MREM FINAL REPORT

Managing Extreme Wind-Events in Halifax's Urban Forest

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Abstract

With an increase in the intensity and frequency of hurricanes expected for Halifax, the city has employed management strategies to adapt its urban forest to future climatic conditions. One such method is through species-selection. Maliheh Rostami (2011) produced a list of 27 tree species that would be suitable for urban planting in Halifax's urban forest under a changing climate. These 27 tree-species were analyzed for their wind-tolerance using a species-specific framework pertaining to wind-tolerance. As a result of the analysis, six tree-species were highly wind-tolerant, eight were moderately wind-tolerant, and 13 were of low wind-tolerance. These results were verified by comparing the wind-tolerance of the tree-species to a planting design manual as well as through expert consultation. Limitations and information gaps regarding the framework and results were discussed, providing opportunities for future research. Lastly, recommendations as to how to better adapt Halifax's urban forest to extreme wind events are offered.

1. Introduction

The earth has undergone an overall trend of warming as a result of human activities (IPCC, 2007). Observed and predicted consequences of an increased global temperature include sea-level rise, melting of snow and ice, and an increase in the frequency and intensity of extreme weather events, among others (IPCC, 2007). Climate is the main determinant of plant distribution globally (Box, 1981). With the onset of climate change, trees are expected to redistribute and migrate northward in latitude or upward in elevation, where the climate is becoming more favourable (Walther *et al.*, 2002).

Climate change has resulted in global changes not only ecologically, but socially and economically as well. Cities, in which half of the world's population currently resides, will be affected by extreme events such as droughts, floods, and storms (Hunt and Watkiss, 2011; IPCC, 2007). Adaptation to climate change, a process which anticipates future conditions and employs management actions that reduce the potential vulnerabilities of natural or human systems, is an important response by urban centres (Ordóñez and Duinker, 2014; Ordóñez *et al.*, 2010). Adaptation strategies in many North American cities have focused on the enhancement of the urban forest (Ordóñez and Duinker, 2014).

Urban trees provide cities with a multitude of social, ecological, and economic benefits. These include microclimate control, storm water management, air filtration, water and soil quality improvements, and carbon storage, among others (Carreiro *et al*., 2008). Additionally, a well-adapted urban forest can aid in mitigating the impacts of climate change by absorbing pollutants, providing shade, reducing energy usage, and cooling air temperatures (Litegi *et al.,* 2007).

Increases in the frequency and magnitude of extreme weather events as a result of climate change will impact the citizens, the infrastructure, and the urban forest of cities (Hunt and Watkiss, 2011). In Halifax, Nova Scotia, the frequency and intensity of hurricanes is predicted to increase (Acadia University, 2014). The structural failure of trees during severe wind-events can pose a significant hazard to human health and life (Schmidlin, 2009). The Urban Forest Master Plan (UFMP), a management document for Halifax's urban forest, has placed a high importance on climate change adaptation by naming it as Operational Principle 1 in the plan. Additionally, climate change adaptation has been placed at the forefront of the plan's research agenda (UFPT, 2013). Methods employed for increasing the urban forest's resiliency to future climatic changes have included tree-species selection, and careful selection of genetic material, including cultivars (UFPT, 2013).

The purpose of this report is to investigate Halifax's urban forest management with respect to extreme wind-events in the face of a changing climate. Other extreme weather events, including droughts and floods are considered outside the scope of this paper. Tree species-specific factors and external forces that contribute to a tree's ability to tolerate extreme wind-events will be investigated. The species-specific factors will be used to create a framework from which 27 tree-species will be evaluated for their wind-tolerance. The 27 tree-species were selected based on their suitability under Halifax's future climate, which was determined by Rostami (2011). Lists of tree-species of high, moderate, and low wind-tolerance will be presented and the verification of these results will be discussed. Two case studies that experience extreme wind-events, Vancouver, British Columbia, and Florida, United States will be examined for wind-management best practices. Lastly, management recommendations and opportunities for future research will be presented.

2. The current state of Halifax's urban forest

2.1 Urban forest management

The management of the Halifax Regional Municipality's urban forest is governed by the UFMP in conjunction with the city of Halifax (UFPT, 2013). The plan was developed by Dr. Peter Duinker and his UFMP Planning Team, consisting of graduate students attending the School for Resource and Environmental Studies (SRES) at Dalhousie University (Halifax Regional Municipality, 2014). The UFMP was adopted by the Halifax Regional Council in 2012, and implemented with the guidance of Halifax staff as well as Peter Duinker and his planning team (Halifax Regional Municipality, 2014).

The primary goal of the plan is to ensure a sustainable future for Halifax's urban forest (UFPT, 2013). Through extensive community engagement activities and research initiatives, the UFMP has integrated social, ecological, and economic criteria that reflect the values of Halifax's citizens (UFPT, 2013). The plan aims to establish indicators, targets, objectives, values and management strategies for the 111 urban forest neighbourhoods included in the UFMP study area (UFPT, 2013). Additionally, the UFMP will evaluate urban forest issues and their potential solutions; adopt changes proposed in the legal and financial realm of Halifax's urban forest; and raise public awareness regarding the importance of urban trees (UFPT, 2013).

2.2 The urban forest

Halifax's urban forest is a diverse combination of old and young trees; consisting of both native and non-native species (UFPT, 2013). There are approximately 709, 000 trees in Halifax's urban forest, which are located along city streets, in public parks, and in more rural, peri-urban neighbourhoods (UFPT, 2013).

The streets of Halifax are lined with old oaks, elms, lindens, maples, and copper beeches (UFPT, 2013). These trees were planted in the early 20th century, and many are reaching the end of their lifespan (UFPT, 2013). Mature, larger trees are generally structurally weaker than smaller, younger trees, and may have a higher propensity to fail during windstorms (Duryea and Kampf, 2007).

Urban trees face stressors that are different from those faced by trees in a rural environment (Nilsson *et al.*, 2008). For example: street trees may be aggressively pruned when in conflict with utility wires (Hauer *et al.*, 2006); they often grow in areas with limited space and compacted soils (Jim, 1998); and they receive high concentrations of de-icing salt (Saebo *et al.*, 2003), among others. Trees located in public parks and peri-urban areas are unique in that they do not face the same degree of urban challenges and, for this reason, have a relatively higher life span than street trees (Saebo *et al.*, 2003). Nonetheless, many park trees in Halifax are older and reaching the end of their life, potentially making them a higher risk for windthrow (UFPT, 2013).

As a way of mitigating potential danger and damage inflicted by mature street trees on the city's infrastructure and citizens, the UFMP has promoted the implementation of a seven-year pruning cycle for all street trees (UFPT, 2013). The current state of Halifax's tree pruning and maintenance is reactionary. With the implementation of a proactive, seven-year cycle, pruning would remain reactionary for the first several years, and then transition into proactive maintenance (UFPT, 2013). The projected annual cost of a seven-year pruning cycle is $600, 000 (UFPT, 2013).

Unfortunately, the rate at which trees are currently being pruned and the rate at which trees need to be pruned in order to achieve a seven-year cycle do not coincide (P. Duinker, personal communication, September 8, 2014). It would require a dramatic increase in labour, money, and trees pruned per year in order to begin a proactive maintenance cycle (P. Duinker, personal communication, September 8, 2014). As a result, alternative methods for increasing the urban forest's resilience to extreme wind-events must be investigated. One such method, species selection, will be discussed in further detail later in the paper.

2.3 Urban tree planting

Planting new street trees is a priority action for the city of Halifax (UFPT, 2013). Of the 709, 000 trees in Halifax's urban forest, 157, 000 have been planted and are managed by the municipality (UFPT, 2013). Despite these planting efforts, research conducted through the UFMP demonstrates that there are still an additional 94, 000 plantable spaces for trees on municipally-owned land (UFPT, 2013).

Planting new trees enhances the structure and function of the urban forest (Nowak *et al.,* 2008). The UFMP aims to increase the species diversity of the trees being planted in the city (UFPT, 2013). This will benefit the urban forest by evening out the forest's age distribution, as well as increasing the representation of native trees in Halifax's urban forest (UFPT, 2013). This is being accomplished by increasing the representation of Acadian old-growth species planted in the street to at least 1%, as well as by ensuring that at least half of the street trees planted are native (UFPT, 2013).

Additionally, the UFMP aims to increase the genetic diversity of the urban forest (UFPT, 2013). This will expand the gene pools of native species, and may aid urban forest climate adaptation and pest resistance (Ledig, 1992). This is being accomplished by increasing the number of cultivars planted for each species, proportional to the number of trees planted (UFPT, 2013).

Action number two of the UFMP action-set identifies planting street trees in HRM neighbourhoods as aligning with citizen's values as well as with three of the plan's operational principles; comprehensive approach, time and timing, and climate change (UFPT, 2013). Climate change, operational principle number one of the UFMP, states that resiliency should be built-into the urban forest model to ensure its long-term sustainability (UFPT, 2013).

Aligning with this principle, Rostami (2011) created a list of appropriate species which are best suited for planting in Halifax's urban forest, given future changes in temperature and precipitation for the area. This list, as well as an evaluation framework created by Rostami and Duinker (2011), has been incorporated into the UFMP as a strategy for managing urban forest adaptation given impending climate change (Rostami and Duinker, 2011; UFPT, 2013).

The tree-species recommended by Rostami (2011) have attributes which make them ideal for Halifax's changing climate. All trees on the list have future climatic ranges in Halifax (Rostami, 2011). Additionally, they are well suited to the stresses of the urban environment and require minimal care and maintenance (Rostami, 2011). These tree-species were incorporated into planting recommendations for the 111 UFMP neighbourhoods (UFPT, 2013). Other treatment criteria for these neighbourhoods include: the recommended number of native trees to be planted; the average number of Acadian old-growth species to be planted per decade; and genera of trees that should not be planted before the year 2020 (UFPT, 2013). This last criterion is recommended as a way of increasing species representation in the urban forest as well as a method for reducing genus-specific pests and diseases (UFPT, 2013).

2.4 Climate change

Extreme weather events are predicted to increase in Nova Scotia (Johnston, 2009). With regard to wind, warmer sea temperatures due to climate change are predicted to cause cyclonic activity to shift northward, resulting in more frequent and intense hurricanes (Acadia University, 2014). As a result, there is a necessity to better understand these changes and take appropriate urban forest management measures to adapt to them.

3. Case studies: what's being done elsewhere?

3.1 Vancouver

The use of Vancouver, British Columbia as a case study was chosen primarily due to its personal connection to the author. However, though Halifax and Vancouver differ in such factors as geographic location and latitude, among others, the two cities share similarities as well.

Halifax, located on the Atlantic Ocean, and Vancouver, located on the Pacific Ocean; both enjoy a less severe climate owing to continentality (Living in Canada, 2014; Duckson, 1987). However, both cities experience periodic extreme wind-events (Scotia, 2005; Kheraj, 2007). As a result, the two cities experienced a severe windstorm early in the millennium which leveled a city park; Point Pleasant Park in Halifax suffered a 70% reduction in canopy in 2003 while Vancouver's Stanley Park lost over 41 ha of parkland in 2006 (Burley *et al.*, 2008; City of Vancouver, 2013). Consequently, the two cities created park management plans and began to closely manage the state of their urban forest (Point Pleasant Park Comprehensive Plan, 2008; Stanley Park Forest Management Plan, 2009).

The Stanley Park Forest Management Plan offers recommendations regarding windthrow management with an emphasis on safety, regeneration, and forest resilience (Stanley Park Forest Management Plan, 2009). Safety is a top priority in the park, which attracts over eight million visitors a year (Tourism Vancouver, 2014). Hazard trees are assessed and managed in the park (Stanley Park Forest Management Plan, 2009). Trees with a high height-to-stem diameter with tall and slender dimensions are removed, as they are generally more vulnerable to windthrow

(Stanley Park Forest Management Plan, 2009). Additionally, when planting replacement trees, the vegetation around the tree is cleared, allowing the establishment of a strong root-system (Stanley Park Forest Management Plan, 2009). Lastly, ditching, draining, or culvert expansion is considered in areas where impaired drainage restricts roots (Stanley Park Forest Management Plan, 2009).

Recommendations in the Stanley Park Forest Management Plan regarding regeneration and forest resilience focus primarily on forestry practices, including thinning and pruning (Stanley Park Forest Management Plan, 2009). First, canopy trees that are located adjacent to a new opening, such as a newly built trail, can be spirally pruned to improve their stability during wind-events (Stanley Park Forest Management Plan, 2009). The plan recommends planting trees in clusters of three to five, with at least two species per cluster (Stanley Park Forest Management Plan, 2009). Lastly, it is recommended that older, more mature stands be assessed and considered for thinning (Stanley Park Forest Management Plan, 2009).

Unlike Halifax, Vancouver currently has no strategic plan to manage their urban forest. However, on April 16, 2014, Council voted to approve the Urban Forest Strategy (City of Vancouver, 2014a). To date, the objectives and means to achieve them have been released to the public (City of Vancouver, 2014a). Objectives include: creating an urban forest inventory; updating management plans, policies, and practices to address climate change; addressing the urban forest lifecycle, from planting to removal; and increasing canopy cover (City of Vancouver, 2014a). Ways of achieving these objectives have been grouped into three categories: protection, planting, and management (City of Vancouver, 2014a).

More specifically, a principle outlined in the Urban Forest Strategy aims to ensure urban forest resiliency to disease and climate change, including rising temperatures and more severe storms (City of Vancouver, 2014b). This will be accomplished by creating an inventory of current urban forest species and making appropriate species-selection for the future (City of Vancouver, 2014b). Additionally, the Strategy currently estimates that approximately 50% of Vancouver's urban forest is comprised of two genera: *Prunus* and *Acer* (City of Vancouver, 2014b). Resiliency will be achieved by increasing the diversity of species that are planted in the city (City of Vancouver, 2014b).

The government of British Columbia released an urban forest climate adaptation guide to help communities in BC identify and prepare for impacts as a result of climate change (British Columbia, 2010). It is likely that Vancouver's Urban Forest Strategy will draw from some of the recommendations made in this guide, and apply those that prove relevant for Vancouver in their own Strategy (B. Wong, personal communication, September 18, 2014).

The guide provides several specific recommendations for communities aiming to increase the wind-firmness of their urban forest. With the aid of a professional arborist, branches from trees should be selectively pruned to make vulnerable trees more wind-firm (British Columbia, 2010). In the event that a tree is deemed hazardous and must be removed, the guide recommends topping the tree at three to five meters, providing habitat for wildlife (British Columbia, 2010). Lastly, it is recommended that heavily-damaged or sick trees be removed to reduce the chance of failure during a wind event (British Columbia, 2010).

The guide also gives broad recommendations regarding species-selection based on current and future tree stressors. For areas subjected to high winds, the guide recommends choosing wind-firm, drought-tolerant species, as wind desiccates plants (British Columbia, 2010). Species should be selected based on certain attributes, including: sound branch attachments, high wood strength, and a well-distributed root-system with lots of available soil and space (British Columbia, 2010). A healthy planting stock with well-developed roots should be chosen; avoiding root-bound container-grown stock (British Columbia, 2010). When possible, trees should be planted in groups, making them more wind-firm than isolated individuals (British Columbia, 2010). Newly planted trees should be staked low on the stem, which ensures the roots remain in place while allowing the upper tree to sway, creating wind resiliency (British Columbia, 2010). Young trees should be pruned so as to develop a structure that can withstand heavy winds (British Columbia, 2010). Lastly, planting trees on ridge-tops subject to winds should be avoided (British Columbia, 2010). Though no specific tree-species are offered due to the nature of the guide, links to where that information can be found is provided (British Columbia, 2010).

3.2 South Florida

The choice to use south Florida as a case study was twofold. First, much like Halifax, it is located along the east coast of North America, and receives hurricanes which reach wind speeds up to and often surpassing150 km h (Sheng *et al.*, 2006; Duryea *et al.*, 2007). Second, extensive research has been conducted in the area regarding urban forest management in the face of extreme wind-events.

Research conducted in south Florida by Duryea *et al.* (2007) began in 1992 when the area was struck by Hurricane Andrew. Measurements of hurricane-level wind damage to urban forests continued when hurricanes struck again in 1995 and 1998. In total, nine hurricanes with varying wind speeds were examined to assess over 80 tree-species and their response to hurricanes. The study reports on the types of tree damage that can occur under heavy winds, possible reasons for the damage, and ways to avert damage in the future (Duryea *et al.,* 2007).

It was found that while some damage is inevitable, other hurricane-induced damage can be avoided through management. Inevitable damage occurred as a result of high-intensity hurricanes with increased rainfall. This caused soils to become overly saturated and generally resulted in higher tree mortality due to uprooting. Additionally, the percent of trees killed in the urban forest was positively correlated with wind speed, with higher wind speeds killing a larger proportion of trees (Duryea *et al.,* 2007).

In some instances, urban forest management effectively reduced wind-induced tree mortality. Dense, unpruned crowns were less wind-resistant than well-distributed, pruned crowns. Lastly, trees growing in groups (defined as five or more trees growing within three metres of each other, not in a row) had 80% survival compared with 70% for those same species of trees growing individually (Duryea *et al.,* 2007).

The study also concluded that tree-species react differently under hurricane conditions. Certain species lost a higher percentage of their branches than other species, affecting their survival rates. Some species showed a greater propensity to break at the stem, rather than uproot. For example, pines were more likely to snap whereas broadleaf species often uprooted. Wood density was positively correlated to a trees ability to withstand strong winds, with a higher wood density (g/cm^3) displaying higher survival rates. Two other measurements of wood strength, the modulus of elasticity and the modulus of rupture were examined. Trees with a higher modulus of elasticity (> 7, 000 MPa) survived better than those with a lower value. Species displaying a higher modulus of rupture (≥ 70, 000 KPa) showed higher survival rates than those with a lower value. Decurrent trees, or those species with no apical dominance, had higher survival rates than excurrent species. Lastly, species that defoliated more readily during high winds showed higher survival rates (Duryea *et al.*, 2007).

The study produced a list of wind-firm tree-species suited to the area, as well as general recommendations for urban forest management. The study recommends that managers choose trees rated as 'high' or 'medium-high' on the wind resistance lists and match them to local site conditions. Trees should be given adequate rooting space, with no obstructions, such as sidewalks or buildings. Additionally, soil properties, including water-table depth and compaction should be taken into consideration when choosing which species to plant. Managers and arborists should consider planting trees in groups when possible, rather than individually. Trees should be given adequate overhead space, taking their crown size and form into consideration. Managers and arborists should evaluate tree health and remove trees that are deemed hazardous. Trees that are deemed to have low wind resistance, based on the authors' list, should be considered for removal. A regular structural pruning program should be established in the urban forest. Managers and arborists should be aware of any root damage inflicted on the tree, or lack of anchoring as a result of nearby construction (Duryea *et al.,* 2007).

As a way of comparing whether the information presented in the study is actually being utilized, the city of Tampa, Florida's Urban Forest Management Plan was reviewed (Northrop *et al.,* 2013). In the plan, the performance criteria for assessing the state of wind-firm tree-species in the urban forest use the Duryea *et al.* (2007) study (Northrop *et al.*, 2013). For example, the majority of Tampa's trees are rated as 'medium' or 'high' in the categories of wind-resistance based on the study's tree-species list (Northrop *et al.*, 2013). Optimally, over the next 20 years, Tampa aims to have over 80% of their urban forest trees rated in the highest category of wind resistance based on the lists produced by Duryea *et al.* (2007) (Northrop *et al.*, 2013). This will be implemented by gradually replacing less wind-resistant species with more windfirm species (Northrop *et al.,* 2013).

4. Factors affecting windfirmness

Wind disturbance plays an important role in the composition and structure of Nova Scotia's forests (Mosseler *et al.*, 2003). At a forest scale, wind damage can range from a single tree to an entire stand (Mosseler *et al.*, 2003). Urban trees experience different wind patterns than trees in uniform forest-stands as a result of factors such as infrastructure (Matheny and Clark, 2009). Wind will accelerate when coming in contact with an object, such as a building, and produce turbulence in the wake of the object (Forest Renewal BC, n.d.) However, trees naturally acclimate to wind-loads as they grow, and open-grown trees generally acclimate more than stand-grown trees (Mitchell *et al.*, 2008). Windthrow, which results in broken and upheaved trees, occurs when the crown is displaced by wind-load and the strength of a tree`s stem or root-system is exceeded (Mitchell *et al.*, 2008). The point at which the strength of the tree is exceeded resulting in windthrow is called the turning moment (Forest Renewal BC, n.d).

Trees differ in their susceptibility to wind-events based on both species-specific traits and non-species-specific, external factors. Some tree-species have stronger, more flexible wood than other species (Duryea *et al.*, 2007). Additionally, certain tree-species defoliate during wind-events more readily than other species as a survival strategy (Duryea *et al.*, 2007). External factors applicable to all species that affect their wind-tolerance include the life-stage, size and pruned form of the tree (Duryea *et al.*, 2007). It should be noted that occasionally, even with meticulous planning and preparation, tree damage from extreme wind-events due to high wind-loads and heavy precipitation may be inevitable (ISA, n.d.). The following section describes species-specific and non-species-specific factors that contribute to a tree`s wind tolerance and were drawn from studies by Francis (2000), Duryea *et al.* (2007), and Barry (1993).

4.1 Non species-specific factors

Certain factors will affect a trees wind-tolerance, regardless of the species. These are often a result of the external environment and management practices, such as pruning.

4.1.1 Life-stage and size

Mature trees approaching the end of their lifespan are generally less decay resistant and possibly more vulnerable to winds (Canham *et al.*, 2001). Studies have concluded that a tree's likelihood to fail during a windstorm increases with an increasing diameter (eg: Canham *et al.*, 2001; Peterson, 2007).

A study performed in southeastern United States by Duryea and Kampf (2007) found that older, larger trees (diameter between 100 and 200 cm) lost a greater percentage of branches during hurricanes than did smaller trees (diameter of 20 cm or less). Additionally, larger, taller trees within a species were uprooted more often than smaller-diameter, shorter trees (Duryea *et al.*, 1996). Furthermore, because tree-species have different lifespans, decay and structural instability will not develop homogenously throughout the urban forest, but rather on a tree-species basis (Duryea and Kampf, 2007).

4.1.2 Crown form and structure

The size and form of a tree contributes to its ability to withstand high wind-loads. Trees with a small stem taper and a large, dense crown located high off the ground generally have a form that is more likely to fail during a windstorm (Gilman *et al.* 2008). It may be possible to reduce damage inflicted on a species by pruning to reduce the crown profile exposed to winds (Duryea, *et al.*, 1996). Additionally, trees with co-dominant stems and tight angles between branches, known as "tight crotching" may form weak unions, known as bark inclusions (Duryea and Kampf, 2007; ISA, 2011a). These inclusions are more susceptible to breakage during wind-events and should be remediated with pruning (Duryea and Kampf, 2007).

A study performed by Duryea *et al.* (1996) found that pruning trees improved their wind-resistance and reduced the likelihood of tree failure. In the study, pruned tree survival was 73%, compared to a 47% survival for unpruned trees. In the same study, the authors found that local tree-species that were considered naturally wind-firm did even better under high wind-loads with the addition of pruning (Duryea *et al.*, 1996).

However, poor pruning practices, including the complete removal of the top of the tree, or the removal of large branches in older trees, may heighten the likelihood of a tree failing under a large wind-load (Duryea and Kampf, 2007). The pruned areas on the tree may act as an entry point for fungi, resulting in decay and higher structural instability during wind-events (Duryea and Kampf, 2007).

4.1.3 Soil characteristics

The soil characteristics of a site may affect the root morphology of the planted tree (Coutts, 1983). Root-system development and anchorage can be improved in urban trees by providing adequate soil depth and space, minimal soil compaction, and a deep water table (Duryea *et al.*, 1996). Additionally, the quality of the stock purchased at the nursery, as well as the way in which the root ball of a tree develops at the nursery (eg: container-grown versus field-grown) could impact the root morphology of a tree and its resulting wind-tolerance (Gilman, 1990).

4.2 Species-specific factors

Certain factors that affect a tree's wind-tolerance are species-specific. The following factors will later be used as a framework to analyze the wind-tolerance of tree-species suitable for Halifax's future climate.

4.2.1 Wood biomechanics

4.2.1.1 Modulus of elasticity

Generally, flexible tree-species are believed to be less susceptible to snapping during high winds than less flexible species (Francis, 2000). Modulus of elasticity, which measures the flexibility of a tree under high wind-loads, is a biomechanical property of wood, often measured in megapascal units (MPa) (Asner and Goldstein, 1997; Francis, 2000). A study performed in the Hawaiian Islands found that native tree-species with a lower modulus of elasticity were more flexible and snapped less during extreme winds than species with a high modulus of elasticity (Asner and Goldstein, 1997). Conversely, a study by Duryea *et al.*, (2007) in the state of Florida found the opposite. Species that were stiffer and had a high modulus of elasticity (ie: ≥ 10,000 MPa) had a higher survival rate than species with a lower modulus of elasticity (ie: < 7,000 MPa).

For the purpose of this report, the author deems the results of Duryea *et al.* (2007) as more applicable to the current study of urban trees in Halifax than trees found on the Hawaiian Islands. Therefore, a higher modulus of elasticity will be considered to be associated with a higher wind-tolerance and a low modulus of elasticity will be considered to represent a lower wind-tolerance in tree-species in this report. However, it is recommended that future research be conducted as to whether a high or low modulus of elasticity is most applicable to tree-species located in Eastern Canada.

4.2.1.2 Modulus of rupture

The modulus of rupture is a biomechanical property of wood that measures the bending stress wood can tolerate before mechanically failing and is measured in kilopascal units (KPa) (Francis, 2000). It is considered to be an accepted criterion of strength (Green, Winandy, and

Kretschmann, 1999). A study by Duryea *et al.*, (2007) found that tree-species with a high modulus of rupture (ie: ≥ 70,000 KPa) had a higher survival rate than species with a lower modulus of rupture (ie: < 50,000 KPa).

4.2.1.3 Specific gravity

The strength of a tree's wood determines the amount of drag force it can withstand before the limbs, roots, or trunk break (Francis, 2000). Specific gravity is a term that represents the ratio of wood substance contained in a piece of wood to the density of water (Green, Winandy, and Kretschmann, 1999). This biomechanical property can be defined by either its 'green weight' meaning freshly cut (and at its heaviest), or its 'dry weight' meaning oven-dried (and at its lightest). Specific gravity was determined it to be an efficient indicator of a tree's resistance to breakage and uprooting in a study performed by Putz *et al.* (1983). A study by Francis (2000) found that stem failure was negatively correlated with specific gravity, indicating that species with denser wood are less likely to snap or uproot during extreme wind-events. Based on a study performed by Woodcock and Shier (2003), temperate tree-species with a specific gravity of > 0.7 was deemed to be high, while tree-species with a specific gravity of <0.5 was deemed as low.

4.2.2 Crown density and defoliation

Defoliation is a survival mechanism used by some tree-species as a way of withstanding high winds (Duryea and Kampf, 2007). Drag force, or the resistance of a tree acting against a wind-load (James, 2003), is reduced with a tree's increasing ability to shed its leaves during prolonged wind gusts (Francis, 2000). A study by Francis (2000) found that species with a low specific gravity defoliate more readily under high wind-loads. However, the method employed for estimating defoliation is through observation; comparing the volume of the crown structure pre- and post-hurricane (Francis, 2000; Duryea *et al.*, 2007). Additionally, tree-species with moderate to open crowns lost fewer branches during wind-events than species with denser crowns (Duryea *et al.*, 2007). Additionally, it has been found that certain densely-crowned species are more easily damaged during wind-events than open-crowned species (Everham and Brokaw, 1996).

It should be noted that crown density and the form of a tree are species-specific factors, but have been included as non-species-specific factors because unsuitable characteristics can be remediated through pruning. As mentioned in section two of this report, pruning and tree maintenance are currently employed in Halifax on a reactionary basis. It would require well-over the originally projected $600, 000 a year to achieve a proactive pruning program. Trees that are currently pruned are done so on a reactionary basis for operational purposes (eg: to avoid interactions between trees and utility wires or to prune a hazardous dead branch).It would require an increased budget in order to prune all trees in the city on a proactive basis for operational purposes. Once proactive pruning is achieved in Halifax, trees can begin to be pruned on a proactive basis for functional purposes (eg: to remove co-dominant stems or to thin the crown). Once functional pruning is implemented in Halifax, than evaluating a species for its crown density would become erroneous in the species-specific framework, as this would be a factor that affected a species wind-tolerance but could easily be remediated through pruning.

4.2.3 Root morphology

The extent and depth of a tree's root-system can contribute to its wind-resistance (Barry, 1993). A deep, strong taproot has shown to better anchor a tree during wind-events than shallow, horizontally-spreading roots (Duryea *et al.,* 2007). Shallow root-systems can predispose trees to windthrow as a result of a failing root plate, which is the thick horizontal matt of roots located at the base of the stem of a tree (Coder, 2008).

5. Species selection

Adaptation is the process of applying management strategies to systems in order to reduce their vulnerability to climate change (Ordóñez *et al.,* 2010). This can be achieved by adapting the systems to anticipated future conditions and their resulting impacts (Ordóñez *et al.,* 2010). If urban forest managers anticipate climate change at an early stage in the adaptation process, negative effects could be minimized while benefits of the potential impacts maximized (Johnston *et al.,* 2009). One biophysical method for urban forest adaptation to climate change is through urban tree species-selection.

A study conducted by Rostami (2011) examined tree-species suitable for the Halifax urban forest of the 21st century. Past studies have focused on either a tree-species' ability to tolerate urban stresses, or the adaptation of tree-species to the changing climate (Saebo *et al.*, 2003; Yang, 2009). Rostami's study incorporates both climate change and urban ecosystem adaptation. A database containing 57 tree-species and 95 tree characteristics was developed (Rostami, 2011). The majority of the tree-species were native to eastern North America with an additional six tree-species native to Europe and Asia, chosen for their widespread planting in North American cities (Rostami, 2011). A full-dispersal scenario, where trees are able to migrate unimpeded to their future climatic ranges and developed by McKenney *et al.,* (2007) was used (Rostami, 2011). A range of scenarios, based on concerns, interest, and arguments that urban forest managers and planners had towards tree-species in an urban setting were developed (Rostami, 2011).

In Rostami's (2011) thesis, categories were defined from characteristics and with the use of an analytical tool, data was translated into colours. Suitable characteristics of a tree were coloured green, the medium-range coloured yellow, and unsuitable characteristics coloured red (Rostami, 2011). If the characteristics of a tree-species were green or a mixture of green and yellow, it received a green in the final results column (Rostami, 2011). If a tree- species had one red characteristic with the rest yellow, it was included but identified as less-suitable for planting in Halifax (Rostami, 2011). Lastly, if a tree-species received multiple red characteristics, a red colour would be inserted in the results column and the species was not included in the scenario (Rostami, 2011).

Additionally, due to the numerous scenarios included in the study, a count analysis was performed by Rostami (2011). The count analysis counted the total number of green, yellow, and red characteristics for each species (Rostami, 2011). Each colour was given a value (red=0, yellow=1, green=2), and this value was multiplied by the number of times they occurred for each species (Rostami, 2011). This gave each species a final numbered result, which was used to rate the species in comparison to other species (Rostami, 2011).

The results of the study produced a list of 27 tree-species with a future climatic range in Halifax (Figure 1) (Rostami, 2011). The species can tolerate most urban stressors and require minimal care and maintenance (Rostami, 2011). They can tolerate winds, salt, and freezing rain. They have a low risk of pest and pathogen invasion, are not considered invasive, and are generally considered attractive (Rostami, 2011). These tree-species provided initial guidance on what should be planted in Halifax's urban forest (UFPT, 2013).

Scientific Name	The combined results of both methods
Acer rubrum□	*
Acer saccharum□	
Betula alleghaniensis□	
Betula papyrifera□	
Fagus grandifolia□	
Fraxinus americana□	
Fraxinus pennsylvanica□	
Picea rubens□	
Pinus strobus□	
Prunus serotina□	
Quercus rubra□	
Thuja occidentalis□	
Tsuga canadensis□	
Ulmus americana□	
Juglans cinerea■	
Quercus macrocarpa■	
Carya cordiformis	*
Gleditsia triacanthos	
Juglans nigra	*
Liriodendron tulipifera	
Magnolia acuminate	
Nyssa sylvatica	
Platanus occidentalis	
Quercus alba	
Quercus velutina	
Robinia pseudoacacia	
Sassafras albidum	

Figure 1: Recommended tree-species for plantation in Halifax under a changing climate. □: tree-species native to NS ■: tree-species native to NB in addition to those native to NS *: tree-species that have received the highest rating from both methods of analysis. Source: Rostami, 2011

5.1 Methods

For the purpose of this report, the 27 tree-species proposed by Rostami (2011) will be further evaluated based on a species-specific framework assessing wind-tolerance. Although one of the original characteristics in Rostami's database identifies wind-tolerance, which is categorized as low, medium, or high, no scenario specifically focused on extreme wind-events. The author justifies reassessing the tree-species for wind-tolerance based on a detailed wind-specific framework, which in turn gives greater detail about the 'how and why' of each specie's tolerance. This can provide managers with insight regarding the specific category or categories in which the species performed well or poorly.

The framework regarding wind-firmness characteristics will be drawn from section four of this report: factors affecting windfirmness. Only factors that are species-specific will be used, as the other factors are a result of external biophysical or cultural forces, such as pruning.

Species-specific factors include:

- Wood biomechanics- further broken down into:
    - Specific Gravity
    - Modulus of rupture
    - Modulus of elasticity
- Crown density
- Root morphology

In the literature, defoliation rates that are included in decision-making criteria for urban tree-species-selection are often based on personal observation by the author pre- and post-hurricane (eg: Duryea *et al.*, 2007; Francis, 2000). Due to time constraints, limited information in the academic literature, and a lack of expertise on the author's behalf, defoliation rates regarding the 27 tree-species were not included in the decision criteria. However, defoliation rates are a contributing factor to tree survival during and after hurricanes and were therefore included in section four of the report.

The ranking scheme was based on Rostami's (2011) methods. The categories in which the ranges of values for the modulus of rupture and the modulus of elasticity were drawn are from Duryea *et al.* (2007). The categories for the ranges of values for specific gravity were drawn from

Woodcock and Shier (2003). Crown density and root morphology characteristics were drawn from Hightshoe (1987), and the categories for these two factors were drawn from academic literature as discussed in section four of this report (Table 1). Categories for each criteria of the framework were then translated into colours, with highly suitable characteristics labeled green, moderately suitable characteristics labeled yellow and unsuitable characteristics labeled red. It should be noted that unlike Rostami, no count analysis was performed as only one scenario was being investigated: wind-tolerance.

Table 1: List of criteria used to evaluate wind-firm tree-species for Halifax, Nova Scotia. *Based on green weight of wood.

Criterion	Category	Colour
Specific gravity*	0.7 or greater	Green
	Between 0.5 and 0.69	Yellow
	0.49 or below	Red
Modulus of rupture (KPa)	70, 000 or greater	Green
	Between 50, 000 and 69, 999	Yellow
	49, 999 or below	Red
Modulus of elasticity (MPa)	10, 000 or greater	Green
	Between 7, 000 and 9, 999	Yellow
	6, 999 or below	Red
Crown density	Open	Green
	Moderate	Yellow
	Dense	Red
Root morphology	Deep	Green
	Moderately deep (or varies with site)	Yellow
	Shallow	Red

5.2 Results

After assessing the criteria, each tree-species received a colour in the results column which was either green, yellow, or red (Figure 2) (see Appendix A for more comprehensive results). Based on these results, three lists of tree-species were produced: high wind-tolerance, moderate wind-tolerance, and low wind-tolerance (Table 2).

Scientific Name	Results
Acer rubrum	
Acer saccharum	
Betula alleghaniensis	
Betula papyrifera	
Fagus grandifolia	
Fraxinus americana	
Fraxinus pennsylvanica	
Picea rubens	
Pinus strobus	
Prunus serotina	
Quercus rubra	
Thuja occidentalis	
Tsuga canadensis	
Ulmus americana	
Juglans cinerea	
Quercus macrocarpa	
Carya cordiformis	
Gleditsia triacanthos	

Lesko (2014)

Juglans nigra	
Liriodendron tulipifera	
Magnolia acuminate	
Nyssa sylvatica	
Platanus occidentalis	
Quercus alba	
Quercus velutina	
Robinia pseudoacacia	
Sassafras albidum	

Figure 2: Results of tree-species selection based on wind-tolerance for Halifax, Nova Scotia.

Table 2: A table displaying tree-species of high wind-tolerance, moderate wind-tolerance, and low wind-tolerance for Halifax, Nova Scotia.

Highly wind-tolerant species	**Moderately wind-tolerant species**	**Low wind-tolerant species**
Betula alleghaniensis	*Prunus serotina*	*Acer saccharum*
Quercus velutina	*Magnolia acuminate*	*Fagus grandifolia*
Carya cordiformis	*Fraxinus americana*	*Picea rubens*
Gleditsia triacanthos	*Fraxinus pennsylvanica*	*Pinus strobus*
Juglans nigra	*Quercus rubra*	*Thuja occidentalis*
Quercus alba	*Robinia pseudoacacia*	*Tsuga canadensis*
	Quercus macrocarpa	*Juglans cinerea*
	Ulmus americana	*Liriodendron tulipifera*
		Nyssa sylvatica
		Platanus occidentalis
		Sassafras albidum
		Acer rubrum
		Betula papyrifera

5.3 Discussion

Based on the criteria, six tree-species were highly wind-tolerant, eight were moderately wind-tolerant, and 13 were of low wind-tolerance. The species of highest tolerance performed moderate to well when evaluated against the criteria. The moderate species performed poorly in at least one criterion and are considered less suitable for wind-prone areas in Halifax. Lastly, the species of low-tolerance performed poorly in more than one criterion.

Through the evaluation process, six species amongst the 27 are considered to be both wind-tolerant and well adapted to Halifax’s future climate. However, it should be emphasized that in no way is this report suggesting that only six species be planted in Halifax’s urban forest. Reducing the number of species planted in the urban forest based on a sole attribute (such as wind-tolerance) is both counter-intuitive and counteracts the original intention of creating a well-adapted urban forest in the face of impending climate change. A diverse urban forest, containing a plethora of tree-species is more resistant to invasions (Rejmanek, 1996) and is more ecologically stable under environmental change (Peterson *et al*,. 1998). Additionally, urban forests with low species diversity may be more susceptible to climatic extremes (Tilman, 1996).

The intention of producing lists of tree-species that differ in their wind-tolerance is to inform managers that certain species are better suited to a particular area than others. For example, as the tree-species under question are well-suited to urban stresses, future climatic conditions, and strong winds, planting them in wind-prone areas such as Barrington Street may prove advantageous. The Halifax Regional Municipality Municipal Planning Strategy requires that adverse wind effects from building developments be considered before construction (Halifax, 2014). Wind studies are generally performed during the planning and design phase to ensure that buildings are designed so that wind levels are ‘acceptable’ on pedestrian routes (Heritage Trust of Nova Scotia, n.d.). Urban planners could plant wind-tolerant trees in wind tunnels and wind-prone areas set for development. The trees would in turn act as a natural windbreak by reducing wind speeds, making the area more pedestrian-friendly while concurrently adding to urban forest benefits as a result of increased canopy cover. Additionally, this could reduce potential wind-related hazards inflicted on citizens such as broken branches, which may arise during strong wind-events.

On a broader scope, coasts are generally windier than inland areas (Green, 2011). Wind-firm tree-species could be planted in coastal areas, which again would reduce the amount of wind-related maintenance required for each tree (such as crown thinning), and could reduce wind-related hazards. Additionally, coastal towns or cities could use the framework created in this report to determine which wind-tolerant species may be most suitable for their area. However, additional research on the salt-tolerance of these wind-firm species should be conducted, as salt from sea-spray may lead to leaf or needle necrosis (Takle Chen and Wu, 2006).

5.4 Verifying the results

Two methods were used to verify the resulting tree lists. The first was using Hightshoe's (1987) planting design manual *Native Trees, Shrubs, and Vines for Urban and Rural America.* The second was with the aid of two tree experts: Peter Duinker and Matt Follett.

Some discrepancies were found when comparing the results in this report to those of Hightshoe (1987). 59% of my results aligned with what was in Hightshoe's manual while 41% did not. For example, *Quercus alba* was determined to be of high wind-tolerance in the results and in Hightshoe's manual, whereas *Acer saccharum* was determined to be of low-tolerance through the evaluation process, but 'very strong' in Hightshoe's manual (see Appendix A for a comprehensive comparison). It should be noted that Hightshoe gives no explanation as to how wind-tolerance is determined in the manual, but simply gives a brief explanation of how each tree-specie's fares with regard to wind and ice events.

Dr. Peter Duinker is a professor at Dalhousie University, chair of Nova Forest Alliance, and member of Point Pleasant Park Advisory and HRM Urban Forest Management Steering Committee (Dalhousie University, 2014). After reviewing the tree lists, he felt some species were appropriately categorized, while others were not. For example, labeling *Quercus rubra* as moderately wind-tolerant was too low, and it should likely be categorized with the other oaks as highly tolerant. *Acer saccharum*, *Fagus grandifolia*, *Tsuga Canadensis*, and *Platanus occidentalis* were all deemed as rated too low (P. Duinker, personal communication, November 17, 2014).

Matt Follett has over 15 years as a practising ISA Certified Arborist (ISA, 2014). After reviewing the tree lists, he felt that *Quercus macrocarpa* should be placed in the highest category of wind-tolerance. In his experience, *Juglans nigra* has a very low wind-tolerance and should be placed in the lowest category. This may result from its propensity to form co-dominant stems with bark inclusions (M. Follett, personal communication, November 19, 2014).

After incorporating expert verification into the analysis, the resulting trees lists would contain eleven highly wind-tolerant species, six moderately wind-tolerant species, and ten species of low wind-tolerance (Table 3). Having experts review and verify the results highlights discrepancies between the results of the analysis and how the same tree-species may be affected by wind in the field. It also emphasizes that there are limitations and information gaps in the framework.

Table 3: A table displaying the resulting tree lists after expert verification. Species highlighted in yellow have been moved from their originally-determined list.

Highly wind-tolerant species	**Moderately wind-tolerant species**	**Low wind-tolerant species**
Betula alleghaniensis	*Prunus serotina*	*Sassafras albidum*
Quercus velutina	*Magnolia acuminate*	*Acer rubrum*
Carya cordiformis	*Fraxinus americana*	*Picea rubens*
Gleditsia triacanthos	*Fraxinus pennsylvanica*	*Pinus strobus*
Quercus alba	*Robinia pseudoacacia*	*Thuja occidentalis*
Acer saccharum	*Ulmus americana*	*Betula papyrifera*
Quercus macrocarpa		*Juglans cinerea*
Quercus rubra		*Liriodendron tulipifera*
Fagus grandifolia		*Nyssa sylvatica*
Tsuga canadensis		*Juglans nigra*
Platanus occidentalis		

5.5 Caveats and limitations

Several limitations and caveats were noted throughout the methods and results of the tree-species selection process. The framework used to assess wind-tolerance was drawn from academic literature, as were the categories for each criterion. For example, a species was considered to have a high modulus of rupture (≥ 70,000 KPa) based on Duryea *et al.* (2007) study of tree-species in southeastern United States. However, what is deemed as a high modulus of rupture for species in this geographic area may not be applicable to tree-species in northeastern Canada. Though both areas experience hurricanes, those in Florida can reach speeds upwards of 235 kph (Duryea *et al.,* 2007). Therefore, a threshold of 70,000 KPa or above may be an overestimation. If the categories were altered to be more inclusive on the assumption that the modulus of rupture and modulus of elasticity were overestimated, the tree-species presented in each wind-tolerant category would change as a result.

Besides stating which categories were evaluated for wind-tolerance, the literature on which the methods were based did not rank or weight the criteria. As a result, each criterion is given an equal weight in the framework. However, it's possible that say root morphology is more-so a product of the environment rather than of the species. In this case, root morphology should have been given a lower weight than other criterion in the tree-species selection process. As no particular hierarchy or order of importance was detailed in the literature, all criteria were of equal weight, potentially skewing the results in favour of some tree-species over others.

The methods used in this evaluation closely followed those of Rostami's (2011). However, they differed in how sources were collected. For consistency, the values imputed for modulus of rupture, modulus of elasticity, and specific gravity came from a single source (ie: Green, Winandy, and Kretschmann, 1999). Both root morphology and crown density came from a single source (ie: Hightshoe, 1987). Rostami, however, used many sources for each variable, some of which conflicted. In the case that different sources proposed characteristics that conflicted with one another for the same species, the characteristics were discussed among experts until the most suitable option was determined. This methodology was not applied to this report due to time limitations and the scope of the project, possibly having an effect on the lists of resulting tree-species.

If other components of Rostami's methods had not been followed, such as how the data was translated into colours, the resulting lists of species would have changed. For example, in the methodology of this report, two or more red characteristics automatically resulted in a red in the results column, much like Rostami's methods. However, if the approach that one red characteristic and one green characteristic neutralized each other to create a yellow rating, the final results may have differed from what was presented.

6. Future research

Throughout this report, research limitations were raised, inviting suggestions for future research regarding wind tolerance in the urban forest.

After the criteria of the framework were reviewed by Matt Follet, it was concluded that too much emphasis was being placed on a tree's load-bearing capacity (ie: wood biomechanical criteria) while only one criterion evaluated the actual load the tree experiences during high winds: crown density (M. Follet, personal communication, November 19, 2014). Often, crown density is assumed to be a good proxy for load. However, it may do little to estimate actual load (M. Follet, personal communication, November 19, 2014). As trees reconfigure their frontal area as wind speed increases, the degree to which they are able to accomplish this depends on certain factors (M. Follet, personal communication, November 19, 2014). These include: stem flexibility (included in this report as modulus of elasticity), leaf shape, petiole flexibility, and petiole length, among others (M. Follet, personal communication, November 19, 2014). Therefore, it is recommended that while undergoing an analysis of tree-species selection for wind-tolerance, the criteria in the framework should be broadened to include criteria for wind-load experienced by a tree.

In addition to adding to, or altering the criteria in the framework, it would be useful to incorporate some of the caveats stated in section five. Recognizing that not all criteria should be weighted equally, research into a weighting scheme for the different criteria in the framework is recommended. Additionally, it is recommended that additional research be conducted regarding the categories of the ranges for modulus of elasticity and modulus of rupture. As stated previously, ranges and how they were categorized for these two wood properties were drawn from literature centred in Florida, and may not be applicable to tree-species in Eastern Canada. A judgement call was made regarding whether a high modulus of elasticity represented high or low wind-tolerance. It is recommended that future research investigate which values for modulus of elasticity would be more appropriate and applicable to trees found in Halifax's urban forest. Lastly, it is recommended that when undertaking an analysis of tree-species selection based on a wind-tolerance framework, expertise be incorporated into the process to verify the results.

When assessing wind-tolerant tree-species that could potentially be planted in coastal towns and cities, research into the specie's tolerance to sea salt-spray should be conducted. As previously mentioned, high concentrations of salt due to ocean spray could injure trees located on the coast and could be factor that is as important as, or more important than a species wind-tolerance.

Future research could investigate gathering field data in Halifax pre- and post-hurricane events. Generalizations were made in the framework with regard to root morphology and crown density. For example, it is likely that not all species that have a dense crown will be killed or severely injured during wind-events. Studying the before and after effects of hurricane events in Halifax's urban forest could provide insight on how urban trees respond to wind-events, potentially providing the opportunity to gather information on defoliation rates of tree-species in the city. From this data, a more suitable and tailored framework that is more representative of Halifax's urban forest could be created.

7. Management recommendations

Current management strategies such as pruning and species selection were investigated, from which recommendations are offered.

First off, it is recommended that wind-tolerant trees be planted in wind-prone areas. On a broad scale, this could mean planting windfirm trees in coastal towns or cities. Additionally, windfirm trees could be planted in wind-tunnels set for development. By planting windfirm trees in wind-prone areas, wind-specific maintenance and pruning costs would be reduced, the trees would act as a natural wind break making the area more hospitable to pedestrians, and wind-related hazards would be reduced.

Many cities maintain a data base regarding street trees (Mitchell *et al.*, 2008). These databases often gather information on a tree-by-tree basis regarding planting date, location, tree condition ect. As a way of better understanding the potential implications extreme wind-events may have on individual trees or on tree-species, a wind-specific database should be created. This database could complement Halifax's urban forest database which collects information on newly planted trees. The wind-specific database could include criteria such as species, location, height (which could be used as a proxy for age), how the tree was damaged as a result of the wind event (eg: blown down, broken braches, and/or broken trunk), and the severity of the wind event. Similar to a study focusing on urban trees in Halifax pre-and post-wind-events mentioned earlier, a wind-specific database could provide the information required to make a more tailored and suitable framework. Additionally, a database would provide researchers with the opportunity to gather data over a longer time period and capture multiple hurricanes with a variety of intensities.

Pruning and form may be as important as or even more important than species-selection when managing for a wind-tolerant urban forest. Pruning can significantly reduce wind-load compared to unpruned trees (Smiley and Kane, 2006). When purchasing nursery trees, it is recommended that the tree has strong form with branches evenly spaced along a central trunk. Branches should be firmly attached to the trunk (ISA, 2011a). Trees displaying branches that form tight angles with one another or grow against the trunk should be avoided, or corrected through pruning (ISA, 2011a). Some tree-species develop well-spaced branches and a trunk with apical dominance naturally (ISA, 2011b). Other species, such as some maples, can form co-dominant stems which contribute to structural weaknesses (ISA, 2011b). Co-dominant stems should be correctively pruned while young (ISA, 2011b). Trees that receive corrective pruning at a young age require less pruning as they mature (ISA, 2011a).

The immediate pruning of young trees should be restricted to the removal of broken or dead branches only (ISA, 2011b). Corrective pruning should take place two to three years after planting as to allow the tree to recover from the stress of transplanting (ISA, 2011b). Mature trees can be thinned to reduce crown density and allow for increased air movement through the foliage (ISA, 2011c). However, over-pruning a mature tree will affect its photosynthetic capacity and could act as an entry point for fungi (ISA, 2011c).

Aligning with pruning and maintenance, focusing on insuring good plant selection with adequate root development at the nursery is an important component of a tree's wind-tolerance (ISA, 2011a). Selecting trees free of root problems at the nursery is recommended. The purchase of burlapped root stock from field-grown trees with damaged or compressed root balls should be avoided (ISA, 2011a). Additionally, the diameter of the root ball should be approximately ten times the diameter of the trunk, measured 15 cm above the trunk flare (ISA, 2011a). Trees grown in containers should not have roots that twist or circle the container (ISA, 2011a). Circling roots may girdle other roots or the entire tree, and can create a more unstable base for the tree once planted (ISA, 2011a). Root circling can be decreased and branching root-systems increased by placing an obstruction inside the container, by introducing holes in the container or by removing the bottom of the container (Gilman, 1990). Additionally, site selection for urban trees with adequate above and below-ground space, aerated soils, and a deep water table is recommended for optimal root development.

8. Conclusion

Climate change will have effect ecological, social, and economic processes. With an overall trend of warming resulting from human activities, trees are expected to redistribute and migrate northwards in latitude or upwards in elevation. With half of the world's population residing in urban centres, cities are beginning to respond to climate change through adaptation strategies. With an increase in the intensity and frequency of hurricanes expected for Halifax, the city has employed management strategies to adapt its urban forest to future climatic conditions. One such method is through species-selection. Maliheh Rostami produced a list of 27 tree species that would be suitable for urban planting and would also be able to tolerate Halifax's future climate. These 27 tree-species were analyzed for their wind-tolerance using a species-specific framework pertaining to wind-tolerance. As a result of the analysis, six tree-species were highly wind-tolerant, eight were moderately wind-tolerant, and 13 were of low wind-tolerance. These results were verified by comparing the wind-tolerance of the tree-species to what was written in a planting design manual as well as with expert consultation. Limitations and information gaps regarding the framework and results were discussed, providing opportunities for future research. Lastly, management recommendations were offered.

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Appendix A

Table 4: Comprehensive results of tree-species selection based on wind-tolerance for Halifax, Nova Scotia. *Based on green weight of wood.

Scientific Name	Specific Gravity*	M. Rupture (Kpa)	M. Elasticity (Mpa)	Crown Density	Root Structure	Results
Acer rubrum	0.49	53,000	9,600	Moderate	Very shallow	
Acer saccharum	0.56	65,000	10,700	very dense	shallow	
Betula alleghaniensis	0.55	57,000	14,970	Moderate	Moderately deep laterals	
Betula papyrifera	0.48	44,000	10,970	Moderate	Deep lateral roots	
Fagus grandifolia	0.56	59,000	9,500	very dense	shallow	
Fraxinus americana	0.55	66,000	9,900	Moderate	shallow	
Fraxinus pennsylvanica	0.53	66,000	9,700	Moderate	shallow	
Picea rubens	0.37	41,000	9,200	dense	shallow	
Pinus strobus	0.34	34,000	6,800	moderate	weak taproot with coarse deep laterals	
Prunus serotina	0.47	55,000	9,000	open	deep coarse taproot	
Quercus rubra	0.56	57,000	9,300	dense	deep laterals	
Thuja occidentalis	0.31	32,000	5,200	very dense	shallow	
Tsuga canadensis	0.38	44,000	7,400	very dense	shallow	
Ulmus americana	0.46	50,000	7,700	moderate	shallow to deep laterals (varies with site)	
Juglans cinerea	0.36	37,000	6,700	open	taproot	
Quercus macrocarpa	0.58	50,000	6,100	open	taproot	
Carya cordiformis	0.6	71,000	10,600	moderate	deep taproot	
Gleditsia triacanthos	0.6	70,000	8,900	open	taproot, deep laterals to shallow (varies with site)	
Juglans nigra	0.51	66,000	9,800	open	taproot	
Liriodendron tulipifera	0.4	41,000	8,400	moderate	shallow to deep laterals (varies with site)	
Magnolia acuminate	0.44	51,000	10,800	moderate	deep coarse laterals	
Nyssa sylvatica	0.46	48,000	7,100	dense	taproot	
Platanus occidentalis	0.46	45,000	7,300	open	shallow	
Quercus alba	0.6	57,000	8,600	moderate	deep taproot and deep laterals	
Quercus velutina	0.56	57,000	8,100	moderate	deep taproot and deep laterals	

Robinia pseudoacacia	0.66	95,000	12,800	open	shallow	
Sassafras albidum	0.42	41,000	6,300	open	taproot with coarse laterals	

Table 5: Comparison between the results of the evaluation and what is stated in Hightshoe (1987) for all 27 tree-species.

Scientific Name	Results	Hightshoe (1987)
Acer rubrum		weak wooded
Acer saccharum		very strong
Betula alleghaniensis		infrequent to wind/ice
Betula papyrifera		strong wooded
Fagus grandifolia		infrequent to wind/ice
Fraxinus americana		brittle
Fraxinus pennsylvanica		brittle
Picea rubens		frequent
Pinus strobus		infrequent to wind/ice
Prunus serotina		infrequent to wind/ice
Quercus rubra		infrequent to wind/ice
Thuja occidentalis		frequent
Tsuga canadensis		infrequent to wind/ice
Ulmus americana		infrequent to wind/ice
Juglans cinerea		frequent-very brittle wood
Quercus macrocarpa		infrequent to wind/ice
Carya cordiformis		infrequent to wind/ice
Gleditsia triacanthos		infrequent to wind/ice
Juglans nigra		infrequent to wind/ice
Liriodendron tulipifera		frequent-weak wooded
Magnolia acuminate		infrequent to wind/ice
Nyssa sylvatica		infrequent to wind/ice
Platanus occidentalis		infrequent to wind/ice

Quercus alba		infrequent to wind/ice
Quercus velutina		infrequent to wind/ice
Robinia pseudoacacia		frequent-weak wooded
Sassafras albidum		frequent-weak wooded