ECONOMIC AND BIOPHYSICAL IMPLICATIONS OF ALTERNATIVE STREET-TREE SPACINGS IN HALIFAX, CANADA

by

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ABSTRACT

Municipalities establish, maintain, and administer trees on the rights of way along streets. In spite of the many benefits trees provide, they are often planted far apart. The overall objective of this study was to explore the optimal spacing of street trees in Halifax. Altogether 2,162 trees were measured with an average spacing of 15.4 metres (m) and standard deviation (SD) of 10.5 m. Regression equations were developed for three-dominant species to predict crown diameter from diameter at breast height (DBH) and used in the simulation to calculate crown coverage over 60 years, at spacings from 5 to 20 m in a 1 hectare (ha) area. A row of street trees at close spacing delivers a greater canopy coverage per unit area. I recommend street-tree spacing between 5 and 10 m. It is important to find an affordable way to plant trees closer together in streets to maximise ecosystem services.

LIST OF ABBREVIATIONS USED

ANOVA	Analysis of Variance
BC	British Columbia
CA	California
CAC	Crown Area Coverage
CAD	Canada
CD	Crown Diameter
CO2	Carbon dioxide
DBH	Diameter at Breast Height
DED	Dutch elm disease
DRC	Diameter at Root Collar
FGM	Fixed Growth Model
ha	Hectare
HRM	Halifax Regional Municipality
m	Metres
MES	Master in Environmental Studies
MREM	Master of Resource and Environmental Studies
NS	Nova Scotia
ON	Ontario
OR	Oregon
SD	Standard Deviation
SK	Saskatchewan
UFMP	Urban Forest Master Plan
UK	United Kingdom
USA	United States of America
USDAFS	United States Department of Agriculture Forest Services
VGM	Variable Growth Model

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CHAPTER 1 INTRODUCTION

1.1 The Spacing Problem

The municipal governments of towns and cities in North America establish and maintain a population of trees in the public rights of way along streets. Among the many decisions municipal urban foresters and arborists have to make is the crucial one of street-tree spacing (i.e., how far apart the new trees are to be planted). This is not a trivial decision, given the trade-offs between the costs of planting street trees and the desire to obtain the myriad benefits associated with the urban forest as soon as possible.

The urban forest provides people with a range of benefits. These benefits are called ecosystem services and can include improved air quality, absorption of pollutants, storm water control, energy savings, and many others (Boyd and Banzhaf, 2007; Fisher, Turner and Morling, 2009; Duinker et al., 2015). Many of the ecosystem services provided by trees, such as shading infrastructure, carbon sequestration and storage, air-pollution abatement, and storm-water attenuation, are directly proportional to the amount of leaf area they bear (Stoffberg, 2010; McPherson et al., 2016). Any site growing trees has a finite capacity to support tree foliage, and that capacity can be equally fulfilled (within limits) by many small trees or a few large trees. The greater the density of trees planted, the earlier a site can approach its capacity to support tree foliage, and therefore the earlier the site will provide the maximum amount of ecosystem services (Xiao et al., 2000; McPherson et al., 2016). Clearly, a site with widely spaced trees will eventually reach full foliage capacity, but because of the wide spacing, this may not occur until several decades after the trees were planted. Trade-offs exist, given both the increased costs and the earlier provision of maximum ecosystem services of closer spacings compared to the lower costs and later provision of maximum ecosystem services of wide spacings. The key uncertainty is this: what is the optimal spacing of street trees?

1.2 Project Overview, and Research Goal and Objectives

In rural tree planting following timber harvesting, trees would be spaced anywhere from 1.5 to 3.0 m apart, with the most common spacing being 2.0-2.5 m (Spurr and Barnes, 1980; Smith, 1986). What about trees in the city, particularly street trees? Many guidelines suggest distances of about 6.0-9.0 m for trees that are small at maturity, and up to 16.0 m for large trees (Miller et al., 2015). Trees are planted far apart, mainly for three reasons. Firstly, consider the cost. Each tree planted in the street is a balled-and-burlapped caliper tree and costs several hundred dollars to install (Halifax Urban Forest Planning Team, 2013). Second, each street tree is considered an amenity tree – it should be aesthetically attractive. It is assumed that the best-looking trees are those with full crowns that have no interference from neighbouring trees during their lifetime. Third, there is abundant infrastructure to avoid when planting street trees – driveways, sidewalks, fire hydrants, street signs, street lamps, utility poles, underground cables and pipes, and more (Halifax Urban Forest Planning Team, 2013).

The above-mentioned reasons for wide street-tree planting apply to Halifax Regional Municipality (HRM) as well. HRM is the capital of Nova Scotia, Canada, and represents the amalgamated communities in the former county of Halifax that includes both rural and urban areas. This study was conducted only in the urban core of HRM representing residential neighbourhoods of Halifax Peninsula and Central Dartmouth, the so-called

City Centre. Throughout this thesis, I have used Halifax to represent Halifax Peninsula and Central Dartmouth.

In the streets of Halifax, trees are planted far apart to minimize the planting costs because planting one caliper tree costs over $400 (CAD) (Halifax Urban Forest Planning Team, 2013). Also, considering the amenity value, street trees are planted wide so that tree crowns do not overlap (Miller et al., 2015). Rather than seeing street trees as amenities, we might look at them as providers of ecosystem services, such as shading of asphalt, cars, and buildings, slowing stormwater flow, storing carbon, reducing air pollution, and others. The quantity and quality of these services are mostly dependent on the amount of tree foliage per unit land area, not the amount of foliage per tree (Stoffberg, 2010; McPherson et al., 2016). In this view, the sooner the area above the street is filled with tree foliage, the better. So, the principal objective of this study is to address the optimal street-tree spacing in Halifax. Therefore, the purpose of this research is:

- To examine alternative spacings of street trees in terms of their effects on financial costs and benefits associated with ecosystem services in Halifax.

In my study, I attempt to answer the following questions:

- What is the range of street-tree spacings in Halifax across a range of tree ages/sizes?
- What is the relationship between DBH and crown diameter of street trees in Halifax?

- What is the canopy cover of a row of street trees planted in a one hectare plot over a-60-year period at spacings 5-20 m?
- How much longer does it take to achieve 50% canopy cover with widely spaced trees compared to closely spaced trees?
- What factors should influence decisions on street-tree spacing?

This study is based on the assumption that trees planted close together can provide much greater tree foliage per unit area, resulting in greater and earlier ecosystem services compared to widely spaced trees. Moreover, it explores the optimal spacing of street trees in Halifax. I wanted to calculate the effect of tree spacing on the provision of ecosystem services. If an urban-forest manager is keen to adopt more-sophisticated tree-spacing protocols, the starting place is to examine present street-tree spacings and what various spacings mean for crown development.

Therefore, to address my questions, several specific objectives were targeted:

- To characterize street-tree spacing, and other street-tree characteristics, in residential neighbourhoods in Halifax.
- To predict the crown diameter of three dominant species (American elm, Norway maple, and linden) observed in Halifax from DBH by carrying out regression analysis.
- To evaluate the canopy coverage of the three-dominant species of street trees observed in Halifax using two growth models over 60 years at spacings 5-20 m in one hectare land.

- To explore the optimal spacing of street trees in Halifax.

1.3 Thesis Layout

The thesis contains five chapters, with two chapters intended for journal submission and therefore in manuscript format. Chapter one outlines the problem statement and purpose of the study. Chapter two provides an in-depth review of tree spacings, both in silvicultural and arboricultural practices, along with street-tree spacing guidelines from several North American cities. Chapters three and four are independent manuscript-format chapters, with the former focusing on characterization of street trees in Halifax based on empirical findings and the latter exploring the optimal spacing of street trees in Halifax. The final chapter presents conclusions drawn from the whole study, with management recommendations and proposals for future research.

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CHAPTER 2 LITERATURE REVIEW

This chapter describes urban forest benefits with a focus on street trees. In addition, it summarises tree growth, crown shapes and development, and effects of tree spacing. Furthermore, it provides street-tree spacing guidelines in North American cities followed by a research framework. Overall, it attempts to present a basic understanding of tree spacings from various literature sources.

2.1 Urban Forestry and its Importance

Trees in the urban environment have been grouped into three categories depending on where they are grown. Nitoslawski and Duinker (2016) define urban forests as consisting of trees in parks, streets, and private lots. These three treed areas provide benefits to urban society. The benefits, also called the ecosystem services, for example, shade, recreation, improved air quality, shelter, fruits, and environmental protection such as stormwater control, absorption of pollutants, and energy savings, are obtained directly or indirectly (Boyd and Banzhaf, 2007; Fisher, Turner and Morling, 2009; Troy et al., 2012; Timilsina et al., 2014; Duinker et al., 2015; Gillner et al., 2015). A treed ecosystem contributes socio-economic benefits plus many other amenity values to urban residents. A tree in the town or city, whether in parks, streets, or private property, is considered part of an urban forest (Jorgensen, 1986; Konijnendijk et al., 2006). The range of ecosystem services delivered by trees along streets is greater than that for trees in other settings (Foster, 2016). This is primarily due to their position along transportation infrastructure.

Street trees are seen on tree lawns which occur between the curb and sidewalk, between the private property and the sidewalk, or in medians (Miller et al., 2015). Steed and Fischer (2007) define street trees as trees planted between the street and the sidewalk, or trees close to a street. Similarly, trees grown on the street right-of-way or trees close to streets are street trees. Unless the roadway is a provincial one (in Canada), all street trees are under municipal administration.

Street trees are considered an important element of urban forestry mainly because of their great value and the range of benefits they provide to residents. For example, annual services of one street tree in Indiana, USA, was valued to be $55.51 (Davey Resource Group, 2010). Apart from this, trees symbolise nature. They confer beauty to an area; trees are regarded as ornaments; they bring peace, joy, and satisfaction (Lipkis and Lipkis, 1990; Miller et al., 2015).

Street trees shade and increase the life of roads compared to unshaded roads which, over time, become weaker and thus require more maintenance (McPherson and Muchnick, 2005). Street trees minimize the urban heat-island effect and provide habitat for birds and other fauna (Nowak et al., 2014; Mullaney et al., 2015). Street trees provide shade to vehicles parked near streets. This helps fuel tanks to remain cool and reduces emissions of harmful gases from parked vehicles, thus conserving fuel (Scott et al., 1999; Akabari et al., 2001). They reduce crime and increase public safety (Kuo and Sullivan, 2001; Tarran, 2009; Donovan and Prestemon, 2012; Troy et al., 2012). Street trees enhance business appeal, because people prefer shopping in areas having more trees (Wolf, 2005, 2009). Some street trees add to a community's identity and enhance tourism, as with the tree-lined streets of Hollywood Boulevard, La Rambla in Barcelona, Champs-Elysees in Paris, and Orchard Road in Singapore (Deng et al., 2010). They increase road safety, reducing vehicular and pedestrian collisions (Mok et al., 2006; Naderi et al., 2008; Halifax Urban Forest Planning Team, 2013). Rows of trees enhance street-side recreation opportunities, for example, running, walking, and relaxing (Nowak et al., 2001; Foster, 2016). Street trees beautify the community and increase property values (Acharya and Bennett, 2001; Donovan and Butry, 2010). Moreover, they provide employment opportunities in planting and maintenance (Foster, 2016).

However, there are some negative impacts from trees, for example, falling of trees and growth of tree roots. During severe windstorms, trees can fall on residents' properties, buildings, cars, electric lines, and people (Mullaney et al, 2015). Such negative impacts can be reduced by planting trees close together because trees planted closely may reduce wind speed thus protecting them from falling (Callaway et al., 2002; Lopes et al., 2009). Similarly, street-tree roots can cause uplifting and cracking of pavements (Blunt, 2008). The uplifting and cracking of pavements from street trees is likely to depend on urban planning, management, and the urban environment (Lopes et al., 2009). Such damages can be minimized by constructing narrow sidewalks with wide tree lawns which can allow more space, and proper movement of water and air thus helping roots to grow well (McPherson, 2000; Lopes et al., 2009). Other impacts from street trees can be falling of fruit and leaves into people's property along with pollen produced by trees, which can cause discomfort from allergies (D'amato et al., 2007).

Urban-forest research is increasing rapidly worldwide. However, there are almost no studies on street-tree spacing despite the many unique benefits of trees so planted. Therefore, the street-tree spacing literature is based on rural forest principles. To understand street-tree spacing better, the terms silviculture and arboriculture are discussed below.

2.2 Tree Spacing in Silviculture and Arboriculture

The practice of planting and managing the growth of trees for timber production is called silviculture (Spurr and Barnes, 1980; Smith, 1986). One assumption in silviculture is that trees planted close together at regular spacings will lead to early full occupancy of the available growing space (Smith, 1986). Conversely, the practice of planting and management of individual trees is called arboriculture (Harris, 1992). The spacing of trees in silviculture and arboriculture differs greatly, given their respective management objectives and histories of practice. The term silviculture is applied to a group of trees to control forest growth and composition, with timber production as a common objective, whereas arboriculture is concerned with the health of individual trees (Spurr and Barnes, 1980; Smith, 1986).

In silviculture, there is no fixed optimal spacing for trees. However, stand density has been used as a spacing parameter. Stand density is the measure of the total tree count on a unit area of land (Smith, 1986; Davis et al., 2001). Some of the commonly used stand density measures are number of trees per unit area, crown competition, tree height, basal area, and volume (Davis et al., 2001). Depending upon these commonly used density measures, the average distance between two trees can be estimated (Spurr and Barnes, 1980; Smith, 1986; Davis et al., 2001). According to the stand density, trees in a rural forest are planted anywhere between 1.5 m to 3.0 m apart (Spurr and Barnes, 1980; Smith, 1986). In addition to a stand density rule, Stoddard (1968) discusses spacing of trees required after thinning by “rule-of-thumb”. This rule determines the space to be left between trees after thinning where tree spacing is calculated as a function of the diameter of trees remaining in the stand. Again, this rule varies depending upon species. For instance, pure ponderosa pine differs from mixed conifers (white pine, larch, ponderosa pine, and Douglas-fir). Similarly, Douglas fir in the West coast differs from redwood (Stoddard, 1968).

Although some spacing standards are used in silviculture, such as stand density, and the “rule of thumb” (Stoddard, 1968; Smith, 1986), there is no universal standard in arboriculture for street-tree spacing. The academic literature on spacing of street trees is sparse and cities have frequently developed their own standards and specifications based on tree sizes. For example, the cities of Vancouver and Hamilton have different spacings for small, medium and large trees at maturity (City of Hamilton, 2010; City of Vancouver, 2012). On the other hand, Miller et al. (2015) recommend a standard spacing of 15 m for all street trees. However, if sizes are considered, 7.6 m, 10.6 and 16.5 m have been suggested for small, medium, and large trees respectively.

Trees are planted far apart in arboriculture practice to allow enough room for crowns not to interfere with each other, whereas trees are planted close together in silvicultural practice to provide trunk growth with quality timber. Since trees are planted at different spacings, there are both pros and cons of planting trees close together as well as far apart.

I argue that street trees planted close together have greater importance, higher benefits, and are better for urban residents than trees planted far apart. The following section discusses the close and wide spacing of trees and their effects.

2.3 Close and Wide Spacing and their Effects

Before diving into the effects of tree spacing, it will help to understand spacing to first describe tree parts and how each part is involved in tree growth. This paragraph explains different tree parts and their functions. A tree is divided into three parts: roots, trunk, and crown. Roots stabilize the tree and spread into and under the soil, absorbing water, minerals, and nutrients. The trunk or the stem transports water and nutrients through conducting vessels, the xylem and phloem. The topmost part, the crown, consists of branches and leaves. Leaves manufacture food (sugar) with the help of sunlight, which is utilised by trees for their growth (Stoddard, 1968; Sharpe, Hendee and Allen, 1976).

Apart from different tree parts, it is also necessary to understand the physical and growing spaces of a tree. The aboveground crown dimensions and the belowground root spread determine the physical space of a tree, whereas growing space is the measure of its share of both above- and below-ground site resources (Smith, 1986). Where growing space is a limiting factor, competition between trees exists, with all trees competing with each other for light, water, and nutrients. This competition becomes intense when trees are crowded or close together and can influence the size of shape of tree crowns (Stoddard, 1968; Smith, 1986).

Trees often do not have a fixed crown shape, even within the same species. Their inherent growth, due to their genetic makeup along with environmental factors such as light, growing space, soil, nutrients, and water, can influence crown shape. Some trees have columnar crowns in high latitudes, because their stems are perpendicular to the light rays (Oliver and Larson, 1990), allowing higher crown exposure to sunlight. Conversely, trees in lower latitudes have either flat-topped or conical crown shape since the sun is overhead, providing maximum light exposure (Oliver and Larson, 1990). Because of flexibility in crown shape, competition between closely planted trees seems to lessen, allowing greater crown plasticity (Getzin and Wiegand, 2007). Crown plasticity is the ability of tree crowns to grow more towards more light (Purves et al., 2007; Olivier et al., 2016). In high-density stands, crowns grow towards more light or gaps, thus changing the crown position, shape, and size (Brisson, 2001; Muth and Bazzaz, 2002, 2003; Seidel et al., 2011; Schroter et al., 2012). Therefore, such crown shape behaviour is likely to reduce neighbourhood competition allowing trees to grow well (Muth and Bazzaz, 2002, 2003; Olivier et al., 2016). Despite competition and the limited resources, trees in close spacing often thrive well and produce abundant tree foliage and biomass.

In high-density stands, nutrients and sunlight are considered to be important factors because nutrients will be shared among trees and sunlight will be blocked by crowded stems, thus slowing tree growth. However, nutrient intake depends on the type of soil and its characteristics rather than stand density, such as texture, water-holding capacity, bulk density, and compaction (Spurr and Barnes, 1980; Smith, 1986; Millward, Poudel and Briggs, 2011). Closely planted trees can have higher root density. Soil having greater root density is more likely to have higher porosity for gaseous exchange and water movement than with lesser root density. Such porous soil provides higher water infiltration with better tree growth, thereby making soil less compacted (Millward, Paudel and Briggs, 2011).

There are various soil layers. The uppermost or the surface layer consists of organic material and acts like a sponge. This sponge absorbs water from rain and snowmelt, storing it for future use. Furthermore, when trees are planted close together, piling of heavy snow during winter is minimized thus making soil less compacted. Also, the forest floor receives a greater amount of tree foliage during leaf-fall. The shed tree foliage decays, allowing recycling of the nutrients into the soil, thus increasing fertility (Kimmins, 1987). On the other hand, when trees are planted far apart, the forest floor tends to pile up with heavy snow in winter making soil compacted. In addition, trees are likely to have less foliage per unit area resulting in lower organic content giving less soil fertility. Therefore, the closer the trees are planted, the greater the organic matter entering the soil, the less the compaction, and the higher the soil fertility (Kimmins, 1987).

From an arboriculture perspective, planting trees close together could result in poor tree health. For example, planting too close can cause transmission of disease through root grafting, as with Dutch Elm Disease (DED) (Miller et al., 2015). Another problem would be the higher cost of pruning and maintenance, given the greater number of street trees under management. Overcrowding can result in higher levels of competition among trees, slowing growth rates and potentially causing stress, thus rendering trees susceptible to insect infestation and disease (Miller et al., 2015). Trees grown in close spacing tend to have smaller trunks, smaller branches, and shorter live crowns. In a high-density stand, there can be increased competition among trees and increased tree mortality, thereby potentially decreasing biomass accumulation of the stand as a whole (Baldwin et al., 2000; Akers et al., 2013).

Although trees planted close together tend to show some drawbacks, studies show that trees grown with closer spacing and no mortality can result in increased tree foliage and stand volume (Herbert et al., 2016). Furthermore, trees in close spacing can attain greater height in their early years of growth which is not observed in wide spacing. This is due to greater soil coverage, soil moisture retention, heat loss minimization, and soil temperature regulation, thereby making a better micro-climate (Erkan and Aydin, 2016). With wider spacing, tree height may be reduced due to lower soil moisture availability resulting from loss of water by evaporation (Harrington et al., 2009; Erkan and Aydin, 2016).

Tree height is a function of tree growth and is affected by a number of factors, including competition, sunlight, and environmental conditions (Smith, 1986; Oliver and Larson, 1990). Trees at tighter spacings can have increased competition; nevertheless, studies show that trees planted in wider spacings show greater competition for space and soil nutrients with herb and shrub species (Liziniewicz and Agestam, 2012; Andrzejczyk, Liziniewicz, and Drozdowski, 2015). Therefore, the growing space and the nutrients utilized by herbs and shrubs can be used by trees if they are planted close together. In addition, forest ecology provides further support for closely planted trees and how they can communicate through roots.

Trees planted close together can transfer resources through mycorrhiza, the association of fungus and root (Simard, 1997). There is a symbiotic association between trees and fungi under the earth's surface. Fungi form a mycelium (i.e. thread-like structure) which is attached to tree roots in the form of a network which collects water and nutrients, such as nitrogen and phosphorus, transferring them to the tree. In return, the tree provides the fungus with photosynthate (Simard, 1997). Simard (1997) and Pickles et al. (2017) used radioactive isotopes of carbon 13 to observe the resource transfer between Douglas fir and paper birch. Experiments carried out in both the laboratory and natural settings showed the transfer of carbon from one tree to the other.

Apart from fungus, trees also shelter diverse bacteria making a microbial community (Ryan et al., 2008; Mengoni et al., 2010) which is increased by increasing tree density. A recent study on forest ecology (Laforest-Lapointe et al., 2017) shows that trees with leaf bacterial diversity can capture resources efficiently, thereby increasing ecosystem productivity. The better ecosystem productivity has been possible, for example, due to atmospheric nitrogen fixation and protection of trees from pathogens. Such an effect is also called the complementarity effect which likely supports tighter spacing (Laforest-Lapointe et al., 2017).

In rural forests, crowded stands, whether of similar or different species, undergo reduced wind and soil instability, and temperature regulation, thereby facilitating tree growth (Callaway et al., 2002). Therefore, facilitation among trees from similar or different species can show complementarity in the utilisation of space and resources, making planting of different tree species probably beneficial at tighter spacing (Simard et al., 1997; Simard et al., 2003; Simard et al., 2012). Such studies showing how trees utilize available space and nutrients efficiently support a stronger argument for growing trees close together. Trees in tighter spacing therefore are likely to grow well. Once trees attain their full height and canopy, the stand can be thinned to allow further growth.

When high-density stands are thinned, crown diameter increases as the residual trees start to expand to fill the voids and occupy the growing space (Tappeiner, Maguire and Harrington, 2007). Tree diameter growth and crown growth are competition-sensitive, with a wide range of variability that is dependent on stand density (Pretzsch et al., 2015). DeBell et al. (2001) state that diameter increases with increasing space, resulting in wider crowns. Some studies have documented differences in diameter at wider spacings, but not significantly different to assure greater benefits (Naji et al., 2014; Naji et al., 2015; Herbert et al., 2016). In addition, trees grown in wider spacing generally have bigger trunks, bigger branches, and taller live crowns. Furthermore, wider spacing can increase stem taper and knots in tree stems, thus reducing tree growth, tree vigour, life span, and foliage production (Zhang et al., 2009; Erkan and Aydin, 2016; Herbert et al., 2016). However, trees planted in close spacing can have higher foliage and wood biomass per unit land area (Macdonald and Hulbert, 2002; Herbert et al., 2016) much earlier than trees planted far apart. The high-stand density could be thinned once trees reach their full canopy in the earlier years of growth which generally is not observed in the wide spacing.

As already mentioned, there is no fixed optimal spacing for all trees. In addition, a spacing rule applied in silvicultural practices does not apply to street trees because the growing environment is markedly different and the urban forest is not dedicated to timber production. However, quality timber stems can nevertheless contribute value and benefits to urban forestry, such as tree vigour, life span, and more tree foliage. Closer spacing can result in branch mortality if not thinned, but after thinning, stem quality is improved (Kerr, 2003; Rais et al., 2014; Erkan and Aydin, 2016). Therefore, numerous studies suggest tree planting with a closer spacing (Erkan and Aydin, 2016) with subsequent thinning as trees mature.

Thinning is carried out to allow enough growing space for the remaining trees to fill the voids, but not necessarily so thin as to invite soil erosion (Smith, 1986). However, infiltration and water runoff is likely to occur in cities not because of few trees, but because of construction and paved surfaces (Trowbridge and Bassuk, 2004; Miller et al., 2015).

Trees planted in close spacings can increase foliage and wood biomass. Some studies show changes in DBH in wide spacings, but not significantly different to assure greater benefits (Naji et al., 2014; Naji et al., 2015). There can be a small increase in lateral growth when trees are planted far apart which means a slight increase in diameter. Nevertheless, there are studies which show high production of foliage per unit area in close spacings (Macdonald and Hulbert, 2002; Naji et al., 2014; Naji et al., 2015). A study by Naji et al., (2015) in Iran on 12-year-old maple (*Acer velutinum*) in three spacings (10,000, 4,444, and 2,500 plants per hectare) having similar temperature, elevation, and soil quality, showed increased tree growth, wood biomass, and canopy cover in areas that had high stem density (Naji et al., 2015).

Other studies show that trees in tighter spacing can utilise the available growing space efficiently with greater crown leaf area and biomass compared to trees in wide spacing (Ceulemans et al., 1990; Benomar et al., 2011; Benomar et al., 2012). Importantly, increasing space between trees produces more tree foliage per tree, but not per unit area (Benomar et al., 2012). A study carried out in the boreal region of Quebec, Canada, on the effects of spacing on growth of young hybrid poplar clones by Benomar et al. (2012) showed 8-20 times greater biomass, as well as taller trees, per hectare in close spacing (1 x 1 m) compared to wide spacing (3 x 3 m and 5 x 5 m), clearly supporting tighter spacing for biomass production.

The spacings of trees in a forest and urban setting are likely to vary because trees in an urban environment are planted and managed intensively so that they all stay alive and provide ecosystem benefits, whereas trees in the forest often are grown naturally (Spurr and Barnes, 1980). Furthermore, in urban settings, the growth of trees is affected by anthropogenic stresses, for example, impervious surfaces due to pavements, infrastructures, buildings (Cushing, 2009), extreme temperatures, winds, salts, less water (Saebo et al., 2003; Johnson, 2004; Rostami, 2011), and unique pests and pathogens (Logan et al., 2003; Kirilenko and Sedjo, 2007). In addition, trees in streets face a higher level of stresses than trees in parks and private properties (Saebo et al., 2003). Despite urban stresses, trees in an urban environment are likely to have higher growth rates than trees in a rural forest (O’Brien et al., 2012). The deposition of a higher amount of nitrogen in soils from vehicles (Lovett et al., 2000), higher emissions of CO_2 in urban areas (Pataki et al., 2003; Ziska et al., 2004), and daytime warmer temperature due to urban heat island effect (Taha, 1997) may have influence on the higher growth rate of trees regardless of the many stresses (O’Brien et al., 2012; Thompson, 2015). Therefore, trees in urban areas, particularly in streets, if planted closer together can provide greater benefits to the urban residents. Rural forestry practice shows enough evidence supporting tighter spacing. Reviewing other jurisdictions from North American cities can provide more contextual background for the tree spacing argument. Therefore, the following section provides the street-tree spacing guidelines in some North American Cities.

2.4 Spacings of Street Trees in North American Cities

The above-mentioned tree spacing rule, such as rules of thumb (Stoddard, 1968) and optimal stand density (Spurr and Barnes, 1980; Smith, 1986) is only used in forests, not on street trees. The literature on street tree spacing is meagre; cities have frequently developed their own standards and specifications based on tree sizes. Miller et al. (2015) recommend standard community spacing of 15 m for all trees in streets. However, if sizes are to be considered, 7.6 m, 10.6 and 16.5 m have been suggested for small, medium-sized, and large trees respectively. If the width of the tree lawn is less than 0.9-1.2 m, some communities do not allow planting trees. Spacings for trees also address distances from intersections, driveways, alleys, hydrants, and utility poles. For intersections, the spacing is 9.1 m, for driveways and alleys 4.5 m, and for hydrants and utility poles 3 m (Miller et al., 2015).

The City of Minneapolis has 94 trees per kilometre or 10.5 m apart, whereas the City of Milwaukee has 89 trees per kilometre (i.e. 11 m apart). On average, the spacings of street trees range from 10 m to 15 m. The City of Visalia, California (CA), has different spacings, depending on the size of the trees at maturity. For small trees, the spacing requirement is 6 m to 8 m, for medium size trees, 8 m to 10 m, and for large trees 9 m to 14 m (Table 1) (City of Visalia, 2005). Vancouver, British Columbia (BC), has a few differences in its guidelines compared to Visalia with regard to street-tree spacings. Small and medium trees are planted with an average spacing of minimum 8 m to 10 m, and large trees with minimum 9 m to 11 m (City of Vancouver, 2012). In Toronto, Ontario (ON), a minimum of 5 m to 10 m is recommended without any specifications for small, medium, or large trees (City of Toronto, 2010).

Table 1. Street-tree spacing specifications in North American cities (minimum spacings required between trees are given for cities marked with '*')

Cities	Street-tree spacings based on tree size (m)		
	Large	Medium	Small
Hamilton*	10	N/A	6
North Vancouver	15-18	8-13	5-9
Vancouver*	9-11	8-10	8-10
Victoria*	12-14	8-12	6-8
Regina*	10	N/A	8
Visalia	9-14	8-10	6-8
	Street-tree spacings based on tree count (m)		
Toronto*	5-10		
Portland*	8		
Richmond	6-12		
Milpitas	5-15		
Buffalo*	9		
Kansas City	10-20		

The City of North Vancouver has different tree spacing specifications compared to Toronto, Vancouver, and Visalia. Small trees in North Vancouver are planted with a spacing of 5 m to 9 m, medium trees have 8 m to 13 m interspaces, and large trees are 15 m to 18 m apart (City of North Vancouver, 2004). The street-tree spacing in Hamilton, ON, is a minimum of 10 m for large and medium-sized trees and a minimum of 6 m for small trees (City of Hamilton, 2010). Tree spacings in Regina, Saskatchewan (SK), depend on tree species rather than the size of plants. The tree spacing for fruits, spruce, and other ornamental species is a minimum of 8 m, whereas a minimum of 10 m is prescribed for maple, ash, linden, elm, poplar, willows, and birch (City of Regina, 2010). The street-tree spacing of Victoria, BC, is also similar to that of Vancouver. Street-tree spacing minima of 6 to 8 m for small trees, 8 to 12 m for medium-sized trees, and 12 to 14 for large trees are recommended (City of Victoria, 2012).

In the city of Portland, Oregon (OR), the spacing of street trees is not specific, but rather an overall spacing of minimum 8 m is prescribed for all trees (City of Portland, 2015). In Richmond, BC, the trees are planted with a spacing of 6 m to 12 m depending on species and size of the plant; generally big trees with large crowns are spaced widely (City of Richmond, 2008). The city of Milpitas, CA, also follows a similar pattern to that of Toronto and Richmond where the spacing ranges from 5 m to 15 m (City of Milpitas, 2000). The city of Buffalo recommends a spacing minimum of 9 m between street trees (City of Buffalo, 2011). Although the spacing specifications of Kansas City are similar to those of Milpitas, even higher spacings are recommended, from 10 to 20 m (City of Kansas, 2014). Halifax, NS, has no specific tree spacings. Trees in some streets are spaced as closely as 2 m to 6 m and as far as 10 m to 20 m (Halifax Urban Forest Planning Team, 2013).

With regard to differing standards and specifications, some North American cities have their street-tree standards based on tree size, depending upon whether they are small, medium, or large at maturity, whereas many cities have their spacing standards based on tree count rather than size. At the time of writing, Halifax has no specific tree-spacing standard, although one is under development. Reviewing street-tree guidelines from

North American cities shows that street trees generally have wider spacing between larger trees and narrower spacings between smaller trees.

Although some spacing standards are used in silviculture, such as stand density and “rule of thumb” (Stoddard, 1968; Smith, 1986), there is no universal standard in arboriculture for street-tree spacing. Also, the basis of setting standards remains uncertain, if there is any at all. Given the variability in street-tree spacing standards and our overall aim to understand better the costs and benefits of alternative street-tree spacings, we sought to characterize the current situation with respect to street-tree spacing in the capital city of Nova Scotia - Halifax.

2.5 Conclusions

The urban forest provides many benefits which can be obtained as long as the trees remain alive and healthy. Numerous studies have shown that trees planted close together can thrive well to provide a greater amount of tree foliage per unit area (Spurr and Barnes, 1980; Smith, 1986), which can increase the ecosystem services. Furthermore, such trees attain greater height during their early stages of growth compared to widely spaced trees (Erkan and Aydin, 2016). An open-grown large tree or many closely planted trees both can provide maximum tree foliage per unit area far into the future, thereby providing maximum benefits. However, the question remains, will an open-grown large tree provide the same amount of early tree foliage compared with many closely planted trees? What is the trade-off between earlier benefits with higher planting and maintenance costs? In silvicultural practice, trees planted in close spacings tend to show more benefits at the earlier stages of tree growth and further growth is supported by thinning (Smith, 1986; Spurr and Barnes, 1980; Oliver and Larson, 1990; Omari et al., 2016).

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CHAPTER 3 HOW FAR APART? STREET-TREE SPACING IN HALIFAX, NOVA SCOTIA

Abstract:

Municipalities establish, maintain, and administer trees on the rights of way along streets. Trees in between sidewalks and the curb, or in special tree pits where there is no tree lawn, are called street trees. They provide many benefits to urban residents, such as improved air quality, energy savings, increased property value, shade to pedestrians, and reduced vehicle accidents, noise, and crime. Many North American cities have tree establishment, care, and protection manuals for the management of street trees. However, street-tree spacing is usually a weak consideration in such manuals. I am interested to question how far apart trees are in current street-tree populations, how far apart new trees should be planted from each other, and what factors should influence decisions on street-tree spacing. The main objective of this study was to characterize street-tree spacings in Halifax, Nova Scotia. Tree data were collected from 188 randomly selected street segments in the urban core. A total of 2,162 street trees was measured for their species, diameter at breast height (DBH), crown diameter, and distance to adjacent tree(s) in the row. Altogether, 53 species were identified with an average spacing of 15.4 m. As expected from previous studies, the street-tree canopy was dominated by Norway maple (Acer platanoides) (39% by stem count), American elm (Ulmus americana) (21%), and little-leaf linden (Tilia cordata) (12%). This study will be useful to city planners in considering tighter spacings of street trees for maximizing ecosystem services.

3.1 Introduction

The municipal governments of towns and cities in North America establish and maintain a population of trees in the public rights of way along streets. Among the many decisions municipal urban foresters and arborists have to make is the crucial one of street-tree spacing (i.e., how far apart the new trees are to be planted). This is not a trivial decision, given the trade-offs between the costs of planting street trees, roughly several hundred dollars (CAD) per tree (Halifax Urban Forest Planning Team, 2013), and the municipal governments' desire to obtain the myriad benefits associated with the urban forest as soon as possible.

Urban forests provide people with a range of benefits including improved air quality, absorption of pollutants, storm water control, energy savings, carbon sequestration and storage, and many others (Duinker et al., 2015). Many of the ecosystem services provided by trees are directly proportional to their size and amount of leaf area they bear (Stoffberg, 2010; McPherson et al., 2016). As a population of street trees grows, the question arises as to what is the influence of tree spacing on the development of leaf area per unit land area. There is a high degree of uncertainty around the optimal spacing of street trees, given both the increased costs of higher-density planting but potentially earlier realization of a streetside site's capacity to deliver ecosystem services.

Many studies have been carried out on urban forests. Some examples are urban forest benefits (Duinker et al., 2015), residents' preferences and attitudes to urban forests and street trees (Kirkpatrick et al., 2012; Dilley and Wolf, 2013), crime reduction from street trees (Donovan and Prestemon, 2012), reduction of antidepressant prescription rates from street trees (Taylor et al., 2015), and species selection (Rostami, 2011; Conway and Vecht, 2015). However, there have been almost no studies on the spacing of street trees. The specific objectives of this study were to characterize street-tree spacing, and structural street-tree characteristics, in residential neighbourhoods in Halifax. If an urban-forest manager is keen to adopt more-sophisticated tree-spacing protocols, the starting place is to examine present street-tree spacings and what various spacings mean for crown development. The study has its roots in the hypothesis that street trees planted at closer spacings provide greater amounts of ecosystem services in a shorter period of time. Although there are high initial costs when planting, the benefits obtained from tighter spacings are achieved sooner compared to wide spacings. This study therefore is based on the following question: what is the range of street-tree spacings in Halifax across a range of tree ages/sizes? We considered only the old residential neighbourhoods, as characterized by Jansen et al. (1992). The study examines different spacings of street trees and what the new understanding may mean for managers in the context of tree spacing and the implications for ecosystem-service delivery.

3.2 Background and Concepts

Every single tree within the city is considered part of the urban forest (Halifax Urban Forest Planning Team, 2013). Nitoslawski and Duinker (2016) define urban forests as consisting of trees in parks, streets, and privately-owned properties. Although street trees typically comprise a small part of the urban canopy in Halifax, they can confer many benefits to residents and are under the direct management of the municipal government. Street trees are seen on tree lawns. Such tree lawns occur mostly between curb and sidewalk, but also between private property and sidewalk and in medians (Miller et al., 2015). There are varying definitions of street trees. Bolund and Hunhammar (1999) include trees that are often found on paved areas adjacent to streets. Steed and Fischer (2007) define them as trees planted between the street and the sidewalk or trees close to a street. For this study, I define street trees as those trees planted in the public right-of-way of streets that are maintained and controlled by municipalities. There is considerable uncertainty in the literature and in the management practices of municipal urban forestry departments around the optimal spacing of street trees. This section provides the basic context of street-tree spacing and an overview of existing standards.

3.2.1 Benefits of street trees

Street trees provide many benefits. Street trees shade and increase the life of roads compared to unshaded roads which, over time, become weaker and thus require more maintenance (McPherson and Muchnick, 2005). Street trees minimize the urban heat-island effect and provide habitat for birds and other fauna (Nowak et al., 2014; Mullaney et al., 2015). Street trees provide shade to vehicles parked near streets. This minimizes heating of fuel tanks, thereby reducing emission of harmful gases from parked vehicles, thus conserving fuel (Scott et al., 1999; Akabari et al., 2001). They reduce crime and increase public safety (Kuo and Sullivan, 2001; Tarran, 2009; Donovan and Prestemon, 2012; Troy et al., 2012). Street trees enhance business appeal, because people prefer shopping in areas having more trees (Wolf, 2005, 2009). Some street trees add to a community's identity and enhance tourism, as with the tree-lined streets of Hollywood Boulevard, La Rambla in Barcelona, Champs-Elysees in Paris, and Orchard Road in Singapore (Deng et al., 2010). They increase road safety by reducing vehicular and pedestrian collisions (Mok et al., 2006; Naderi et al., 2008; Halifax Urban Forest

Planning Team, 2013). Rows of trees enhance street-side recreation opportunities, for example, running and walking (Nowak et al., 2001). Street trees beautify the community and increase property values (Acharya and Bennett, 2001; Donovan and Butry, 2010). Moreover, they provide employment opportunities in planting and maintenance. For most of the benefits listed above, if street trees are planted close together, the benefits are much greater compared to trees planted at wider spacings.

3.2.2 Tree spacing in silviculture and arboriculture

Trees are planted with a closer spacing in silviculture compared to arboriculture (Smith, 1986). The practice of planting and managing the growth of trees for timber production is called silviculture and is essentially synonymous with forestry (Spurr and Barnes, 1980; Smith, 1986). One assumption in silviculture is that trees planted close together will lead to early full occupancy of the available growing space by trees (Smith, 1986). Conversely, the practice of planting and management of individual trees is called arboriculture (Harris, 1983). The spacing of trees in silviculture and arboriculture differs greatly, given their respective management objectives and histories of practice. The term silviculture is applied to a group of trees to refer to forest growth and composition, with timber production as a common objective. On the other hand, arboriculture is concerned with the health of individual trees (Spurr and Barnes, 1980; Smith, 1986) and is typically practiced in urban areas.

In silviculture, there is no fixed optimal spacing for trees. However, many foresters use stand density as a spacing parameter. Stand density is the measure of the total tree count on a unit area of land (Smith, 1986). Depending upon the number of trees per unit area, the average distance between two trees can be estimated (Smith, 1986; Spurr and Barnes, 1990). Apart from a stand density rule, Stoddard (1968) discusses the spacing of trees required after thinning by "rule-of-thumb" which determines the space to be left between trees after thinning. The tree spacing is calculated as a function of the diameter of trees. This means that remaining trees in the stand have increasing spacing with the increasing diameter. Again, this rule varies depending upon species. For instance, spacing of pure ponderosa pine (*Pinus ponderosa*) differs from that of mixed conifers (white pine *(Pinus strobus),* larch *(Larix spp.)*), ponderosa pine, and Douglas-fir *(Pseudotsuga menziesii*) and Douglas fir differs from redwood (*Sequoia sempervirens*) (Stoddard, 1968). Tree spacing is also based on tree height, crown spread and crown volume (Davis et al., 2001).

3.2.3 Effects of tree spacing

From an arboriculture perspective, planting trees really close together could result in poor tree health. For example, planting too closely can cause transmission of disease through root grafts, as with Dutch Elm Disease (DED) (Miller et al., 2015). Another problem would be the higher cost of pruning and maintenance, given the greater numbers of street trees under management. Overcrowding can result in higher levels of competition among trees, slowing growth rates and potentially causing stress, thus rendering trees susceptible to insect infestation and disease (Miller et al., 2015). Trees grown in close spacing tend to have smaller trunks, smaller branches, and shorter live crowns. In a high-density stand, there can be increased competition among trees and increased tree mortality, thereby potentially decreasing biomass accumulation of the stand as a whole (Baldwin et al. 2000; Akers et al., 2013).

Although trees planted close together tend to show some drawbacks, studies show that trees grown with closer spacing and no mortality can result in increased tree foliage and stand volume (Herbert et al., 2016). Furthermore, trees in close spacing can attain greater height in their early years of growth which is not observed in wide spacing. This is due to greater soil coverage, soil moisture retention, heat loss minimization, and soil temperature regulation, thereby making a better micro-climate (Erkan and Aydin, 2016). With wider spacing, tree height may be reduced due to lower soil moisture availability resulting from loss of water by evaporation (Harrington et al., 2009; Erkan and Aydin, 2016).

Tree height is affected by a number of factors, including competition, sunlight, and environmental conditions (Smith, 1986; Oliver and Larson, 1990). Trees at tighter spacings can have increased competition; nevertheless, studies show that trees planted in wider spacings show greater competition for space and soil nutrients with herb and shrub species (Liziniewicz and Agestam, 2012; Andrzejczyk, Liziniewicz, and Drozdowski, 2015). Therefore, the growing space and the nutrients available in wide spacing utilized by herbs and shrubs can be used by trees if they are planted close together. Once trees attain their full height and canopy, the stand can be thinned to allow further growth.

When high-density stands are thinned, crown diameter increases as the residual trees start to expand to fill the voids and occupy the growing space (Tappeiner, Maguire and Harrington, 2007). Tree diameter growth and crown growth are competition-sensitive, with a wide range of variability that is dependent on stand density (Pretzsch et al., 2015). DeBell et al. (2001) state that diameter increases with increasing space, resulting in wider crowns. Some studies have documented differences in diameter at wider spacings, but not significantly different to assure greater benefits (Naji et al., 2014; Naji et al., 2015; Herbert et al., 2016). In addition, trees grown in wider spacing generally have bigger trunks, bigger branches, and taller live crowns. Furthermore, wider spacing can increase stem taper and knots in tree stems, thus reducing tree growth, tree vigour, life span, and foliage production (Zhang et al., 2009; Erkan and Aydin, 2016; Herbert et al., 2016). However, trees planted in close spacing can have higher foliage and wood biomass per unit land area (Macdonald and Hulbert, 2002; Herbert et al., 2016).

There are both potential benefits and costs associated with planting trees at higher density. A major potential cost is putting the tree in the ground because one caliper tree costs roughly $400 installed (Halifax Urban Forest Planning Team, 2013). Other costs include pruning, maintenance, and tree-health treatments. However, planting trees close together has greater benefits which can overshadow these costs. For example, high density increases the amount of tree foliage per unit land area (Xiao et al., 2000; Stoffberg, 2010; McPherson et al., 2016), thereby increasing the ecosystem services. The earlier benefits that can be obtained from tighter spacings may outweigh the overall costs (i.e. a fixed quantity of ecosystem services can be obtained earlier by planting trees close together). In general, trees planted in close spacings tend to be smaller in size but larger in volume per unit area (Herbert et al., 2016), supporting the argument for higher density stands if small individual tree size is not a disbenefit.

3.2.4 Spacing of street trees in North American cities

Cities frequently develop their own standards and specifications for street-tree spacing. This results in variability in street-tree standards across cities, ranging from 100 trees/km to 65 trees/km. For instance, the City of Minneapolis has 94 trees/km, whereas the city of Milwaukee has 89 (Miller et al., 2015). With regard to differing standards and specifications, some North American cities have their street-tree standards based on tree size, depending upon whether they are small, medium, or large at maturity, whereas many cities have their spacing standards based on tree count rather than size. Some cities, for example, the City of Visalia, California, Vancouver and Victoria have spacing standards depending upon tree size (i.e., small, medium, and large trees). The spacing ranges from 5 m to 18 m (See Table 1) with wider spacings for larger trees and narrower spacings for smaller trees (City of North Vancouver, 2004; City of Visalia, 2005; City of Victoria, 2012; City of Vancouver, 2012). A few cities, such as City of Hamilton and City of Regina have their spacing standards based on tree size which are grouped into small trees and large trees, with planting anywhere from 6 to 10 m apart (City of Hamilton, 2010; City of Regina, 2010). Many cities, such as City of Toronto, Portland (OR), Richmond (BC), Buffalo, and Kansas City, have spacing standards based on tree count, ranging from 5 to 20 m (City of Milpitas, 2000; City of Richmond, 2008; City of Toronto, 2010; City of Buffalo, 2011; City of Kansas, 2014; City of Portland, 2015). Some cities provide minimum spacings and some do not. For example, Hamilton, Vancouver, Victoria, Regina, Toronto, Portland, and Buffalo require minimum spacings between trees. On the other hand, some cities (North Vancouver, Visalia CA, Richmond, Milpitas CA and Kansas City) do not specify a minimum spacing. At the time of writing, Halifax has no specific tree-spacing standard, although one is under development. Reviewing street-tree guidelines from North American cities shows that street trees generally have wider spacing between larger trees and narrower spacings between smaller trees.

Although some spacing standards are used in silviculture, such as stand density and “rule of thumb” (Stoddard, 1968; Smith, 1986), there is no universal standard in arboriculture for street-tree spacing. Also, the basis of setting standards remains uncertain if there is any at all. Given the variability in street-tree spacing standards and the overall aim to understand better the costs and benefits of alternative street-tree spacings, I sought to characterize the current situation with respect to street-tree spacing in the capital city of Nova Scotia - Halifax.

3.3 Methods and Approach

3.3.1 Study area

The study was conducted in Halifax (also known as Halifax Regional Municipality (HRM)), Canada, with the study area confined to the Halifax Peninsula and Central Dartmouth, which together occupy the City Centre (Fig. 1c). Throughout the paper, I have used Halifax to represent Halifax Peninsula and Central Dartmouth. I used the sampling method of Jaenson et al. (1992), dividing the city into three zones: old residential neighbourhoods, new residential neighbourhoods, and downtown areas. According to Jaenson et al. (1992), old residential neighbourhoods tended to be established around the city core with rectilinear streets, sidewalks, and a high proportion of the street-tree population. A grid pattern of streets is called a rectilinear street area. Halifax also follows a similar pattern, having the highest proportion of city trees located between the curb and sidewalk in old residential neighbourhoods compared to other

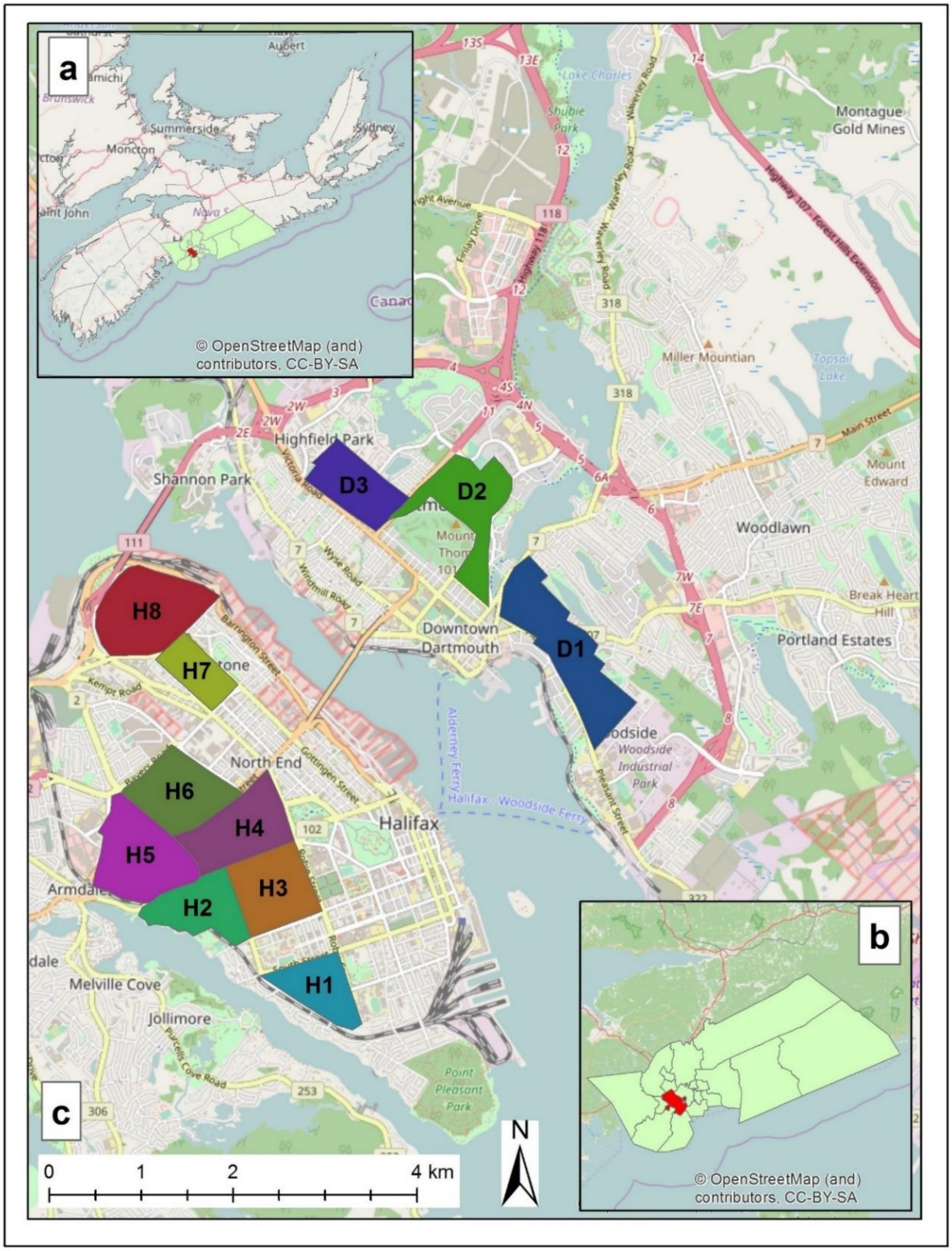


Fig. 1. Location of eight neighbourhoods in Halifax Peninsula and three neighbourhoods in Central Dartmouth (c), Halifax Regional Municipality (b), and the Maritime Provinces (a).

neighbourhoods. To keep the study's scope manageable, I measured street trees in this zone only. Newer residential neighbourhoods were not considered because they are often built with no sidewalks and have far fewer street trees. Similarly, I did not consider downtown areas because of a paucity of street trees, few planting sites, and high mortality rates (Jaenson et al., 1992).

Eight neighbourhoods in Halifax Peninsula and three in Central Dartmouth were identified (See Fig. 1c). For convenience and consistency, I have denoted H in figures and tables to indicate Halifax Peninsula and numbered them 1-8 to represent each neighbourhood. Likewise, I have used D for Central Dartmouth and numbered them 1-3 to indicate each neighbourhood.

3.3.2 *Sampling*

Street segments for this study were identified in residential areas having sidewalks with a tree lawn and a length of over 100 m between street intersections. Many street segments in Halifax are in the range of 100-400 m, though some are shorter than 100 m. Some short segments may have only one tree which makes calculation of average spacing impossible. Therefore, a minimum segment length of 100 m was chosen. A complete street segment inventory for the 11 neighbourhoods was compiled and each street segment was clearly demarcated with a street segment number, its two ends (starting point and finishing point), side (North or South, and West or East), and its total length in metres. Altogether, 457 street segments (399 in Halifax Peninsula and 58 in Central Dartmouth) were identified.

The total area of the eight delineated neighbourhoods in Halifax Peninsula is considerably larger than that of the three in Central Dartmouth, so one third of the measured segments in Halifax Peninsula and half of those in Central Dartmouth were chosen randomly, making 188 in all. At least 10 segments were chosen in each neighbourhood (see Table 2).

Table 2: Number of street segments and trees measured in Halifax

Halifax	Total street segments	Total measured segments	Total measured trees	Total segments length (m)	Measured segments length (m)	Measured segments (%)
D1	17	10	71	2,849	1,806	59
D2	22	11	97	4,543	1,995	50
D3	19	10	78	3,890	3,485	53
H1	37	13	156	6,987	2,239	35
H2	30	14	155	5,242	2,507	47
H3	77	34	418	12,532	5,711	44
H4	53	26	452	11,553	5,888	49
H5	33	12	129	7,014	2,476	36
H6	74	25	304	13,800	4,638	34
H7	51	18	148	6,235	2,190	35
H8	44	15	154	7,994	2,533	34
Total	457	188	2,162	82,639	35,468	41

(D1, D2, D3 = neighbourhoods in Central Dartmouth; H1, H2, H3, H4, H5, H6, H7, H8 = neighbourhoods in Halifax Peninsula)

3.3.3 Data collection

Trees in the 188 street segments were measured between April and August 2016. The length of each street segment was measured in metres. Each tree was measured for its diameter at breast height (DBH), (i.e. 1.3 m from the ground). Two crown dimensions were measured, including one crown diameter parallel to the street and the other crown radius perpendicular to and towards the street. For measuring crown diameter perpendicular to the street, permission from the residential property owner would have been necessary to trespass onto the private property and therefore was avoided. Thus, crown radius was measured instead. Each crown radius was doubled and the mean of the two diameters was used to obtain the final crown diameter value. Also, I measured distance to the next tree(s) and distance from street end to the first and last tree in each segment.

3.3.4 Data analysis

Since an objective of this study was to document the full range of tree spacing in Halifax, I measured the length of each segment and counted the total number of trees in that segment. I then calculated the average tree spacing for each segment in that neighbourhood and summed all segment lengths and total tree count in each neighbourhood. For the average spacing of street trees, I used the following formula:

$$Average\ Spacing = \frac{Length\ of\ each\ segment\ (m)}{Number\ of\ trees\ in\ each\ segment}$$

For the comparison of spacings between neighbourhoods, I examined mean distribution and variability using charts and box plots. Furthermore, I performed one-way ANOVA to determine whether average spacings of the neighbourhoods' trees were significantly different. One-way ANOVA showed at least one inequality. To examine the variability of spacings between neighbourhoods, I ran individual one-way ANOVA for 55 possible combinations. There are 11 neighbourhoods and therefore the total combination pairs are

55 (N (N-1)/2) where N stands for neighbourhood. I set the P level of significance to α = 0.05.

3.4 Results

3.4.1 Characteristics of the street-tree population in Halifax

To explain the spacing of street trees, characterisation and understanding of species and sizes of street-tree population was necessary. Overall, I measured 2,162 tree stems and identified 53 species. Norway maple (*Acer platanoides*) accounted for 39% of measured street trees, followed by American elm (*Ulmus americana)* at 21%, little-leaf linden (*Tilia cordata)* at 12%, seven other species at 14%, and the 43-remaining species at 28% (Fig. 2).

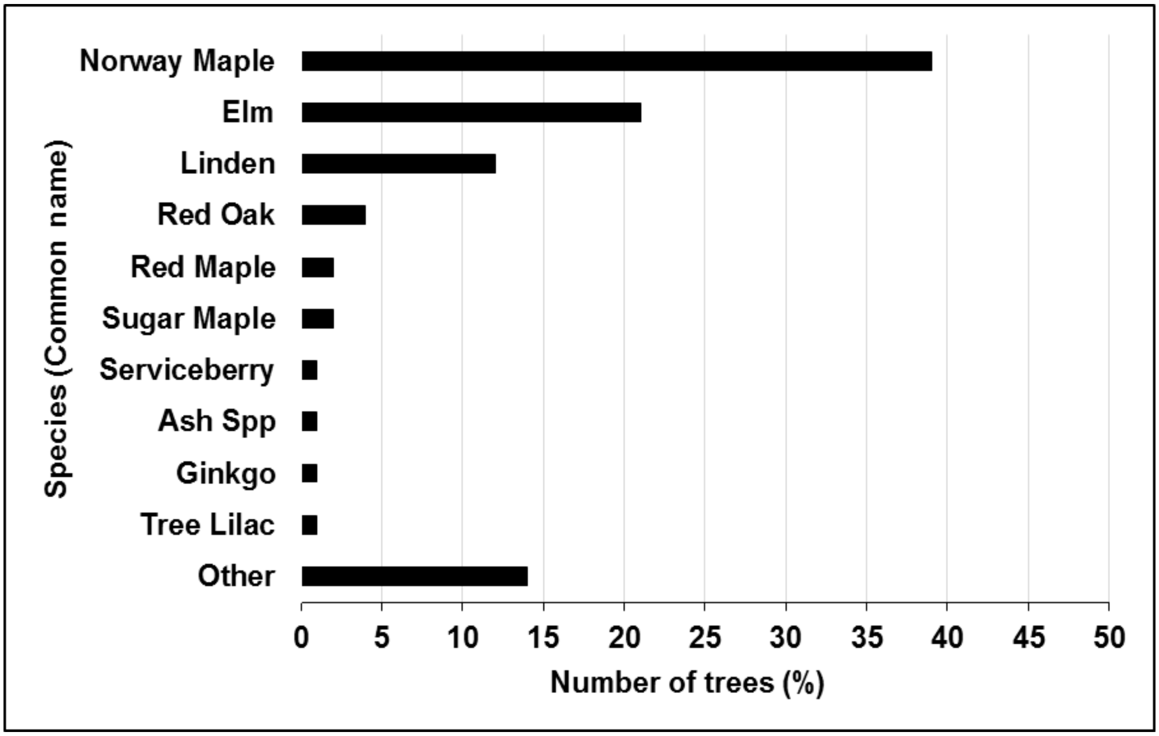


Fig. 2. Tree species distribution by number of stems for the dominant species in Halifax

The street-tree population is not uniformly distributed. Although street trees in Halifax seemed diverse, three species (i.e. Norway maple, American elm and little-leaf linden) dominated the tree population. Likewise, the cumulative basal area (i.e. cross-sectional area of stem measured at 1.3 m above the ground) distribution of each species showed that Norway maple was over-represented at 43%, followed by American elm at 34% and little-leaf linden at 13% (Fig. 3).

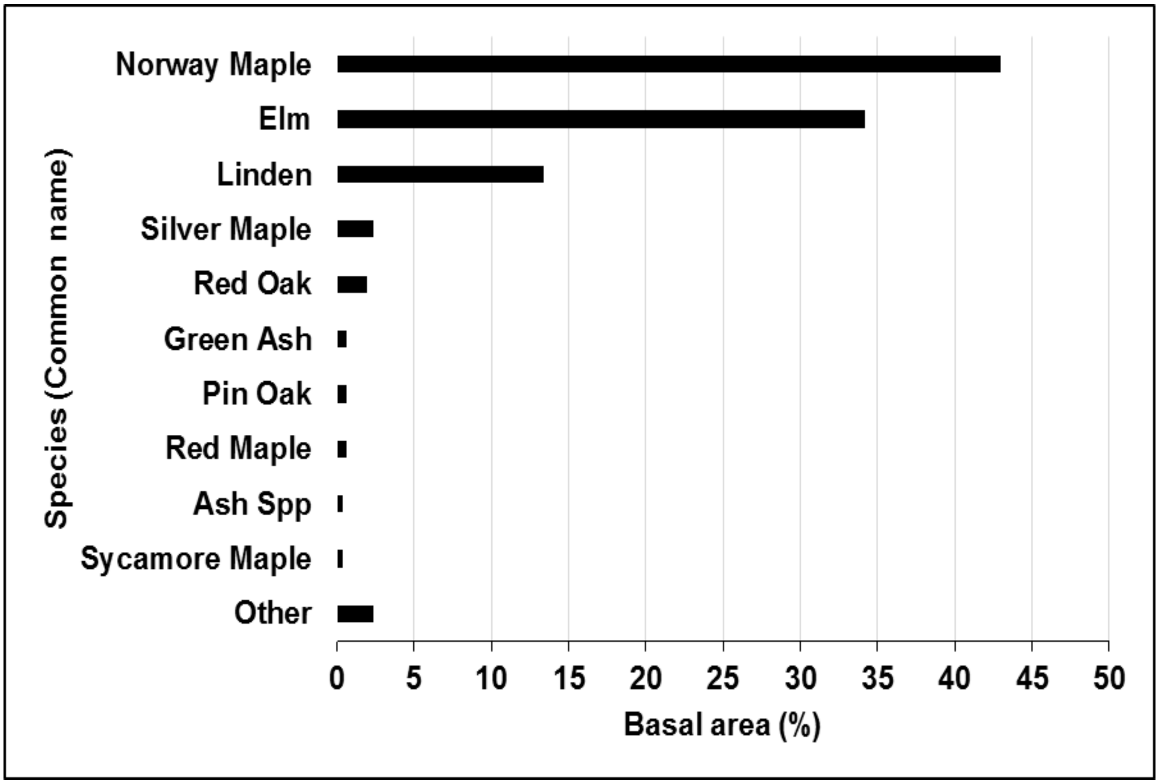


Fig. 3. Tree species distribution by basal area for the dominant species in Halifax

The stem count of American elm trees was much lower compared to Norway maple, but slightly higher than little-leaf linden. Observation of their basal area showed that American elm trees were closer to Norway maple (i.e. in terms of basal area compared to tree count) but much greater than little-leaf linden. Because of these differences in tree count and stem cross-sectional area, it may be deduced that American elm trees were relatively abundant and much larger among all trees in the population, and indeed casual observation of street trees in the City Centre corroborated this. Looking at the basal area of three dominant species, only 10% was accounted for by the other 50 remaining species. Furthermore, silver maple (*Acer saccharinum*) and sycamore (*Acer pseudoplatanus)* were also large-diameter trees, given that their cumulative basal area was relatively higher in the context of their stem counts compared to red oak (*Quercus rubra)*, sugar maple (*Acer saccharum)*, and tree lilac (*Syringa reticulata).*

This study revealed an imbalanced size diversity among street trees. Approximately 20% of the measured species had a DBH less than 20 cm, 24% between 20-50 cm, 48% range from 50-80 cm, 7% of species have DBH of 80-100 cm and only 1% of species had DBH higher than 100 cm (Fig.4).

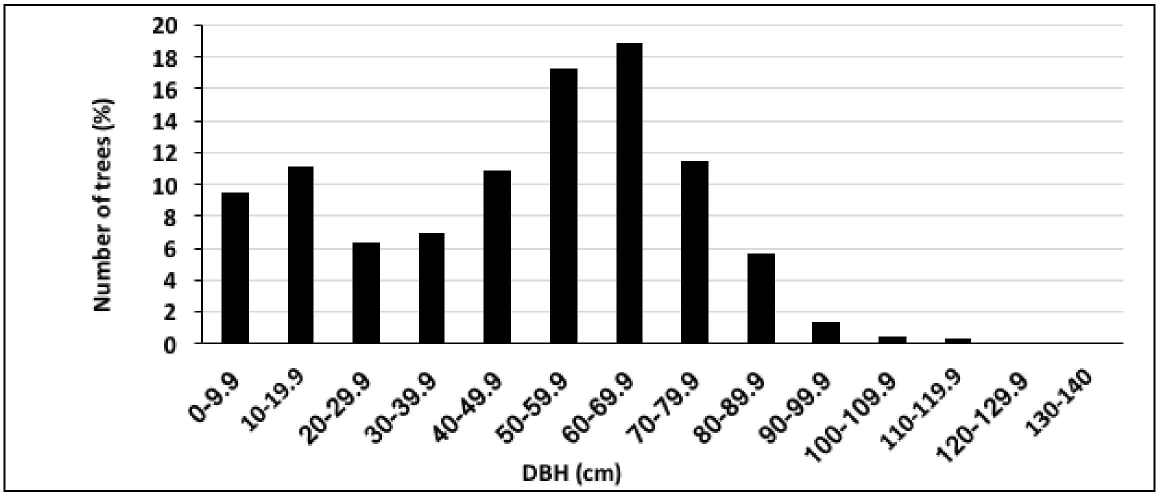


Fig. 4. DBH distribution of street trees measured in this study

Furthermore, 10% of tree stems have DBH less than 10 cm. The highest tree numbers (25%) were in the range of 60-70 cm followed by 17% between 50 and 60 cm. There was a paucity of trees with larger diameters (i.e. 80 cm and above).

3.4.2 Spacing of street trees in Halifax

Street trees in Halifax had an average spacing of 15.4 m. The average spacing of street trees in Halifax Peninsula was lower than in Central Dartmouth (Fig. 5). Mean spacing ranged from 12.7 m in neighbourhood 4 in Halifax Peninsula to 25.4 m in neighbourhood 1 in Central Dartmouth.

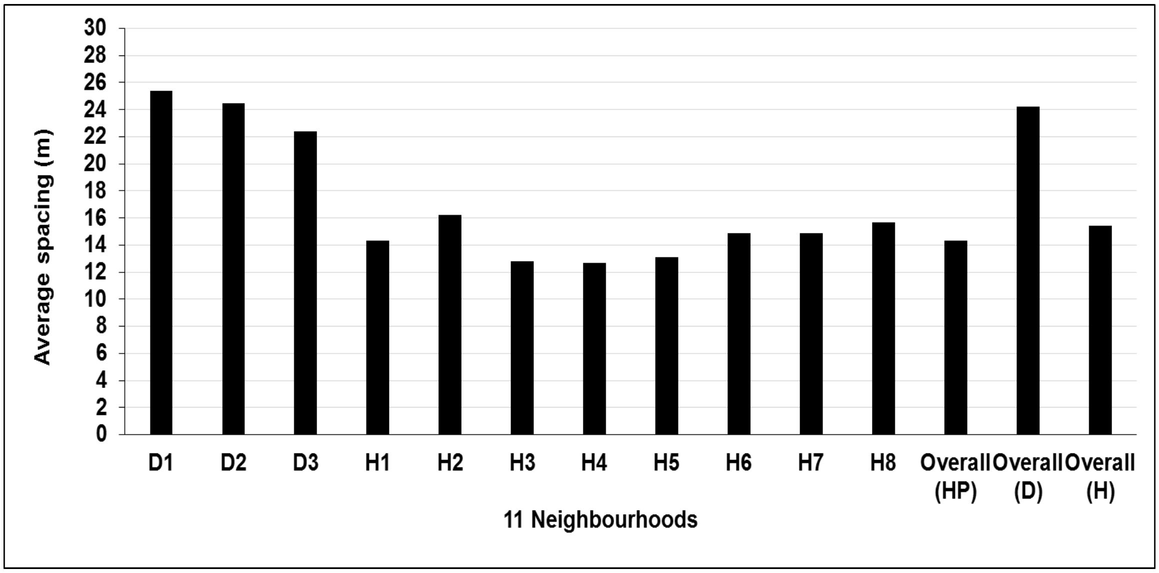


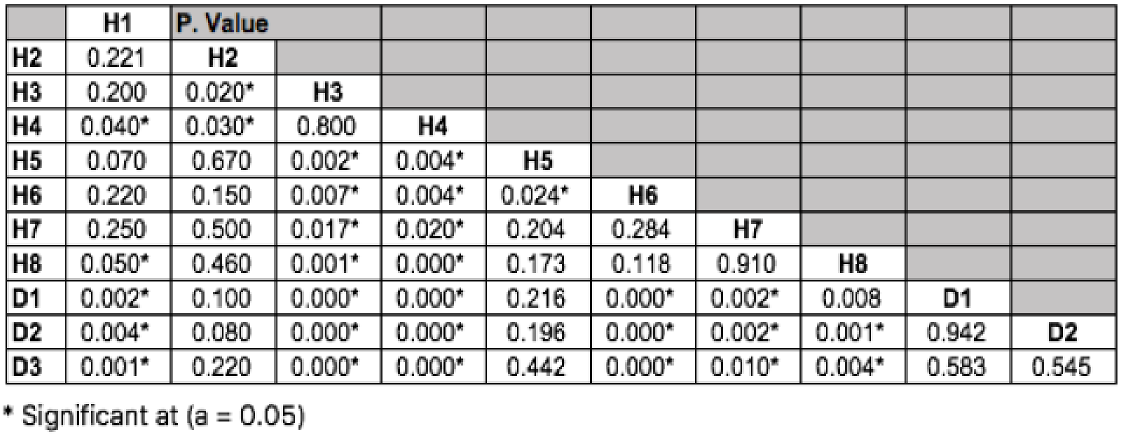
Fig. 5. Average spacing of street trees of the 11 Halifax neighbourhoods. (D1, D2, D3 = neighbourhoods in Central Dartmouth, H1, H2, H3, H4, H5, H6, H7, H8 = neighbourhoods in Halifax Peninsula, HP = Halifax Peninsula, D = Central Dartmouth, H = Halifax)

Neighbourhoods 1, 6, and 7 in Halifax Peninsula were in the range of 14 m, while neighbourhoods 3 and 4 had almost equal average spacing, at 12.8 m and 12.7 m respectively. The other three neighbourhoods in Halifax Peninsula (i.e., 2, 5 and 8) had an average spacing just over 15 m. Likewise, the average spacing of the three neighbourhoods in Central Dartmouth was over 22 m. The average spacing of street trees in all eight neighbourhoods of Halifax Peninsula was 14.3 m with SD 9.1 m and all three neighbourhoods in Central Dartmouth was 24.2 m with SD 16.1 m (Table 3). The overall average spacing of street trees in the study area was 15.4 m with 10.5 m SD, an average clearly dominated by the preponderance of trees measured on the Halifax Peninsula.

3.4.3 Comparison of average spacing between different neighbourhoods

The one-way ANOVA showed at least one inequality. Multiple comparisons (55 possible pairs) demonstrated average spacings of a few neighbourhoods to be similar and many neighbourhoods to be different (Table 3). For example, average spacing of neighbourhood 3 in Halifax Peninsula was similar to 1 and 4 but different from the rest. Likewise, neighbourhood 4 in Halifax Peninsula was similar to neighbourhood 3 but differed from the rest. Average spacings of neighbourhoods 2 and 5 from Halifax Peninsula and all Central Dartmouth neighbourhoods were similar. Apart from neighbourhoods 2 and 5 in Halifax Peninsula, average spacings of the 6 other neighbourhoods differed from Central Dartmouth. The box plots and standard deviation error bars (Figs.6 and 7) showed the variation of street-tree spacing similar to ANOVA.

Table 3: Analysis of Variance of Spacing Means for the 11 Neighbourhoods in Halifax



	H1	**P. Value**								
H2	0.221	**H2**								
H3	0.200	0.020*	**H3**							
H4	0.040*	0.030*	0.800	**H4**						
H5	0.070	0.670	0.002*	0.004*	**H5**					
H6	0.220	0.150	0.007*	0.004*	0.024*	**H6**				
H7	0.250	0.500	0.017*	0.020*	0.204	0.284	**H7**			
H8	0.050*	0.460	0.001*	0.000*	0.173	0.118	0.910	**H8**		
D1	0.002*	0.100	0.000*	0.000*	0.216	0.000*	0.002*	0.008	**D1**	
D2	0.004*	0.080	0.000*	0.000*	0.196	0.000*	0.002*	0.001*	0.942	**D2**
D3	0.001*	0.220	0.000*	0.000*	0.442	0.000*	0.010*	0.004*	0.583	0.545

* Significant at (a = 0.05)

(D1, D2, D3 = neighbourhoods in Central Dartmouth; H1, H2, H3, H4, H5, H6, H7, H8 = neighbourhoods in Halifax Peninsula)

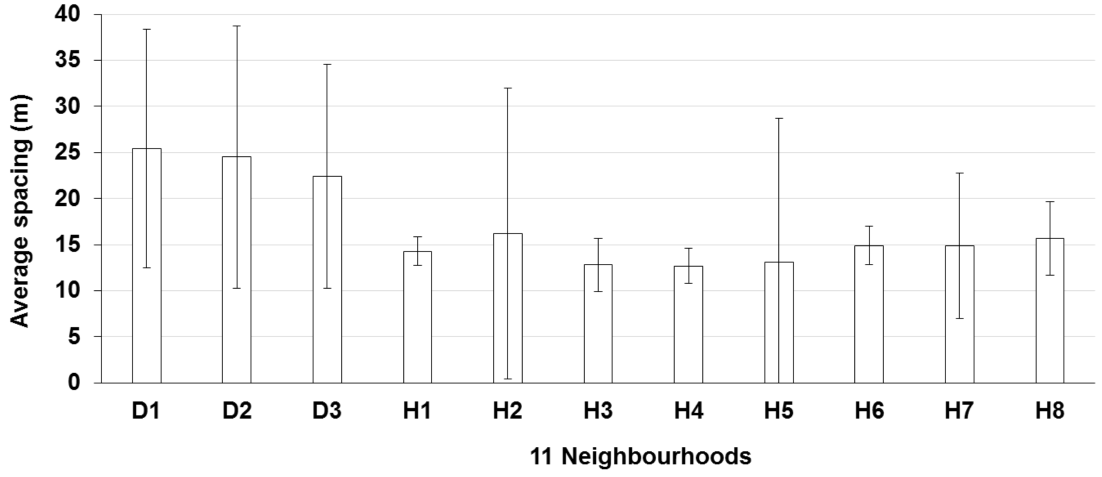


Fig. 6. Averages and variability of street-tree spacings in 11 neighbourhoods using standard deviation error bars in Halifax (D1, D2, D3 = neighbourhoods in Central Dartmouth; H1, H2, H3, H4, H5, H6, H7, H8 = neighbourhoods in Halifax Peninsula).

Looking at the standard deviation error bars (Fig.6), the average spacing of neighbourhoods 3 and 4 of Halifax Peninsula were similar, having similar ranges of data spread, as did Halifax Peninsula 1 and 6. Neighbourhoods 2 and 5 in Halifax Peninsula and all three neighbourhoods from Central Dartmouth had similar ranges of data spread but were different from the rest. In Halifax Peninsula, neighbourhoods 1, 3, 4, and 6 showed less variability in spacing compared to neighbourhoods 2 and 5.

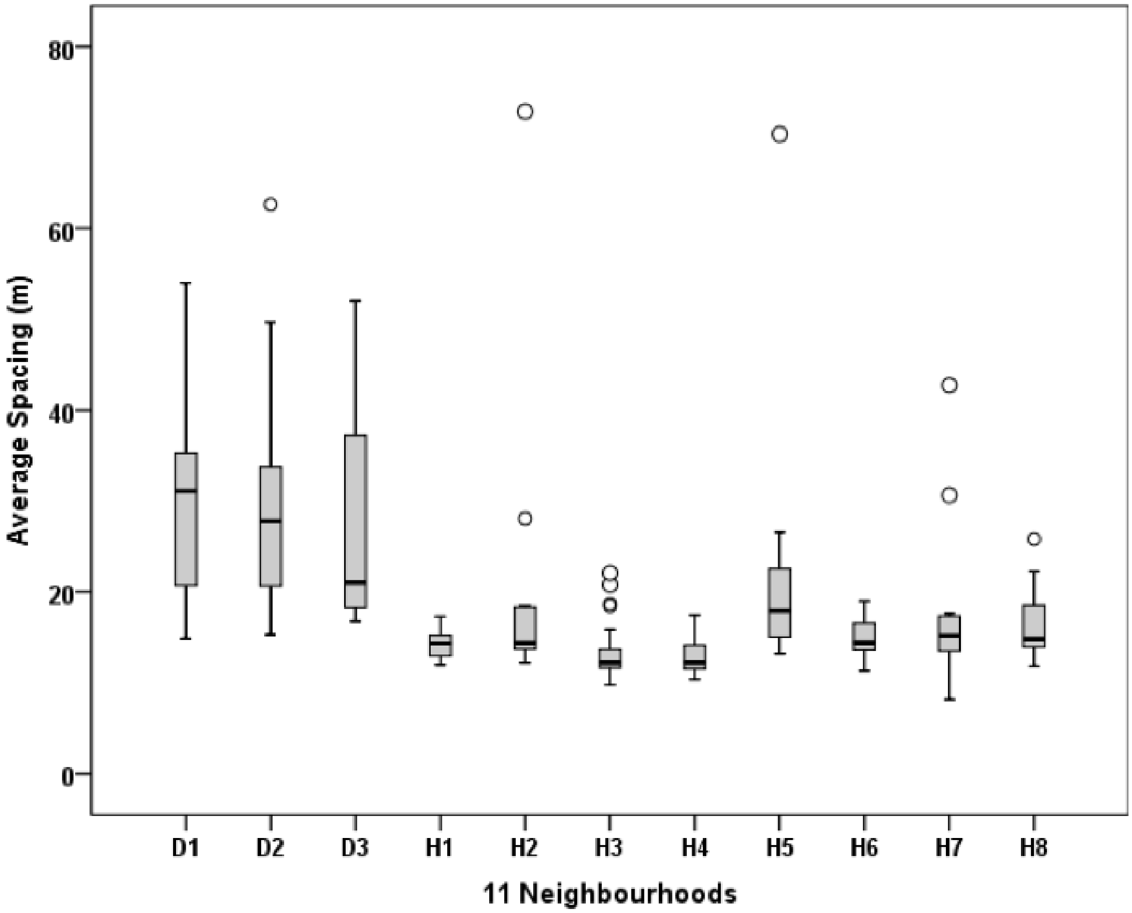


Fig. 7. Averages and variability of street-tree spacings in 11 neighbourhoods using box plots in Halifax (D1, D2, D3 = neighbourhoods in Central Dartmouth; H1, H2, H3, H4, H5, H6, H7, H8 = neighbourhoods in Halifax Peninsula).

Although the average spacing of neighbourhoods 2, 5, and 7 in Halifax Peninsula were not very different, the high spread of the data showed that there was a high variability of actual spacing. All three neighbourhoods in Central Dartmouth showed high variability of average spacing of street trees compared with neighbourhoods in Halifax Peninsula.

Further comparison of average spacing of street trees using box plots (Fig. 7) showed neighbourhoods 3 and 4 in Halifax Peninsula to be similar, with almost equal medians and inter-quartile ranges, and minima and maxima having low variability. Similar results were seen in neighbourhoods 1 and 6 in Halifax Peninsula. However, the high variability observed using ANOVA and standard deviation error bars in neighbourhoods 2 and 5 from Halifax Peninsula was mainly due to outliers, because neighbourhoods 2 and 5 had narrow inter-quartile ranges. Nevertheless, all three neighbourhoods in Central Dartmouth showed a high spread of data, having the lowest minima and the highest maxima.

3.5 Discussion

Some patterns were observed in the street-tree population of Halifax. Before talking about street-tree spacing, it is necessary to discuss these patterns and how they could affect variability in tree spacing. In the study area, 53 species were identified, dominated by Norway maple, American elm, and little-leaf linden. Out of these 53 species, Norway maple comprised 39% (Fig.2), showing an over-abundance. After the Second World War, Norway maple was considered to be one of the best street trees for an urban setting, not only in Halifax but across North America (Nowak and Rowntree, 1990). Its popularity was mainly for three reasons. First, it was considered to have an amenity value because of its pleasing round crown shape (Nowak and Rowntree, 1990). Next, Norway maple has the capacity to react quickly to new environmental conditions and grow in diverse soils (Thuiller et al., 2008). It also has the ability to tolerate many urban stresses, having a strong early growth rate (Nowak and Rowntree, 1990; Qian and Ricklefs, 2006). Third, there were high losses of American elm trees in North American cities due to DED (Nowak and Rowntree, 1990). Considering the amenity value of Norway maple in relation to its rounded crown, each street-tree will only look attractive when its full crown shape is visible (i.e. without any interference from other trees). Furthermore, Norway maple is considered to be a large tree, having a fully-grown crown radius of 10 m and above (Leeds City Council, 2011). Therefore, to avoid crown overlaps and thus maximizing its aesthetic value, this species could have been planted far apart in Halifax. However, Halifax stopped planting Norway maple more than two decades ago because of its invasiveness, among other issues (Halifax Urban Forest Planning Team, 2013).

Street-tree species are not diverse in the sense of evenness in Halifax, because 72% of the three-dominant species mentioned above account for 90% of tree basal area (Fig.3), showing old and large trees in the city. Santamour (2004) recommends a 10-20-30 rule for diversity and uniformity, meaning no more than 10% of one species, no more than 20% of one genus, and no more than 30% of one family. Although Halifax does not follow Santamour’s rule, some cities in Canada claim to do so, including Mississauga and St. Catharines (City of St. Catharines, 2011; Mississauga Urban Forest Planning Team, 2014). Apart from species diversity, it is equally important to consider the functional diversity (trees having unique functions) (Manes et al., 2012; Nock et al., 2013). Nock et al. (2013) recommend higher tree density at the local scale in urban areas because urbanization reduces functional diversity. Any ecosystems with species diversity can increase functional diversity thereby increasing adaptive capacity to changes in environment (Manes et al., 2012; Nock et al., 2013).

Halifax lacks tree-size diversity showing old and large trees that are near the end of their lifespan. The imbalance of tree sizes could be because most American elms in Halifax were not affected by DED. Furthermore, too many Norway maples were planted in the last half of the 20th century. To avoid high mortality in a short period of time, maintaining a diversity in the age and structure of the urban forest with relatively even representation of large (old), medium, and small (young) trees is crucial. With regard to lack of species diversity in Halifax which is dominated by three species, these old and large trees could have been planted far apart to avoid crown overlap and to keep costs under control.

Street-tree spacing standards in North American cities tend towards wide planting. When the actual street-tree spacing in Halifax was compared with that of North American specification guidelines, the tree spacing in Halifax was found to be wide and highly variable. There could be a number of reasons for this variability of tree spacing, the major factors being discussed below.

First, trees in privately owned properties could have resulted in wider spacings in some neighbourhoods of Halifax Peninsula and all neighbourhoods from Central Dartmouth. Some neighbourhoods in Halifax Peninsula, for example, neighbourhoods 2 and 5, contain trees near street rights-of-way on private property. In addition, many areas of Central Dartmouth have rows of privately owned trees in residential properties adjacent to streets. In areas where privately owned trees are present, there are no trees adjacent to streets because of these residential tree planting. This could have resulted in wider spacing in all neighbourhoods of Central Dartmouth and some neighbourhoods (2 and 5) of Halifax Peninsula.

Another reason that could explain high variability is the decline and mortality of Norway maples. During the data collection, I observed some stressed trees, mainly Norway maple. Many of the Norway maples observed had dieback and dead limbs. Norway maple seems to be declining because of its age and girdling roots (Manion, 1981), among other potential factors. Studies show the life expectancy of urban Norway maples to be 60 to 80 years (Manion, 1981; Nowak and Rowntree 1990), but in poor quality urban sites it may be much lower. Many of these Norway maple trees in Halifax are over 50 years old. Furthermore, I observed Norway maple being removed in neighbourhoods 2, 5, 8 in Halifax Peninsula and neighbourhoods 1, and 2 in Central Dartmouth. Such dead and felled trees left large gaps, thus increasing the average spacing of street trees. Given the dominance of Norway maple along with the decline of the aging population and tree removal, it is likely that these factors explain the wider spacing.

The third possible reason for variability in street-tree spacing is construction and re-construction of sidewalks. In some areas of Central Dartmouth, many sidewalks were constructed much later than the initial creation of the neighbourhood. Roots on two sides of trees (parallel to the streets) were likely cut during construction (Trowbridge and Bassuk, 2004). During this later period of sidewalk construction, tree death occurred in some areas, creating voids in streets. As with the aging Norway maple, this development practice could have resulted in wider spacing.

The next reason for the spacing variability could be the implementation of the urban forest master plan (UFMP). Halifax began implementing its UFMP in 2013 (Halifax Urban Forest Planning Team, 2013). This plan selected five priority areas for targeted tree-planting emphasis during the first five years of plan implementation. The majority of neighbourhoods in Halifax Peninsula and all three neighbourhoods in Central Dartmouth are outside the UFMP priority areas (Halifax Urban Forest Planning Team, 2013). Therefore, there has not been much planting or replacement of dead trees in recent years in these areas. Tree planting is still ongoing and observed specimens are comparatively wide apart (Halifax Urban Forest Planning Team, 2013). I think that the spacing of trees would have been even higher in some neighbourhoods under UFMP priority areas if there had been no recent tree planting.

Another possible reason for wide spacing in Halifax is the lack of financial resources. The city has been planting large (i.e. 60 mm root-collar diameter) caliper trees in the streets of Halifax (Urban Forest Planning Team, 2013). Although there are small-size caliper trees for planting in streets, the city considers the possibility of losing them through vandalism. As a result, only large caliper trees are chosen (Urban Forest Planning Team, 2013). Planting such large caliper trees is costly and has been estimated to be over $400 (CAD) per tree (Halifax Urban Forest Planning Team, 2013). Therefore, choosing to plant large caliper trees and the usual constraints on financial resources could have resulted in wide spacing, and high spacing variability, of street trees.

Finally, neighbourhood 7 in Halifax Peninsula has a unique historical design making this neighbourhood different from others. There are large boulevards with wide medians and back service lanes, with corresponding abundance of plantable spaces for street trees.

Throughout the neighbourhood, trees are planted in medians with unique tree-lined boulevards and a garden city streetscape (Soward et al., 2008). Such a historical design of tree planting in large, wide medians could have increased the average spacing of this neighbourhood compared to other neighbourhoods from Halifax Peninsula.

3.6 Conclusions

There is almost no research on spacing of street trees in the literature. If trees in urban areas can provide myriad benefits to urban residents (Duinker et al., 2015), then street trees should be given a high priority requiring more research. As the findings show, average spacing of street trees in Halifax is wide (14.3 m in Halifax Peninsula, 24.2 m in Central Dartmouth, and overall 15.4 m) and actual spacings are highly variable. Furthermore, many trees are large, old, and dominated by three species. Although a single large tree at maturity provides greater benefits than a small tree, many of the potential benefits from street trees are uncaptured by planting them far apart. This is because many ecosystem services are directly related to the amount of tree foliage per unit area, not per tree. In this view, the sooner the area above the street is filled with tree foliage, the better. The best way to achieve a full canopy soonest is to plant trees close together.

The variability of tree spacing issues discussed above will be useful to the city planners in considering tighter spacings of street trees for maximizing ecosystem services. Planting trees close together is expensive in the initial phase, but the earlier benefits obtained from tighter spacings are much greater compared to trees planted at wider spacings. This is because the full canopy in narrower spacing is achieved much sooner than in wider spacings. Although issues such as installation costs and the city's inadequate financial resources may not support the tighter spacing argument, installation costs can be reduced by planting smaller trees. Replacing large-size caliper trees by small ones can reduce the installation costs per tree by up to tenfold (J. Simmons, personal communication, February 2017). Therefore, the benefits obtained from planting street trees close together may well outweigh the overall costs, thus providing greater benefits compared to trees planted far apart. In my view, we need to find an affordable way to plant trees closer together in the urban streetscape

3.7 References

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CHAPTER 4 OPTIMAL SPACING OF STREET TREES IN HALIFAX, CANADA

Abstract:

Street trees provide many benefits, including improved air quality, amelioration of air pollutants, and the shading of asphalt, cars, and buildings. In spite of the many benefits they provide, trees in streets are planted far from one another with large gaps. This raises the question as to what should be the distance between street trees. I wanted to calculate the effect of tree spacing on the provision of ecosystem services, namely how much longer it takes to achieve the same level of services with widely spaced trees than it does with closely spaced trees. Therefore, the main objective of this study was to explore the optimal spacing of street trees in Halifax. First it was necessary to determine actual tree spacings as well as the relationships between trunk diameter and crown diameter for the main tree species. Tree data were collected from 188 randomly selected street segments in the urban core. Altogether, 2,162 street trees were measured for their species, diameter at breast height (DBH), crown diameter, and distance to an adjacent tree(s) in the row. A Total of 53 species was identified with an average spacing of 15.4 m, dominated by Norway maple (Acer platanoides) (39% by stem count), American elm (Ulmus americana) (21%), and little-leaf linden (Tilia cordata) (12%). Regression equations were developed for the three-dominant species (Norway maple, elm, and linden) to predict crown diameter from DBH ($R^2 > 0.60$). Using a simple tree growth model and the three regression equations, growth of the three-dominant species was simulated to calculate crown coverage, year by year over 60 years, at spacings from 5 to

20 m in a one-hectare area representing a street landscape (500 m by 20 m). A row of street trees at close spacing delivers a greater canopy coverage per unit area, particularly when the trees are young. Trees planted at 5 m spacing provide greater ecosystem services much sooner compared to trees planted at 20 m spacing. Concomitantly, the initial cost per unit distance along with the unit cost will be increased while establishing the trees. The spacings of street-tree plantings of all species between 5 and 10 m apart has been recommended. It is important to find an affordable way to plant trees closer together in the urban streetscape to maximise ecosystem service supply.

4.1 INTRODUCTION

The populations of trees in the public rights of way along streets are maintained and controlled by the municipal authorities and are called street trees (Miller et al., 2015). They provide the human community with a range of ecosystem services. Street trees ameliorate air pollutants, slow down stormwater, and increase property values (Duinker et al., 2015). They provide shade and increase the longevity of roads (McPherson and Muchnick, 2005). Street trees shade vehicles parked near streets. This reduces emissions of harmful gases from parked vehicles, thus conserving fuel (Akabari et al., 2001; Scott et al., 1999).

Many of these benefits are directly related to the amount of leaf area the trees can produce (Stoffberg, 2010; McPherson et al., 2016). Any site growing trees has a finite capacity to support tree foliage. That capacity can be equally fulfilled (within limits) by many small trees or a few large trees. The greater the density of trees planted, the earlier a site can approach its maximum capacity to support tree foliage, and therefore the earlier the site will provide the maximum amount of ecosystem services. Clearly, a site with widely spaced trees can, within limits, eventually reach full foliage capacity, but because of the wide spacing, this may not occur until several decades after the trees were planted. The key uncertainty concerns trade-offs associated with alternative spacings of street trees, given both the increased planting costs and the earlier provision of maximum ecosystem services of closer spacings versus the lower costs and later provision of maximum ecosystem services of wide spacings.

It is useful to compare tree spacing practices between silviculture and arboriculture. Silviculture is the practice of planting and managing a group of trees, particularly for timber production (Smith, 1986). On the other hand, the term arboriculture is applied to the planting and management of individual trees and is more concerned with the health of single trees (Harris, 1992). Each individual tree is considered for its amenity value and much of the focus is on the shape and aesthetics of the tree crown. Trees are often planted far apart thus allowing each one to have greater space to grow so that crown overlap is avoided, as this may be seen to lessen their aesthetic appeal and health. Urban forestry, particularly street-tree planting and maintenance, is heavily influenced by arboricultural practices.

If we look at trees as providers of ecosystem services rather than only seeing them as amenities, planting trees close together is more effective than far apart. This is because street tree benefits depend on the amount of tree foliage per unit land area, not on the amount of foliage per tree. This means the sooner the area above the street is filled with foliage, greater the benefits for the residents. In order to achieve a full canopy soonest, it may be worthwhile to revisit current and established wide tree-spacing practices in arboriculture and look perhaps to silvicultural practices as a guide.

It can be argued that trees planted with a tighter spacing are likely to have limited growth. Some relevant factors include limited growing space (Miller, 2000), deficiency of nutrients, lack of sunlight, and interference of crowns from crowded stems (Smith, 1986). It can be assumed that these growth-limiting factors are likely to result in slower growth rates, leading to poor tree health and perhaps eventually the unwanted premature death of a tree (Spurr and Barnes, 1980). Hence, one may conclude that trees planted closer together will not thrive well. However, this is less likely in a single row of trees than in a crowded stand.

By planting trees close together (within limits, of course), growing space is not necessarily decreased nor growth slowed; rather, trees attain greater height in their early years of growth (Benomar et al., 2012; Erkan and Aydin, 2016). This is due to greater soil coverage, soil moisture retention, heat loss minimization, and soil temperature regulation, thereby making a better microclimate close to the ground (Erkan and Aydin, 2016). With wider spacing, tree height may be reduced due to lower soil moisture availability resulting from loss of water by evaporation (Erkan and Aydin, 2016). In addition, studies show that trees in tighter spacing can utilise the available growing space efficiently with greater crown leaf area and biomass compared to trees in wide spacing (Ceulemans et al., 1990; Benomar et al., 2011; Benomar et al., 2012). Importantly, increasing space between trees produces more tree foliage per tree, but not per unit area (Benomar et al., 2012). The study carried out by Benomar et al. (2012) in the boreal region of Quebec, Canada, in young hybrid poplar clones on the effects of spacing on growth showed 8-20 times greater biomass, as well as taller trees, per hectare in close spacing (1 x 1 m) compared to the wide spacing (3 x 3 m and 5 x 5 m), clearly supporting tighter spacing for enhanced biomass production.

Trees compete for nutrients, water, and light (Smith, 1986; Oliver and Larson, 1990). In high-density stands, nutrients and sunlight are considered to be important factors because nutrients will be shared among trees and sunlight will be blocked by crowded stems, thus slowing tree growth. However, nutrient uptake depends on the type of soil and its characteristics rather than stand density, such as texture, water-holding capacity, bulk density, and compaction (Spurr and Barnes, 1980; Smith, 1986; Millward, Poudel and Briggs, 2011). Closely planted trees can have higher root density. Soil having greater root density is more likely to have higher porosity for gaseous exchange and water movement than with lesser root density (Millward, Paudel and Briggs, 2011).

Trees often do not have a fixed crown shape, even within the same species. Their inherent growth due to their genetic makeup, along with environmental factors such as light, growing space, soil, nutrients, and water, can influence crown shape. Some trees have columnar crowns in high latitudes, because their stems are perpendicular to the light rays (Oliver and Larson, 1990), allowing higher crown exposure to sunlight. Conversely, trees in lower latitudes have either flat-topped or conical crown shape since the sun is overhead, providing maximum light exposure (Oliver and Larson, 1990). Because of flexibility in crown shape, competition between closely planted trees seems to lessen, allowing greater crown plasticity (Getzin and Wiegand, 2007). Crown plasticity is the ability of tree crowns to grow more towards more light (Purves et al., 2007; Olivier et al., 2016). In high-density stands, crowns grow towards more light or gaps, thus changing the crown position, shape, and size (Brisson, 2001; Muth and Bazzaz, 2003; Seidel et al., 2011; Schroter et al., 2012). Therefore, such crown shape behaviour is likely to reduce neighbourhood competition allowing trees to grow well (Muth and Bazzaz, 2003; Olivier et al., 2016). Despite competition and limited resources, trees in close spacing often thrive well and produce greater tree foliage and biomass per unit area.

Although street trees are usually grown on arboricultural principles, this study is based on the principles of silvicultural practice. I argue that trees planted closer together can provide much greater tree foliage per unit area in the early decades of a street-tree planting despite possible trade-offs around competition and planting costs, resulting in greater ecosystem services compared to widely spaced trees.

There have been ongoing studies on urban forests such as urban forest benefits (Duinker et al., 2015), residents' preferences and attitudes to urban forests and street trees (Kirkpatrick et al., 2012; Dilley and Wolf, 2013), crime reduction from street trees (Donovan and Prestemon, 2012), species selection (Rostami, 2011; Conway and Vecht, 2015), and surveys of street-tree density (Kalmbach and Kielbaso, 1979). The study by Kalmbach and Kielbaso (1979) showed one tree per home but did not show how far apart they were. There are hardly any published studies on actual street-tree spacings or on the supply of ecosystem services from street trees at different spacings. Therefore, this study explores the optimal spacing of street trees in Halifax. I wanted to calculate the effect of tree spacing on the canopy cover development, that is how much longer it takes to get the same level of canopy development with widely spaced trees compared to closely spaced trees. The specific objectives of this study were to evaluate the canopy development of street trees at spacings of 5 to 20 m to explore the optimal spacing of street trees. I used a simple tree-growth model and simulated tree growth over 60 years for the three-dominant species (Norway maple, elm, and little-leaf linden) observed in Halifax.

4.2 Materials and Methods

4.2.1 *Study area*

The empirical portion of this study (see Chapter 3 for the empirical results) was carried out on street trees in Halifax, Canada (Fig.8). Data were collected describing street trees in residential neighbourhoods in the urban centre of Halifax. The city was divided into three zones: old residential blocks, new residential blocks, and downtown areas, following the approach of Jaenson et al. (1992). Only the old residential neighbourhoods were considered since they have a high proportion of street trees. These zones were further divided into eleven neighbourhoods, with eight located in the Halifax Peninsula and three in Central Dartmouth.

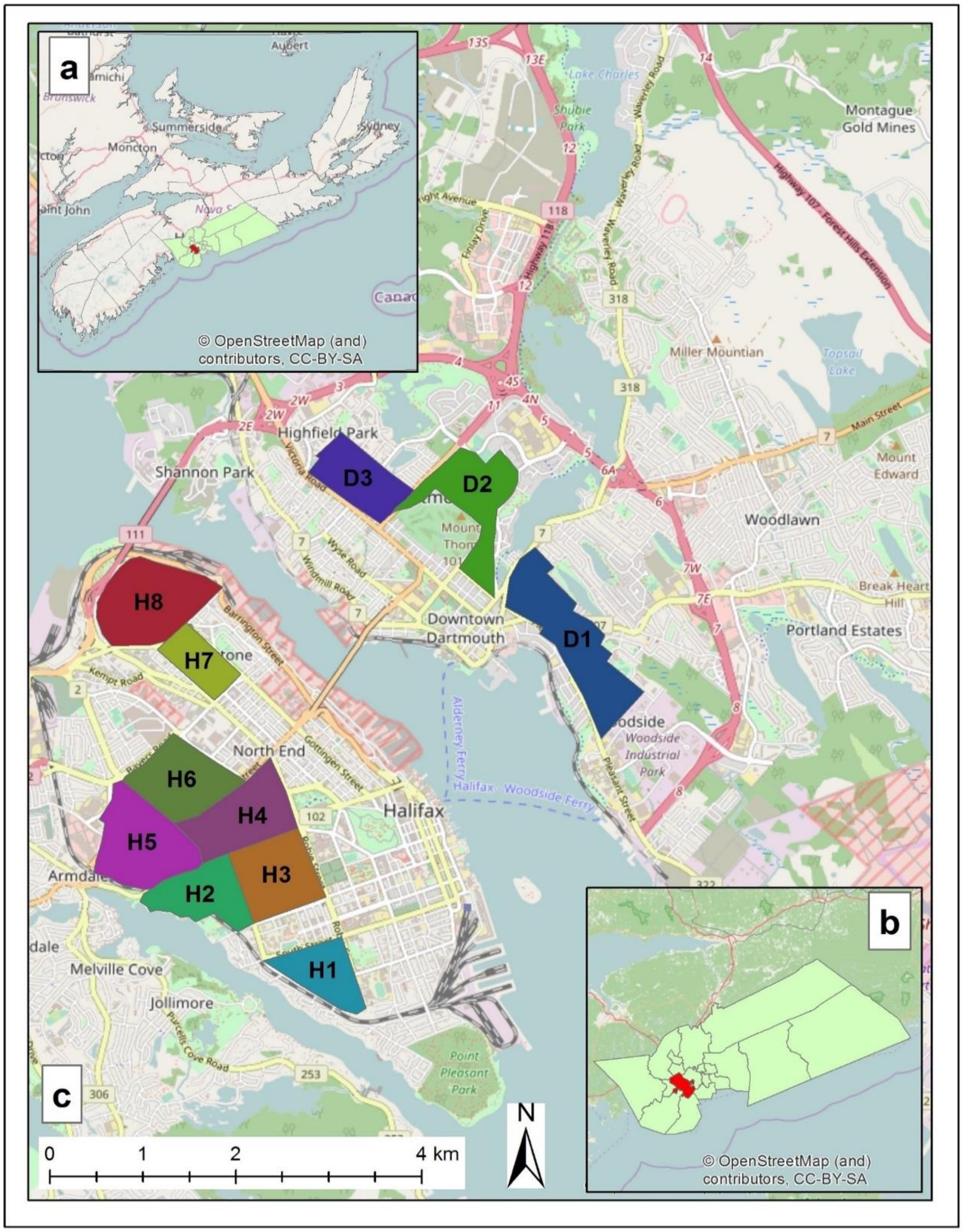


Fig. 8. Location of eight neighbourhoods in Halifax Peninsula and three neighbourhoods in Central Dartmouth (c), Halifax Regional Municipality (b), and the Maritime Provinces (a).

Trees were measured in the spring and summer (May-August) of 2016. The measurements were confined to residential streets with a tree lawn (or verge) between the sidewalk and the curb in the public right of way. Streets were divided into street segments, where a street segment was defined as one side of a street between intersections with other streets. Only streets with a tree lawn between the sidewalk and the curb were considered. Street segments shorter than 100 m were not taken. Some short segments have only one tree making the calculation of average spacing impossible. Therefore, a minimum segment length of 100 m was chosen and all shorter ones excluded.

4.2.2 *Data collection*

A complete street segment inventory was generated and altogether 457 street segments (399 in Halifax Peninsula and 58 in Central Dartmouth) were considered to be eligible. Overall, 188 segments were randomly selected for measurement with at least 10 from each neighbourhood (157 in Halifax Peninsula and 31 in Central Dartmouth).

In total, 2,162 street trees were measured. Each tree was measured for its diameter at breast height (DBH) at 1.3 m from the ground. Two-crown dimensions were measured, including crown diameter parallel to the street and crown radius perpendicular to and towards the street. For measuring crown diameter perpendicular to the street, permission from the residential property owner would have been necessary and was avoided due to access and timing constraints. Each crown radius was doubled to estimate the diameter and the mean of the two diameters was used to obtain the final crown diameter value.

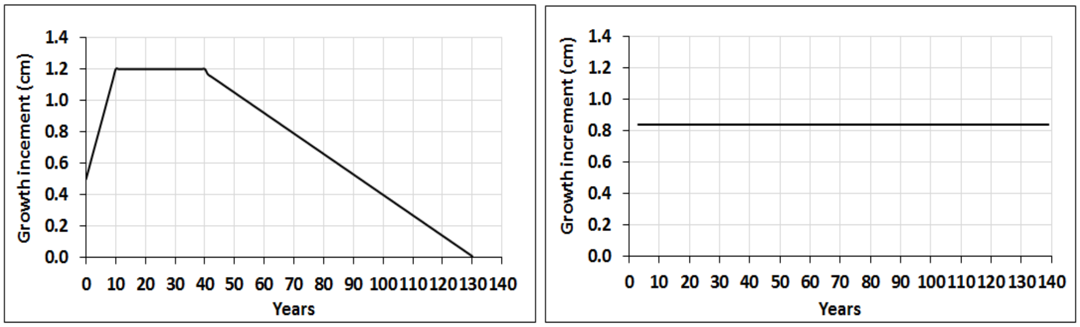
4.2.3 Simulation and analysis

Since the street-tree population in Halifax is dominated by three species (Norway maple *(Acer platanoides) (39%),* American elm *(Ulmus americana) (21%),* and little-leaf linden *(Tilia cordata) (12%)*), I developed three linear regression equations to calculate crown diameter from stem DBH:

$$\boldsymbol{y = \beta 0 + \beta 1} * \boldsymbol{x}$$

Where y = predicted crown diameter, x = DBH, β0 = y-intercept and β1 = slope.

This regression is used in simulations of tree growth for several parameters. The simulation provides estimates of urban forest growth under various conditions. Spacing of trees, DBH, crown diameter and period of growth are investigated. For example, growth over a period of 60 years and spacings of 5-20 m are examined. Next, I developed two diameter growth models for the simulations. The first one is Duinker's simple, variable-growth model (VGM) which is based on his professional judgement (Fig.9), and the second one is the standardised fixed-growth model (FGM). This model has a fixed growth increment which is adjusted by factors such as tree height, site conditions, availability of nutrients, and light (Nowak et al., 2008).



(a) (b)

Fig. 9. Two tree growth models, (a) Variable Growth Model (VGM), and (b) Fixed Growth Model (FGM).

The difference in these two models is that the VGM model shows different diameter growth increments with an increasing growth rate in the earlier years of tree growth, which then remains constant for some years after which it declines. On the other hand, the Nowak et al. (2008) diameter growth model shows a fixed growth increment (0.83 cm/year) throughout the complete lifespan of a tree.

Apart from these two growth models, Griffin et al. (2017) show a range of DBH increment for young elm cultivars and Peper et al. (2014) for fully grown urban ash trees. The diameter growth increment reported by Griffin et al (2017) ranges from 0.7 cm/year to 1.7 cm/year, whereas Peper et al. (2014) ranges from 1 cm/year to 1.6 cm/year. Moreover, Bowman et al. (2013) state that diameter increment increases in the early years of tree growth and gradually declines as trees grow older. I think a variable growth model is better than a fixed one for the entire life of a tree because trees do indeed grow at different rates of diameter increment over their lifetimes (Bowman et al., 2013; Peper et al., 2014; Griffin et al. 2017).

In the simulation, I used 5-cm DBH trees at the start of all simulations, since this is typical of newly planted street trees. Most of the newly planted trees measured in Halifax were in the range from 4 – 6 cm DBH. Using the VGM for one set of calculations and the FGM for another, I calculated the DBH from year zero followed by year one to year sixty for the three species. I then used regression equations to calculate a crown diameter from year zero to year sixty for the three species at every time step (Table 4).

Table 4. Diameter at breast height (DBH) and crown diameter (CD) of three species from the regression equations and variable tree growth model.

Years	Annual increment	American Elm		Norway Maple		Little-leaf Linden	
		DBH (cm)	CD (m)	DBH (cm)	CD (m)	DBH (cm)	CD (m)
0	0.50	5.00	4.51	5.00	5.41	5.00	5.74
1	0.57	5.50	4.59	5.50	5.49	5.50	5.80
2	0.64	6.07	4.69	6.07	5.57	6.07	5.87
3	0.71	6.71	4.80	6.71	5.66	6.71	5.95
4	0.78	7.42	4.91	7.42	5.77	7.42	6.04
5	0.85	8.20	5.05	8.20	5.89	8.20	6.13
6	0.92	9.05	5.19	9.05	6.01	9.05	6.24
7	0.99	9.97	5.34	9.97	6.15	9.97	6.35
8	1.06	10.96	5.51	10.96	6.30	10.96	6.47
…...	…...	…...	…...	…...	…...	…...	…...
…...	…...	…...	…...	…...	…...	…...	…...
…...	…...	…...	…...	…...	…...	…...	…...
…...	…...	…...	…...	…...	…...	…...	…...
52	1.02	62.47	14.16	62.47	13.94	62.47	12.80
53	1.01	63.50	14.34	63.50	14.09	63.50	12.92
54	1.00	64.51	14.51	64.51	14.24	64.51	13.05
55	0.99	65.51	14.67	65.51	14.39	65.51	13.17
56	0.97	66.49	14.84	66.49	14.54	66.49	13.29
57	0.96	67.46	15.00	67.46	14.68	67.46	13.41
58	0.95	68.42	15.16	68.42	14.82	68.42	13.53
59	0.93	69.37	15.32	69.37	14.96	69.37	13.64
60	0.92	70.30	15.48	70.30	15.10	70.30	13.76

After generating a DBH table for sixty-one years, I simulated tree growth in a one-hectare linear strip (500 m x 20 m). Since the maximum calculated crown diameter of the three-dominant species at 100 years is close to 20 m, I selected an area for the street-tree row of width 20 m. I then generated a table showing the number of trees that can be planted in the linear strip at spacings 5 m to 20 m (Table 5).

Table 5. Number of trees that can be planted in each spacing from 5 m to 20 m in 1 ha (500 m x 20 m).

Spacings (m)	Number of trees in a row	Spacings (m)	Number of trees in a row
5	100	13	38
6	83	14	36
7	71	15	33
8	63	16	31
9	56	17	29
10	50	18	28
11	45	19	26
12	42	20	25

I began the simulation in year zero at a spacing of 5 m. Since the length of the row is 500 m and spacing is 5 m, the number of trees in the row is calculated using the following formula.

$$\text{Number of trees in a row} = \frac{\text{Lenth of the row}}{\text{Tree spacing}}$$

To calculate the number of trees in the spacing scenarios from 6 to 20 m, the same process was applied.

For calculating the total canopy coverage, I first started the simulation at a spacing of 5 m in year zero. Trees were arranged linearly with a spacing of 5 m and calculated the canopy coverage of the row twice, once including crown overlaps and the other excluding crown overlaps. When closely spaced trees mature, their crowns widen, intermingling with each other (i.e., overlapping crowns). In a given simulated row of trees there can be a single overlap (i.e., overlap of crowns between two trees) or multiple overlaps (i.e., overlap between three or more trees when the trees are close together and grow large). Single overlaps were observed in many of the simulations and multiple overlaps in the simulations with mature, closely spaced trees. I assumed that the crowns would grow into each other with the same crown shape and crown expansion rate as would occur if the trees did not touch at all, as per the regressions on extant Halifax street trees. This resulted in two sets of calculations, one with canopy coverage including single and multiple crown overlaps and the other without overlaps (See Fig. 10). The degree to which leaf area and the density of foliage will increase in these areas of overlap is uncertain. On the low extreme, leaf area might be equal to what it would be as an individual tree, while on the high extreme it might be double that value. Both of these extremes were simulated in this study to capture the full range of likely variability.

Although two or more closely planted trees are likely to share each other's growing space due to crown intermingling, nevertheless I wanted to exclude single and multiple crown overlaps for the sake of estimating the minimum canopy coverage for comparison with the maximum. Also, I wanted to avoid possible errors because of potential crown interference from closely planted trees.

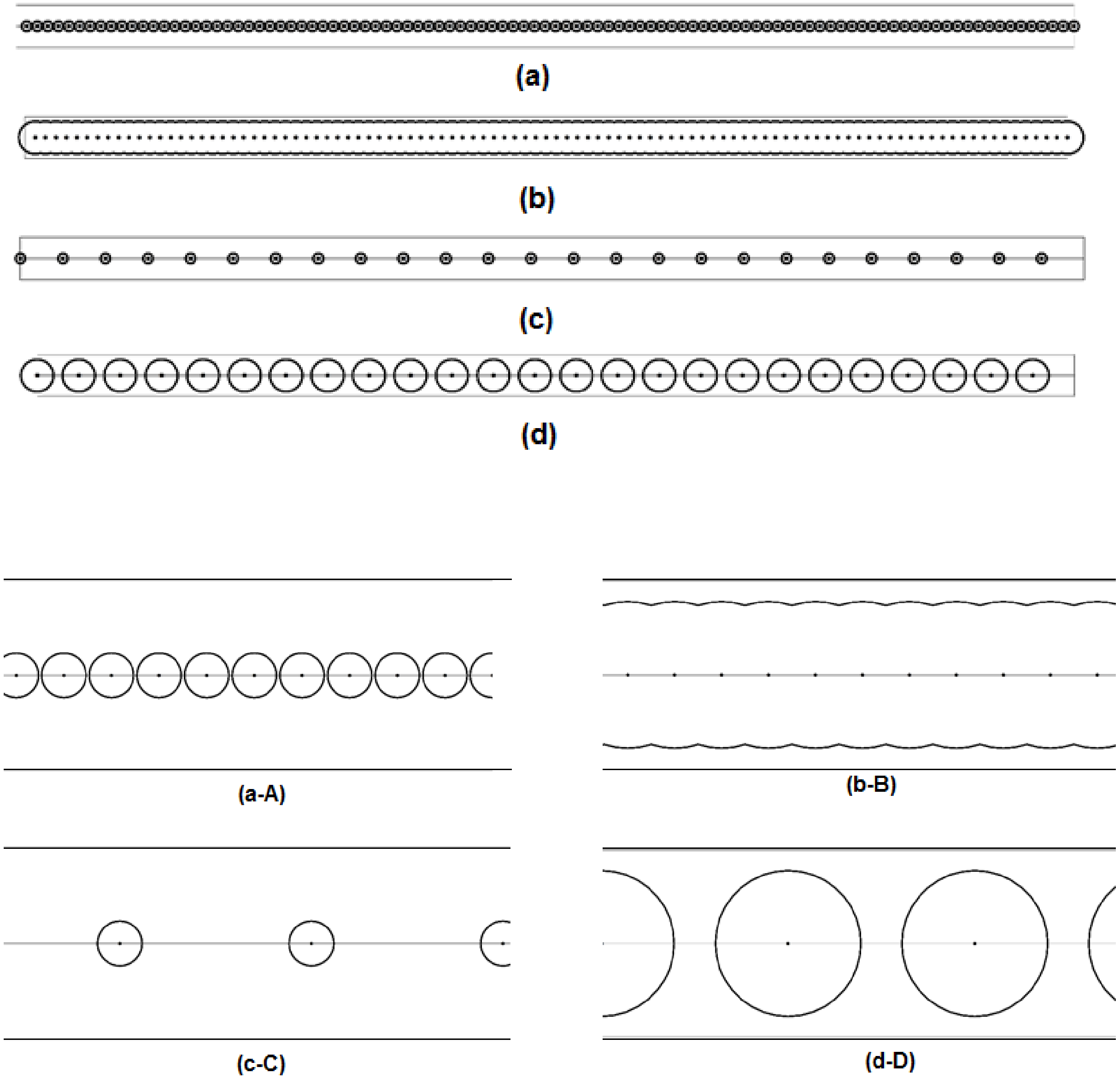


Fig. 10. Canopy coverage of American elm in one hectare (500 m x 20 m) in different years: (a) one year after initiating the simulation at 5 m spacing, canopy coverage = 17%, (b) sixty years after initiating the simulation at 5 m spacing, canopy coverage = 78%, (c) one year after initiating the simulation at 20 m spacing, canopy coverage = 4%, (d) sixty years after initiating the simulation at 20 m spacing, canopy coverage = 47%; (a-A) an enlarged portion one year after initiating the simulation at 5 m spacing, (b-B) an enlarged portion sixty years after initiating the simulation at 5 m spacing, (c-C) an enlarged portion one year after initiating the simulation at 20 m spacing, (d-D) an enlarged portion sixty years after initiating the simulation at 20 m spacing.

To calculate the area of the canopy, I used crown radius values. It is assumed that the shape of the crown is circular. Widely planted trees are likely to have roughly circular crowns, whereas my measurements on rows of closely planted trees in various settings around Halifax (i.e., spacings as low as four metres, with DBH ranges from 30 to 110 cm) demonstrate that such trees can actually have an elliptical crown. The canopy coverage obtained from the slightly elliptical crown of a tree interacting with its row neighbours is assumed to be roughly equal to the area calculated for a tree with the same DBH that has no crown interactions with its row neighbours. This is based on the assumption that the crown diameter perpendicular to the row for closely spaced trees is actually slightly greater than the perpendicular crown diameter for a tree not interacting with neighbours. Therefore, I have assumed that despite the prospect that closely spaced trees would in reality develop an elliptical crown, calculating its area as a circle would be an acceptable error.

The maximum canopy coverage scenario was calculated using the assumption that each tree bears its full canopy in the overlap zones. This likely overestimates leaf area per unit land area. I wanted to evaluate the theoretical maximum canopy coverage and compare it with the minimum canopy coverage. To calculate the maximum canopy coverage, I used the following formula;

Equation # 1………………………… $CAC = \pi r^2 n$

Where CAC = Canopy area (coverage), r = Crown radius, and n = number of trees in a row.

The minimum canopy coverage scenario was determined by removing the overlap of crowns. For calculating canopy area excluding overlaps, ArcMap 10.3.1 is used. Using ArcMap's geometry function, single and multiple overlaps were removed. I then used the same process for obtaining canopy area at 5 m spacing in years one to sixty. The same method was applied to calculate the canopy area at a spacing of 6 m to 20 m from year zero to sixty. Identical methods were used for each of the three species.

4.2.4 Street-tree Costs

To calculate the costs related to street-tree planting and maintenance, I have assumed that maintenance costs after planting would be the same per unit of street length regardless of spacing. However, I decided to test the financial implications of considering two sizes of planted trees: small ones which have a diameter at root collar (DRC) of 20 mm and large ones with DRC of 60 mm. These two sizes differ greatly in terms of installation expense, the large 60-mm trees costing $400 per tree, whereas $40 suffices for the 20-mm trees (J.Simmons, personal communication, February, 2017). By choosing to plant small stock, the installation costs are dramatically reduced for a street-tree planting of equal spacing. The total costs for each of the 5-20 m spacing simulations were calculated. I then compared different spacings from 5 to 20 m to see which spacing can produce greater tree foliage. For the comparison of results across spacings, I estimated the total time taken to cover 50% of the land area in the one-hectare street section.

4.3 Results

4.3.1 Regression Equations

I conducted simple linear regression for the three-tree species (American elm, Norway maple, and little-leaf linden) to predict their crown diameter from their DBH. The DBH and crown diameter of these three species were positively correlated. The regression equations demonstrated a good fit for all three species ($R^2 > 0.60$) (Fig. 11, Table 6). However, Norway maple exhibited stronger relationships ($R^2 = 0.65$) compared to American elm ($R^2 = 0.61$) and little-leaf linden ($R^2 = 0.61$). The scatter plots showed most America elms had the largest DBH, ranging from 50 cm to 100 cm. Similarly, Norway maples DBH ranged from 40-80 cm and little-leaf linden 40-90 cm.

Table 6. Regression equations of three dominant species (American elm, Norway maple and Little-leaf linden) observed in Halifax; β1 and β0 are the regression coefficients, R^2 the adjusted coefficient of determination, and n the total number of observations. Regression equations were calculated using: $(y = \beta 0 + \beta 1 * x)$ All three equations were statistically significant at an alpha level of 0.05.

Species	$\boldsymbol{\beta 1}$	$\boldsymbol{\beta 0}$	**R^2**	**n**
American Elm	0.169	3.667	0.614	453
Norway Maple	0.148	4.669	0.650	828
Little-leaf Linden	0.123	5.125	0.610	266

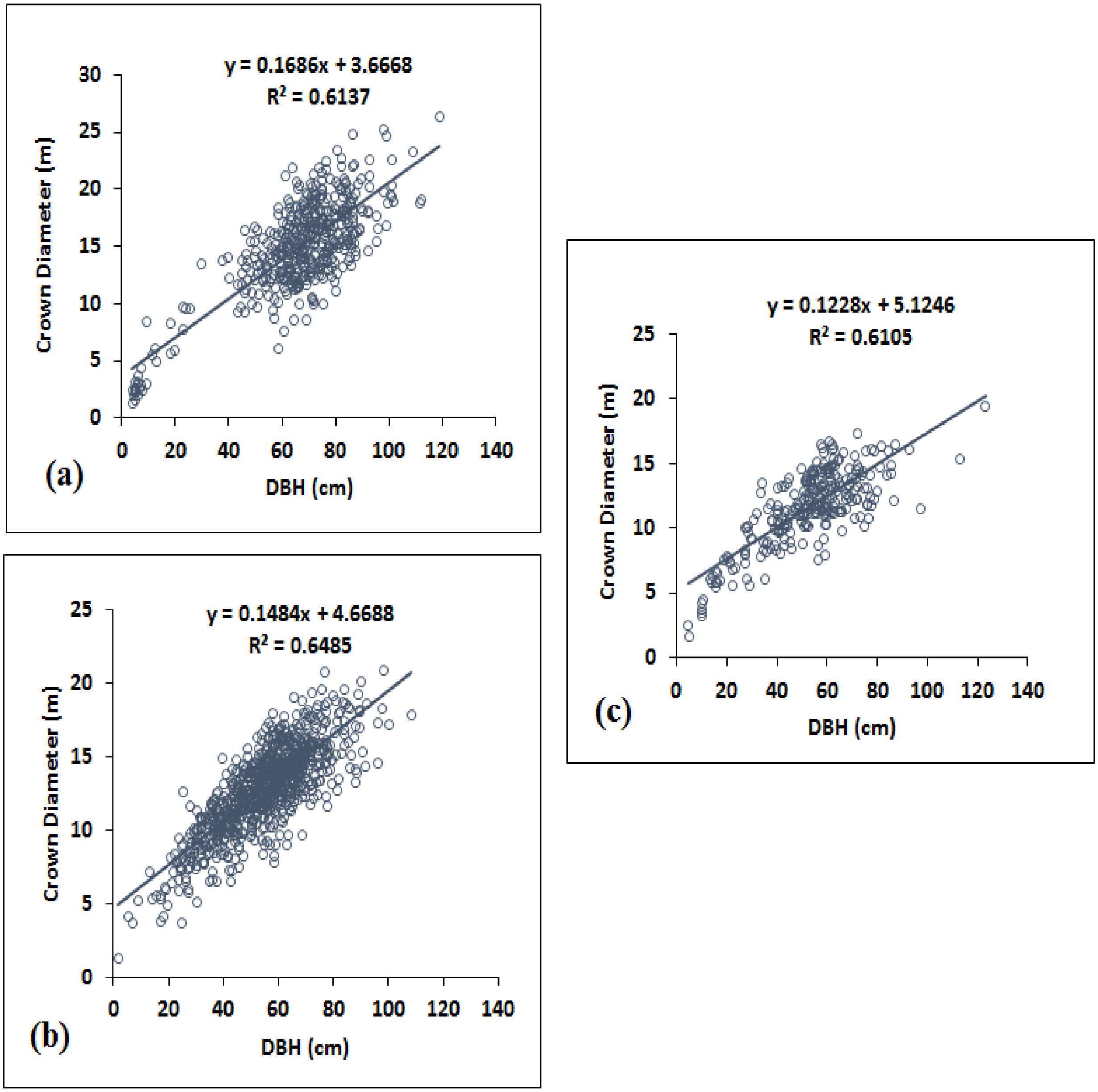


Fig.11. Scatter plots showing the relationship between DBH and crown diameter of (a) American elm, (b) Norway maple, and (c) Little-leaf linden.

4.3.2 Simulation Results

Simulations were run for three species (American elm, Norway maple, and Little-leaf linden) with two growth models (VGM and FGM) at sixteen spacings (from 5 m to 20 m) for two overlap assumptions: one excluding all overlaps and the other including all overlaps. Therefore, the total number of simulation runs was 192 (i.e. 3 species x 2 growth models x 16 spacings x 2 overlap assumptions = 192 simulations). I have used hectares of crown area per hectare of land area as the key simulation results indicator, which is a unitless proportion; this has been reported as the proportion of crown cover reached at a specific year, and the year when 50% crown cover was reached.

4.3.3 Simulation of American elm using VGM and no overlap

The differences among the crown-coverage developments across the four spacings (i.e. 5 m, 10 m, 15 m, and 20 m) were directly proportional to the differences among the spacings until the time of crown intersections (i.e. increasing the spacing decreased the canopy coverage) (See Fig 12). Crown intersection began at 5 years at 5-m spacing, 31 years at 10-m spacing, and 57 years at 15-m spacing. There was no crown intersection at year 60 at 20-m spacing (See Figs. 12 & 10, Table 7). At year 60 into the simulation, crown coverage was 78% for 5-m spacing, 72% for 10-m spacing, 62% for 15-m spacing, and 47% for 20-m spacing (Table 8). The time to reach 50% canopy cover was 32 years at 5-m spacing, 39 years at 10-m spacing, 50 years at 15-m spacing, and over 60 years at 20-m spacing (i.e. actual year unknown as the simulation ended at year 60 year) (See Table 9).

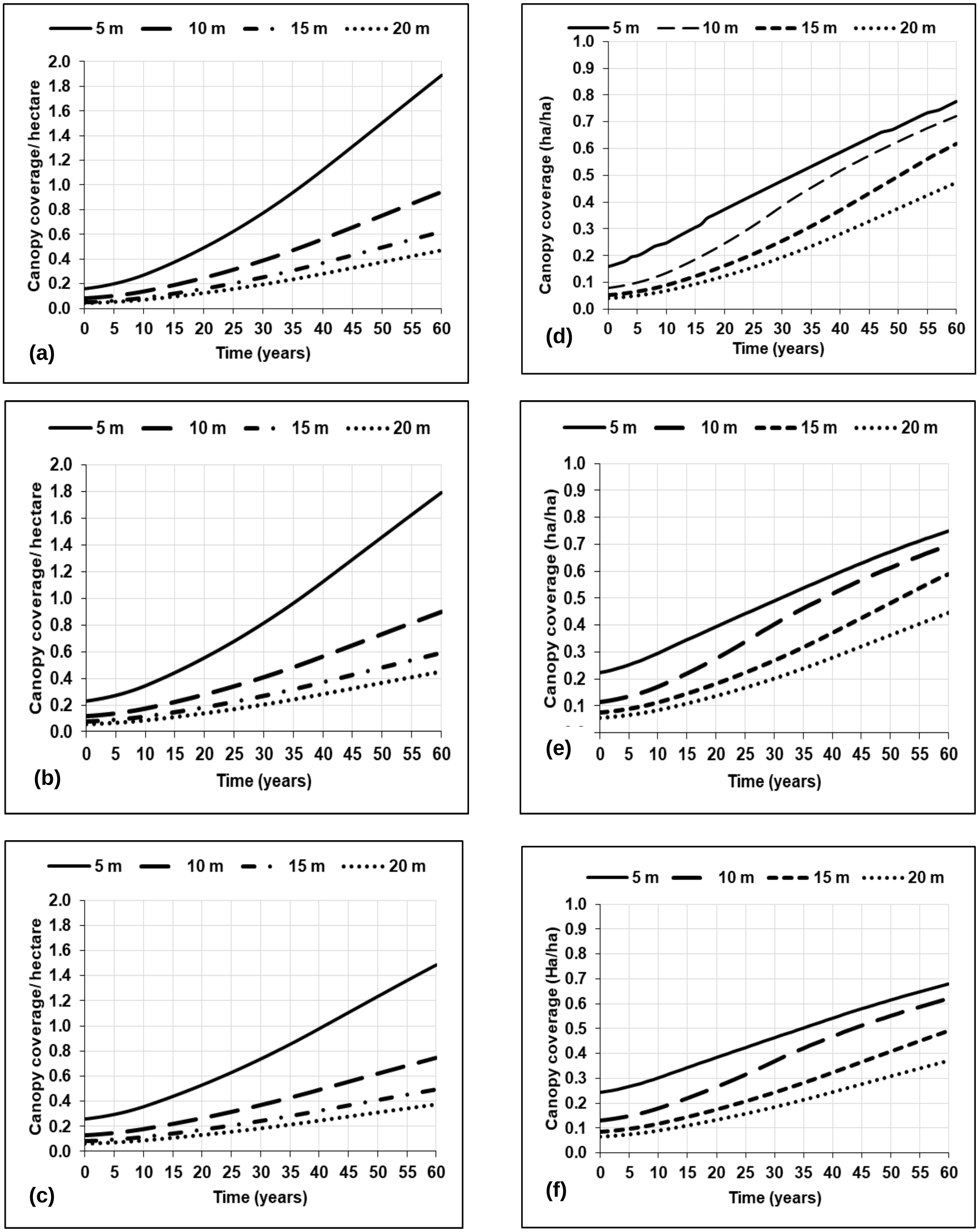


Fig. 12. Using VGM, canopy coverage in one hectare after simulating trees at spacings 5-20 m over 60 years including and excluding overlaps for (a) & (d) American elm, (b) & (e) Norway maple, (c) & (f) Little-leaf linden.

Table 7. Timing of the onset of crown intersection of American elm, Norway maple, and Little-leaf linden using VGM and FGM over 60 years. Blank cells indicate no crown intersection.

Spacings (m)	American elm		Norway maple		Little-leaf linden	
	VGM	FGM	VGM	FGM	VGM	FGM
5	**5**	**4**	**0**	**0**	**0**	**0**
6	11	11	6	5	4	3
7	16	18	13	13	12	13
8	21	25	18	21	19	22
9	26	32	24	29	26	32
10	**31**	**39**	**29**	**37**	**33**	**42**
11	36	46	35	45	39	51
12	40	53	41	53	46	
13	46	60	47		54	
14	51		53			
15	**57**		**60**			
16						
17						
18						
19						
20						

Table 8. Proportion of canopy cover at 60 years into the simulation using VGM and FGM in two scenarios: excluding overlaps and including overlaps

Spacings (m)	Excluding overlaps						Including overlaps					
	American elm		Norway maple		Little-leaf linden		American elm		Norway maple		Little-leaf linden	
	VGM	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**
5	**78**	**64**	**75**	**63**	**68**	**58**	**189**	**133**	**179**	**130**	**149**	**112**
6	76	63	74	62	67	57	157	110	149	108	123	93
7	75	62	73	61	66	56	134	94	127	93	105	79
8	75	61	73	61	66	55	119	84	113	82	94	70
9	74	60	72	59	64	54	106	74	100	73	83	63
10	**72**	**58**	**70**	**57**	**62**	**51**	**95**	**66**	**90**	**65**	**74**	**56**
11	70	55	68	55	60	49	85	60	81	59	67	50
12	70	54	67	54	59	47	79	56	75	55	62	47
13	66	50	64	50	55	42	72	50	68	50	56	42
14	65	48	63	47	53	40	68	48	64	47	53	40
15	**62**	**44**	**59**	**43**	**49**	**37**	**62**	**44**	**59**	**43**	**49**	**37**
16	59	41	55	40	46	35	59	41	55	40	46	35
17	55	39	52	38	43	32	55	39	52	38	43	32
18	53	37	50	37	42	31	53	37	50	37	42	31
19	49	35	47	34	39	29	49	35	47	34	39	29
20	**47**	**33**	**45**	**33**	**37**	**28**	**47**	**33**	**45**	**33**	**37**	**28**

Table 9. Time to reach 50% canopy cover for American elm, Norway maple and little-leaf linden using VGM and FGM in two scenarios: excluding overlaps and including overlaps. Blank cells indicate failure to reach 50% canopy cover within 60 years.

Spacings (m)	Excluding overlaps						Including overlaps					
	American elm		Norway maple		Little-leaf linden		American elm		Norway maple		Little-leaf linden	
	VGM	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**	**VGM**	**FGM**
5	32	41	31	40	35	45	21	25	18	21	19	22
6	33	43	32	41	36	47	25	30	22	27	24	29
7	35	45	34	43	38	49	28	35	26	33	29	36
8	36	46	35	45	39	51	31	39	30	37	33	42
9	37	48	36	47	41	53	34	44	33	42	37	48
10	39	50	38	50	43	57	37	48	36	47	41	54
11	41	54	41	54	47		40	52	40	52	45	60
12	42	56	42	56	49		42	55	42	55	48	
13	45	60	46	60	53		45	60	46	60	53	
14	47		48		56		47		48		56	
15	50		52				51		52		60	
16	53		55				53		55			
17	56		58				56		58			
18	57		60				58		60			
19												
20												

5.3.4 Simulation of Norway maple using VGM and no overlap

Crown intersection for Norway maple started much earlier than American elm (i.e. soon after initiating the simulation or year zero) at 5-m spacing (See Fig. 12, Table 7). The overlapping of crowns at year zero is unrealistic because caliper trees that are sold in markets have trimmed crowns. However, calculating crown diameter using regression of Norway maple results in over 5-m crown diameter. At 10-m spacing, crown intersection began two years earlier than American elm, however, at 15-m spacing, crown overlap occurred three years later compared to American elm. Similar to American elm, there was no crown intersection at year sixty at 20-m spacing. Sixty years after initiating the simulations, the canopy coverage was slightly lower than American elm in all spacings (Table 8). The time to reach 50% canopy cover was a year earlier at 5-m and 10-m spacings, however two years slower at 15-m spacing, and was not reached at 20 m spacing (Table 9).

4.3.5 Simulation of Little-leaf linden using VGM and no overlap

Similar to Norway maple, crown intersection for little-leaf linden began soon after initiating the simulation (i.e. year zero) at 5 m spacing. However, at 10-m spacing, crown intersection was two years slower than American elm, four years slower compared to Norway maple and no crown overlap observed within sixty years at 15-m, and 20-m spacings (Fig. 12, Table 7). The crown coverage sixty years after initiating the simulations was slightly less than Norway maple but much less compared to American elm. For example, the canopy cover of American elm at 10-m spacing was much greater than the canopy coverage of little-leaf linden at 5-m spacing and at 15-m spacing of American elm was equal to 10-m spacing of little-leaf linden (Table 8). Like-wise, the time to reach 50% canopy cover at 5-m spacing was slightly longer compared to both American elm and Norway maple, however much longer at 10-m, 15-m and 20-m spacings (Table 9). In fact, the canopy cover did not reach 50% within sixty years at 15-m and 20-m spacings.

Increasing the spacings (i.e., from 5 m to 20 m) showed a sharp decline in canopy coverage in the earlier years of tree growth followed by a gradual decline as trees matured. At fifteen years, when moving from 5 m to 10 m, the canopy coverage was reduced by 39%, from 5 m to 15 m, by 62% and from 5 m to 20 m, by 71% (Table 10). Thirty years after initiating the simulations, there was a decrease in canopy coverage, but not as much as that in fifteen years (i.e., 19% at 10 m, 46% at 15 m and 60% at 20 m spacing). Forty-five years after initiating the simulations, the rate of decrease in canopy coverage was lower compared to 30 years, and at 60 years lower than 45 years. This showed that trees in closer spacings can attain greater canopy coverage per unit area much sooner compared to trees far apart.

Table 10. Maximum canopy coverage (including the overlaps) and minimum canopy coverage (excluding the overlaps) over sixty years (after 15, 30, 45 and 60 years initiating the simulations) at spacings 5 m, 10 m, 15 m and 20 m using variable growth model.

Years after initiating the simulation	Spacing (m)	Maximum Canopy coverage of different species			Years after initiating the simulation	Spacing (m)	Minimum Canopy coverage of different species		
		American Elm	Norway Maple	Little-leaf Linden			American Elm	Norway Maple	Little-leaf Linden
15	5	0.37	0.44	0.44	15	5	0.31	0.35	0.34
	10	0.19	0.22	0.22		10	0.19	0.22	0.22
	15	0.12	0.15	0.14		15	0.12	0.15	0.14
	20	0.09	0.11	0.11		20	0.9	0.11	0.11
30	5	0.77	0.81	0.74	30	5	0.48	0.49	0.46
	10	0.39	0.41	0.37		10	0.39	0.40	0.37
	15	0.26	0.27	0.24		15	0.26	0.25	0.24
	20	0.19	0.20	0.18		20	0.19	0.20	0.18
45	5	1.31	1.29	1.11	45	5	0.64	0.63	0.58
	10	0.66	0.65	0.55		10	0.57	0.57	0.51
	15	0.43	0.43	0.37		15	0.43	0.43	0.37
	20	0.33	0.32	0.28		20	0.33	0.32	0.28
60	5	1.89	1.79	1.49	60	5	0.78	0.75	0.68
	10	0.95	0.90	0.74		10	0.72	0.70	0.62
	15	0.62	0.59	0.49		15	0.62	0.59	0.49
	20	0.47	0.45	0.37		20	0.47	0.45	0.37

4.3.6 Simulation of American elm, Norway maple and Little-leaf linden using FGM and no overlap

Using FGM, American elm had crown intersection only at 5-m, and 10-m spacings within 60 years of simulation. Crown coverage was the highest at 5-m spacing; however, it was much less compared to VGM for all spacings (See Fig. 13, Table 8). Only 5-m and 10-m spacings were able to reach 50% canopy cover within sixty years of simulations taking a longer time than VGM for all spacings (Table 9). Similar to American elm, Norway maple had crown overlap and reached 50% canopy cover only at 5-m and 10-m spacings. There was crown coverage reduction of 16-27% in all spacings when compared to VGM (Table 9). Little-leaf linden had crown overlap and reached 50% canopy cover only at 5-m, and 10-m spacings which was similar to American elm and Norway maple. The time to deliver 50% canopy cover by little-leaf linden took longer time (over five years) compared to American elm and Norway maple, however, much longer time (over 10 years) compared to VGM. The crown coverage of little-leaf linden was the least (i.e. less than 60% for all spacings after sixty years of simulation) compared to other two species as well as VGM.

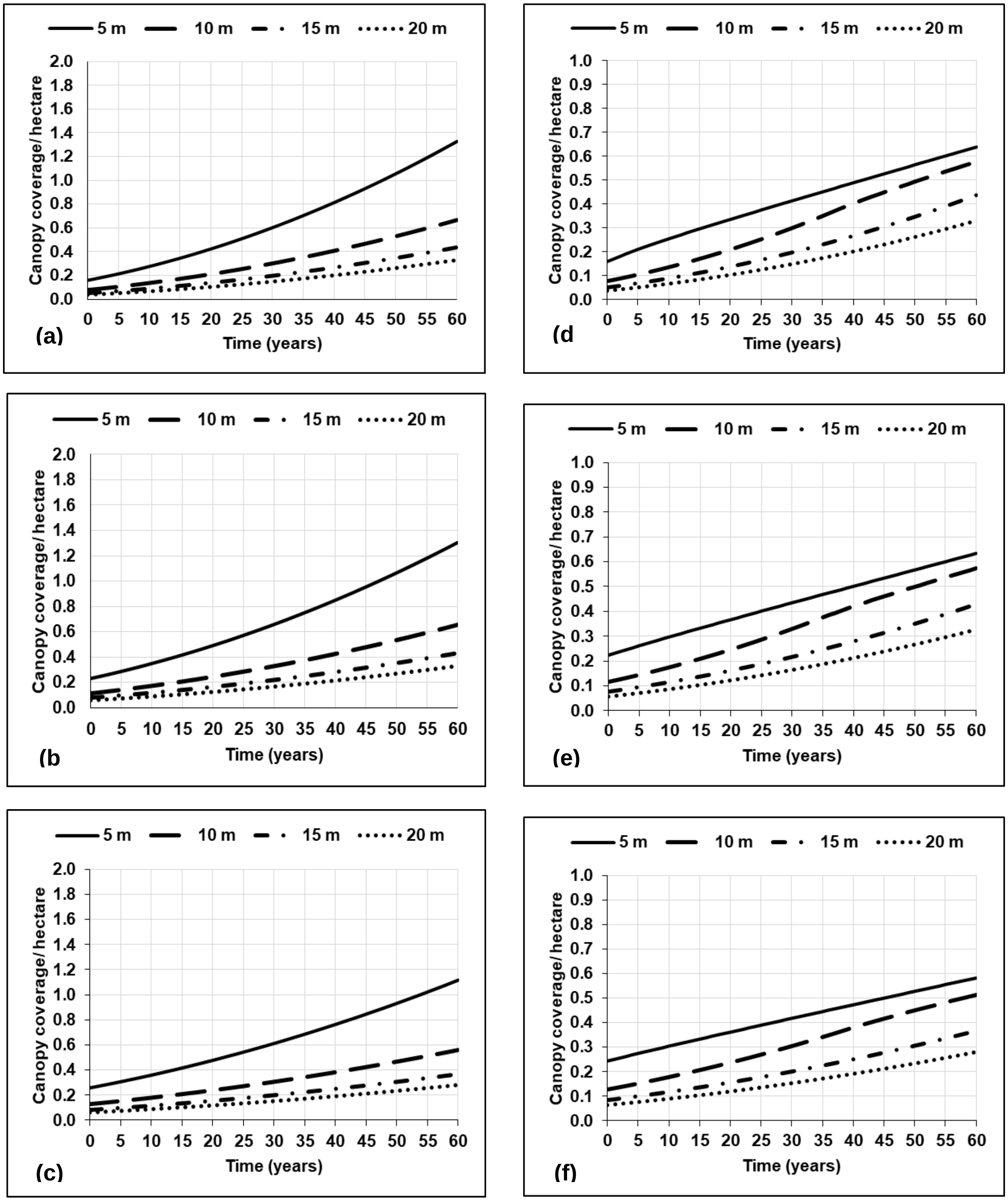


Fig. 13. Using FGM, canopy coverage in one hectare after simulating trees at spacings 5-20 m over 60 years including and excluding overlaps for (a) & (d) American elm, (b) and (e) Norway maple, (c) and (f) Little-leaf linden.

4.3.7 Simulation of American elm, Norway maple and Little-leaf linden using VGM for the overlapped canopies

Simulating three species using VGM, crown intersection began at the same time as that of the non- overlap scenario. However, at year 60 into the simulation, crown coverage of all three species at 5-m spacing was the highest compared to 10 m, 15 m, and 20 m spacings (i.e. American elm was 189%, Norway maple 179%, and little-leaf linden 149%) (See Figure 12, Table 8). The time to reach 50% canopy cover was much less (10-15 years) in all three species at 5-m spacing compared to non-overlap scenario. However, at 10-m and 15-m spacings, all three-species reached 50% canopy 1-2 years earlier compared to non-overlap scenario, but at 20-m spacing, all three-species failed to reach 50% crown coverage.

4.3.8 Simulation of American elm, Norway maple and little-leaf linden using FGM for the overlapped canopies

Similar to VGM, simulating three species using FGM, crown intersection began at the same time as that of the non-overlap scenario. At year 60 into the simulation, crown coverage of all three species was the highest at 5-m spacing (American elm was 133%, Norway maple 130%, and little-leaf linden 112%), however, less than VGM (See Fig. 13, Table 8). The time to reach 50% crown cover for all three species was less compared to both VGM and FGM non-overlap scenario; however, it was more when compared to VGM overlap scenario (Table 9). For all three species, 50% crown coverage was only reached at 5-m and 10-m spacings, failing to reach at 15-m and 20-m spacings.

4.4 Discussion and Conclusion

All three-species demonstrated DBH/ Crown diameter relationships of over 60% ($R^2 > 0.606$). The regressions show that American elm crowns expand the greatest for a given increment in DBH, Norway maple second, and little-leaf linden third. Thus, for example, at 60 years of age, an American elm tree is estimated to have a crown diameter of 16 m, Norway maple of 15 m, and little-leaf linden 14 m (See Table 4). In my experience, at maturity elms have a broad umbrella-shaped crown, Norway maples a rather round crown, and little-leaf lindens a crown close to a vertical ellipse.

The increase of crown cover over time varies with different spacings and is perfectly linear until crowns intersect. In the areas of crown intersection (i.e. single, double or even triple overlaps), I have used ArcMap’s geometry function to remove the crown overlaps, assuming no higher density of foliage in the areas of overlap. The canopy cover is likely to lie between the two extremes (i.e. minimum scenario without the crown overlap, and the maximum with the overlap), and surely not outside them.

Using two growth models, differences in the growth rate are seen, bringing a change in crown diameter. Using VGM, sixty years after initiating the simulations, the crown diameter of the three species is higher compared to the crown diameter obtained using FGM (i.e., using VGM, crown diameters are 16 m, 15 m, and 14 m for American elm, Norway maple, and little-leaf linden respectively; using FGM, crown diameters are 13 m, 13 m, and 12 m for American elm, Norway maple and little-leaf linden respectively). Using FGM, there is higher canopy cover for the first five years and this is obvious because of its higher growth rate compared to VGM, nevertheless showing less canopy cover over sixty years. Using VGM justifies coming to conclusions about the spacing's effects on crown cover, because the growth of trees varies over their lifetimes, generally showing higher growth increment when young and lower as trees mature. VGM growth increment is supported by other studies (Griffin et al. 2017; Peper et al., 2014; Bowman et al., 2013) and is likely to give a reasonable estimate of crown cover over their lifetimes.

The temporal development of tree crowns is important because the urban population benefits more from a given street's trees the sooner they develop a high canopy cover. In this case, tighter spacing is the solution, but how close is too close? Based on the results of my study, the minimum spacing of 5-m and the maximum of 10-m are most appropriate. Furthermore, in Halifax, I have observed several instances of trees planted along streets and property boundaries at a spacing of about 5-6 m. At maturity, there is no mortality in these rows of trees. They are each as large in trunk diameter as more widely spaced trees, and their canopies (and surely their root systems) are highly intermingled. Therefore, the reasonable conclusion is to plant all species of street trees at an average of between 5 and 10 metres apart.

Assuming American elm, using VGM and full overlap accounting, my results suggest that one can expect 50% crown cover on a hectare of street ecosystem in 21 years using 5-m spacing, installing 100 trees, and having spent $40K at the time of establishment, 37 years using 10-m spacing installing 50 trees, and having spent $20K, 51 years using 15-m spacing, installing 33 trees, and having spent $13.2K and over 60 years using 20-m spacing, installing 25 trees, and having spent $10K (Fig. 14, Tables 5 and 9).

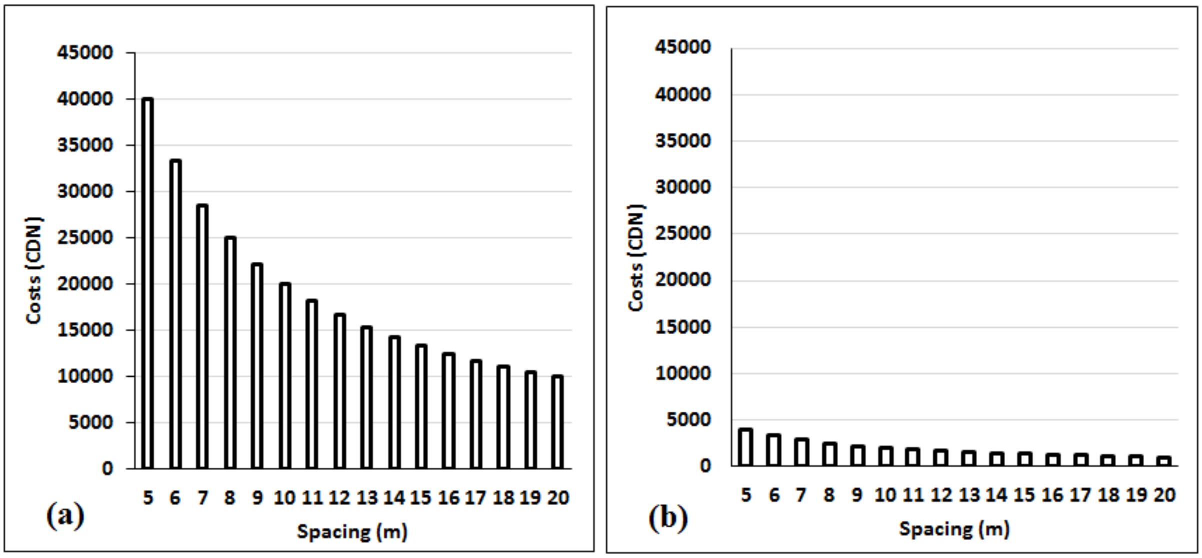


Fig. 14 Total costs for planting a 500-m stretch of street at each spacing (5-20 m) of 60-mm (DBH) trees installed (a), and 20-mm trees installed (b).

Urban stresses and their impacts on street trees can bring a decline in street-tree population. However, studies show street tree mortality as low as 4% (Nowak et al., 2004) and as high as 19% (Nowak et al., 1990). Considering previous studies, a reasonable assumption of mortality might be 10%, which means that the 50% canopy coverage would take commensurately longer to establish. If I use 20-mm potted tree stock instead of 60-mm balled-and-burlapped stock, at $40 each installed, the commensurate costs become $4K at 5-m spacing, $2K at 10-m spacing, $1.3K at 15-m spacing, and $1K at 20-m spacing (See Fig. 14 and Table 5). Let us suppose a 5-yr lag before the 20-mm stock catches up to the size of 60-mm stock (a generous gesture toward the 60-mm stock, as Duinker has his professional-judgement evidence that small stock catches up with larger stock within a few decades because of superior root development). Then the time to delivery of 50% canopy cover over the above spacings of American elm with no crown overlap would be 37, 44, 55, and over 60 years (See Fig. 14, Tables 5 and 9). The costs of installation would be $4K, $2K, $1.3K, and $1K, respectively, a tenth of the cost of the 60-mm stock. One might assume a higher mortality rate due to things like vandalism, accident, etc., but I am unaware of any data to substantiate such an assumption.

Thus, the cost of planting a 500-m stretch of street with 60-mm DRC stock of American elm at 5-m spacing would be $40K, which would deliver 50% canopy coverage with no crown overlap in 32 years (See Table 9 and Fig. 14). At 15-m spacing, a commonly recommended spacing for street trees gaining large stature at maturity, the cost would be $13.2K, yielding 50% canopy coverage in 51 years. However, at 5-m spacing with 20-mm potted stock, the cost of planting at 5-m spacing is $4K, generating 50% canopy coverage in 36 years (See Fig. 14, Tables 5 and 9). I believe there are strong arguments for changing both the spacing and planting-stock specifications for urban street-tree plantings. For small planting stock, higher rates of mortality may occur, but I am unaware of any studies that have definitively demonstrated this.

Street trees planted far apart have large gaps between them. In such conditions, the amount of tree foliage produced per unit land area at the earlier stages of tree growth is relatively low. There is finite capacity to support tree foliage on any site growing trees, and that capacity can be equally fulfilled (within limits and given sufficient time) by many small trees or a few large trees. This means that the closer the trees are planted, the earlier a site will reach its maximum canopy cover, and the earlier the site will provide the maximum amount of ecosystem services (Xiao et al. 2000; McPherson et al, 2016).

Therefore, street-tree spacing is clearly a critical factor in determining the timing of delivery of ecosystem services that depend on the quantity of tree foliage.

Although closer spacing can provide much greater tree foliage in a short period of time and thus providing greater ecosystem services, I identify four potential issues that may arise as a result of close spacing: (a) plantable spots, (b) mortality due to biological competition and urban stresses, (c) soil volume, and (d) higher costs. As for plantable spots, the question arises as to whether they actually exist with so much infrastructure in the tree-lawn ecosystem. My observations in the streets of Halifax, however, show plenty of plantable spots where trees can be installed.

The next issue is tree mortality due to increased biological competition and urban stresses. Biological competition is observed in forest ecosystems where trees are planted as close as 1-3 m (Spurr and Barnes, 1980; Smith, 1986). For example, over 45 years of growth of mixed hardwood and middle-aged trees growing in St. Mary's River Island between Ontario and Michigan, the stand showed some tree mortality resulting from competition. Initially, 1,354 trees per hectare (2.7 m apart) were planted. There was some tree mortality due to biological competition with a gradual decline of some trees. After 45 years, the remaining tree count was observed to be 655 (i.e. 3.9 m apart) trees per hectare (Spurr and Barnes, 1980). In the street-tree spacing, I have considered a minimum of 5 m spacing, considerably more than the forest silviculture spacing mentioned above (i.e. 2.7-3.9 m). I think it is less likely that street trees planted as closely as 5 m will face an issue related to biological competition and eventually death of a tree. Besides, in most street settings, the trees seldom interact with any trees perpendicular to the single line of street trees. Any competition with other trees happens only with other trees in the row.

Apart from biological competition, tree mortality could also result from urban stresses. Some abiotic urban stresses include freezing, de-icing salts, water shortages, insufficient light, soil conditions, wind, temperature, and street architecture (Callaway et al., 2002; Saebo et al., 2005). Other urban stresses include drought, lower tree vigour, reduced leaf area (Kane et al., 2014; Greenwood et al., 2017), and topographic factors such as aspect, elevation and slope (Van Gunst et al., 2016). One could argue that because street trees face so much stress from all these factors, we should not add to that stress by planting them close together. However, in rural forest ecology, trees in crowded stands may, themselves, ameliorate some of these stresses, such as wind, and soil instability by obstructing and regulating temperature thereby facilitating tree growth (Callaway et al., 2002). This scenario may not apply to street trees because trees in streets are planted linearly which is different to what we see in a rural forest. However, by planting trees close together, there are some chances of reduced wind speed and temperature impacts from two sides through greater tree foliage.

Trees in tighter spacing communicate through roots, resource transfer being likely to occur through mycorrhizae (Simard, 1997; Pickles et al., 2017). Furthermore, increasing tree density may increase the bacterial community, thereby increasing ecosystem productivity (Ryan et al., 2008; Mengoni et al., 2010; Laforest-Lapointe et al., 2017). Therefore, facilitation and communication among trees from similar or different species can show complementarity in the utilisation of space and resources, probably making planting of different tree species beneficial at tighter spacing (Simard et al., 1997; Simard et al., 2003; Simard et al., 2012).

Despite urban stresses, studies show higher rates of tree mortality due to pest and diseases (Millar et al., 2012; Sproull et al., 2015; VanGunst et al., 2016). For example, in some North American cities, DED destroyed many street trees (Gibbs, 1978). Additionally, other cities in North America lost much of their urban canopy through pathogens such as Emerald ash borer and Asian long-horned beetle (Herms and McCullough, 2014). Therefore, when trees are planted close together, higher rates of tree mortality are likely to occur from pests and diseases rather than urban stresses or biological competition.

The third issue in closely planted trees could be limited by soil volume, limiting nutrients available to trees. Uptake of nutrients depends not on stand density, but on soil type and characteristics, for example, soil texture, compaction or bulk density, and water holding capacity (Spurr and Barnes, 1980; Smith, 1986; Milllward, Poudel and Briggs, 2011). Generally, soil in streets tends to be compacted (Kristoffersen, 1999), limiting root growth. Bulk density higher than 1.6 g/cm^3 is said to limit root growth (Mullins, 1991). When trees are planted close together, higher root density is likely to make soil less compacted (Millward, Poudel and Briggs, 2011). This means more trees, more roots, and more pores in the soil which provide extra rooting space, thus intercepting and absorbing greater rainfall thereby reducing stormwater damage (Bartens et al., 2008). A deeper rooting system minimizes damage, such as uplifting of pavements with reduction in repair costs (Smiley et al., 2006; Buhler, Kristoffersen and Larson, 2007).

Regarding soil volume and uptake of nutrients for trees in cities, James Urban (2012) recommends 28 m^3 for trees of over 40 cm DBH. If the volume of the pit is considered to be fully cubic (i.e. length, width and depth, all to be equal), then one tree would stretch its roots as far as 3 m. It would be unrealistic to go 3 m deep; however, street trees being planted in a row, the perpendicular expansion of roots is not limited. Therefore, trees with greater root density, possibly less compacted soil with additional rooting spacing and having minimum of 5 m tree spacing, soil volume and uptake of nutrients should not be a problem in closely planted trees.

Another issue of closely planted trees could be the higher costs of installation and maintenance. Planting trees close together is expensive in the initial phase, but the earlier benefits obtained from tighter spacings are much greater compared to those obtained from trees planted at wider spacings. This is because the full canopy in narrower spacing is achieved much sooner than in wider spacings resulting in greater tree foliage (Herbert et al., 2016). Although the benefits are often indirect or intangible and longer term whereas the costs are direct and come from municipal budgets, I believe the aesthetic value and the social benefits we receive from street trees are likely to be much higher than the extra expenditures.

Additionally, high costs can be minimized by planting smaller trees instead of planting larger stock (i.e., 60 mm DRC). However, survival of small trees also needs to be considered. According to the conventional wisdom of arborists, higher rates of mortality may occur but would not be a problem because of the sheer number of trees planted. If small trees are considered for planting, installation costs per tree can be reduced by up to tenfold (J.Simmons, personal communication, February, 2017). Therefore, the benefits obtained from planting street trees close together may well outweigh the overall costs, thus providing greater benefits compared to trees planted far apart.

The population of street trees is influenced by municipal budgets and urban development. Increasing the distance between trees is likely to save municipal expenditure. However, the delivery of many ecosystem services from closely planted trees would be lost. Therefore, my recommendation is to plant all species of street trees at an average of between 5 and 10 m apart. Rather than specify the distance between trees, I prefer a specification for the number of trees per 100 m of street length (e.g., 13 trees/100 m) with no trees spaced further than 12 m apart and none closer than 6 m. This gives the street designer flexibility to consider better how to position built infrastructure – e.g., driveways, power poles, fire hydrants – into the tree lawn. The key is to make a tree lawn wide enough (at least 1.5 m for cities where frequent snow removal from streets is required), and to concentrate infrastructure (e.g., wires, pipes, and driveways) to give trees room to grow, both aboveground and underground.

If street trees are established with closer spacing than is customary, costs will concomitantly rise per unit street length as long as stock sizes remain constant. However, when smaller planting stock such as 20-mm is considered, acquisition and installation costs would be much lower per unit length, allowing densification of new street trees with financial savings. Thus, resultant savings could be used for maintenance and to defray the heavier expense of planting large trees where these are considered necessary. Therefore, finding an affordable way to plant trees closer together in our urban streets is a long-term solution for a sustainable urban forest.

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CHAPTER 5 CONCLUSIONS

5.1 Synthesis and Management Implications

The overall objective of the study was to explore and evaluate the optimal spacing of street trees in Halifax. Specifically, the aims of the study were to characterise street-tree sizes and spacings using empirical data and to simulate tree growth over 60 years at spacings of 5-20 m. From the empirical data, three regression equations were derived the relationship between crown diameter and DBH for the three-dominant species (i.e., American elm, Norway maple, and Little-leaf linden) observed in Halifax. Using a simple tree growth model (based on the collective professional judgement of the research team) and the three regression equations, I simulated tree growth over 60 years at spacings of 5-20 m.

5.1.1 Empirical Findings

The empirical data show that the overall average spacing of street trees in Halifax is 15.4 m with SD of 10.5 m (14.3 m in Halifax Peninsula, and 24.2 m in Central Dartmouth). Looking at the spacing guidelines for North American cities, street trees tend towards wide planting. When the actual street-tree spacing in Halifax was compared with that of North American specification guidelines, the actual tree spacing in Halifax was found to be wide and highly variable. I considered six potential causes of this variability and they are:

- Trees in privately owned properties adjacent to streets.

Some neighbourhoods in Halifax Peninsula and all neighbourhoods in Central Dartmouth have rows of privately owned trees in residential properties adjacent to streets. In such areas, there are no trees adjacent to streets thereby resulting in wider spacing.

- The presence of many old and large, stressed, and dead Norway maples.

Many of the Norway maples observed in Halifax during my data collection had dieback and dead limbs. Studies show that Norway maple are susceptible to early decline due to age and girdling roots (Manion, 1981; Nowak and Rowntree, 1990). Also, some dead and felled trees were observed leaving large gaps, thus increasing the average spacing of street trees.

- Construction and re-construction of sidewalks in Central Dartmouth resulting in weak root systems.

In some areas of Central Dartmouth, many sidewalks were constructed much later than the initial creation of the neighbourhood. During construction, roots on two sides of trees (parallel to streets) were likely cut resulting in weak root systems, causing death of some trees (Trowbridge and Bassuk, 2004), thereby creating voids in streets.

- Implementation of the urban forest master plan (UFMP)

Under the UFMP implementation strategy (i.e. implementation of the master plan started in 2013), five priority areas were selected for immediate tree planting due to fewer street trees (Halifax Urban Forest Planning Team, 2013). Only three neighbourhoods of this study in Halifax Peninsula come under UFMP implementation strategy. The spacing of trees would have been even higher in these neighbourhoods if there had been no tree planting.

- Lack of municipal financial resources and the planting of large caliper trees (i.e. 60 mm root-collar diameter).

The city has been planting large caliper trees in the streets of Halifax instead of small size trees to lower the risk of damage through vandalism. Municipal budgets are limited and planting such large trees is costly, over $400 (CAD) (Halifax Urban Forest Planning Team, 2013). This could have resulted in fewer trees in streets thus leading to higher tree spacing.

- A unique historical design of neighbourhood 7 in Halifax Peninsula.

Neighbourhood 7 in Halifax Peninsula has a historical design favouring large boulevards with wide medians and back service lanes (Soward et al., 2008). Throughout the neighbourhood, trees are planted in medians, and these trees were not considered street trees which could have increased the average spacing of this neighbourhood compared to other neighbourhoods in Halifax Peninsula.

5.1.2 Simulation findings

The simulation results, as expected, showed increasing canopy coverage per unit land area when spacing between trees decreased and decreasing canopy coverage when the spacing increased. Sixty years after initiating the simulations, the highest canopy coverage was found at 5 m spacings and the lowest at 20 m spacings. Species-wise, both the highest and the lowest were observed in American elm, the highest coverage being in the range of 0.78-1.89 ha/ha at 5 m spacings and the lowest ranging from 0.37-0.47 ha/ha at 20 m spacings. Street trees planted 5 m apart delivered 50% canopy coverage in 18-33 years, whereas the same species planted 10 m apart delivered only in 36-57 years, 15 m apart over 50 years, and 20 m apart did not reach 50% canopy coverage within 60 years (See Table 9). The simulation results showed closely spaced trees (5-10 m) delivering a specified level of canopy coverage within a mere fraction of the time it takes to reach the same level of canopy coverage from street trees planted far apart (i.e. the amount of tree foliage produced at the earlier stages of tree growth is greater in closely planted trees).

Planting trees closely incurs higher costs. However, there is a trade-off. Looking at the simulation results, the benefits obtained from tightly planted trees are much greater than the money invested compared to widely planted trees. For example, 50% canopy cover is reached in 18-33 years at 5-m spacing. However, at 20-m spacing, the same 50% is not achieved even after 60 years (See Table 9). It is a question of whether having this higher site capacity and more ecosystem services for that extra 27-42 years justify the higher cost of planting or not. Urban forest studies show many benefits from trees, which are given a dollar value. For example, McPherson et al. (2005) calculated benefits from street and park trees in five cities of the USA. Their findings show that the benefits obtained annually per tree are almost double the money spent (i.e. money invested annually for one tree was $13-65, whereas the benefits obtained was $31-$89 (McPherson et al., 2005). When the cost-benefits at 5 m spacings is compared to 20 m spacings, the benefits that could be obtained from the extra 42 years at 5 m spacings outweigh the costs incurred while planting trees at closer spacing. In fact, we will be losing a huge sum if we are planting trees far apart.

It therefore can be concluded that, the closer the trees are planted, the earlier a site will reach its maximum canopy cover, the greater the amount of ecosystem services. Hence, planting trees close together increases the canopy cover, thereby providing greater ecosystem services.

5.1.3 Implications of the findings

Ongoing urban development has resulted in limited spaces for trees (Trowbridge and Bassuk, 2004). Also, lack of privately owned space (Conway and Vander Vecht, 2015) and threats posed by large trees (Lopes et al., 2009) are likely to influence residents' preferences and attitudes towards trees small at maturity (Flannigan, 2005; Schroeder, Flannigan and Coles, 2006). Planting small trees with an arboricultural perspective having wide distances between them without much canopy is likely to be meaningless, although it might tend to satisfy city dwellers' preferences and attitudes. We know that a single large tree at maturity provides greater benefits than a small tree. In trying to achieve greater benefits from a single large tree, we lose many other benefits that could be obtained from planting trees far apart because trees that are large at maturity will take years to fully develop its maximum canopy cover, whereas canopy cover occurs much sooner with closely planted trees. Ecosystem services are directly related to the amount of tree foliage per unit land area, not per tree. In this view, the sooner the area above the street is filled with tree foliage, the better. The best way to achieve a full canopy soonest is to plant trees close together. Therefore, by planting trees close together, greater amount of tree foliage could be obtained much earlier hence maximising street-tree benefits.

5.2 Recommendations and Future Research

If street trees are established with closer spacing than is customary, costs of planting and maintenance will concomitantly rise per unit street length as long as stock sizes remain constant. However, when smaller planting stock such as 20 mm is considered, acquisition and installation costs would be much lower per unit length, allowing densification of new street trees with financial savings. Thus, resultant savings could be used for maintenance and to defray the heavier expense of planting large trees where these are considered necessary. Therefore, finding an affordable way to plant trees closer together in our urban streets is a long-term solution for sustainable urban forest.

Street-tree spacing in Halifax helped me to identify some future research areas. The first possible area could be investigating the influence of crown projection from crown interaction. My own observation of trees planted close together (i.e., as close as 5 m and over 50 years), suggests that there is not much change in the canopy coverage compared to trees planted far apart (i.e., as far as 20 m and over 50 years). However, observation alone is not enough to back up my claim and therefore, exploring and comparing crown behaviour in a row of closely planted trees versus widely planted trees could enhance knowledge of street-tree spacing.

Another area for research could be soil volume requirement for street-trees. Although James Urban (2012) has given the soil volume required for trees in urban setting (i.e. a tree with 40 cm DBH requires 28 m^3), the depth of the soil sufficient for roots as deep as 1 m is not clear. Investigating the depth of the roots in soil will help to find the soil volume required for street trees. Furthermore, evaluating soil volume through categorization of tree species by size would support street-tree spacing decisions.

Finally, exploring the spacing of trees based on their sizes is worth researching, because many cities are planting trees that are small at maturity, mainly ornamental trees. Since I here have presented optimal spacing of street trees based on the simulation of three-dominant species observed in Halifax, considering different sizes of trees can increase knowledge of tree canopy coverage in the city streetscape.

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