The impact of environmental stresses on the survivability of the urban landscape: A review of the literature and recommendations

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KEY FINDINGS AND RECOMMENDATIONS

- Eleven key factors were identified that critically influence establishment and survival of urban trees: species selection, translating, site selection and preparation, soil compaction, moisture stress, mulching, salt and de-icing products, root damage, light, temperature and post-planting management
- Most research uses simulated plot designs rather than actual urban landscapes making it difficult to interpret the results for the urban landscape. Finding ways to incorporate actual urban landscape plantings into research would help to draw stronger conclusions as to how stresses actually influence trees
- Inadequate skills and knowledge in species selection has been identified as a possible factor that contributes to poor survival
- Given the importance of provenance, a best practice for species selection would be to focus on subspecies, ecotypes and cultivars rather than simply picking a species
- To facilitate informed decisions on species selection, a review of tree species with morphological and physiological tolerances to specific stresses is recommended. Furthermore, there is a need for the development of best practices for species selection and site selection
- As the optimal time for transplanting is species and location specific, there is a need for research in hardiness zones 2-5 to determine optimal transplanting times
- While a common practice, the long term benefits of reducing deflected roots is unknown and requires further study
- Short-term studies have shown that deeper planting can interact with poor drainage (i.e. water stress) to decrease growth, water relations, and photosynthetic gas exchange. There is a need for additional studies that not only look at the interaction between these factors, but also for the investigation into family (or species) specific optimal planting depths
- As a transplant amendment, hydrogel dips have been evaluated as methods to ameliorate the establishment of various species with equal or better success than undipped bare root plantings. Hydrogel dips amended with an ectomycorrhizal fungus have been shown to increase tree establishment after transplanting through quick root regeneration
- Urban planting designs and plans need to be an integral part of overall initial development designs, including the calculation and allocation of sufficient soil volume for proper growth (both above and below ground)
- Models using climatological data to estimate the soil volume needed to provide adequate moisture for the growing conditions have been developed, as have allometric equations that permit better decision-making on the spacing of plantings based on expected growth and space requirements. These are promising tools and should be considered for adaption and adoption in Ontario
- It has been estimated that 80% of the problems urban trees face can be attributed to poor soil, and that these poor soils act synergistically to increase the damage from other stresses. The changes in soil structure found in urban soils compared to natural soils is said to be one of the greatest limiting factors to tree growth and survival
- Various soil substrates are becoming popular as methods to reduce soil compaction found in and around tree pits. Most notable are structural soils, which are used to increase soil pore

size while still providing structural and load bearing support. Structural soils may also provide greater stability than conventional soil as they induce deeper roots
- Despite the fact that suspended concrete has shown benefits in alleviating the effects of soil compaction, open top pits have been associated with improved growth. Therefore, finding ways to reduce soil compaction while leaving the surface exposed might be the best method and warrants further investigation.
- Nutrient loading essentially forces the plant to stockpile nutrient in its tissues for later use when soil nutrient availability is poor. However, this results in a lower root:shoot ratio along with greater pest susceptibility (from the increased nitrogen in the leaves) and it is unknown if this outweighs the benefits of nutrient loading.
- Soil compaction is among the most consistent stresses that street trees must deal with. Soil bulk densities above 1.6 g/cm^3 are often found in the urban environment and can be much higher. Soil compaction tends to reduce the usable soil outside of the tree pit in the load bearing soils, compounding the limiting factors of soil compaction and soil volume. “Super pits” (12m^2 of loose unsealed surface area and 15m^3 of loosened soil volume) have been shown to maximize the volume of loose soil, increasing the rate of establishment and long term health of urban trees.
- Soil moisture can be stressful in two different ways for urban landscape trees: drought stress and waterlogged soils. There is little research on the effects of flooding in the urban landscape, and even less on remediation methods.
- It seems the benefits of mulching are contested in the literature. Most of the work that showed no benefit was conducted in Florida, while most of the work that showed a benefit occurred in the Illinois. The affects of mulching on urban trees in hardiness zones 2-5 warrants further investigation.
- Alternatives to sodium chloride have been proposed, but for various reasons have yet to be adopted. As such, there is a need for research on more tree-friendly de-icing products.
- There is a need for a trenching code of practice to ensure that the best methods are used to preserve urban trees.
- Soil injections of sucrose at >25g/L of water has been shown to stimulate root growth and can be used to regenerate fine roots more rapidly after mechanical damage such as from construction. Yet, there is a lack of available literature to confirm the effectiveness of this regenerative approach.
- A threshold of 80% of the total potential irradiance is needed for optimal growth. Choosing sites with greater light might therefore be an important factor in the future and warrants futher research.
- There is limited research available that characterizes the effects of low or high temperatures on tree survival, particularly the urban heat island effect.
- Sunscald is defined as “the death of cambium tissue on the south to southwest side of trees due to rapid changes in temperature”. While sunscald is not a major concern, it does appear to be a source of mortality to urban trees, especially during the first winter they are in the urban landscape. There does not appear to be much research on the prevention and management of sunscald.
- Wind is a persistent and dynamic force, which induces a physical stress to individual trees and entire stands. Tree stability systems have been under development for quite some time, to

help newly planted trees become established in the soil. Various commercial stabilization systems exist.

- While pruning can be an effective way to manage the root:shoot ratio of trees to increase their survivability, the objective most urban pruning is to maintain a smaller canopy rather than promote root growth to retain a positive root:shoot ratio.
- It was found that flush cutting that was previously used in landscape pruning resulted in greater dieback of the cambium and decreased wound closure compared to branch collar cutting suggested by the Hamburg Tree Pruning System.
- Street trees are often limited in their ability to utilize precipitation because of the small surface area available to allow for infiltration into the root zone. Tree canopies and buildings also intercept precipitation, further reducing the amount of water that reaches the soil. This indicates that even mature trees with established root systems are water limited in their growth and therefore require irrigation. Notably, irrigation volume does not compensate for infrequent irrigation.

PROJECT RATIONAL, OBJECTIVES AND METHOD

Landscape Ontario has recognized that failed urban plantings are a concern for the industry. To address this issue, a steering committee was formed, which through their collective experience have concluded that a variety of environmental stresses and unfavorable environments are likely to blame for the decreased survivability of urban landscape plantings. Alone and in combination, factors such as soil compaction, moisture stress, and light availability all influence tree survival. To further direct the steering committee, Landscape Ontario has requested that a literature review be completed on the available research which focuses not only on the stresses in the urban landscape, but as well as on the research towards potential solutions or mitigation strategies for these issues. The literature review is expected to provide a better understanding of the harsh urban landscape and guide the landscape sector towards the development of purchasing, planting, and maintenance specifications and standards. Additionally, this literature review provides direction for research initiatives that are intended to fill existing knowledge gaps and achieve a better understanding of the stresses which impact tree survival.

The review is informed by the Campbell systematic review method (http://www.campbellcollaboration.org/what_is_a_systematic_review/index.php). Using various databases (e.g. Science Direct, Google Scholar, and Web of Science), the scientific literature was searched using a variety of keywords in combination with and without various Boolean connectors (i.e. and, or, not, near, etc.): urban landscape, tree survivability, environmental stress, moisture stress, drought, flood, light availability, soil compaction, soil fertility, soil pollutants, maintenance, road salt, deicing, air pollutant, exhaust fumes, and air quality. Four review articles (Jutras *et al.,* 2010; Koeser *et al.*, 2014; and Waston *et al.,* 2014a, 2014b) provided the majority of the information for this review. As there was limited research available for hardiness zones 2 -5, research conducted in other hardiness zones is included in the review.

The results of the searches were analyzed to group the literature by environmental stress and by solution/mitigation strategy. The literature on each identified stress was reviewed individually and considered in combination with other stresses (such as drought and soil compaction) where the literature allowed such comparisons. The synthesis of the literature includes recommendations and strategies with particular focus on specification, purchase, planting and maintenance practices for improving the "success rate for caliper trees installed in harsh urban environments". The analysis of the literature also identified existing knowledge gaps, which provides the basis for decisions on research funding priorities in the nursery industry. Areas where further research is needed are highlighted in **bold** throughout the report.

Very little of the research actually took place in urban areas. Most research used simulated plot and the authors acknowledged the difficulty interpreting the results for the urban landscape. Finding ways to incorporate actual urban landscape plantings into research would help draw stronger conclusions as to how stresses actually influence trees. Some studies were successful in incorporating actual urban plantings by using university campuses as study sites (Swetts and Brown, 2000; Harris *et al.*, 2008).

INTRODUCTION

Greening the urban landscape has recently become a top priority for most municipalities. It is generally acknowledged that trees in the urban landscape provide a multitude of services. Some are environmental, such as: limiting the island heat effect, decreasing storm water run-off, and cleaning the air; while others are social, such as increasing happiness, and economic, such as raising property values (Roy *et al.,* 2012; Mullaney *et al.*, 2015). For those reasons and many more, increasing the number of trees in the urban landscape would be beneficial. This greening initiative has placed a demand on nurseries and landscapers to provide large quantities of trees that can survive and thrive in the harsh urban environment. For example, the City of Toronto has pledged to increase its canopy cover to 40% by the year 2060. To accomplish this, 57,000-114,000 trees would need to be planted annually on public land (City of Toronto, Parks, Forestry and Recreation, Urban Forestry, 2013). Yet, simply increasing the number of urban plantings is not the answer. Tree establishment and long-term survival are also key goals in a long-term plan to increasing canopy cover.

It is generally accepted that trees planted in the urban landscape do not live as long as those in natural areas; the life span of urban trees is often less than 15 years (Nowak *et al. 1990*). This is even more prominent when we look at the survivability of trees planted along major roadways and high-density urban areas compared to secondary or rural roadways and parks. These areas are typically characterized as having high soil compaction, variable water availability, limited soil fertility, and the presence of harmful chemicals and pollutants along with many other abiotic stressors. Unfortunately, all these stresses result in urban areas being less than ideal areas for the survival of trees. Jutras *et al.* (2010) studied the effects of urban environmental stresses in Montreal and found that many of these stresses result in measurable growth losses and even tree death. Failed urban plantings have become a major concern not only for the landscape industry, but also municipalities, who invest significant resources in urban landscaping.

General consensus is that the myriad of environmental stresses act not only alone but also in combination to greatly reduce the growth and survival of urban trees. Variability within the surviving urban trees is also a problem, with urban trees (e.g. *Tilia cordata*) showing significantly more variable growth (5.0-6.3%) than trees planted in a park environment (2.6%) (Buhler et al 2006). Remarkably, a tree with a 75cm diameter trunk is able to sequester 90 times more carbon, intercept 10 times more pollution and add 100 times more canopy cover than a tree with a 15cm diameter trunk (City of Toronto, Parks, Forestry and Recreation, Urban Forestry, 2013). Therefore, growth is also important towards attaining the benefits of increased canopy cover. The great environmental heterogeneity compounded with the stresses of an urban environment only further complicates the issue of urban tree survival.

Formal definitions for the concepts of "establishment" and "survivability" exist within the literature. For example, Levinsson *et al.* (2015) states "To become successfully established at the new growing site, the trees need to be coupled to the hydrological cycle of the site so that it may support the canopy with sufficient amounts of water without extra irrigation". Yet, the goal of urban landscape plantings is generally not for the canopy to be connected to the hydrological cycle. But rather, to provide a service, whether it is environmental, climatic, or aesthetic, and therefore a more colloquial definition of "established" will be used in this review. "Established" plantings will henceforth be defined as when a transplanted tree has adapted to its new environment and is generally regarded as in good health. Simply put, tree establishment refers to when the tree has rooted into its new environment, and is no longer experiencing the additional stress associated with transplanting (i.e. root loss and acclimatization to new environment) and normal growth rates begin to occur through a restoration to a balance root:shoot ratio such as described in Levinsson (2015). It is during this establishment phase that the highest mortality occurs for urban trees (Harris and Bassuk, 1994). Therefore, a majority of the literature available looks at increasing the establishment rate of trees with a goal of increasing the long-term survival.

In 2011 the City of Toronto commissioned a study to provide make recommendations for best practices that would allow the City to grow trees with a 40+ year life span and a 40 cm diameter at breast height. A best practices manual was completed in 2013: Tree Planting Solutions in Hard Boulevard Surfaces: Best Practices Manual. The study included an evaluation of existing municipal tree planting practices in eight North American municipalities, as well as consultations with multiple city departments and utility stakeholders, manufacturers and soil suppliers. The Best Practices Manual provides guiding principles, design details and specifications for tree planting and would be a valuable resource that could be adapted for and adopted by the landscape industry. It is available at https://www1.toronto.ca/city_of_toronto/parks_forestry__recreation/urban_forestry/files/pdf/TreePlantingSolutions_BestPracticesManual.pdf

Based on the review of the literature, eleven key factors were identified that critically influence the establishment and survival of urban tress: species selection, transplanting, site selection and preparation, soil compaction, moisture stress, mulching, salt and de-icing products, root damage, light, temperature, and post-planting management. Each of these factors is discussed in more detail below.

KEY FACTORS INFLUENCING ESTABLISHMENT AND SURVIVABILITY

1.0 Species Selection

Many common landscape trees are early successional species (i.e. rapid growth but low competitiveness), such as elms (*Ulums sp.*), green ash (*Fraxinus pennsylvanica*), red maples (*Acer rubrum*), and paper birch (*Betule papyrifera*) because of their shallow roots and rapid growth which facilitate transplanting and establishment (Larimer and Struve, 2002). Yet, this is rarely optimal for the long-term health and survival of landscape trees. Proper tree selection is likely the most important criteria in terms of achieving greater tree survival. The urban landscape is unique in that each planting site represents a distinctive environment. Therefore, understanding the requirements (soil, light, space, water, and nutrient) for individual tree species is imperative when making species selections. Inadequate skills and knowledge in species selection has been identified as a possible factor that contributes to poor survival (Conway and Vander Vecht 2015). Conway and Vander Vecht (2015) quote one survey respondent: "in my experience, most landscape architects don't have [appropriate] qualifications, and I often find myself wondering why it is the landscape architects who specify the trees, and not Urban Foresters" (p.4). They further report that 58% of the landscape architects who responded to their survey classify their knowledge of tree requirements as "good" as opposed to "excellent".

In addressing the need for proper species selection the City of Toronto employs Forestry Data Collectors to determine suitable planting sites and recommend species. The results of a survey involving four main actors in urban landscaping in the GTA (landscape architects, non-profit organizations, retail garden centers and nurseries, and city urban forestry staff) identified the parameters involved when selecting a tree species: sun exposure, available space, intended use, and proximity to other structures (Conway and Vander Vecht 2015). The Forestry Data Collectors in Toronto apply the most stringent parameters including native status, soil condition, diversity of nearby trees, and tree pests and diseases. The non-profit organizations identified that the species already present were an important factor in species decision, but not always to increase diversity. The NGOs mentioned that the species present gave clues as to what could survive in that area. Nurseries and garden centers use customer demand to determine which species to stock, but half said that the native status influenced their decision. Most notable is the remark from R. Vendrig (p.7) in which he claims that when a nursery cannot fulfill the city's demand, they will often purchase stock from other nurseries in the United States. Conway and Vander Vecht (2015) claim this is concern as out-of-country stock is relatively unknown in terms of growing practices as well as quality control. Furthermore, it is possible that the stock originates from a warmer climate leading to decreased survival during the harsh Canadian winters. Ware (1994) outlines the importance of provenance (geographic place of origin from naturally occurring populations) in the species selection decision. He recommends selecting "tough trees for tough situations"). This means selecting breeding stock from areas in their natural range which are prone to certain abiotic stresses (i.e. floodplains); or from areas near the border of their range as these relatively harsher environments and should produce more tolerant trees. For example, red maple (*Acer rubrum*) has a geographic range from Ontario (Hardiness zone 3-5) to Florida (Hardiness zone 8-11), yet trees that originate in hardiness zone 8 would fare poorly in hardiness zone 5 (Santamour, 1976). It would therefore be a best practice to select plants with a focus on matching the hardiness zone by considering subspecies, ecotypes and cultivars rather than simply picking a species.

The justification for tree species selection is not always based on increasing the survivability of the tree. The argument has been made that species selection can also contribute to biogenic volatile organic compounds and ozone production (Churkina *et al.*2015) and particulate matter reduction (Beckett *et al.,* 2000; Sæbø *et al.* 2012), which can be important factors in dense urban areas.

Resources are available to assist landscapers and city foresters in proper species selection. Decision support systems such as the models and software described by Kirnbauer *et al.* (2009) for Hamilton, Ontario are designed to incorporate expert knowledge, field data, and rule-based algorithms to aid in the species selection process (available from McMaster University's Sustainable Communities Research Group at:

http://www.eng.mcmaster.ca/civil/sustain/downloads.html). Grabosky and Gilman (2004) developed a predictive model for growth reduction based on soil volume in parking lots. While proper species and site selection are critical to the success of the urban landscape, it should be noted that species and site selection cannot compensate for poor planting practices (Grabosky and Gilman, 2004).

To facilitate landscapers and city foresters in making informed decisions on species selection, **it is advisable that a review of the literature concerning the tolerance of specific tree species be conducted.** Such work was done by Sjoman and Nielsen (2010) regarding eight species that are frequently planted in urban areas in Scandinavia. The authors reviewed the literature, both scientific and extension (i.e. nursery catalogues), regarding the urban use and tolerances of the species. The goal of the review was to condense and simplify the available knowledge to make it more accessible for those actually making the decisions on species selection. Other species-specific reviews have been conducted on maple (Swetts and Brown, 2000) and linden (Tenche-Constantinescu *et al.,* 2015) to determine their exact tolerances and uses in the urban landscape. A review of tree species with morphological and physiological tolerances to specific stresses in hardiness zones 2-5 would be recommended. Furthermore, there is a need for the development of best practices for species selection and site selection.

2.0 Transplanting

2.1 Transplanting Date

Transplanting date plays in an important factor towards the survival of a tree even in the most favourable environment. The optimal time for transplant occurs when the tree has time for root regeneration before winter, but not when it has fully leafed out as the increased evaporative demand would induce great water stress. It is important to leave time for root regeneration, as cold temperatures (ranging between 2-11˚C) will halt root growth (Watson *et al.* 2014a). The optimal time for transplanting therefore differs for each species and each location. Harris and Bassuk (1994) examined the effect of transplanting dates on four species (Scarlet oak (*Quercus coccinea),* green ash (*Fraxinus pennsylvatica),* Turkish hazelnut (*Corylus colurna),* and tree lilac (*Syringa reticulate*)) and found that, while there were general trends regarding the season, the most successful dates differed by species. It was concluded that the optimal transplanting date does not coincide with the period of active root growth as previously believed. It is also possible based on root:shoot ratios of red maple or red oak that a mid-summer transplant would result in greater stress than an early- or mid-fall planting (Larimer and Struve, 2002). **This suggests that species-specific information needs to be determined for hardiness zones 2-5 to determine optimal transplanting times.**

2.2 Transplanting Shock

Transplanting nursery stock into the urban landscape is one of the key sources of stress in urban tree plantings. Struve *et al.* (2000) defines transplant shock as "a temporary condition of distress resulting from injuries, depletion, and impaired function". Over the course of just a few hours, a tree leaving a nursery can be subjected to major changes in sunlight, water availability, nutrient availability, temperature, and even hardiness zone (Koeser, *et al.*, 2009). In order to reduce transplant shock, Gilman (1997) recommends a method to "harden off" trees in a nursery: field grown trees are dug, ball & burlapped and the root ball is irrigated frequently, while the foliage receives misting, which is gradually reduced over several months before the trees are planted in the landscape. This method is favourable as leaf loss after digging reduces the rate of evaporation and the roots, which are regenerated within the ball, can make immediate contact with the backfill soil after transplant. Moreover, these "hardened off" trees even acclimatize to the increase water stress from root loss, further increasing their survival once transplanted (Beeson & Gilman, 1992a). Transplant shock can be partially mitigated based on the timing of transplant (Larimer and Struve, 2002) as described above.

2.3 Production Methods

2.3.1. Container Production

Container production is more common for smaller caliper trees. Container trees that are transplanted are subject to severe water stress. This is likely related to the roots, even though there is limited damage to the roots (Gilman and Beeson, 1996; Fini *et al.*, 2014). Inadequate root ball volume, as well as circling roots, reduces the transplanted trees' ability to absorb water (Gilman *et al.,* 2003). The issues with transplanting container stock can be exacerbated if they are planted mid-season when they are fully leaved. This is due to the abrupt change in growing conditions (i.e. water shortages and increased sunlight). However, Fini *et al.* (2014) found that it was possible to pre-condition container grown *Fraxinus ornus* to be more drought tolerant in the landscape by increasing the sunlight irradiance for two months after bud break. Essentially, plants that were grown in full sunlight had the morphological and anatomical features (cuticle thickness, granular trichrome frequency, etc.) required to better tolerate the drought stress and increased sunlight irradiance once transplanted. Increased irradiance is typically only an issue for trees in less dense urban areas, and will be discussed along with the effects of poor irradiance in more detail below.

Because of the restricted volume for the root zone in container production, deflected roots are often a problem in conventional containers. This can result in long-term health issues for trees once transplanted in the landscape (Marshall and Gilman, 1998). While containers are effectively designed to prevent root deflection, **the long term benefits of the reduction in deflected roots is unknown, however; it is likely that trees are healthier in the long run** (Marshall and Gilman, 1998). The most successful container was a standard black plastic container with cupric hydroxide ($Cu(OH)_2$) applied at 100g/L with a latex carrier to the inside of the container (Marshall and Gilman, 1998). All the same, both Gilman *et al.* (2003) and Marshall and Gilman (1998) found that for red maple frequent irrigation was a more important factor than container type when evaluating containers designed to prevent root deflection.

2.3.2 Field Production

Field production involves digging trees from the field rather than containers to be prepared for transportation to the area where they will be transplanted. This method is extremely destructive to the root system of the tree. Field production tends to produce larger caliper trees. However, a smaller tree is able to retain a greater percentage of its root system, and can establish more quickly once transplanted. It is possible for a 10cm caliper tree to outgrow a 25cm caliper tree within a few years of being transplanted (Watson, 1985). This is because in more northern weather (hardiness zone 5) it can take 1 year per 1 inch of trunk diameter for the tree to achieve pre-transplant growth rates again (Watson, 2005). Smaller trees anchor into the ground quicker than larger trees, and are therefore able to withstand extreme weather conditions earlier (Gilman and Masters, 2010; Gilman *et al.,* 2013).

Ball and burlap (B&B) is a popular method of field production, which involves wrapping the root ball of a dug tree in burlap to prevent root desiccation; the burlap covered root ball can then be enclosed in a wire basket to protect its integrity. The removal of the wire basket has been controversial, yet Koeser *et al.* (2015) found that keeping the wire basket did not result in any decrease in growth and even provided greater stability support compared to partial or complete removal of the basket. It is recommended that the soil moisture of the root ball be monitored once a tree has been dug and is being stored (Koeser *et al.,* 2009). It is important to note that the root severance caused while digging is different and much more traumatic than the damage caused when root pruning. Along with root severance, it was found that the handling of dug trees was a considerable source of stress as the shaking and vibration of the skid steer or other mechanical equipment caused additional damage to the root ball (Koeser *et al.*, 2009).

Another method of digging trees is the bare root method, which involves digging trees during their dormant state to transplant. It is a riskier method of transplanting, especially for larger trees (>50mm caliper). Because of the harvest method, bare root trees can have 200% the amount of roots B&B trees have. Bare root trees are also much easier to move and plant, fitting in the bed of a truck and only needing a shovel. This makes them very convenient for urban planting (Buckstrup and Bassuk, 2000). When B&B, bare root, and fine root stimulation measures (i.e. air potted, root pruned, and fabric container grown) were compared for planting success, it was found that no specific production method produced red oak (*Quercus rubra*) and sweet cherry (*Prunus avium*) that fared significantly better in the urban landscape. It was also suggested that trees which underwent fine root stimulation measures required more irrigation than the other methods to remain healthy (Levinsson *et al.*, 2014). Similar results were found for green ash (*Fraxinus pennsylvatica*) (Hensley, 1993). Another study determined that the decision to plant either B&B or bare root is species specific, but most species under 50mm caliper should be able to be planted bare root if they are dipped in hydrogels and receive proper after planting maintenance (i.e. mulching and irrigation) (Buckstrup and Bassuk, 2000).

2.4 Transplant Depth

The depth at which a tree is planted has also been considered as a factor in successful establishment. Work done by Arnold *et al.* (2007) in Texas looked at five families of trees and shrubs, two of which are grown in Southern Ontario (*Fraxinus pennsylvanica* and *Platanus occidentalis*). When these trees were planted with their root collars 7.6cm below grade, there was a significant decrease in tree height and trunk diameter compared to at grade plantings. Gilman *et al.* (2010) and Gilman *et al.* (2015) both found that plantings below the root collar results in an increase in roots growing over the root collar, which can girdle the stem and create chronic stress or even tree death. However, these results conflict with the work done by Gilman and Grabosky (2004), which found no effect from the root collar planting depth on the survival and growth of live oak (*Quercus virginiana*). Soil type and irrigation regime differences have been recognized as possible reasons as to why the two studies found conflicting results (Arnold *et al.*, 2007). Bryan *et al.* (2011) found that planting trees above grade resulted in a decrease in tree stability with more trees being knocked over by the wind. Short term studies have shown that deeper planting can interact with poor drainage (i.e. water stress) to decrease the growth, water relations, and photosynthetic gas exchange of live oak (Bryan *et al.* 2005, 2006). **There is a need for additional studies that not only look at the interaction between these factors, but also for the investigation into family (or species) specific optimal planting depths.**

2.5. Transplant Amendments

The time between lifting and planting is incredibly stressful to plants as roots are very prone to desiccation. Root dipping techniques have been shown to effectively minimize the effects of root desiccation in conifers (Sloan, 2004), yet conflicting results exist on their use in deciduous trees (Heiskanen, 1995; Specht and Harvey-Jones, 2000). Hydrogel dips have been evaluated as methods to ameliorate the establishment of various species such as common hackberry (*Celtis occidentalis*), American hophornbeam (*Ostrya virginiana)*, and swamp white oak (*Quercus bicolor)* (Buckstrup & Bassuk, 2000), red oak (*Quercus rubra)* (Apostol *et al.*¸2008), and European beech (*Fagus sylvatica)* (Beniwal, *et al.,* 2011) with equal or better success than undipped bare root plantings. Hydrogrel root dips are able to store up to 150 times their own weight in water, protecting the roots from desiccation (Beniwal *et al.,* 2011). Most concerns regarding hydrogel are the potential phytotoxicity or their lack of benefit in less stressful environments, but the technique appears to be justified in soils with low water holding capacity (Apostol *et al.*, 2008) such as urban areas. Beniwal *et al.* (2011) took it one step further and examined the effects of a hydrogel root dip (Stockosorb K400, Stockhausen, Krefeld, Germany), which was also amended with *Paxillus involutus*, an ectomycorrhizal fungus. The results showed that the amended beech (*Fagus sylavatica*) had greater nitrogen uptake through increased fine root stimulation and production compared to the untreated bare root seedlings. These results suggest that a hydrogel dip, which is amended with an ectomycorrhizal fungus could increase tree establishment after transplanting through quick root regeneration.

3.0 Site Selection and Preparation

A proper understanding of a trees' below ground system is necessary for proper selection and preparation of a site, which will provide the greatest chance of survival. Jim (2003) outlines the misconceptions, which are often used to characterize root systems and states the reality of what occurs below ground: Essentially, most trees do not penetrate deeply into the ground and 1m of soil depth is sufficient. Roots tend to ground laterally rather than vertically, and can spread more than three times the diameter of the crown.

Finally, it is the fine roots that supply the majority of the water uptake and not the larger roots. These facts must be considered when selecting a planting location, especially in limited areas such as road boulevards and street sides.

A program was developed in Seattle to facilitate communication between developers and the city's urban foresters to protect urban trees. The Seattle Department of Transportation (SDOT) and the Seattle Department of Construction and Land Use (DCLU) work together to ensure that the street trees in the city receive the proper attention and care from developers and construction companies. Essentially both of the municipal departments provide the arboricultural knowledge and decision making for the developers to ensure trees are protected during planning and construction. This process is initiated when developers submit an "Early Design Guidance Review" to the DCLU to get a Master Use Permit. A city forester is then sent to the field site to evaluate the street trees and determine which trees need to be preserved and how. This opens a dialogue between the city and the developer, which continues until the completion of the development. The city forester oversees all excavations and provides an Air Spade (Guard Air Corporation)[1] to the developers to facilitate safe root excavation. The forester also makes periodic site inspections to ensure the developer is taking tree protection seriously. The developer cannot receive his Certificate of Occupancy until all city inspectors, including the forester, have signed off on the completion of the project (Ames and Dewald, 2003).

Through the literature it becomes apparent that urban planting designs and plans need to be an integral part of overall initial development designs, including the allocation of sufficient soil volume for proper growth (both above and below ground). This recommendation is emphasized in the work of Kuhn *et al.* (1985) and Meyers (1985), which evaluated the soil volume necessary based on expected crown size. Recommended soil volumes are also provided in the Tree Planting Solutions in Hard Boulevard Surfaces Best Practices Manual prepared for the City of Toronto (as described in the introduction).

[1] An Air Spade (Guard Air Corp.) is a tool that uses hypersonic blasts of air to fracture soil and safely expose roots.

Kent *et al.* (2006) evaluated the condition of 1,127 trees planted in Walt Disney World parking lot and found that trees that were planted in greater than 28m^3 of soil were all rated as good. DeGaetano (2000) developed a model that uses climatological data to estimate the soil volume needed to provide adequate moisture for the growing conditions that are likely for specific areas. For example, it was predicted that a tree in New York City, New York, with a 6m crown planted in 17m^3 of soil would face a water deficit every other year, if it did not receive additional irrigation (DeGaetano 2000). Furthermore, Troxel *et al.* (2013) developed allometric equations that permit better decision making on the spacing of plantings based on expected growth and space requirements. **These are promising tools and should be considered for adaption and adoption in Ontario.**

3.1 Soil substrate

The soil (including both the physical and chemical characteristics) provides water, nutrients, and anchorage for the tree. Yet, urban soils are often deficient in providing such needs. Far too often urban soils are taken for granted, and while the quality of planting stock might be detailed in the contract, the tree is planted in whatever soil is present (Jim, 2014). It has been estimated that 80% of the problems urban trees face can be attributed to poor soil, and that these poor soils act synergistically to increase the damage from other stresses (Watson *et al.,* 2014a). The changes in soil structure found in urban soils compared to natural soils is said to be one of the greatest limiting factors to tree growth and survival (Stewart and Scullion 1989).

Various soil substrates are becoming popular as methods to reduce soil compaction found in and around tree pits. Most notable are structural soils, which are used to increase soil pore size while still providing structural and load bearing support. Popular structural soils consist of 80% stone (CU Soil, Amereq Inc), 80% Stalite (Carolina Stalite Company) with 20% sandy clay loam and a hydrogel or 75% lava rock and 25% mineral soil (Davis soil, Xiao and McPherson, 2008). The benefit of soil substrates is that soil remains uncompacted in the spaces between the stones and allows for air exchange, water retention and root penetration. However, because the substrate is only ~20% soil, water and nutrient availability can be limited (Smiley *et al.,* 2006). Experiments with lava rock and expanded clay have shown that these structural soils have sufficient water storage capacity and the increased permeability facilitates rewetting (Braun and Fluckiger, 1998). Structural soils may also provide greater stability than conventional soil as they induce deeper roots (Bartens *et al.*, 2010).

Other cost effective methods such as increasing the amount of sand in the backfill have typically provided adequate results (Rahman *et al.*, 2011). This facilitates drainage as well as aeration in the root zone while still allowing water infiltration and large soil volumes. Nevertheless, Jutras *et al.* (2010) noted that sandy/gravel soils were linked to lower growth rates for trees. Suspended concrete over uncompacted soil has also been used to alleviate soil compaction in urban areas such as Charlotte, North Carolina, however; this greatly affects water infiltration and load bearing capability (Smiley *et al.,* 2006). While permeable surfaces have shown some success in alleviating the effects of water infiltration and limited soil volumes, they are not a viable technology in hardiness zones 2-5 because of the cold weather. **Despite the fact that suspended concrete has shown benefits in alleviating the effects of soil compaction, it has been shown that pear trees (*Pyrus calleryanna*) grew almost twice as much in open top pits compared to pits covered with suspended concrete (Rahman *et al.*, 2013). Therefore, finding ways to reduce soil compaction while leaving the surface exposed might be the best method and warrants further investigation.**

3.2 Soil Fertility

When in the nursery, trees are often in very fertile high nitrogen situations. This is optimal for rapid aboveground growth, yet detrimental to the root:shoot ratio, which is important once transplanted into the urban landscape (Larimer and Struve, 2002). Soil in the urban landscape is rarely as fertile as in the nursery. For that reason, fertilizer can be applied at transplant to increase soil fertility. Yet, this is not beneficial to all species. Slower growing and later successional species such as red oak show a more proportional response between root and shoot growth under increasing nitrogen rates. In contrast, early successional and faster growing species like red maple show more shoot growth (Larimer and Struve, 2002). This means that fertilizer applied to faster growing species will result in a lower root:shoot ratio, which is detrimental to tree establishment.

Increasing the nitrogen level available through fertilization at transplant has not been shown to provide a benefit to landscape trees. For example, Day and Harris (2007) found that B&B red maple and linden, which were transplanted in infertile but uncompacted soils did not benefit from fertilizer applications at twice the recommended rate. Furthermore, eleven species, including pin oak (*Quercus palustris),* eastern redbud *(Cercis Canadensis),* pears *(Pyrus spp.),* apples *(Malus spp.),* and ash (*Fraxinus spp.)*, do not demonstrate any response to different nitrogen levels during establishment (Shoup *et al.,* 1981). It is likely that improving soil conditions with organic matter, limiting soil compaction, and increasing soil volume provide a greater benefit than fertilization at planting (Harris *et al.*, 2008; Scharenbroch and Watson, 2014).

Nutrient loading has been used during nursery production to limit the effects of poor soil fertility in conifers (Xu and Timmer, 1999) and hardwood (Birge *et al.*, 2006; Salifu *et al.*, 2009), as well as to stimulate post-transplant growth. Nutrient loading is the increase in mineral nutrient content in leaf tissue while not causing a significant increase in plant growth (Malik and Timmer, 1995). **Nutrient loading essentially forces the plant to stockpile nutrient in its tissues for later use when soil nutrient availability is poor. However, this results in a lower root:shoot ratio along with greater pest susceptibility (from the increased nitrogen in the leaves) and it is unknown if this outweighs the benefits of nutrient loading (Larimer and Struve , 2002).**

3.3 Soil amendments

Urban soils, especially those found in street tree pits are typically low quality. Many commercial products such as Stockosorb (Evonik Industries), Drought Releaf (Selvig Corporation), and paclobutrazol are marketed as backfill amendments, which can alleviate moisture stress to increase growth and survival of landscape plantings. Unfortunately, unlike the marketing brochure claims, there is no evidence in the literature that these products provide noticeable benefits (Pellet 1971; Schulte and Whitcomb 1975; Ingram et al. 1981; Corley 1984; Smalley and Wood 1995; Ferrini and Nicese 2002;

Gilman, 2004). Nevertheless, there is unpublished evidence that amending highly compacted clay soils with organic matter such as compost can increase the growth of newly planted trees (Gilman, 2004). Adding organic matter (256,000kg/ha) into a sandy soil has also been shown to increase the establishment and growth of ornamental landscape plants (Loper *et al.,* 2010). According to Corley (1984), sites amended with 33% pine bark by volume required frequent irrigation to prevent damage compared to non-amended sites.

Soil pH is another growing condition can greatly affect the survival and growth of trees. A neutral or slightly acidic pH is optimal for most trees in the urban landscape, but often soil pH fall outside of this optimum. Granular sulfur works the best to lower soil pH, while lime works best to raise it (Messenger, 1984).

4.0 Soil Compaction

Soil compaction is among the most consistent stresses that street trees must deal with. Soil bulk densities above 1.6 g/cm^3 are often found in the urban environment (Jim, 1998) and can be much higher. Both english oak (*Quercus robur*) (Grabosky and Bassuk 1995) and apple (*Malus domestica*) (Ferree et al. 2004) exhibit impeded root growth when soil bulk density exceeded 1.5g/cm^3. Additionally, soil compaction tends to reduce the usable soil outside of the tree pit in the load bearing soils, compounding the limiting factors of soil compaction and soil volume (Buhler *et al.,* 2007). In fact, to limit the effects of soil compaction, it is recommended that "super pits" (12m^2 of loose unsealed surface area and 15m^3 of loosened soil volume) be dug when possible to maximize the volume of loose soil, increasing the rate of establishment and long term health of urban trees (Buhler *et al.*, 2007).

Soil compaction can influence the moisture content in the root zone. Compacted soil tends to form a crust at the surface, greatly reducing infiltration while increasing surface run-off, which is detrimental to storm water management and tree survival. Additionally, compacted soils along the sides and bottom of a tree pit can restrict the ability of water to disperse, causing oversaturation in the root zone and eventually root death (Watson *et al.*, 2014a). Smaller pore spaces in compacted soils result in greater water holding and thereby restrict gas diffusion, lowering oxygen levels (Currie, 1994). Ideally, the goal is to increase the volume of easily penetrable soil for the roots. One way to remediate a planting site, which has compacted soil is to dig trenches radially away from the tree and replace the soil with a more suitable backfill such as a sandy loam or vermiculite (Day *et al.*, 1995). This method can be further elaborated into root paths that create tunnels for root growth, leading them from their restrictive planting pits to areas of open space beyond the pavement (Watson *et al.*, 2014b). Vertical mulching is another possible remediation technique for soil compaction. This method involves drilling a series hole, approximately 2 inches in diameter to a depth of 12-18 inches no closer than 3 feet from the trunk. These holes are then backfilled with a suitable soil substrate such as peat moss or mulch (Johnson, 1998). Metal grating over street trees is effective at limiting the effects of pedestrian compaction, but results show no significant difference in soil compaction levels when they are present. It is likely that the vibrational forces of heavy traffic are the cause the soil compaction (Jutra *et al*., 2010). Similarly, covered surfaces with gaps such as flagstone or bricks do not improve gas diffusion issues associated with compacted soils (Weltecke and Gaertig 2012).

Intensive site preparation, which includes harrowing and disking of the soil up to 60cm deep, is an effective way to increase tree establishment and early growth. Yet, this is impractical for the confined spaces found in the urban landscape and with underground infrastructure such as utilities (Harris *et al.*, 2008). Laying plywood over the soil on construction sites was not an effective way to minimize soil compaction, but mulch or gravel placed over a geotextile showed some effectiveness (Donnelly and Shane 1986; Lichter and Lindsey 1994).

5.0 Moisture Stress

Soil moisture can be stressful in two different ways for urban landscape trees. On one hand, drought stress is one of the most common, and serious, stresses that threaten the establishment of urban plantings (Watson *et al.*, 2014a). Low infiltration caused by compacted or impermeable surfaces coupled with greater atmospheric evaporative demand due to higher temperatures often leave urban trees with limited water availability

(Levinsson, *et al.*, 2014). On the other hand, because of the poor soil quality or poor management practices such as over mulching, trees can be subjected to waterlogged soils, oxygen starvation in the root zone, and increases in root rot diseases such as *Phytophthora* (Hanslin *et al.*, 2005). In most urban situations it seems that a lack of moisture is a more prominent stress.

5.1. Drought

Unfortunately, when a tree is transplanted into the urban landscape it is possible that as little as 5% of its root system comes with it, often leading to major water stress (Percival *et al.*, 2006), regardless of water availability (Buhler *et al.*, 2006). One method to combat drought, and a consistent theme with other suggestions in this review, is to provide landscape trees with a larger soil volume. Unlike other reasons mentioned for greater soil volume, this allows trees to maintain a greater root:shoot ratio and thereby exhibit features associated with drought-tolerant species (Prevete *et al.* 2000). It is necessary that a tree have a root system with water absorbing capacity that is proportional to the transpiration rate of its canopy (Beeson and Gilman, 1992) hence the need for a large root:shoot ratio. Species selection can be incorporated into this aspect: species with high root:shoot ratios such as bur oak (*Quercus macrocarpa*) can be used in areas where there are greater soil volumes, which allow the tree to fully utilize this drought tolerance mechanism. Consequently, in urban areas where soil depths are typically shallow, a less deeply rooted tree with greater water use efficiency such as chestnut oak (*Quercus prinus*) would have a greater survival (Drunasky and Struve, 2005). Dirr (1998) confirmed that chestnut oak perform well in harsh urban areas such as parking lots. Yet, the deep rooting tendencies of most oaks makes them rather unsuccessful in small soil volume areas. Production method also plays a role in drought tolerance. For example live oak (*Quercus virginiana*) (Gilman *et al.*, 1998), laurel oak (*Quercus laurifolia*), East Palatka holly (*Ilex x attenuate* 'East Palatka') (Gilman and Beeson, 1996), and slash pine (*Pinus elliottii*) (Beeson and Gilman, 1992b) from field production all demonstrated a greater tolerance drought conditions compared to similarly produced container trees.

5.2 Flood

High soil moisture also results in a lower root:shoot volume through delayed root growth and root death, while the above ground biomass sees a slower decrease in growth (Watson *et al.*, 2014a). The decreased root:shoot ratio caused by flooding also decreases the drought tolerance. The transpirational demand of the larger canopy becomes greater than what can be supplied by the root system (Kozlowski, 1985). There are flood tolerant species, ranging from the ability to survive a few hours of flooding up to the ability to survive weeks of flooding at a time; with deciduous trees showing more tolerance than conifers (Watson *et al.,* 2014a). **There is little research on the effects of flooding in the urban landscape, and even less on remediation methods.** Ideally, trees should be planted in sites where water is able to drain, such as in planters with drain hole. Most oversaturation issues arise from soil compaction, and therefore most methods used to reduce soil compaction can also help with oversaturation.

6.0 Mulching

Mulching the surface area around the root ball is often used to shade the soil, reduce compaction, and prevent weed growth near the root ball of trees. Nevertheless, it is not beneficial to tree survival. Gilman and Grabosky (2004) found that applying 7.5 or 15 cm of shredded and chipped mulch around newly planted live oak resulted in lower infiltration by both precipitation and irrigating, which resulted in severely stressed trees. It took 5cm of water to rehydrate the mulched root balls after two days without water. Mulching right after planting was detrimental to the trees survival and required frequent and heavy irrigation to survive. Likewise, mulching has also been shown to negatively influence oxygen diffusion into the soil, reducing oxygen levels to below 2% after heavy rain when 5cm of mulch was applied over the root ball (Hanslin *et al.*, 2005).

Gilman *et al.* (2015) claim that no studies have indicated that mulching landscape trees increases their survival. Furthermore, the benefits of mulch could be emulated by keeping the surrounding ground free of turf grass, indicating that reducing the competition from turf grass might be more beneficial than mulching in terms of tree survival (Gilman *et al.*, 2015). This same study found compounding effects of planting depth, root remediation, and mulching. Trees that had received root remediation to correct for roots growing over the root collar were show to be at a greater risk of girdling. This is because the previously remediated roots would regrow over the root collar, but only when the tree was mulched. This suggests that trees that receive root remediation should not be mulched at all.

Conversely, Watson *et al.* (2014a) suggests there are plenty of benefits from mulching such as reduce evaporation from the soil and reducing the need for irrigation; insulating the soil, which provided 6˚C warmer soil in the winter compared to unmulched ground; and increasing fine root growth while reducing competition from grasses. However, Watson *et al.* (2014a) point out that a coarsely textured mulch will provide such benefits, while finer mulches will result in the negatives outlined previously.

It seems the benefits of mulching are contested in the literature. Most of the work which showed no benefit was conducted in Florida, while most of the work that showed a benefit occurred in the Illinois. **Determining the affects of mulching in hardiness zones 2-5 is an area warranting future research.**

7.0 Salt and De-icing Products

It is well known that salts (most commonly sodium chloride) and other de-icing materials (e.g. calcium magnesium acetate) have deleterious effects on roadside vegetation, yet certain species (e.g. honey locust (*Gleditsia triacanthos*) and white cedar (*Thuja occidentalis*)) have a greater tolerance (Townsend, 1980). Salt damage affects trees in two ways. The first is through direct contact with the foliage, caused by vehicular spray, which causes the foliage to experience a water deficit from the high salt concentration outside of the cells (Bryson and Barker, 2002). This form of injury is related to the distance from the road, and most of the damage is found within 30 feet of the road (Holmes and Baker, 1966). Salt deposition on the foliage causes greater direct damage than soil concentrations of salt, but as most de-icing and salt application occurs during the winter it is more of a concern for conifers than deciduous trees. That is not to say that salt deposition on dormant buds is not a concern, simply that there is much greater surface area on conifer needles when the salt is actively present (Holmes, 1960).

The second method of damage is through the increased salt concentrations found in roadside soils (Bryson and Bakker, 2002). For woody perennials, it is the concentration of chloride that is more toxic, as the woody roots and stems effectively prevent the sodium from reaching the leaves (Munns and Tester, 2008). Therefore, excluding chloride from de-icing products could be beneficial. As the trees' demand for water increases in the spring, so does the translocation of the salt into the roots and foliage. Furthermore, greater concentrations of sodium in the soil are also able to replace potassium, leading to nutrient deficiencies (Holmes, 1960), and influencing the granulation of soils, effectively increasing soil compaction and decreasing its drainage capability (Dirr, 1976; Day and Bassuck, 1994). This can be significant for trees planted in the median and in parking lots as they are very near salt sources from vehicle sprays, and have smaller soil volumes, which are unable to dilute the salts. Soil type and quality also contributes to the exacerbated issue in street side trees as poor drainage impedes the salts from being leached out of the root zone (Miyamoto, 2012). Saline conditions in the soil also lead to reduced root growth (Hanslin, 2011), and this can also be a problem for new urban plantings. As trees planted in the urban environment are already stressed by water availability, it is likely that a saline environment would exacerbate the stress, reducing survival.

The selection of salt tolerant species, as well as recommendations for eliminating salt damage, were discussed by Dirr (1976). Most notably, he compiled a review of the previous work done on the tolerance of tree species to salt and identified Honey locust (*Gleditsia triacanthos inermis*) as one of the most tolerant species to salt deposition on its foliage, due to waxy branches and protected buds. However, it is strongly noted that a trees' tolerance to foliar salt deposition does not infer tolerance to soil salt concentrations or vice versa. For example, white cedar (*Thuja occidentalis*) is identified as a species with tolerance to high soil concentrations but not to foliage deposition. Pines and sumacs were found have the lowest salt tolerance across a range common tree species found in Massachusetts, while maples and oaks showed little to no visible salt damage, even along highly trafficked roads (Bryson and Bakker, 2002). Johnson and Sucoff (1999) provide a comprehensive list of street trees in the state of Minnesota that are tolerant to high levels of soil salt. Some of the tolerant trees common in Southern Ontario include white poplar (*Populus alba*), Austrian pine (*Pinus nigra*), black cherry (*Prunus serotina*), and white oak (*Quercus alba*). Interestingly, even in areas where there was high salt damage on trees, no damage was found on either grasses or ferns (Byson and Bakker, 2002).

Alternatives to sodium chloride have been proposed, but for various reasons have yet to be adopted. For example, calcium magnesium acetate (CMA) has been proposed as an alternative to sodium chloride for de-icing roads in Europe and North America (Horner, 1988). However, while this product is less phytotoxic and corrosive, it is also able to mobilize trace elements (e.g. lead, nickel, iron, chromium) in the soil, which in turn are phytotoxic. Levels of trace metals in roadside soils have been increasing with the increase in emissions from vehicles (Amrhein *et al.*, 1992). Calcium chloride ($CaCl_2$) is another less phytotoxic de-icing salt, but is not widely used because of the increased cost and handling difficulty (Rich, 1972).

Aside from the selection of tolerant species, buffers/fences, and sodium chloride alternatives, Dirr (1975) suggests that trees in locations prone to receiving large amounts of de-icing material could benefit from a thorough irrigation to leach out some of the salt from the soil. This would not be a viable option on a large scale, but could be beneficial as a suggestion to homeowners looking to increase the survival of their at risk trees. Gypsum can also be applied to areas with high salt concentrations as the sulfate ions within the gypsum can bind with the sodium, while the remaining calcium can bind with clay, which will increase the soil permeability and aeration (Bartlett Tree Research Lab Technical Report #72). However, as gypsum needs to be applied at rates of 20-40lbs per 100 square feet, it does not seem like a viable solution for anyone but homeowners. **As such, there is a need for research on more tree-friendly de-icing products.**

8.0 Root Damage

The root zone of urban trees, especially street trees, is often shared with utilities and is therefore frequently disturbed by construction and below ground maintenance. It is clear that a healthy root system is imperative for the survival urban trees, meaning that limiting the damage to or increasing the regenerative capacity of the root system is vital for maintaining healthy urban trees. Roots tend to grow fairly straight for the first half meter before deflecting unless they are impeded at an earlier point (Stout, 1956). Therefore, it is important to consider that the above ground appearance of root location might not be the reality below ground. The critical root radius method proposed by Johnson (1999) to protect root zones involves allowing 1.5 feet of undisturbed soil for each inch of trunk diameter at breast height. While arborists and city foresters commonly use tree protection zones, Moore (2008) claims that such a general approaches are not sufficient. Rather, soil sampling and root system measuring should occur on site to protect the major (>50mm diameter) roots. The use of modern technology like ground penetrating radar is also recommended (Cermak *et al.*, 2000).

Trenching for the installation or maintenance of utilities has been reported as a major cause of urban tree failure. However, it has been shown that if the trench is dug three times the trunk diameter or more in distance from the tree on at most 2 sides of the tree, no observable reduction in growth occurs in pin oak (*Quercus palustris*) (Watson, 1998). Jim (2003) outlines various trenchless methods for installing or maintaining utilities, which co-occur in the soil with trees. For example, impact moles use ramming force to pass a pipe through the soil to create a pilot bore hole. The idea is to eliminate the need to dig trenches near the root zones of trees. Trenches can be dug as normal when outside of the root zone of any tree and the use of trenchless technologies can then be adopted near trees. For pliable utilities like cables, this can be done using a curved bore hole to go below the root system originating near the surface (Figure 1A). For rigid utilities such as pipes, the bore will have to originate at a depth below the trees roots to allow for a horizontal bore hole that goes below the root system (Figure 1B). The use of these methods greatly reduces the damage to roots. **Jim (2003) further suggests that a code of practice be developed for professionals involved in trenching, to ensure that the best methods are used to preserve urban trees.**

Occasionally, the below ground space occupied by trees needs to be excavated as part of construction or maintenance projects. While this can be done without killing the tree, root desiccation during excavation can been of concern. Yet, results suggest that it is a species specific response, and some species show no deleterious effect of root desiccation when excavated (Watson *et al.*, 2014a). As mentioned previously, the City of Seattle makes an Air Spade available to developers to minimize the physical damage to the roots during excavation (Ames & Dewald, 2003). Providing an optimal environment for a tree about to undergo root damage will increase its chances of surviving. Therefore, fertilization and irrigation around the tree base before and during the excavation will reduce the stresses associated with root loss such as water and nutrient demands by providing ample water and nutrients to the remaining roots (Johnson, 1998).

Root damage can also occur to roots near structures such as sidewalks and buildings when they undergo construction. To reduce this damage, it is ideal to prevent root growth into these areas in the first place. Root barriers, which impede root growth, can be used to stop roots from expanding into sidewalks and other urban infrastructure. This will reduce damage to infrastructure and to root systems during construction (Smiley *et al.*, 2006). Root barriers have not been shown to decrease tree growth or stability (Watson *et al.*, 2014a).

Percival *et al.* (2004) report that soil injections of sucrose at >25g/L of water stimulates root growth and can be used to regenerate fine roots more rapidly after mechanical damage such as from construction. Yet, there is a lack of available literature to confirm the effectiveness of this regenerative approach. Additionally, as roots regenerate from the point of severance, proper care should be given to damaged roots. For example, when roots are severed it would be beneficial to locate the point of severance and ensure that they are properly placed in a new soil profile (Watson and Himelick, 1982).

9.0 Light

Because of tall buildings in the urban environment, light can be a limiting factor in tree health. The effect of low light intensity is often compounded with the effects of high temperature and evapotranspiration, leading to increased stress on the tree. Shade tolerant species are better suited for the urban environment as they have a lower photosynthetic compensation point - the point where photosynthesis matches the rate of respiration (Saebo *et al.*, 2003). Jutras *et al* (2010) found that trees in residential areas of

Montreal received 1495 hours of light during the active vegetative growth period, while trees in commercial zones received only 205-480 hours. It was suggested that a threshold of 80% of the total potential irradiance is needed for optimal growth. The authors noted that trees that had strong growth in areas that typically provided poor growth were intercepting at least 80% of the total potential irradiance during the active growing season in Montreal. **Choosing sites with greater light might therefore be an important factor in the future and warrants future research.**

Trees that are planted close to streetlights tend to retain their leaves longer, especially on the side closest to the light. This results in trees becoming dormant later, increasing the risk of cold damage to new buds (Chaney, no date). Planting trees closer to street lights also increase the chance of root disturbance through construction and light maintenance.

10. Temperature

Trees play an important role in regulating temperature in the urban landscape. However, they are also subject to the stress associated with high temperatures, such as moisture stress caused by greater water use, or the inhibition of photosynthesis from above optimal temperatures (Leuzinger *et al.*, 2010). The urban heat island effect can cause a significant rise in air temperature relative to rural locations. In fact, a significant increase in canopy temperature was found in street trees compared to park trees for all species examined in Basel, Switzerland (Leuzinger *et al.*, 2010). **There is limited research available that characterizes the effects of low or high temperatures on tree survival, particularly the urban heat island effect.**

Temperature can also influence the root systems below ground. Soil temperatures were found to be 3.13˚C warmer in an urban playground compared to a forested area in New York City, New York (Mount *et al.,* 1999). Furthermore, soil temperatures under pavement can exceed 34 ˚C in the northern United States, with unpaved areas being 10˚C cooler (Halverson and Heisler 1981; Graves and Dana 1987). Watson *et al.* (2014a) states that while the upper temperature threshold is species specific, root growth stops at temperatures between 25-38˚C. On the other hand, temperatures below -5˚C can kill roots. Root development has also been shown to stop at temperatures between 2-11˚C (Watson *et al.,* 2014a).

Sunscald is defined as "the death of cambium tissue on the south to southwest side of trees due to rapid changes in temperature" (Roppolo and Miller, 2001). While sunscald is not a major concern, it does appear to be a source of mortality to urban trees, especially during the first winter they are in the urban landscape. This issue relates back to the root damage and water stress caused during transplanting. **There does not appear to be much research on the prevention and management of sunscald.** However, Litzow and Pellet (1983) found that Foylon 7018 and Ross TreeGards (no manufacturers information provided) work best at preventing a drop in temperature in the tree cambium. It is also likely that watering transplanted trees during their first year will provide protection against sunscald (Roppolo & Miller, 2001).

11.0 Post Planting Management

Proper after-planting management is essential for promoting good establishment and survival of urban trees. As it is obvious that the urban landscape is a stressful environment, it is crucial that we nurture urban trees longer than their rural counterparts. Visual assessments are often done to determine the health or vitality of a tree in the urban landscape. While this type of assessment is quick and inexpensive, the parameters used are both subjective and not always appropriate. For example, the water status of red oak (*Quercus rubra*) cannot be determined based on leaf colour (Levinsson *et al.,* 2015). Nevertheless, other assessments such as starch content, cambial electrical resistance, and bark chlorophyll fluorescence may be more accurate measures of tree health and establishment but are not viable options because of the associated complexities and costs. Koeser *et al.* (2014) reviewed the tree planting program in Florida and found that irrigation during the first year after transplant resulted in the greatest survival of the various post planting management techniques. The authors note that tree survival was exceptionally high compared to the northern US, Canada, and the UK, and so irrigation is not necessarily the limiting factor in our colder climate.

11.1 Stability

Typically biotic and abiotic stresses are considered in determining survivability, while physical stresses such as wind are often ignored. Trees in urban environments receive unique wind loads compared to trees in natural environments. Wind is a persistent and dynamic force, which induces a physical stress to individual trees and entire stands (James *et al.*, 2006). While rough surfaces reduce wind speeds, tall buildings create wind tunnels, which funnel the wind to create a greater exposure compared to natural environments (Kontogianni *et al.,* 2011). Uneven distribution of roots, because of impediment to their growth in one direction, will reduce the anchorage of the tree (Sundstrom and Keane, 1999), making the tree more susceptible to wind damage. Wind can cause bending and twisting to trees, which results in the breakage of tree parts or even uprooted trees should the supporting root system fail (Kontogianni *et al.*, 2011). Even the most careful site preparation can all be undone by a tree being knocked over by high wind conditions. Tree stability systems have been under development for quite some time, to help newly planted trees become established in the soil. Various commercial stabilization systems exist. Eckstein and Gilman (2008) evaluated nine systems (Figure 2) and found that Terra Toggle (Accuplastics, Inc.), Brooks Tree Brace (Brooks Adjustable Tree Brace System), and 2 x 2’s used to anchor the root ball provided the best stability. Above ground tree stabilization systems have been shown to damage the trunk, and therefore in combination with their results, the authors suggest the use of root ball anchoring methods.

11.2 Pruning

In 2002 Dujesiefken and Stobber published the results of a study that evaluated the effectiveness of the Hamburg Tree Prunning System (Figure 3) (first developed in 1989). It was found that flush cutting, which was previously used in landscape pruning, resulted in greater dieback of the cambium and decreased wound closure compared to the branch collar cutting suggested by the Hamburg Tree Pruning System. Essentially, branches with a collar should be pruned with an angled cut above the collar, while branches without a collar should be pruned with a parallel cut outside the branch bark ridge. Furthermore, it is recommended that dead branches be removed only beyond the swelling at the base, as this is living tissue from the stem. This method strongly suggests the avoidance of any radical pruning, which contradicts the interesting published results of Yang and McBride (2003), who suggested a very radical pruning of large trees (Figure 4). Yang and McBride (2003) mention that this method is only for rapid large scale plantings of large caliber trees. This method will likely never take hold for urban areas because of the poor visual appearance. However, it does have the ability to “repurpose” large trees that need to be removed. It also reduced cost of planting by decreasing management and planting costs through easier handling of the compact large caliper trees. While pruning can be an effective way to manage the root:shoot proportion of trees to increase their survivability, Ware (1994) compares urban pruning to the creation of large bonsai trees; pruning maintains a smaller canopy rather than promote root growth to retain a positive root:shoot ratio.

11.3 Irrigation

Street trees are often limited in their ability to utilize precipitation because of the small surface area available to allow for infiltration into the root zone. Tree canopies and buildings also intercept precipitation, further reducing the amount of water that reaches the soil. Irrigation of *Tilia* resulted in an increase in growth for established street trees even in a year when precipitation was 17% above the 30-year average for the region (Buhler *et al.,* 2006). This indicates that even mature trees with established root systems are water limited in their growth. Notably, irrigation volume does not compensate for infrequent irrigation (Gilman and Beeson, 1996). If irrigation is not going to occur frequently and no “hardened off” B&B trees are available, it is recommended that container produced trees be planted, rather than freshly dug field produced trees, to achieve a more rapid establishment (Harris and Gilman, 1993).

Gilman (2004) found that live oak which received three weekly irrigations of 7.6L of water initially performed better than trees that received a single irrigation of 7.6L of water every 10 days; yet after establishment (about 8 months) there was no difference in growth. However, similar trials done on red maple, which is less drought tolerant, indicated that frequent irrigation after transplanting led to a doubling in root growth compared to infrequent irrigation (Marshall and Gilman, 1998). Therefore, the need for irrigation is likely species dependent, and more important for less drought tolerant species.

It is important to note that excessive irrigation will reduce root growth as the tree experiences little to no water stress. This will prevent the tree from being able to retrieve enough water on its own should irrigation be stopped (Gilman *et al.*, 2009).

APPENDIX A - FIGURES

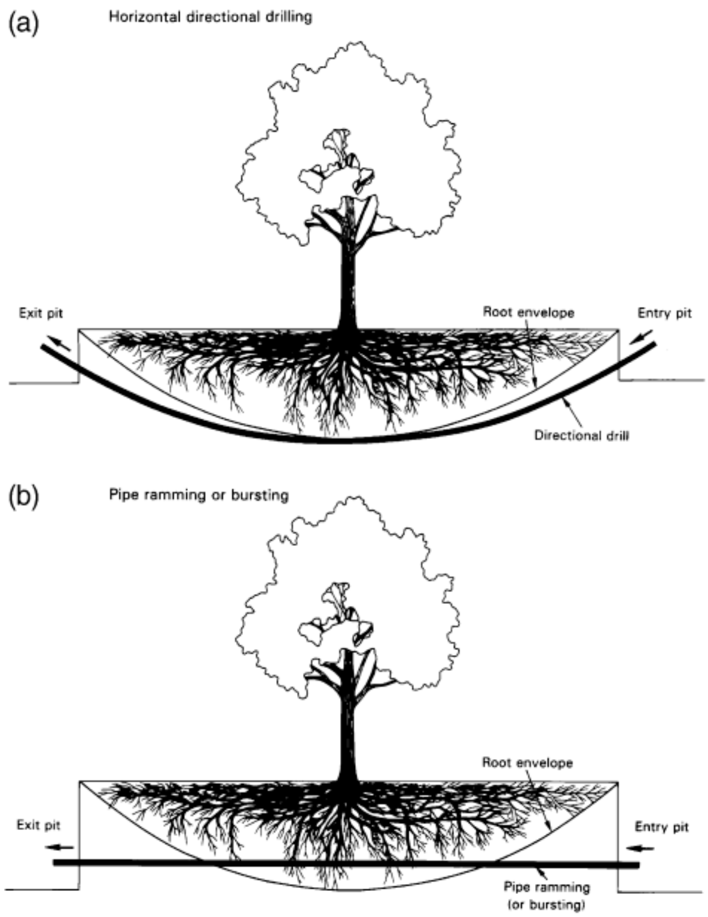

Figure 4 Trenchless methods can avoid damaging tree roots. (a) Horizontal directional drilling with a precision guidance system can bore under the root envelope and hence avoid any damage. Due to the relatively short distance involved in such tree protection work, it is suitable for the installation of flexible utility lines such as cables rather than rigid pipes. (b) Pipe ramming can be adopted to drive a metal pipe, either close- or open-end, largely under the root envelope. Pipe bursting or other analogous techniques without the need to open a trench can rehabilitate an existing pipe

Figure 1: Trenchless methods to install utilities without damaging tree roots (Jim, 2003).

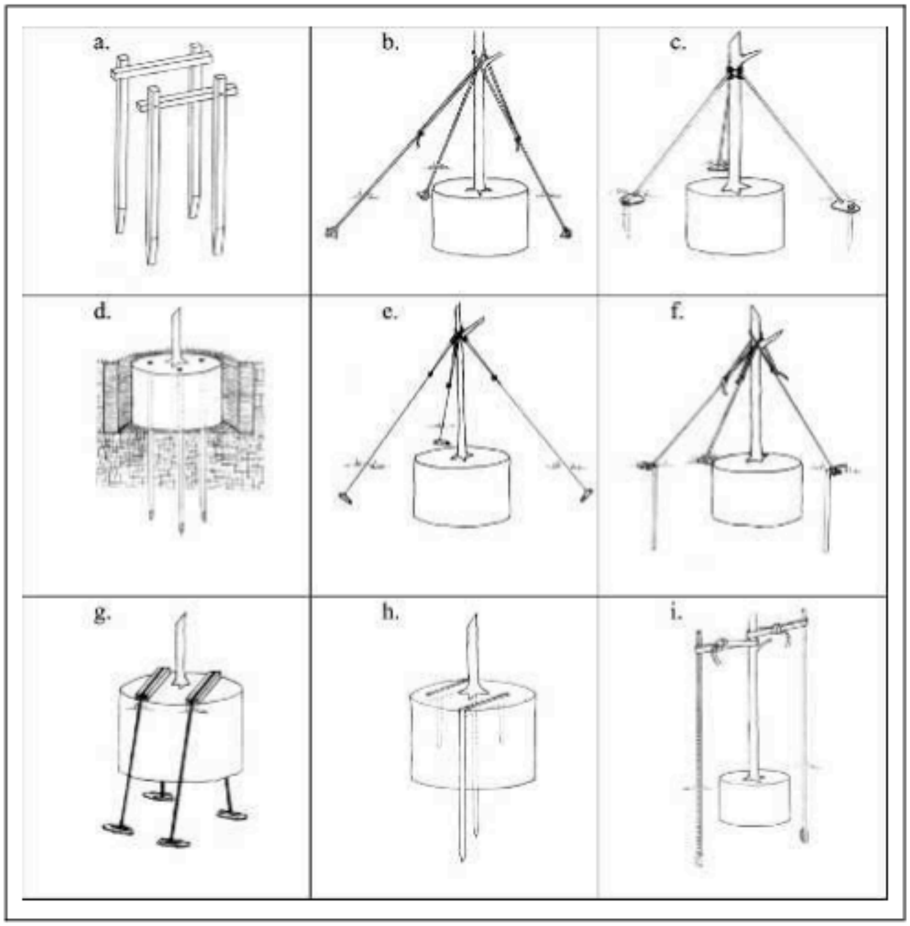

Figure 2. Illustrations of (A) 2 × 2's, (B) ArborBrace®, (C) Brooks Tree Brace®, (D) dowels, (E) Duckbill®, (F) rebar and ArborTie®, (G) Terra Toggle™, (H) Tree Staple™, and (I) T-stakes.

Figure 2: Different tree stability methods which were evaluated by Eckstein and Gilman (2008). Terra Toggle (G), Brooks Tree Brace (C), and 2 x 2's (A) were the most effective.

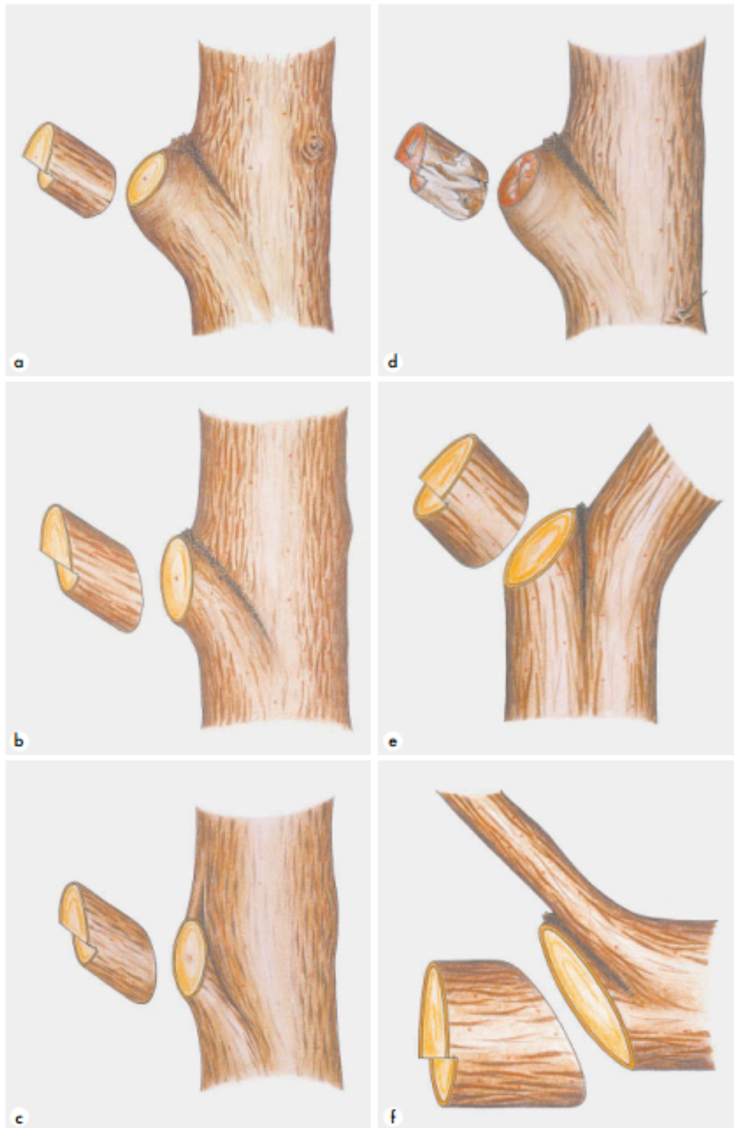

Fig. 12a–f. The Hamburg Tree Pruning System. **a:** The branch collar must remain at the stem, because it belongs to the stem tissue. The cut must be outside the branch bark ridge slanting downwards in accordance of the shape of the branch collar; **b:** Branches without a branch collar must be pruned outside the branch bark ridge and the cut must be straight to avoid cambial dieback; **c:** Branches with included bark must be pruned outside the lip-like rib or ridge and the cut must be straight. In spite of proper pruning it is possible that there is no cambial growth on top of the wound. Because of the included bark the cambium in this direction is poorly supplied with assimilates; **d:** Pruning of dead branches: the distinctive swelling at the base of the branch must remain at the stem. **e:** Codominant stems with more than 5 or 10 cm in diameter should only be partially reduced rather than removed completely. If removal is unavoidable the cut must be made outside the branch bark ridge and often the cambium at the lower side of the wound dies back several centimetres, because it can not be supplied with assimilates; **f:** For pruning to a lateral branch (reducing cut, in this case to the side) the cut must be made outside the branch bark ridge. Illustration: Gunnar Kleist.

Figure 3: The Hamburgh Pruning System created by Dujesiefken and Stobber (2002) which details how to prune branches based on branch collar and health.

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