.

MATERIALS AND METHODS

Study Area

This study was conducted in the urban centre of Halifax, Canada (Figure 1). Data collection was restricted to older residential neighbourhoods, including 3 neighbourhoods in the community of Dartmouth and

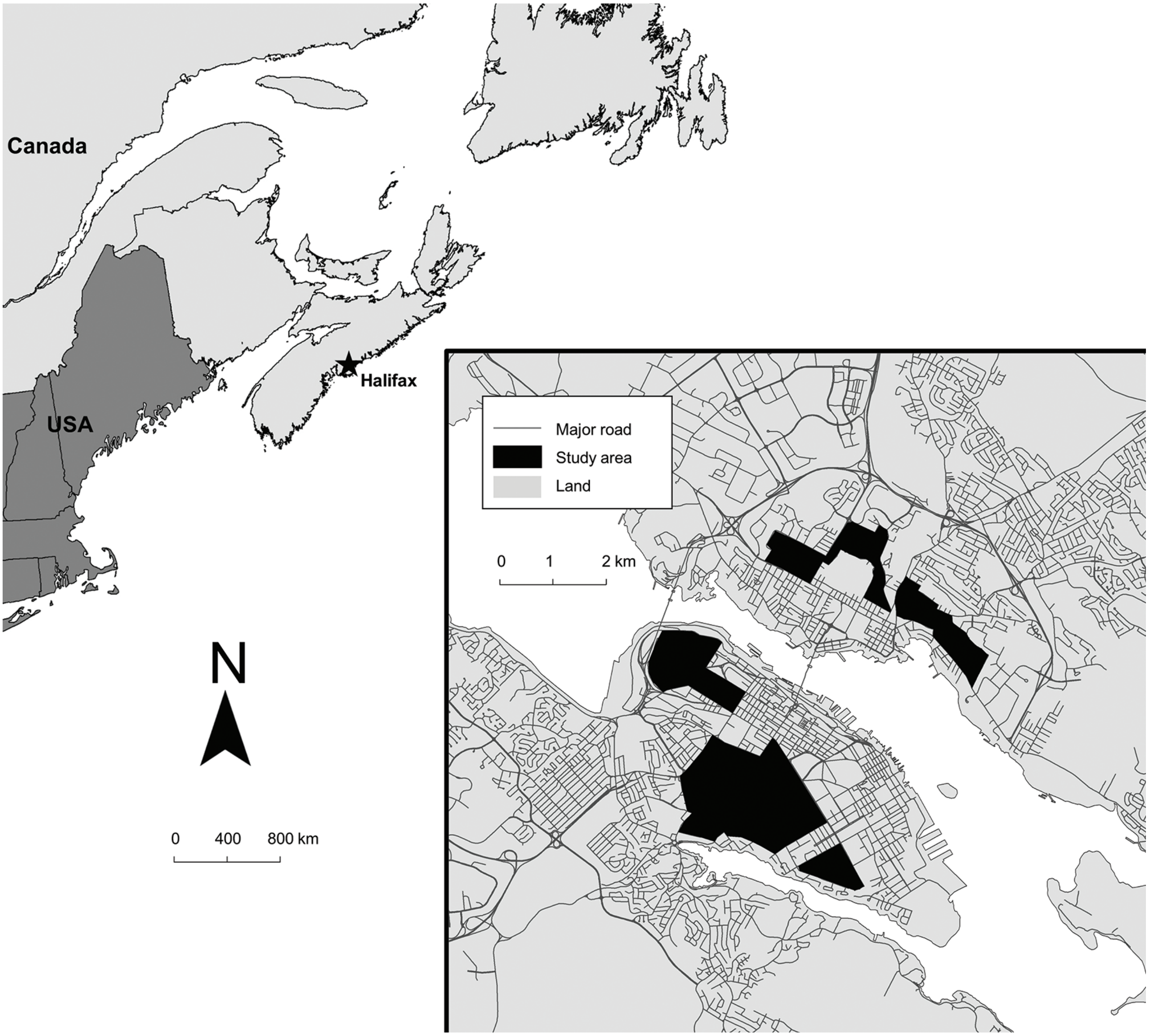

Figure 1. Neighbourhoods selected for field data collection in Halifax, Canada.

8 neighbourhoods on the Halifax Peninsula. This was done in order to have a sufficient street tree population and variability of spacings to conduct a sufficient analysis. Halifax is situated in the Acadian Forest Region, where dominant tree species in residual and surrounding forests include red spruce (*Picea rubens*), white pine (*Pinus strobus*), balsam fir (*Abies balsamea*), and red maple (*Acer rubrum*)(Loo and Ives 2003). Dominant tree species within urban areas of Halifax include Norway maple (*Acer platanoides*), American elm (*Ulmus americana*), and littleleaf linden (*Tilia cordata*)(Foster and Duinker 2017). Halifax is in the humid continental climate region, with an average annual precipitation in the last 3 decades used for normals calculations (1981–2010) of 1,468 mm, ranging from 96 mm in August to 151 mm in November (ECCC 2021). Halifax is located in the 6a Canadian plant hardiness zone, with temperatures ranging between −4 and 19 °C (ECCC 2021).

Data Collection

We measured street trees on sampled street segments in the 11 residential neighbourhoods. Sampled street segments had to have sidewalks with a tree lawn (i.e., grass strip between curb and sidewalk) and a length of over 100 m between street intersections. Shorter segments were ignored, as they often had only 1 or 2 trees, making calculation of average spacing relatively meaningless. A complete street segment inventory for the 11 neighbourhoods was compiled using a geographic information system (GIS), and each street segment was demarcated with a street segment number and total length, which was measured using aerial imagery. Altogether, 457 street segments (399 in the Halifax Peninsula and 58 in Dartmouth) were identified. The total area of the 8 delineated neighbourhoods in the Halifax Peninsula is considerably larger than that of the 3 in Central Dartmouth, so one-third of the measured segments in the Halifax Peninsula and half of those in Dartmouth were chosen randomly using a random number generator and the unique identification number of each street segment, giving a total sample of 188 street segments (Table 1). At least 10 segments were sampled in each neighbourhood.

Trees in the 188 street segments were measured between April and August of 2016. Each tree was measured for its species, diameter at breast height (DBH), crown diameter perpendicular to the row of trees (i.e., street), and crown diameter parallel to the row of trees. Crown diameter summaries across DBH classes are shown in Figure 2. Street tree DBH was measured using a diameter tape, and crown diameter was measured using a 25-m measuring tape for 3 of the 4 radii of the crown, followed by summation to achieve the 2 crown diameter measurements. For measuring the perpendicular crown diameter, permission from hundreds of residential property owners would have been necessary. Consequently, the perpendicular crown radius away from adjacent properties was measured and doubled to get diameter values.

Table 1. Number of street segments and street trees measured in old residential neighbourhoods in the Halifax Peninsula (H) and Dartmouth (D).

Neighbourhood	Total street segments	Total sampled segments	Total measured trees	Total segments length (m)	Measured segments length (m)
H1	37	13	156	6,987	2,239
H2	30	14	155	5,242	2,507
H3	77	34	418	12,532	5,711
H4	53	26	452	11,553	5,888
H5	33	12	129	7,014	2,476
H6	74	25	304	13,800	4,638
H7	51	18	148	6,235	2,190
H8	44	15	154	7,994	2,533
D1	17	10	71	2,849	1,806
D2	22	11	97	4,543	1,995
D3	19	10	78	3,890	3,485
Total	**457**	**188**	**2,162**	**82,639**	**35,468**

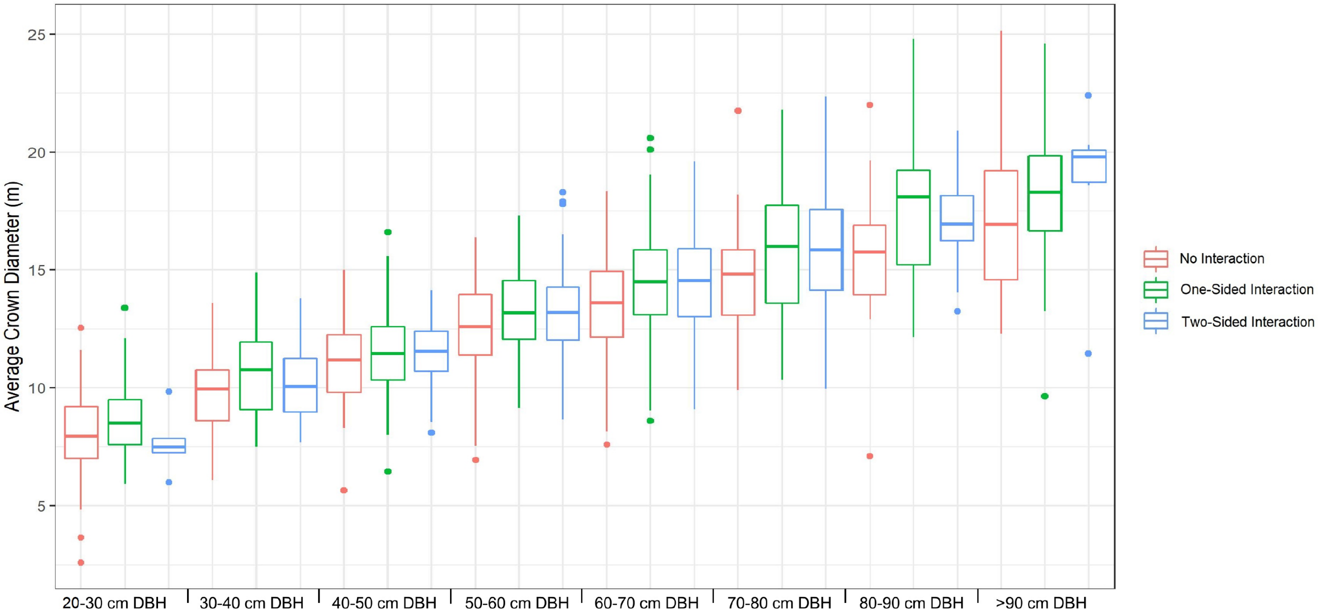

Figure 2. Average crown diameter (m) of street trees in each of the 8 DBH classes in each of the 3 categories of crown interaction with neighbouring trees (no interaction, one-sided interaction, or two-sided interaction).

This relies on the assumption that the crown radii are equal on average and could be a source of error and uncertainty in our findings. Importantly, measured street trees were all planted in the tree lawn in the public right of way. These tree lawns are typically far enough from adjacent buildings in the residential neighbourhoods of our study that the studied trees have no crown interactions with them. Street tree crown interactions with adjacent buildings were rarely observed in the field, though this was not quantified. To get street tree spacing values, we measured distance to the next tree(s) in the row of street trees and distance from the street segment end for the first and last tree in each row. The centre of every tree stem served as the end point for distance measurements. A total of 2,162 trees were measured.

Data Analysis

We measured all trees in the sampled street segments regardless of tree size or spacing. However, for the analysis we only considered trees with a minimum DBH of 20 cm to focus on the crown behaviour of mature trees, since below this threshold there were very few trees interacting with adjacent trees. Lastly, trees that were on the end of a row of street trees/street segment were omitted to ensure that analyzed trees could have crown interactions with neighbouring trees on both sides. We calculated the degree of crown overlap between street trees as:

$$\text{Crown Overlap} = (r1 + r2) - d$$

where $r1$ is the crown radius of the first tree in a pair of two neighbouring trees, $r2$ is the crown radius of the second tree in the pair, and d is the distance between the two trees. Using this formula, a positive value would be generated where crown overlap exists, while negative values indicate no crown overlap (i.e., two trees spaced far enough apart to have no crown interaction) and were converted to zero. Where positive crown overlap values existed, it was possible for a given street tree to have an overlap with a neighbour on one side or on both sides. The analysis was conducted on all 3 categories of tree interaction: (1) no interactions, (2) interactions with one neighbour, and (3) interactions with two neighbours. The removal of small-stature trees below 20-cm DBH and removal of trees without a neighbouring tree on each side reduced the number of measured trees included in the analysis from 2,162 to 1,338.

We calculated the ratio of the perpendicular crown diameter to the parallel crown diameter to see if crown interactions in the row of trees were explaining differences in crown dimensions. We also calculated crown projection area (m^2) for every tree included in the analysis:

$$\text{Crown Projection} = \pi \times a \times b$$

where a is the parallel crown radius (m), and b is the perpendicular crown radius (m). The parallel and perpendicular crown radii (a and b) is half the total parallel diameter of the crown. For each DBH class, we calculated average crown projection for all 3 categories of tree interaction. Lastly, to test for significant differences, we used a two-way analysis of variance (ANOVA) with DBH classes and crown interactions (i.e., no interaction, one-sided, or two-sided) used as the two factors and both the crown diameter ratio and crown projection area as the dependent variables. We then used Tukey's honest significant difference (HSD) post hoc test where ANOVA revealed significant relationships. All included variables were inspected for normality, equality of variance, and other assumptions of ANOVA testing.

RESULTS

The 1,338 street trees included in the analysis were dominated by Norway maple, American elm, and littleleaf linden (Table 2). The distribution of trees across the 3 categories of crown interaction (i.e., no interaction, one-sided interaction, or two-sided interaction) was fairly even (Table 3, Table 4). Street trees in the 60- to 70-cm DBH class were the most abundant, with decreasing abundance of both smaller and larger trees. As expected, mean crown diameter and mean canopy cover per tree of a given DBH class consistently increased with tree size.

Table 2. Species composition (count and %), mean and standard deviation (SD) of tree size (cm DBH), and mean and SD of spacing (m) between neighbouring trees for measured street trees included in the analysis.

Species	Count (%)	DBH (SD)	Spacing (SD)
Norway maple	634 (47.4)	56.1 (15.3)	16.5 (10.8)
Elm	334 (24.9)	71.1 (13.4)	15.2 (8.9)
Linden	201 (15.0)	56.8 (16.4)	13.2 (6.7)
Red oak	40 (3.0)	46.6 (15.9)	8.8 (15.8)
Sugar maple	8 (0.6)	35.4 (12.3)	12.3 (4.6)
Other (20 species)	121 (9.0)	45.3 (23.3)	15.1 (11.4)
Total	**1,338 (100)**	**58.5 (17.9)**	**15.3 (9.6)**

The comparison of the perpendicular and parallel crown diameters revealed an interesting trend (Figure 3). Where crown interactions existed, the crown diameter that was parallel to the row of street trees was consistently smaller than the estimated values, while the crown

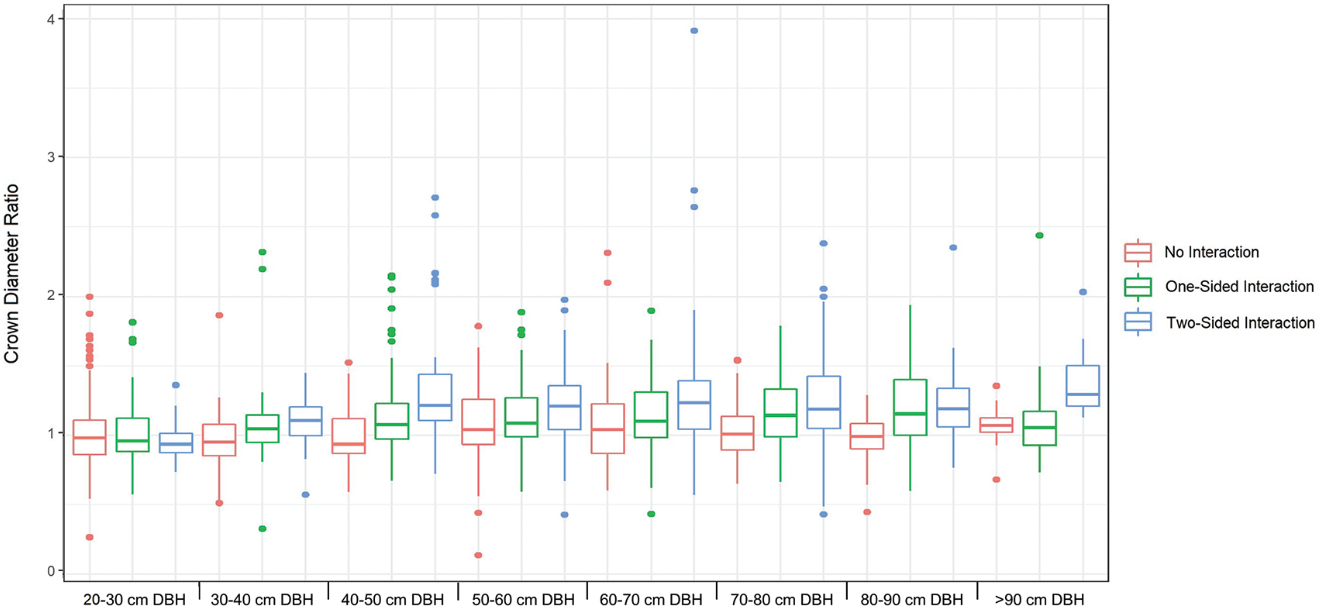

Figure 3. The ratio of the perpendicular crown diameter to the estimated crown diameter for street trees in each of the 8 DBH classes in each of 3 categories of crown interaction with neighbouring trees (no interaction, one-sided interaction, or two-sided interaction).

diameter value that was perpendicular to the row was consistently larger. In other words, when street trees interacted more with neighbouring trees, the crowns became more elliptical, extending away from the direction of competition. Trees with one-sided interactions had a 9.6% higher diameter ratio (i.e., more elliptical crown) than trees with no interactions, while trees with two-sided interactions had a 19.5% higher diameter ratio.

An objective of the analysis was to measure whether street tree crowns were not only more elliptical when interacting with neighbours, but whether there were also significant increases or decreases in crown projection area with increasing interaction. There was a consistent trend in looking at the differences in crown projection within each DBH class across the 3 different categories of crown interaction (Figure 4). Street trees with one- or two-sided crown interactions had consistently greater canopy cover, especially among larger trees. For instance, there was a 24.1 and 21.2 m^2 increase in crown projection for one-sided and two-sided interactions compared to no interactions, respectively. Additionally, street trees often had greater canopy cover with one-sided crown interactions compared to two-sided interactions, most notably in the 80- to 90-cm DBH class.

The two-way ANOVA revealed several significant relationships (Table 5, Table 6, Table 7). There were significant differences in the crown diameter ratio variable across crown interaction categories and the DBH classes. The crown projection variable showed significant differences across both the crown interaction categories and DBH classes. There were no significant interactions between the DBH and crown interaction factors in both ANOVA tests. The Tukey's post hoc test for the crown diameter ratio variable and crown interaction factor (Table 6) showed significant differences in crown diameter ratios between the no interaction and interaction (i.e., one-sided and two-sided) categories, where crown diameter ratios tended to be larger (i.e., more elliptical) in the interaction categories. The Tukey's post hoc test for the DBH class factor with the crown diameter ratio variable only showed significant relationships against the smallest DBH classes (Table 7), indicating that tree size may not be influential on crown interaction dynamics. As would be expected, the differences between crown projection across all DBH classes were significant, and these results are not included for the sake of brevity.

Table 3. Total number of analyzed street trees in the 3 categories of crown interaction with neighbouring trees and their mean spacing (m) between neighbouring trees.

DBH (cm)	No interaction	One-sided interaction	Two-sided interaction	Total	Mean spacing (m)
20–30	69	35	5	109	15.5
30–40	61	36	15	112	17.5
40–50	60	67	33	160	15.3
50–60	88	108	95	291	15.1
60–70	85	129	112	326	15.4
70–80	44	76	82	202	15.3
80–90	21	46	33	100	15.8
> 90	69	35	5	109	16.6
Total	**436**	**520**	**382**	**1,338**	**15.5**

Table 4. Minimum, maximum, and mean spacing (m) between street trees in the 3 categories of crown interaction with neighbouring trees.

Crown interaction category	Minimum	Maximum	Mean	Count
No interaction	5.0	76.4	16.6	436
One-sided interaction	5.6	51.6	14.8	520
Two-sided interaction	3.1	46.3	13.4	382
Total	**3.1**	**76.4**	**14.9**	**1,338**

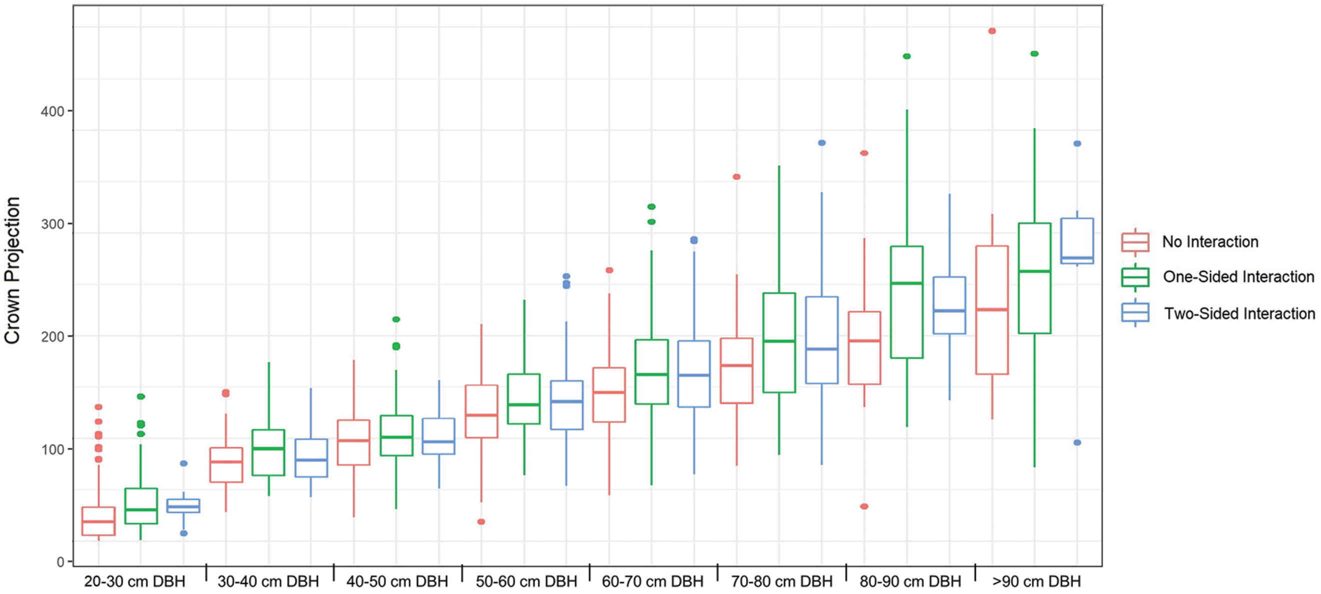

Figure 4. Average canopy cover (m²) for street trees in each of the 8 DBH classes in each of 3 categories of crown interaction with neighbouring trees (no interaction, one-sided interaction, or two-sided interaction).

Table 5. Two-way ANOVA results for both the crown diameter ratio and crown projection area (m²) variables.

Variable	df	*F*	*P*-value
Crown diameter ratio			
DBH	7	7.95	< 0.001
Crown interaction	2	49.80	< 0.001
Crown projection			
DBH	7	1,422.93	< 0.001
Crown interaction	2	13.43	< 0.001

DISCUSSION AND CONCLUSION

The findings of this study are two-fold. First, we found that the effect of closer tree spacing and increased crown interactions in rows of street trees in Halifax, Canada, translated to altered crown dimensions, with crowns extending away from the direction of interaction. This effect was far more pronounced in trees of medium size (i.e., 20 to 40 cm DBH) and not larger trees, the reason for which is uncertain and requires further research. Street trees typically started having crown interactions at maturity with a spacing between 10 and 15 m, while the crown diameter ratio tended to increase noticeably (i.e., elongation of the crown) below 10-m spacing. Second, among larger trees, these differing crown dimensions were also associated with increases in crown projection area and canopy cover. However, some important limitations of this study are that it did not explicitly consider or quantify the effects of management on street tree crown architecture, in particular pruning, and it did not consider other drivers of urban forest structure that may influence crown architecture, such as the surrounding built environment (e.g., impervious surfaces), other land uses, and citizen stewardship of urban trees (Vogt et al. 2015; Steenberg et al. 2019). These should be included in future research. Moreover, future research might also address species and light availability (e.g., using aspect) effects of shading on crown interactions, inclusive of trees that are in close proximity but not physically interacting. Other limitations include the restriction of data collection to older residential neighbourhoods, which introduces potential bias given the social processes across different neighbourhood types that can influence urban tree health and structure (Vogt et al. 2015; Steenberg et al. 2019).

There are several factors that might explain these findings. In addition to genetics, environmental factors influence tree crown dimensions, such as light availability, growing space, soil, nutrients, and water. Indeed, many studies have shown that trees tend not to have fixed crown shapes at maturity, even within the same species (Brisson 2001; Getzin and Wiegand 2007; Purves et al. 2007; Schröter et al. 2012; Olivier et al. 2016). This flexibility in crown shape, along with

Table 6. Two-way ANOVA Tukey HSD post hoc test for the crown interaction factor with the crown diameter ratio and crown projection (m²) variables.

Crown interaction category (*I*)	Crown interaction category (*J*)	Mean difference (*I* − *J*)
Crown diameter ratio		
No interaction	One-sided interaction	**−0.096****
	Two-sided interaction	**−0.195****
One-sided interaction	Two-sided interaction	**−0.099****
Crown projection		
No interaction	One-sided interaction	**−24.121****
	Two-sided interaction	**−21.197****
One-sided interaction	Two-sided interaction	−4.212

* Significant at the α = 0.05 level
** Significant at the α = 0.01 level

crown plasticity where tree crowns grow in the direction of more light (Purves et al. 2007; Olivier et al. 2016), might lessen the potential adverse effects of competition on overall canopy cover in linear settings. In high-density forest stands, crown plasticity is highly evident in the form of different sizes and crown positions (Brisson 2001; Muth and Bazzaz 2002, 2003; Seidel et al. 2011; Schröter et al. 2012). With the case of street trees, crowns that extend away from the tree row towards areas of reduced competition and more resources (Muth and Bazzaz 2003) may balance the adverse effects of competition within the row. We were unable to find prominent examples of these effects in linear tree assemblages documented in the literature, but our findings suggest that this may indeed be the case for street trees. Consequently, closer street tree spacing standards could be implemented without adverse effects around declines in canopy cover and associated ecosystem services.

Many documented ecosystem services obtained from street trees are directly associated with the amount of tree foliage (Nowak et al. 2008). These documented ecosystem services from street trees include improved air quality, stormwater control, energy savings, carbon sequestration and storage, and reduced urban heat stress, to name a few (Duinker et al. 2015). However, while the research on ecosystem services is extensive, there is little to no research on optimal street tree spacing standards; existing municipal standards are often highly variable and poorly enforced (McPherson et al. 2016; Aryal 2017). With closer spacing standards and practices, it may be possible to achieve higher canopy cover, especially in a shorter period of time after planting, which could translate to

Table 7. Two-way ANOVA Tukey HSD post hoc test for the DBH class factor with the crown diameter ratio variable.

DBH class (*I*)	DBH class (*J*)	Mean difference (*I* − *J*)
20–30 cm	30–40 cm	−0.030
	40–50 cm	**−0.155****
	50–60 cm	**−0.152****
	60–70 cm	**−0.175****
	70–80 cm	**−0.189****
	80–90 cm	**−0.175****
	> 90 cm	−0.161
30–40 cm	40–50 cm	**−0.125***
	50–60 cm	**−0.122***
	60–70 cm	**−0.145****
	70–80 cm	**−0.159****
	80–90 cm	**−0.145***
	> 90 cm	−0.131
40–50 cm	50–60 cm	0.003
	60–70 cm	−0.019
	70–80 cm	−0.033
	80–90 cm	−0.019
	> 90 cm	−0.005
50–60 cm	60–70 cm	−0.023
	70–80 cm	−0.037
	80–90 cm	−0.023
	> 90 cm	−0.009
60–70 cm	70–80 cm	−0.014
	80–90 cm	0.000
	> 90 cm	0.014
70–80 cm	80–90 cm	0.014
	> 90 cm	0.028
80–90 cm	> 90 cm	0.014

* Significant at the α = 0.05 level
** Significant at the α = 0.01 level

higher rates of ecosystem service supply (Nowak and Greenfield 2012).

In addition to increased canopy cover and ecosystem services from street trees, there may be some possible co-benefits from closer street tree spacings. A decrease in built-surface and building-facade temperatures associated with urban trees has been documented in previous research (Bajsanski et al. 2019). Trees in tighter spacings can utilize the available growing space more efficiently, with greater crown leaf area and biomass compared to trees in wider spacings (Ceulemans et al. 1990; Benomar et al. 2011; Benomar et al. 2012). Conversely, low-density forest conditions can lead to reduced soil moisture availability resulting from increased evaporation rates (Erkan and Aydin 2016). Further empirical research on microclimate and soil conditions among different street tree spacings to test whether these co-benefits are possible in urban conditions and linear planting arrangements would be valuable.

It may also be possible that closer street tree spacing standards and practices would have negative outcomes. First, it is important to note that street trees face a myriad of stressors and disturbances associated with their location next to streets in heavily built-up and high-traffic areas. These include de-icing salt, water shortages, insufficient light, degraded soil conditions, pollution, and vandalism, among others (Lu et al. 2010; Steenberg et al. 2017). These translate to increased rates of tree mortality and reduced growth rates (Jutras et al. 2010). While mortality from competition (e.g., suppression and stem exclusion) typically occurs at very close spacings in forest settings, the cumulative effect of any additional stress associated with increased biological competition between street trees at closer spacings might exacerbate these adverse conditions and lead to even higher mortality rates and reduced growth rates.

If closer spacing standards were to be adopted and implemented for street tree management, the challenge associated with increased costs must be addressed. The costs of street tree planting will of course increase proportionally with closer spacings. The potential for increasingly constrained municipal urban forest management budgets is possible, given both the existing low planting densities of street trees (McPherson et al. 2016) and existing sparse budgets for many municipal urban forest programs (Kenney and Idziak 2000; Haaland and Konijnendijk 2015). However, it is important to consider both trade-offs between costs and benefits and the temporal dynamics of these trade-offs. Our findings suggest that closer spacings will potentially achieve a given level of tree crown per unit area in a shorter period of time compared to wider spacings, if indeed canopy extent can be larger with crown interactions, which can offset some of the costs of increased tree planting and maintenance. Stock type and size constitute another possible mitigative factor for increased street tree planting costs, with lower costs associated with smaller nursery stock. While smaller stock may have higher rates of damage and mortality than larger stock (Roman and Scatena 2011), their considerably lower price could still improve the feasibility of closer spacing standards in the long term. In other words, the increased price of more trees may be offset by the lower cost of smaller stock even with known challenges of planting smaller stock in urban settings.

This study and further research in this area could be useful for municipal urban forest practitioners. Publicly owned street trees, while being a smaller proportion of the total number of trees in a given city, represent a large proportion of municipal management activities and investment. Street tree spacing standards and practices should be based on empirical research that addresses both the supply of ecosystem services and any adverse outcomes associated with competition and increased costs. This study does not provide evidence for how to design new street tree spacing standards, which will be needed in future research. However, its findings do suggest that closer spacing may not necessarily be a disadvantage for canopy cover of street trees. Urban forest ecosystems are a vital resource for North America's increasingly urban population and the increasing exposure of urban landscapes to the changing climate. It is critical that urban forest management be firmly rooted in evidence and scientific research for supporting best practices.

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Résumé. Les arbres urbains offrent aux citoyens tout un éventail de services écosystémiques. Les arbres plantés le long des rues ont fait l'objet de nombreuses recherches et pratiques en matière de forêt urbaine alors que les villes investissent des ressources importantes pour leur survie. Cependant, l'espacement optimal des arbres d'alignement n'est pas traité dans la littérature scientifique et les normes municipales existantes en matière d'espacement sont très variables et mal appliquées. Pour cette recherche, nous examinons la variabilité de la forme et de la taille des houppiers afin de valider les effets d'interaction possibles avec des espacements moindres. Nous avons mesuré la variabilité des diamètres des houppiers parallèlement et perpendiculairement aux alignements d'arbres de rues afin de vérifier si les changements dans la taille des houppiers pouvaient être expliqués par des effets d'interaction avec les arbres voisins, puis si les interactions entre les houppiers entraînaient une réduction de la surface totale de projection au sol des arbres (c'est-à-dire la couverture de la canopée). Nous avons mesuré les dimensions des houppiers et le diamètre à hauteur de poitrine de 1338 arbres d'alignement à Halifax, au Canada. Nous avons utilisé une analyse de variance à deux voies pour vérifier si la forme et la surface de projection au sol du houppier étaient affectées par les interactions entre les ramures et l'espacement entre les arbres. Nous avons constaté que l'effet d'un espacement plus réduit et d'interactions (c'est-à-dire que les houppiers se touchent/se chevauchent) entre les arbres se traduisait par des ramures s'éloignant à l'opposé des zones d'interaction. Nous avons également constaté que ces changements de dimension des houppiers étaient associés à une augmentation de l'étendue de la canopée. Les écosystèmes forestiers urbains sont une ressource vitale pour une population urbaine croissante. Il y a une nécessité de mener des recherches empiriques sur les normes et pratiques d'espacement afin d'étudier leur influence sur la fourniture de services écosystémiques, tels que la rétention des eaux de pluie, l'élimination de la pollution atmosphérique et le rafraîchissement urbain.

Zusammenfassung. Stadtbäume versorgen die Menschen mit einer Reihe von Ökosystemleistungen. An Straßen gepflanzte Bäume sind ein großer Bestandteil der Stadtforstforschung und -praxis und die Kommunen investieren erhebliche Mittel in ihren Erhalt. Der optimale Abstand von Straßenbäumen wird jedoch in der wissenschaftlichen Literatur nicht behandelt. Außerdem sind die bestehenden kommunalen Abstandsnormen für Straßenbäume sehr variabel und werden nur unzureichend durchgesetzt. In dieser Studie untersuchen wir die Variabilität der Kronenform und -größe von Straßenbäumen, um mögliche Interaktionseffekte bei engeren Abständen zu testen. Wir haben die Variabilität der Kronendurchmesser sowohl parallel als auch senkrecht zu den Straßenbaumreihen gemessen, um zu testen, ob Änderungen der Kronenabmessungen durch Interaktionseffekte mit benachbarten Bäumen erklärt werden können und ob Kroneninteraktionen zu einer Verringerung der gesamten Kronenprojektionsfläche (d.h. des Kronendaches) führen. Wir haben die Kronenabmessungen und den Durchmesser in Brusthöhe von 1.338 Straßenbäumen in Halifax, Kanada, gemessen. Wir verwendeten eine Zwei-Wege-Varianzanalyse, um zu testen, ob Kronenform und Kronenprojektionsfläche durch Kroneninteraktionen und Abstände beeinflusst wurden. Wir fanden heraus, dass der Effekt von engeren Abständen und Interaktionen (d.h. sich berührende/überlappende Kronen) zwischen Bäumen zu Kronen führte, die sich von der Richtung der Interaktion entfernten. Wir fanden auch heraus, dass diese sich ändernden Kronenabmessungen mit einer Zunahme des Kronendaches verbunden waren. Städtische Waldökosysteme sind eine wichtige Ressource für die zunehmend urbane Bevölkerung. Es besteht ein Bedarf an empirischer Forschung zu Abstandsnormen und -praktiken, die deren Einfluss auf die Bereitstellung von Ökosystemleistungen wie Regenwasserrückhaltung, Beseitigung von Luftverschmutzung und Klimatisierung zu untersuchen.

Resumen. Los árboles urbanos proporcionan a la gente una gama de servicios ecosistémicos. Los árboles instalados a lo largo de las calles han sido un gran foco de investigación y práctica de bosques urbanos y los municipios invierten recursos significativos en su supervivencia. Sin embargo, el espaciamiento óptimo de los árboles de las calles no se aborda en la literatura científica y los estándares municipales existentes de espaciamiento de los árboles de las calles son muy variables y no se aplican apropiadamente. En este estudio, se examina la variabilidad en la forma de la copa y el tamaño de los árboles de la calle para probar los posibles efectos de interacción en espaciamientos más cercanos. Se midió la variabilidad en los diámetros de las copas, tanto paralelas como perpendiculares a las hileras de árboles de la calle, para probar si los cambios en las dimensiones de la copa se pueden explicar por los efectos de interacción con los árboles vecinos y si las interacciones de la corona conducen a una reducción en el área total de proyección de la corona (es decir, la cobertura del dosel). Se midieron las dimensiones de la corona y el diámetro a la altura del pecho de 1,338 árboles de la calle en Halifax, Canadá. Se utilizó el análisis bidireccional de la varianza para probar si la forma de la corona y el área de proyección de la corona se vieron afectadas por las interacciones de la corona y el espaciamiento. Se encontró que el efecto de un espaciamiento más estrecho y las interacciones (es decir, coronas que tocan / superposición) entre los árboles se traduce en coronas que se extienden lejos de la dirección de la interacción. También se vio que estas dimensiones cambiantes de la corona se asociaron con aumentos en la cubierta del dosel. Los ecosistemas forestales urbanos son un recurso vital para la población cada vez más urbana. Se necesitan investigaciones empíricas sobre normas y prácticas de espaciamiento que investiguen su influencia en el suministro de servicios ecosistémicos, como la retención de aguas pluviales, la eliminación de la contaminación del aire y el enfriamiento.