Predictive equations for crown diameter and trunk flare diameter at ground line for four urban landscape tree species in Minnesota

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Abstract

Trees are an integral part of the urban landscape, from our backyards to lining our streets. Media outlets cover disease and invasive pest issues in urban forests, but there is little mention regarding infrastructure and planting challenges facing urban foresters. Research has shown urban trees have numerous benefits for society, many of which are not realized until trees have grown to a significant size. However, many trees are removed every year due to their negative impacts on urban infrastructure before their benefits are fully realized. Trunk flares and roots can lift sidewalks, and tree canopies often interfere with buildings or overhead utilities. This study's intent was to create biological growth models for two tree genera that are commonly used as street trees in Minnesota landscapes with the goal of reducing infrastructure damage as a result of conflicts with urban trees. The models will provide urban foresters and urban planners with a practical method for predicting trunk diameter at ground line and crown width in order to improve urban infrastructure planning that involves hardscapes and trees.

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Introduction

Brief history of urban forestry

Urban forestry includes the planting and maintenance of trees on streets and in natural areas within the built environment. The term "urban forestry" came into common usage during the 1960's (McPherson E. G., 2006; Johnston, 1996). However, urban forestry as a practice is considered to have started in North America during the late 1700's. Prior to the 1700's, European immigrants who settled in the New England states dedicated much of their time to clearing heavily forested land. Cleared land became the location for agricultural fields and early settlements. In 1896, Massachusetts passed the first tree warden laws, which enabled municipalities to appoint tree wardens who were responsible for the maintenance and planting of municipal trees (Ricard, 2005).

Planting trees in the urban environment was initially done as an effort to beautify villages and towns as they grew in population and economic prosperity. Trees for shade and ornamentation were often planted by private citizen organizations (McPherson E. G., 2006). Tree selection was based on species that remained after the land had been cleared or species brought from settlers' country of origin. By the late 19th century, new professions were being created to manage and maintain trees in the rapidly urbanizing New England states. During this period, educational institutions and governmental agencies worked to address the issues in the burgeoning field of urban forestry. Educational programs and laws were developed to define the responsibilities of tree wardens and urban foresters (Ricard, 2005).

Many of the trees in newly developed towns were planted in “tree-lawns”, which were wide strips of land typically between streets and buildings (Ricard, 2005). The practice of creating and maintaining wide strips of land between buildings and streets was adopted from boulevard designs originated in France. The original design intent of boulevards was to provide pedestrian access to shops and as a means to provide ornamental landscape features, such as trees, to busy Parisian streets. The term boulevard represents three basic designs. First, the central median boulevard design is characterized by a wide landscaped area, usually planted with trees, flanked by roads. These medians were designed as a pleasant space to walk through a particular section of town. Second, the multi-way boulevard is characterized by a large roadway built to accommodate through-traffic with generous tree lined sidewalks on either side and secondary roads on the opposite side of the sidewalk for slower local traffic. The multi-way boulevard style has not been widely adopted in the United States. The third boulevard type is a wide street flanked by tree-lawns and sidewalks (Jacobs, MacDonald, & Rofe, 2002). This third style is the most common in the United States and is the primary focus of the following research.

Due in part to the efforts of landscape architects such as Fredrick Law Olmstead, the importance of incorporating natural systems into urban areas became a reality in many U.S. cities. Parks and boulevards helped establish trees as part of urban infrastructure (Jacobs, MacDonald, & Rofe, 2002). However, as technology advanced, roads were widened to accommodate increased automobile traffic. The widened streets recruited more space, which was generally taken from boulevard planting space thus narrowing the amount of space available for trees. Additional technological advancements in centralized water, sewer, gas, and electrical transmission lines also reduced available boulevard planting space. Trees were allocated less growing space and any remaining space needed to be shared with the increased technological infrastructure (Miller, 2007). Functional street and boulevard designs took precedence over designs incorporating trees.

Benefits of urban trees

Over the last two decades, the field of urban and community forestry has seen a paradigm shift from aesthetic objectives to objectives encompassing economic, environmental, and societal benefits (McPherson E. G., Urban Forestry in North America, 2006). Collectively these new objectives are often referred to as simply the benefits of trees.

Economic benefits include an increase in property values. Residential property values can be increased by as much as 9.5% in areas where property has abundant tree canopy cover (Morales, 1980; Dimke, Sydnor, & Gardner, 2013). When large healthy trees are within 100 m of a single family home, property values are positively affected. Single family homes in Minnesota with healthy trees experienced an average increase in price of $1,371 (Sanders, Polasky, & Haight, 2010).

Generally, and not surprisingly, large trees with broad canopies provide the greatest economic benefits (McPherson E. G., 2003). An estimated annual savings of $3.8 billion for U.S. cities has been attributed to the removal of over 700 thousand metric tons of air pollutants by urban trees canopies. Air pollutants are removed through interception of particulate matter by leaf surfaces and uptake of pollutants via the leaf stomata (Nowak, Crane, & Stevens, 2006). It stands to reason, all else being equal, that larger tree canopies in an urban area provide greater value in terms of air pollution mitigation. In Modesto, California, the estimated economic benefit of street trees ranged from $\$55/_{tree}$ for small trees to $\$183/_{tree}$ for large shade trees annually. Economic benefits include energy savings, air quality improvement, CO_2 reduction, storm-water runoff mitigation, and aesthetic valuation (McPherson E. G., 2003).

Global climate change is currently an international issue, with much of the public discourse centering on increased levels of atmospheric carbon dioxide (CO_2). Increased levels of atmospheric CO_2 are believed to be responsible for everything from an increase in acidification of oceans resulting in decreased fish populations to warming of soils in boreal forests (Hoegh-Guldberg & Bruno, 2010; Melillo, et al., 2011). Urban trees have been estimated to sequester between 350-750 million metric tons annually of atmospheric carbon (Nowak, 1993). Total atmospheric CO_2 reduction is attributed not only to the sequestration of carbon by trees, but also to reduced energy consumption (and subsequence reduction in CO_2 emissions) as a result of shade and evaporative cooling by trees (Brack, 2002).

An additional environmental benefit provided by trees is the reduced leaching of soil nutrients and increased retention of soil water. Reduction of leached nutrients and retention of soil water is achieved, in part, through hydraulic redistribution via tree root systems. Tree roots have been shown to retain water and nutrients as well as move water both vertically from the roots to the canopy and laterally through soils from wetted soil surfaces to drier soils (Burgess, Adams, Turner, & Ong, 1998). Redistribution of soil water from an area of low water potential to an area of high water potential adds to our understanding of the importance of healthy tree roots and available rooting volume in mitigating the impacts of storm-water runoff and nutrient leaching. Tree roots, unaided, can alter drainage and water storage capacity of compacted urban soils. Infrastructure enhancements such as, suspended pavement systems and engineered soils, can increase rooting volume available to urban trees, which in turn increases storm-water infiltration and reduces runoff (Bartens, Day, Harris, Dove, & Wynn, 2008).

Tree canopies also contribute to mitigating storm-water runoff through interception of rainfall and trunk flow delivery of rain water to the soil surface where infiltration and root absorption can begin. Storm-water intercepted by the canopy slows water reaching the soil surface, ultimately increasing infiltration, and creates evaporative losses of storm-water (Bartens, Day, Harris, Dove, & Wynn, 2008). Reduction in urban storm-water runoff lessens the total amount of polluted or nutrient enriched water reaching lakes and rivers, as well as an abatement of storm-water treatment and increased flood avoidance (Xiao & McPherson, 2002). Mature, large, healthy trees with broad canopies provide the greatest benefits (McPherson E. G., 2003).

Roots in the urban environment

Tree canopies are highly visible and when a tree canopy is compromised through cultural practices or natural events it is readily apparent. Smaller canopy means less storm-water and pollution mitigation as well as less shade, creating noticeable impacts on a community. Acknowledging that the distribution of roots varies among sites and species, the root structure of most tree species are below ground, making root damage more difficult to see. However, the impacts of damaged roots are equally, if not more deleterious than canopy damage. The horizontal and vertical distribution of roots affects a tree's ability to obtain water and nutrients, impacting the growth and health of a tree.

Tree roots do not sense water or nutrients and root growth is considered genetically plastic. Roots grow randomly into the surrounding soil, dying if conditions are unfavorable or expanding and growing in areas conducive to growth (Harris, Clark, & Matheny, 2004). Tree roots grown from seed in their natural habitats are influenced by the interaction of genetics and soil characteristics. However, transplanted trees have rooting characteristics more heavily influenced by cultural practices and soil characteristics than by genetics (Carlson, Preisig, & Promnitz, 1980). Favorable growth conditions for roots are found in any soil or growing medium having adequate levels of moisture and oxygen for a given species (Urban, 2008).

Urban soils are often of poor quality, shallow, highly disturbed, and tend to be heavily compacted. Compacted urban soils induce a shallow rooting response in most trees (Patterson, 1976). Impervious surfaces near trees results in reduced water availability from precipitation and reduced available rooting space. The compacted nature of urban soils and impervious surfaces contribute to the tendency of tree roots to grow near the soil surface, regardless of species (Patterson, 1976; Cermak, Hruska, Martinkova, & Prax, 2000).

Uses of porous pavements have gained some popularity, in recent years, over impervious pavements as a means to decrease storm-water runoff and increase tree growth. However, when a compacted subgrade and gravel base are used with porous pavement tree growth in height and diameter is no different than that of trees growing near impervious pavement (Morgenroth & Visser, 2011).

Cermak, et al. (2000) found roots near infrastructure were no deeper than 1.4 m and few living roots were found past curbing under asphalt paved roads. Areas with compacted soils had less relative root growth as compared to soils that were not compacted. Trees developed less total rooting area and fewer number of roots in confined and compacted spaces (Cermak, Hruska, Martinkova, & Prax, 2000) resulting in greater stress on trees and reduced overall tree health (Manion, 1981). Species unable to develop shallow roots do not perform well in urban soils, as the root systems remain under-developed reducing their ability to obtain water and nutrients (Patterson, 1976).

Urban tree health and condition

Trees in poor health and condition do not grow as large or provide the same level of benefit as compared to trees in good or excellent health and condition. Factors considered important in street tree health are detailed in Table 1 and Table 2.

Table 1. Biotic and abiotic factors considered most important in tree health (Berrang, Karnosky, & Stanton, 1985).

Factor	Health implication
Excess soil moisture	Decreased health
Mounding of soil over roots	Decreased health
Soil salt	Decreased health
Overall root system size	Smaller root system – decreased health

Table 2. Cultural and biotic factors attributed to decreased health in street trees (Chacalo, Aldama, & Grabinsky, 1994).

Factors
Planting in inappropriate locations (e.g. space too small for mature size)
Poor species selection (e.g. selecting a large tree for use under utility lines)
Lack of planning and maintenance (e.g. no consideration for space or species needs)

Factors listed in Table 1 and Table 2 can be distilled to the right tree, in the right place, planted correctly, and maintained over time. However, a complete analysis of a planting site is difficult and costly when dealing with an entire urban forest. Sanders, Grabosky, and Cowie (2013) recommend a more reasonable approach to site analysis wherein the total surface space available for planting is assessed. The ultimate goal is to provide space for larger, healthier, and longer lived trees capable of providing the many benefits previously described.

Infrastructure and urban trees

The benefits provided by urban trees do not come without costs. Annual costs of maintaining street trees in Modesto, California, ranged from $7.66 to $54.31 in 2002, with larger, faster growing trees costing more to maintain. Costs for urban trees are primarily attributed to pruning, with removal a distance second, and planting/establishment costs contributing the least amount to the total costs (McPherson E. G., 2003). The economic impact per tree can be expected to vary based on location, species, and size; however, the general economic trend is a net benefit provided by urban trees. It should be noted that the cost of managing urban trees cited above does not include the costs to infrastructure damaged attributed to trees.

Survival of urban streets trees is a complex issue involving many factors from species to planting site conditions. The estimated mean life of urban street trees is 28 years with a population half-life of 20 years (Roman & Scatena, 2011). Tree longevity is a function of species, adjacent land use, and tree health. Intense commercial land use has a high concentration of impervious surfaces reducing the total amount of water available for tree use and trees adjacent to intense commercial land use fare the poorest (Nowak, Kuroda, & Crane, 2004).

Overall urban street trees grow slower than their open grown[1] urban counterparts. Using the surface site analysis technique developed by Sanders, Grabosky, and Cowie (2013), *Acer platanoides* was found to be an average of 7.6 cm DBH greater in size for mature trees in open-grown conditions compared to trees in boulevard style restricted spaces. *Acer saccharinum* had an average of nearly 15.2 cm greater DBH for open-grown trees than trees grown in boulevard planting spaces. DBH is positively associated with canopy size (Ek, 1974; Frelich, 1992), meaning a reduction in DBH will, on average, result in reduced total canopy size (Sanders, Grabosky, & Cowie, 2013). Reduced canopy results in reduced net benefit of street trees.

Comparisons made using known ages and DBH showed slower growth for trees in restricted spaces, which can be attributed to reduced water available as a result of

[1] Open grown as defined by Sanders, Grabosky, and Cowie (2013), means no growing space restriction within the drip.

impervious surfaces and reduce soil volume typical for two or more sides of urban street trees (Quigley, 2004). Quigley (2004) noted the ultimate size in DBH reached by trees in both open-grown areas and street trees have at least the potential to be the same if boulevard planting spaces are improved.

Sidewalks

Impervious surfaces or infrastructure refers primarily to sidewalks and curbing constructed from asphalt or concrete. The current design needs of sidewalks in the urban landscape are addressed principally from an engineering perspective and tree placement is of secondary concern. The placement of trees is a function of available boulevard planting space after sidewalk and other abiotic infrastructure concerns have been addressed (Lee, Jang, Wang, & Namgung, 2009).

Designers and managers of urban sidewalks must be cognizant of the Americans with Disabilities Act (ADA). Sidewalk design that limits mobility in a community contributes to social isolation resulting in a negative social impact. A United States 5th Circuit Court of Appeals ruling concluded that sidewalks are an essential means of access for persons with disabilities and that sidewalks made or altered since 1992 must be made reasonably accessible (Ferleger, 2012). Sidewalks damaged due to conflicts with trees should be considered a design flaw that ultimately limits people with and without disabilities and therefore not in compliance with ADA requirements.

The concrete slab system of sidewalk design is commonly used and consists of individual concrete sections laid contiguously, usually parallel to the adjacent street, with a thickness between 10 and 15 cm. Paving with concrete is preferred due to the relative durability and low maintenance compared to other materials. However, the concrete slab system has been shown to have the most deleterious environmental impacts when compared with other systems without regard to slab thickness (Oliver-Sola, Josa, Rieradevall, & Gabarrell, 2009). Deleterious effects of concrete slab pavement systems include reduced storm-water infiltration and increased CO_2 concentration in soils under and near pavement, which may inhibit tree root growth (Viswanathan, Volder, Watson, & Aitkenhead-Peterson, 2011).

Concrete used in sidewalks is typically composed of cement, coarse aggregate (maximum size of 19mm), and a slump measure of 50 to 100 mm and air entrainment of 5.5 to 8% to produce strength of 25 to 35 MPa. A sub-base is prepared by grading and compacting the native soil to provide a uniform base upon which the concrete will be poured. Sub-base is typically 15 cm in thickness with a 15 cm thick sidewalk. The removal of the native soils and replacement with a granular sub-base is recommended in order to reduce the expansion and contraction stress differences to the concrete slabs. The average service life of concrete sidewalks is 20 years (Rajani B. , 2002).

Sidewalk damage can result if sub-base compaction is not uniform or the native soils used as a sub-base have a tendency to shrink and swell with changes in the moisture gradient. Concrete tensile strength is approximately 15% of the compressive strength and freeze-thaw cycles can produce a tensile force that exceeds the tensile strength of concrete sidewalks resulting in cracked sidewalks (Rajani & Zhan, 1997). When the sub-base is adequately prepared, damage resulting from freeze-thaw or tree root expansion is seen as lifting (Rajani & Zhan, 1997; Oliver-Sola, Josa, Rieradevall, & Gabarrell, 2009). The space between a concrete sidewalk and soil surface often provides an ideal combination of moisture and oxygen. Root presence under sidewalk joints located within two meters of the trunk was found nearly 100% of the time, regardless of species (D'Amato, Syndor, Hunt, & Bishop, 2002). Greater attention should be given to sidewalk design which balances the deleterious impacts of abiotic infrastructure with development needs including biotic infrastructure.

Conflicts and economics of urban trees

Conflicts between sidewalks and trees are not new. Sidewalk damage is hazardous to people and it is costly to repair. In 1975, California estimated sidewalk repair due to damage by tree roots at $27,000 annually (Wagar & Barker, 1983). In 2012, Hutchinson, Minnesota spent $87, 655 on sidewalk, trail, and walkway maintenance and repair. Thirty-three thousand dollars were spent to repair concrete sidewalks throughout the city, of which 15% of the repair costs were attributed to damage by tree roots. Asphalt trails were repaired at a cost of $25,400, 40% of which was attributed to damage by tree roots (Olson, 2012). Damage to sidewalks has been found to increase with increasing DBH and decreasing boulevard width. Curbing was damaged less frequently than sidewalks, suggesting the greater depth of curb construction creates an environment that is less hospitable to root growth (Wagar & Barker, 1983).

Sidewalk damage from roots is highly variable as deep rooted species may become shallow rooted in respond to compacted soil conditions. In the City of Los Angeles, California, site inspections of sidewalks to be repaired showed that 90% of damaged sidewalks had tree roots in the damage zone. Inspectors attributed restricted growing space as the leading cause of conflicts between trees and sidewalks (Gonzalez, 2006). Damage that occurred to paved areas could be attributed primarily to changes in the environment under the paved area (Rajani & Zhan, 1997) and the majority of sidewalk damage caused by trees occurred when the sidewalk was in close proximity to the trunk flare (Centre for Ecology & Hydrology, 2006).

Cincinnati, Ohio spends $2 million annually on sidewalk repair, and trees were reported as a major factor in sidewalks needing repair. Despite significant dollars spent on repairs, 21 lawsuits were filed as a result of sidewalk damage in 2000. Sidewalks in Cincinnati have a planned service life of 20-25 years and significant damage to sidewalks from tree roots begins when tree reach 25.4 cm in DBH (Sydnor, et al., 2000). Using equations derived by Frelich (1992) *Fraxinus pennsylvanica*, a common street tree, reaches an estimated 21.8 cm in DBH in 20 years and an estimated 28.9 cm in DBH in 25 years. At approximately year 22, *Fraxinus pennsylvanica* reaches an estimated 25.4 cm in DBH. This means some sidewalks reach end of service life cycle before trees cause damage, in which case tree roots are likely damaged during end-of-life sidewalk maintenance. Trees that reach 25.4 cm in DBH before sidewalks enter their end-of-life have a higher probability of damaging the sidewalk, quickening the need for repair or replacement. The interaction between trees and certain soil complexes may be responsible for sidewalk lifting (Sydnor, et al., 2000). Conflicts between tree roots and sidewalks are highly probable where large mature trees are present with restricted rooting volume, shallow top soil, and a distance between the trunk and sidewalk of less than 3 m (Randup, McPherson, & Costello, 2001). Sydnor, et al., (2000) points out that sidewalks failing outside of the service life (20 years) should not be considered the fault of the tree. Trees damage sidewalks and sidewalk maintenance damages trees in a seemingly cyclical pattern.

A survey of 18 cities in California estimated $70.7 million was spent on infrastructure repairs (McPherson E. G., 2000). Sidewalk repair accounted for $23 million, curb and gutter repairs $11.8 million, and legal costs associated with trip-falls at around $10.1 million annually. Restricted planting space and species selection were attributed as the primary factors of infrastructure damage. Tree root related repairs accounted for 70% of all sidewalk repairs, 48% of all curb repairs, and only 3% of all street repairs. In the 18 cities participating in the study, a total of 2,993 trees were removed in one year as a result of infrastructure incursions at an average cost of $537 per tree. Trees removed were typically in the range of 50.8 to 63.5 cm DBH. An awareness of public safety, conflicts between trees and sidewalks typically resulted in the removal of trees (McPherson E. G., 2000).

Root barriers have been and are used as a solution to tree root and sidewalk conflicts. The primary purpose of root barriers is to deflect roots away from infrastructure in order to avoid conflicts between tree roots and infrastructure. Gilman (2006) reported some root barrier treatments did have a statistically significant effect on rooting depth; however, he noted actual instances of installation were of minimal value in terms of protecting infrastructure. Roots growing beyond barrier depths often grew back toward the soil surface where pore space and moisture are at a premium (Gillman, 2006). Smiley (2008) found that use of root barriers were somewhat successful at reducing infrastructure conflicts only in specific soil and site conditions. Root barriers were found to have no negative impacts on tree stability (Smiley, 2008).

Overall, root barriers do not appear to be a long term or cost effective solution for reducing tree and sidewalk conflicts. More reasonable solutions appear to be those solutions that do not require root severance or restricting rooting space, but rather increase the available rooting space. Use of meandering sidewalks that go around trees, sidewalk ramps that go over tree roots or the use of flexible pavements can increase rooting space and reduce repairs without reducing functionality of the sidewalks or trees (McPherson, Gonzalez, Monfette, & Lorenzen, 2006).

Not all tree and sidewalk interactions are negative; trees can provide a benefit to the life span of sidewalks. A survey of sidewalks revealed sidewalks without tree canopy cover had more cracks when compared to sidewalks with cover by tree canopy. The increase of sidewalk damage in the absence of trees was attributed to soil complexes under the sidewalk experiencing wider temperature and moisture fluctuations (Sydnor, et al., 2000).

Sidewalks are not the only casualty in conflicts between trees and sidewalks. Construction activities such as street widening, curb and sidewalk repair or replacement negatively affect tree survival and condition, which in turn negatively impacts the value of street trees (Hauer, Miller, & Ouimet, 1994). Injury to tree roots, particularly within 1.2 m of the trunk at ground line, greatly reduces tree health. The reduction in tree health is attributed to the presence of a high number of water-absorbing roots located close to the trunk. Central root systems of trees extend 1.8 to 2.1 m outward from the trunk and provide support and anchoring. Large roots originating from the trunk tend to taper rapidly within 1.8 to 3 m and contain the majority of sinker roots which provide stability. In order to maintain stability, root severance should be avoided within 1.8 to 3 m of the trunk (Hamilton, 1988).

Street trees present at the time of construction activities have lower survival rates than trees in similar spaces where no construction activity has taken place. As boulevard planting width decreases, the condition of trees decreases with or without construction activity (Hauer, Miller, & Ouimet, 1994). The association between planting width and tree condition suggests there is an optimal rooting volume needed by trees in order to maintain a good condition. A general soil volume recommendation is to allocate approximately two cubic feet of soil for every one square foot of crown width desired (Urban, 2008). Hauer, Miller, and Ouimet (1994), found *Fraxinus pennsylvanica* and *Acer platanoides* planted in small boulevards that had undergone construction damage had lower condition ratings than trees which had not undergone construction damage. Reduction in value of street trees due to decreased condition was estimated at approximately $500,000 and a loss of $250,000 due to tree morality as a direct result of construction damage in Milwaukee, Wisconsin (Hauer, Miller, & Ouimet, 1994).

Societal aspects

As living in cities becomes a reality for more U.S. citizens, greater attention needs to be paid to the impacts of urban infrastructure on the social aspects citizen's lives. A recent study illustrated the importance of trees along sidewalks and streets based on the perception of people using city sidewalks. Urban landscapes with less than 30% overall biotic infrastructure (trees and shrubs) in relation to the amount of constructed infrastructure (sidewalks, roads, building) resulted in a negative perception and experience for people frequenting those areas. Negative perception was not limited to the relative amount of trees and shrubs but also included poorly established or poorly maintained trees. However, when the relative amount of trees and shrubs increased to 60%, positive attitudes were associated with the area. Larger planting spaces and larger trees also generated greater positive attitude toward an area (Lee, Jang, Wang, & Namgung, 2009). The interactions between the built landscape and the natural landscape are important economically, environmentally, and socially.

Urban areas are estimated to occupy 35% of the lower 48 United States with an average urban canopy cover of 27% (Dwyer, Nowak, Noble, & Sisinni, 2000). As urban areas increase in physical size, distribution, and population, increased importance will be placed on urban forests. In a nationwide survey, when people were asked about attitudes toward urban trees, 83% of strongly agreed with the statement "you consider trees important to your quality of life" regardless of their demographic characteristics (Lohr, Pearson-Mims, Tarnai, & Dillman, 2004). The longer and healthier that trees are maintained the more benefits are (including increased quality of life) provided within the limits of species expected life span.

Large mature trees provide the most benefit environmentally and economically (Scott & Betters, 2000). Trees that live longer and are healthier provide the most benefit relative to a given species in a given location (i.e. a large, mature, and healthy elm in an open field will provide a different set of benefits when compared to a similar tree on a city street). Damage to street trees and sidewalks is a costly issue economically, environmentally, and socially. Based on research the seemingly obvious way to avoid damage to sidewalks and trees is to plant trees that are small statured at maturity or plant large trees an appropriate distance from infrastructure (Francis, Parresol, & de Patino, 1996).

Background

Minnesota has four distinct ecological provinces as defined in the Ecological Classification System developed by the Minnesota Department of Natural Resources (MN DNR) and U.S. Forest Service. Provinces are land units defined by the major climate zones and native vegetation (Minnesota Department of Natural Resources, 2013). The four ecological provinces in Minnesota are: Eastern Broadleaf Forest, Laurentian Mixed Forest, Prairie Parkland, and Tallgrass Aspen Parkland (Appendix A – Study Maps). In 2009, as part of MN DNR and U.S. Forest Service emerald ash borer community preparedness grant, six communities in Minnesota were chosen by the University of Minnesota Department of Forest Resources research team to participate in community conducted sample inventories of their respective urban forests. The six communities were selected based on population, urban forestry management structure, and their locations among or near the four ecological provinces of Minnesota. The six communities were as follows: Crookston, Hendricks, Hibbing, Hutchinson, Morris, and Rochester.

Volunteers from each community were trained in tree identification and inventory techniques by University of Minnesota researchers. By August 2011, all six of the communities had completed their sample inventories, which included both publicly and privately owned trees. Using the sample inventory data from each community the top genera (those representing 5% of more of urban trees) in each community were determined. In all of the communities the following genera represented 5% of more of the urban forest: *Acer, Fraxinus, Picea,* and *Malus.* These results were compared with a 2006 MN DNR rapid field tally an assessment of 700 Minnesota communities which reported the top ten genera in urban areas (Holman & Epperly, 2011). The top four genera from the MN DNR rapid field tally were consistent with 2011 community inventories.

Using the 2011 community inventory data the genera *Acer* and *Fraxinus* were found to be the most abundantly planted as city street trees; trees planted in a boulevard planting space between sidewalk and street. *Picea* and *Malus* were not genera commonly found as street trees.

The six communities represent population sizes of 713 (Hendricks) to 106,769 (Rochester) people. Communities are often faced with limited financial resources and limited space where tree management is concerned (McPherson E. G., 2006) and the six study communities had a range of resources to deal with urban tree related issues. Smaller communities often are the most limited in terms of resources available to handle the management of their urban forests and sample inventory techniques can lead to valuable information (Maco & McPherson, 2003). Measurements taken during the sample inventories included DBH and crown width. The measurement of DBH is simple and fast even for novice volunteers to collect, however, crown width proved to be more difficult for volunteers to measure. Crown width provides valuable information on pollution uptake, storm-water mitigation, and energy savings that can be used to justify additional funding (Nowak, 1993; Peper, McPherson, & Mori, 2001b; Maco & McPherson, 2003; Martin, Chappelka, Loewenstein, Keever, & Somers, 2012).

Trained volunteers are tremendous resources in the area of urban forestry, but there are limits to demands placed on volunteers (Johnson, 1995; Jack-Scott, Piana, Troxel, Murphy-Dunning, & Ashton, 2013). Difficult to measure aspects of urban trees can benefit from models that estimate certain tree characteristics such as crown width and trunk flare at ground line. Understanding the growth characteristics of trunk flare and crown width can help communities assess, plan, and manage their urban forests. The location and sizes of the six communities provided a valuable opportunity to measure and create state-wide predictive models of trunk flare diameter at ground line and crown width for the two most prevalent Minnesota street tree genera, *Acer* and *Fraxinus*.

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Literature Review

Trees provide many benefits including but not limited to: reduced in air pollution, carbon sequestration, reduced energy consumption, and increased in property values. (Dwyer, Nowak, Noble, & Sisinni, 2000; Brack, 2002; Sanders, Polasky, & Haight, 2010). Urban trees also have a positive cultural effect by improving quality of life for people living near trees as well as reduced crime in areas with tree cover (Lee, Jang, Wang, & Namgung, 2009; Donovan & Prestemon, 2012). All trees are not equal in terms of the benefits provided. However, regardless of species the larger, longer lived, and healthier trees are the more benefits they provide (Scott & Betters, 2000; McPherson E. G., 2003; Nowak, Crane, & Stevens, 2006).

Trees with large canopies are capable of providing a greater amount shade and an increase in transpirational cooling resulting in reduced energy demand (Akbari, Pomperantz, & Taha, 2001). Carbon sequestration is another benefit of trees that increases with larger trees as they produce and maintain greater quantities of wood over longer periods of time (Akbari, Pomperantz, & Taha, 2001). However, larger trees also cause more conflicts with built infrastructure. When sidewalks and trees conflict there are losses in benefits provided by sidewalks and trees. Sidewalk damage attributed to trees is greatest when boulevard width decreases and DBH increases (Wagar & Barker, 1983). Tree condition and health decrease as the distance between sidewalks and trunks decreases. Injuries to tree roots that occur within 1.2 m of the trunk are the most damaging to tree health (Hauer, Miller, & Ouimet, 1994).

The probability of root and sidewalk conflicts increases when large mature trees are less than 3 m from sidewalks and the trees are 25.4 cm in DBH or greater (Sydnor, et al., 2000; Randup, McPherson, & Costello, 2001). Stability of trees is important to tree health and public safety; damage or severance of tree roots should be avoided within 1.8 to 3 m of the trunk in order to maintain stability (Hamilton, 1988). Small boulevards have restricted growing space for trees, which leads to a greater potential of sidewalk damage and also a reduction in tree canopy size (Sanders, Grabosky, & Cowie, 2013). Determining crown width and trunk flare diameter at ground line as a function of species and DBH can provide valuable planning and management information for managers of urban forests while reducing the amount and cost of data collection in the field.

Crown width can be estimated by taking two diameter measurements at the widest and narrowest section of the crown at approximately 90^o. The two measurements are then averaged to give mean crown diameter (Ek, 1974; USDA Forest Service, 2012). Crown width can be predicted using models and models using open-grown trees represent a potential maximum of tree dimensions assuming optimum growing conditions (Hasenauer, 1997). Ek (1974) fitted data for crown width of open-grown trees on DBH using non-linear least squares regression techniques. The genera of *Acer* and *Fraxinus* were included in the analysis and the model form is presented in Table 3 (Ek, 1974). Frelich (1992), completed size measurements of 221 trees from 12 species of open-grown shade trees in the Minnesota, Twin Cities metropolitan area using the same model form as Ek (1974). The model forms in Table 3 demonstrates a clear relationship between crown width and DBH.

Tree crowns differ between open-grown trees and tree crowns that are restricted through management or site conditions. Many urban street trees have crowns that have been manipulated by pruning practices and restricted growing spaces. Models predicting crown width as a function of DBH and species have been established specifically for street trees as their form often differs from that of open-grown trees (Peper, McPherson, & Mori, 2001a; Semenzato, Cattaneo, & Dainese, 2011). The various model forms summarized in Table 3 demonstrate the relationship between crown width and DBH in different site conditions and locations.

Table 3. Crown width predictions with DBH as the independent variable.

Model Form	Site	Locale
(Ek, 1974)		
$CW=b_0+b_1DBH^{b_2}$	Open-grown	Wisconsin, USA
(Frelich, 1992)		
$CW=b_0+b_1DBH^{b_2}$	Open-grown	Twin Cities, Minnesota, USA
(Peper, McPherson, & Mori, 2001a)		
$CW=EXP\{MSE/2+(b_0+b_1log(log(DBH+1)$	Street Trees	San Joaquin Valley, California, USA
(Semenzato, Cattaneo, & Dainese, 2011)		
$CW=b_0+b_1DBH+ b_2DBH^2+ b_3DBH^3$	Street Trees	Various Cities, Italy
(Martin, Chappelka, Loewenstein, Keever, & Somers, 2012)		
$CW=b_0+b_1DBH+ b_2DBH^2$	Open-grown	Auburn, Alabama, USA

b_0 = intercept, b_n = regression coefficient, CW= Crown width, DBH=diameter at breast height, EXP= inverse of the natural log, MSE= means standard error, log= natural log

Where the relationship between crown width and DBH has been well established for a variety of species and locations, the relationship between DBH and trunk flare diameter at ground line has been less well studied. As trees age their trunk flare diameter at ground line and the lateral roots typically increase in size, potentially out-growing a restricted growing space and causing damage to sidewalks. Trunk flare diameter at ground line for urban street trees in restricted growing spaces can be a valuable measurement for planning and management of urban infrastructure helping to reduce infrastructure damage through adequate design of growing spaces for trees as they age.

Trunk flare is produced by lateral tree roots which are attached to the trunk typically at or near the soil surface. Lateral roots taper rapidly as they grow outward from the trunk (Wagar & Barker, 1983; Gilman, 1990). The presence of stem girdling roots can change the appearance of the trunk flare diameter at ground line. Stem girdling roots are roots that grow perpendicular and tangential to the trunk, where the radial growth of the trunk and the root can be distorted and reduced (Watson & Clark, 1997). In some cases where the girdling root is just below the soil surface, the trunk may bulge at ground line producing what appears as a larger than typical trunk flare (Gouin, 1983). In either case stem girdling roots can distort the trunk flare shape or size, and often reduces the tree's canopy as water and nutrients are both restricted (Gouin, 1983; Watson & Clark, 1997; Johnson & Hauer, 2000).

A tree's trunk flare at ground line has been associated with damage to sidewalk and curbs (Costello & Jones, 2003). Costello and Jones (2003) established a methodology for measuring trunk flare diameter at ground line in order to create a trunk diameter ratio (TDR) for use in planning and management of trees near urban infrastructure. Diameter of the trunk flare at ground line was measured on a minimum of 15 specimens per species. Using the method developed by Costello and Jones (2003), trees measured were open-grown, had achieved a mature size for the given species, and were relatively free from defects. Diameter above trunk flare (approximately 1 foot above) is then measured. The TDR is established by dividing the trunk diameter at ground line by the trunk diameter above the trunk flare. The TDR can be used to aid in determining planting space size requirements (Costello & Jones, 2003).

Some tree species have been evaluated for their tendency to surface root and cause damage to infrastructure. Among the species mentioned are *Acer platanoides, Acer saccharinum, Acer saccharum,* and *Fraxinus spp* (Rindel, 1995; Gilman, 1997; Costello & Jones, 2003). However, methods of evaluation vary greatly between sources. Trees in urban conditions without regard to species have a higher potential to be surface rooting close to the trunk and any species capable of obtaining a large size has an increased probability of causing damage to infrastructure (Wagar & Barker, 1983; Centre for Ecology & Hydrology, 2006; Urban, 2008).

Problem Statement

Models which help to predict tree crown width can and are currently being used to estimate the benefits provided by trees. Predictive models which are derived from locally collected data have proven to provide the best estimates. However, regional or statewide models may provide estimates that are accurate enough to serve as the basis for planning and management objectives. Crown width is a useful measurement for understanding the tree canopy cover for communities throughout Minnesota; however, crown width can be difficult and time consuming for communities in Minnesota to measure. The first objective of this study was to create a methodology for improved measurements of crown width and, using those measurements, create models for use by urban communities throughout Minnesota.

The second objective of this study was to establish a technique for the measurement of trunk flare diameter at ground line and to create predictive models of trunk flare diameter for the state of Minnesota. Urban trees and urban infrastructure, specifically sidewalks, often come into contact causing conflicts that can be hazardous to citizens and costly to remedy. While many professional arborists would agree that species selection is an important part of planting, currently there is a gap in the literature with regard to species-specific trunk flare development at ground line.

Trunk flare at ground line and the roots that originate from the trunk flare are part of the conflicts between trees and urban infrastructure. The genera of *Acer* and *Fraxinus* represent the two most common urban street trees in Minnesota communities; they served as the test species for the study methodology and measurement techniques. Predictive models of crown width and trunk flare diameter at ground line can be used by urban communities throughout Minnesota for improved planning and management of their urban forests.

Material and Methods

The study area was selected based on communities originally chosen to participate in a Minnesota Department of Natural Resources and U.S. Forest Service grant awarded to the University of Minnesota Department of Forest Resources. The purpose of the grant was to investigate the impact of emerald ash borer (*Agrilus planipennis*) on communities in greater Minnesota. Communities were selected based on population size and proximity to the four ecological provinces in Minnesota (Appendix A - Study Maps). The six study communities were as follows: Crookston, Hendricks, Hibbing, Hutchinson, Morris, and Rochester.

The communities completed an inventory or a sample inventory of their urban forest. The sample inventory areas in each community were identified by University of Minnesota researchers using a modified rapid sampling method of public and private trees as detailed by Jaenson, Bassuk, Schwager, & Headley (1992). Community volunteers were then trained to identify, measure, and condition rate urban trees in their community. The results of the inventories were used to determine the top genera in each community. The top genera for street trees (trees planted in the right of way typically between a sidewalk and the street) were determined to be *Acer* and *Fraxinus*.

Using the inventory data from each community, blocks containing either *Acer* or *Fraxinus* in the public right of way were selected as study blocks. Trees in the public right of way were assumed to have been managed (i.e. pruned). The objective in each community was to collected data from a minimum of 80 trees and a maximum of 130 trees. In communities with large numbers of *Acer* and *Fraxinus*, a random subsample of blocks was used to reduce the total number of study trees. Community maps containing the selected blocks were printed in preparation for data collection. Data was collected in Rochester, Hendricks, and Hutchinson between June and August 2012. Data collected in Crookston, Morris, and Hibbing was completed between May and June of 2013.

All study sites were visited by two researchers who recorded tree measurements and site data using paper data sheets. Table 4 details the data collected for each study tree. All measurements were completed using English system of measurement. A pre-assigned sequential number was added to each observed tree as a unique identifier. Diameter at breast height (DBH) of the trunk was measured to the nearest inch at 4.5 feet from the ground using a Forestry Suppliers English fabric diameter tape (Figure 1). Trunk flare circumference at ground line was measured to the nearest tenth of a foot. Exposed lateral roots were not included in the trunk flare measurements. Trunk flare diameter was calculated post data collection by dividing the trunk flare circumference by π.

Table 4. Field data collected for each study tree.

Data Category	Data Collected
City	Study city name
Tree Number	Pre-assigned sequential number
Block Number	Sample block number corresponding to survey map
Species	Categorical: visual assessment Common name of tree species
Diameter at breast height (DBH)	Trunk diameter measured at 4.5 feet from ground line. Measured to the nearest inch.
Trunk flare	Circumference to the nearest tenth of an inch
Crown radii	Four radii: two radii measured perpendicular to the street and two radii measured parallel to the street. Measured feet to the nearest one-hundredth of a foot.
Boulevard	The planting space between the sidewalk and street measured in linear feet to the nearest foot.
Sidewalk damage	Categorical: visual assessment no damage, crack, lift, replaced or repaired, no sidewalk present
Stem girdling root (SGR)	Categorical: visual assessment SGR visually present, SGR not visually present, stem encircling roots
Trunk flare (at ground line) shape	Categorical: visual assessment Circular, oval, egg

Boulevard width is the planting space between the sidewalk and the street. Boulevard width was measured to the nearest foot using an English units measuring tape. Where no sidewalks existed, boulevard widths were measured from the street edge of the trunk at ground line to the roadway.

Figure 1. From left to right: DBH measurement, trunk flare measurement, crown radius measurement

Crown radii were measured to the nearest one-hundredth of a foot using a Bosch DLR130K laser distance measurer connected to a height adjustable pole (Figures 1 & 2). The height of the pole was adjusted to ensure the laser was level and measurement was taken from the crown drip line to trunk at 4.5 feet from the ground.

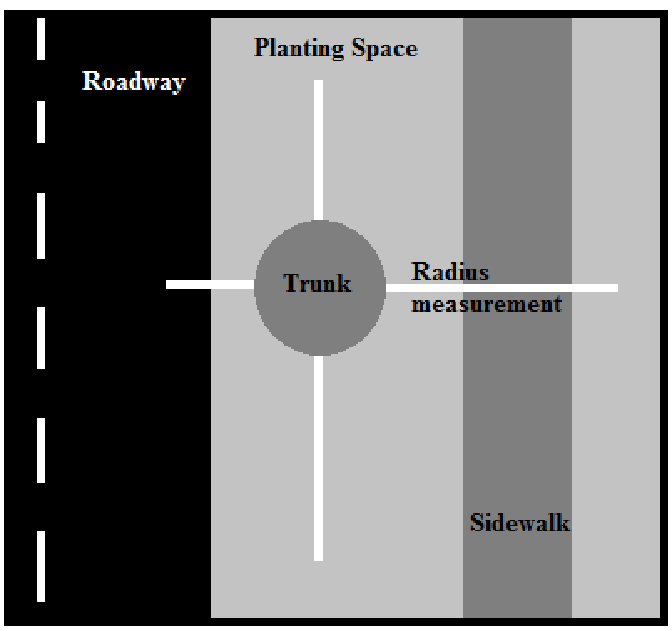

Figure 2. Diagram of crown radii measurements

Crown width was determined mathematically by summing the four radii and dividing by two to provide an average crown width. Tree species was observed and recorded, however, no attempt was made to identify specific varieties or cultivars. Trunk flare at ground line shape was determined via a visual assessment as either circular, oval, or egg shaped (Figure 3, Figure 4, and Figure 5).

Figure 3. Circular shaped trunk flare at ground line.

Figure 4. Oval shaped trunk flare at ground line

Figure 5. Egg shaped trunk flare at ground line

The presence of stem girdling roots or stem encircling roots was determined via a visual assessment. Stem girdling roots are roots that have grown into contact with the trunk causing compression or deformation in the trunk issue typically at or near ground line (Johnson & Hauer, 2000). Sidewalk damage was visually assessed for cracks, lifts, repairs or recent replacement and recorded. After each field data collection visit, data was entered into a Microsoft Access® database and statistical analysis was completed using R 3.0.1 with R Commander.

Results

Tree species, measurement, and site assessment data was collected in the six study communities for a total of 619 trees (Table 5 & 6).

Table 5. Number of trees measured by city and species.

City	Species	Number	Total trees
Crookston	*Acer platanoides*	2	85
	Acer rubrum	0	
	Acer saccharinum	8	
	Acer saccharum	2	
	Fraxinus americana	0	
	Fraxinus pennsylvanica	73	
Hendricks	*Acer platanoides*	42	127
	Acer rubrum	2	
	Acer saccharinum	10	
	Acer saccharum	6	
	Fraxinus americana	0	
	Fraxinus pennsylvanica	67	
Hibbing	*Acer platanoides*	0	117
	Acer rubrum	5	
	Acer saccharinum	38	
	Acer saccharum	5	
	Fraxinus americana	18	
	Fraxinus pennsylvanica	51	
Hutchinson	*Acer platanoides*	17	114
	Acer rubrum	0	
	Acer saccharinum	6	
	Acer saccharum	47	
	Fraxinus americana	0	
	Fraxinus pennsylvanica	47	
Morris	*Acer platanoides*	11	97
	Acer rubrum	0	
	Acer saccharinum	26	
	Acer saccharum	1	
	Fraxinus americana	0	
	Fraxinus pennsylvanica	59	
Rochester	*Acer platanoides*	28	79
	Acer rubrum	0	
	Acer saccharinum	8	
	Acer saccharum	14	
	Fraxinus americana	1	
	Fraxinus pennsylvanica	28	

Table 6. Total number of trees observed for each species.

Species	Total
Acer platanoides	100
Acer rubrum	7
Acer saccharinum	96
Acer saccharum	72
Fraxinus americana	19
Fraxinus pennsylvanica	325

The species *Acer rubrum* and *Fraxinus americana* were excluded from data analysis due to the small sample sizes. *Acer platanoides, Acer saccharum, Acer saccharinum,* and *Fraxinus pennsylvanica* all contained sufficient number of individuals to be included in the analyses.

Trunk flare at ground line shape was coded as either circular or non-circular due to inconsistency in differentiating between egg and oval during field data collection. Trunk flare shape was seen as potentially important due to the possible influence on diameter of trunk flare at ground line. Crown symmetry was analyzed and considered to be severely asymmetric when any one of the four radii was greater than twice the length of any other radii. The presence of SGR was also analyzed to assess the potential influence on diameter of trunk flare at ground line. Severe SGR may result in a non-characteristic trunk shape and crown development. Non-circular trunk flare, severely asymmetric crowns, and presence of SGRs are all observed characteristics which contribute to the form and variability of urban trees and were considered to have potential influence on tree morphology (Table 7).

Table 7. Number and percent of observed trees with selected characteristics of potential influence on predictive models.

Species	Trunk flare shape non-circular	Crown asymmetry	Presence of SGR
Acer platanoides	22/100 ~ 22%	15/100 ~ 15%	9/100 ~ 9%
Acer saccharinum	3/96 ~ 3%	25/96 ~ 26%	3/96 ~ 3%
Acer saccharum	19/72 ~ 26%	11/72 ~ 15%	8/72 ~ 11%
Fraxinus pennsylvanica	19/325 ~ 6%	120/325 ~ 37%	1/325 > 1%

Table 8 provides the summary statistics for DBH, trunk flare diameter (TFD), and crown width for each species included in analysis.

Table 8. Descriptive statistics for DBH, TFD, and crown width (CW) by species.

species	n	variable	mean	standard deviation	median	min.	max.
Fraxinus pennsylvanica	325	DBH (in.)	16.96	5.85	17.00	6.00	34.00
		TFD (ft.)	1.99	0.70	1.94	0.64	4.65
		CW (ft.)	29.08	9.86	28.00	6.00	61.00
Acer platanoides	100	DBH (in.)	14.99	6.35	15.00	4.00	29.00
		TFD (ft.)	1.76	0.81	1.72	0.51	4.07
		CW (ft.)	27.15	8.74	26.50	10.00	49.00
Acer saccharinum	96	DBH (in.)	19.49	9.75	19.00	4.00	44.00
		TFD (ft.)	2.45	1.25	2.18	0.57	5.98
		CW (ft.)	35.83	12.73	35.00	12.00	64.00
Acer saccharum	72	DBH (in.)	16.12	6.21	18.00	4.00	28.00
		TFD (ft.)	1.88	0.77	2.05	0.48	3.41
		CW (ft.)	32.07	10.71	33.00	6.00	62.00

Trunk flare diameter models

The correlations in Table 9 show a strong positive relationship between TFD and DBH for the species included in analyses. The correlations combined with the scatter plots in Figure 6 suggest a strong linear relationship between TFD and DBH.

Table 9. Correlation between DBH and TFD.

Species	Correlation
Acer platanoides	0.914
Acer saccharinum	0.951
Acer saccharum	0.938
Fraxinus pennsylvanica	0.950

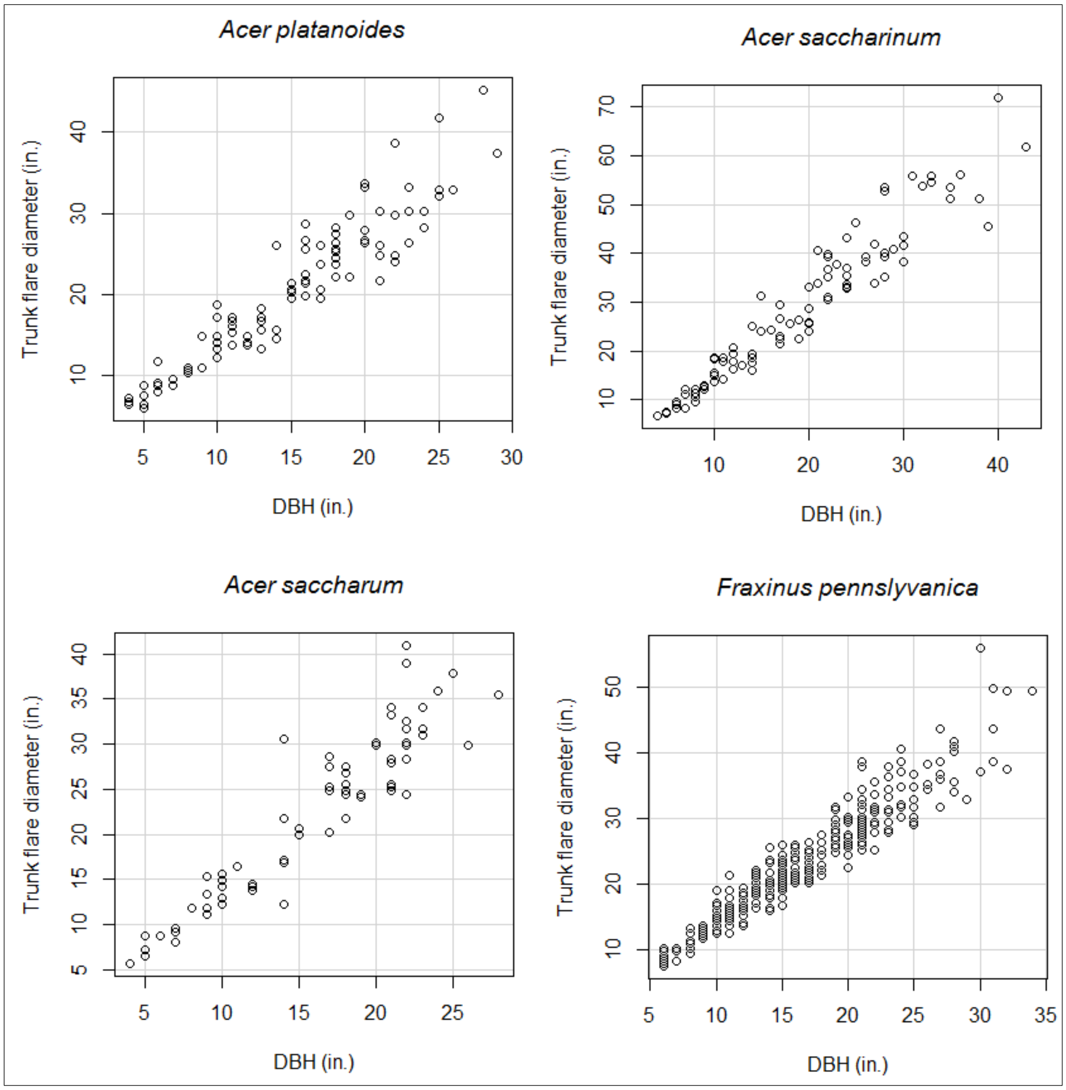

Figure 6. Scatter plots of TFD on DBH for all species.

Models for predicted values of TFD were tested using DBH and boulevard width as the independent variables. Boulevard width was found to be non-significant and was not included in the final model.

Outliers were identified visually and through the use of Cook's Distance analysis. Each suspected point was then individually investigated to determine the appropriateness of inclusion or exclusion from analysis. Individual trees identified as potential outliers were investigated to determine if the characteristics identified in Table 7 resulted in either a TFD or crown width which was not representative of the trees in the population. The identified potential outliers were excluded from analyses if the tree had two or more characteristics detailed in Table 7. In total, twenty-four (~4%) trees were excluded from the model analyses for TFD on DBH and crown width on DBH. No greater than seven trees from any one species were excluded. Of the trees excluded from analyses, two trees were identified as columnar varieties of *Acer* and one tree had incorrectly recorded data.

Transformations of the *Acer platanoides* data were tried; however, the transformations did not improve the linearity of the model. Ordinary least squares (OLS) regression was initially used to model TFD on DBH. The residual plots of the OLS regression analysis showed some increase in variance with increasing DBH. Weighted least squares (WLS) regression was considered as a method to stay in line with regression assumptions. Each species analyzed had multiple observations for nearly all DBH measurements. Weights were estimated using the inverse of the variation in TFD measurement for a given measurement of DBH. WLS produced residual plots showing no patterns and constant variation (Figure 7).

The model form and coefficients for prediction of TFD are detailed in Table 10. The intercept (b_0) was not highly significant for any species except *Fraxinus pennsylvanica*. The intercept (b_0) was not significant for *Acer saccharinum* or *Acer saccharum* likely due to the lack of observations for small diameter trees.

Table 10. TFD on DBH predictive model form, coefficients, and relevant statistics. Coefficients, TFD, MAD, and RMSE given in inches.

Model form: $\widehat{TFD} = b_0 + b_1 * DBH$						
Species	**n**	**b_0**	**b_1**	**Adjusted R^2**	**Mean absolute deviation (MAD)**	**RMSE**
Acer platanoides	96	1.121*	1.302***	0.912	9.652	3.012
Acer saccharinum	95	-0.115	1.525***	0.937	18.070	4.236
Acer saccharum	70	0.038	1.400***	0.921	8.303	3.202
Fraxinus pennsylvanica	324	0.662***	1.369***	0.908	8.120	2.599

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Data points from specific communities were randomly distributed in the residual plot. The predicted values of TFD plotted on the observed values of TFD provide additional evidence of a linear relationship between TFD and DBH (Figure 8). Figure 9 gives the fitted values with the prediction intervals.

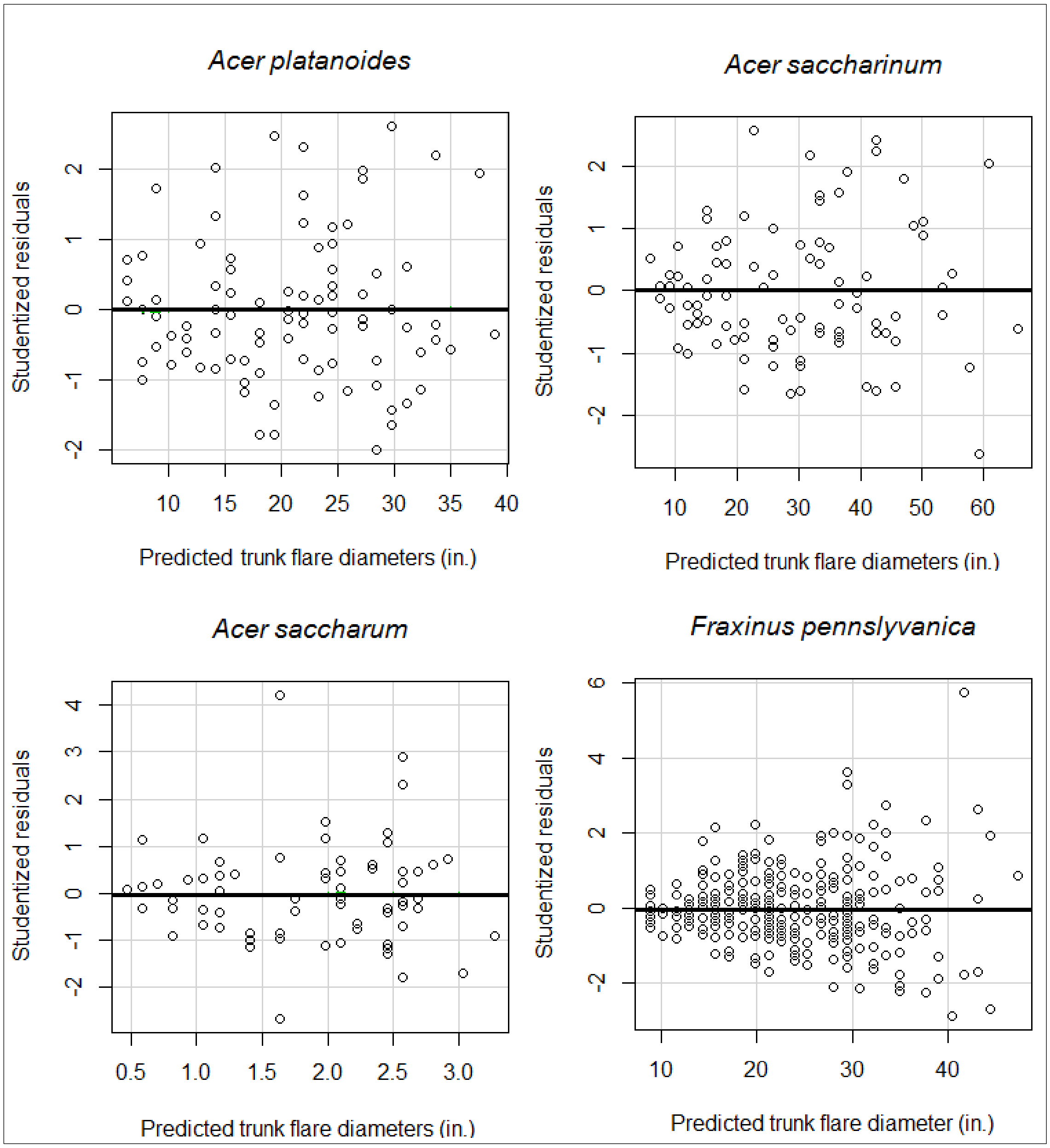

Figure 7. Residual plots of predicted trunk flare

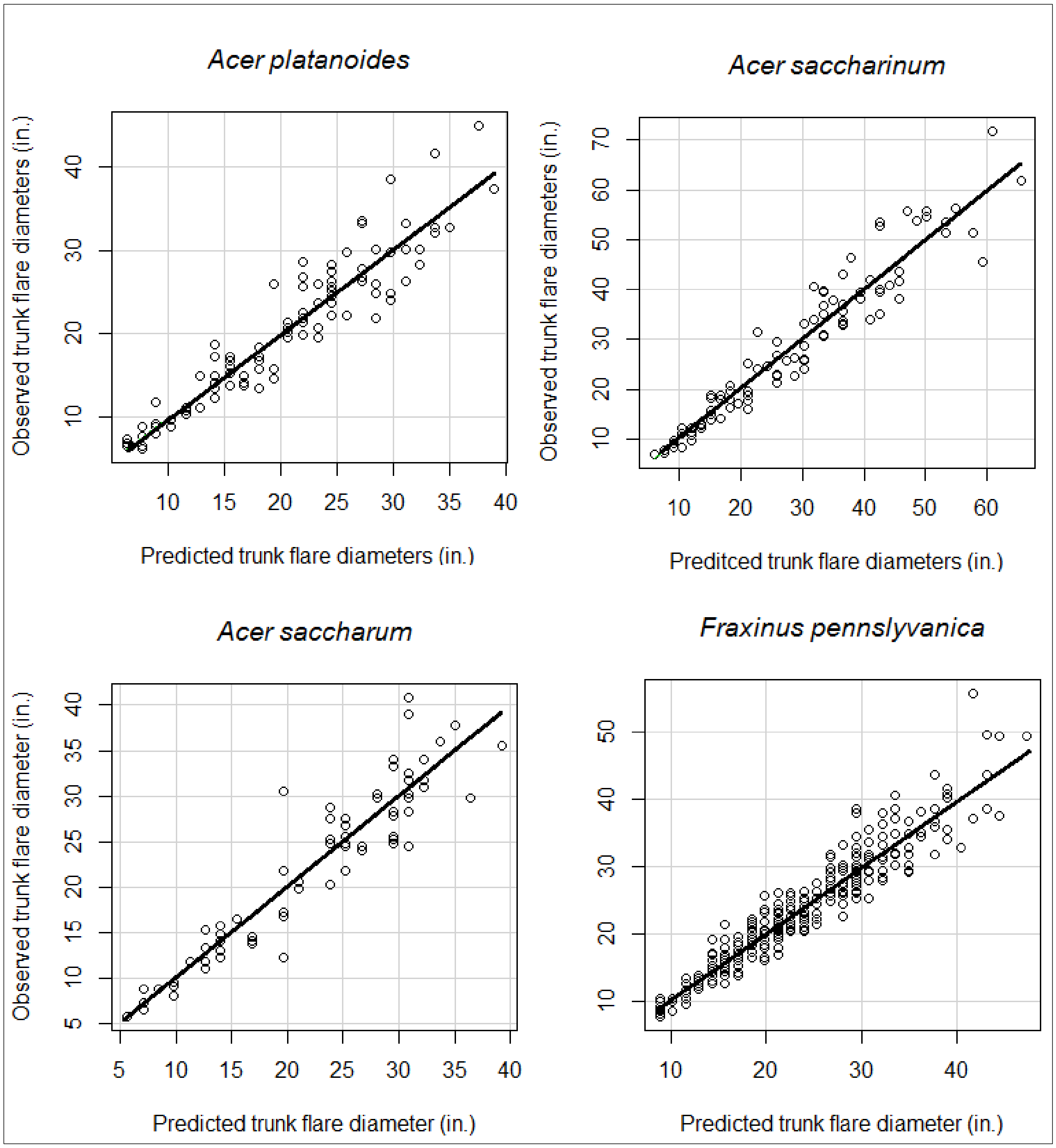

Figure 8. Predicted TFD plotted on observed TFD

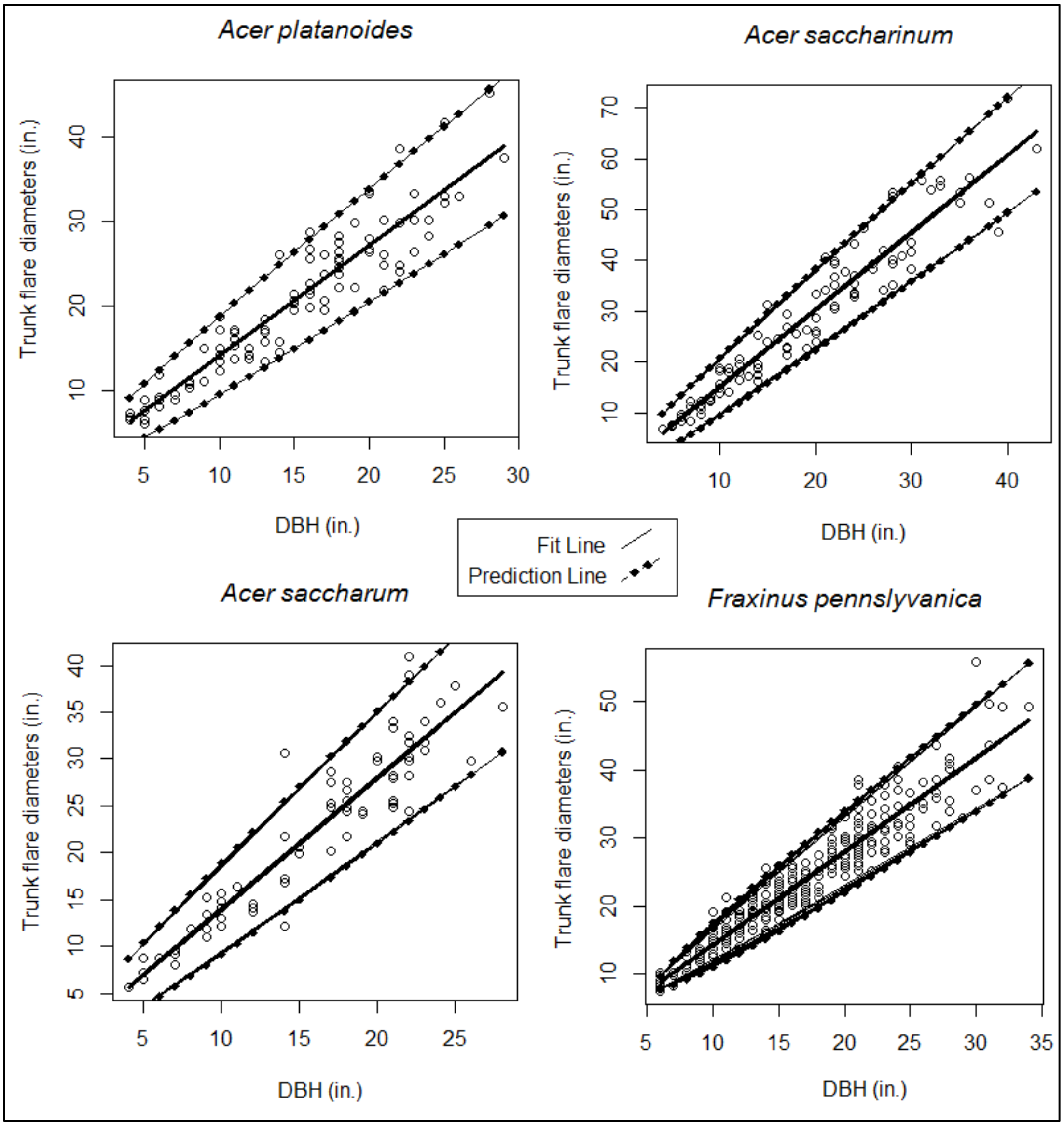

Figure 9. TFD on DBH with fit line, upper and lower prediction intervals.

Crown width models

Correlation between crown width and DBH shows a strong positive relationship (Table 11). *Fraxinus pennsylvanica* correlation between crown width and DBH is less strong when compared with the species in the genus *Acer*, which may suggest greater variation of crown width exists in *Fraxinus pennsylvanica*. Figure 9 shows scatter plots of crown width on DBH. Crown width on DBH was analyzed with DBH as the independent variable. Four model forms were investigated for predictive value of crown width (Table 12). Only model D in Table 12 had significant coefficients and residual plots with unbiased errors, showing only a slight increased variation with increased DBH. Outliers were determined using visual assessment of plots and Cook's Distance analysis. Suspected outliers were then individually inspected to determine their inclusion or exclusion from the model. Outliers were excluded when two or more morphologic characteristics from Table 7 were present and deemed to be non-representative of the population as a whole.

Table 11. Correlation of crown width and DBH.

Species	Correlation
Acer platanoides	0.808
Acer saccharinum	0.866
Acer saccharum	0.778
Fraxinus pennsylvanica	0.682

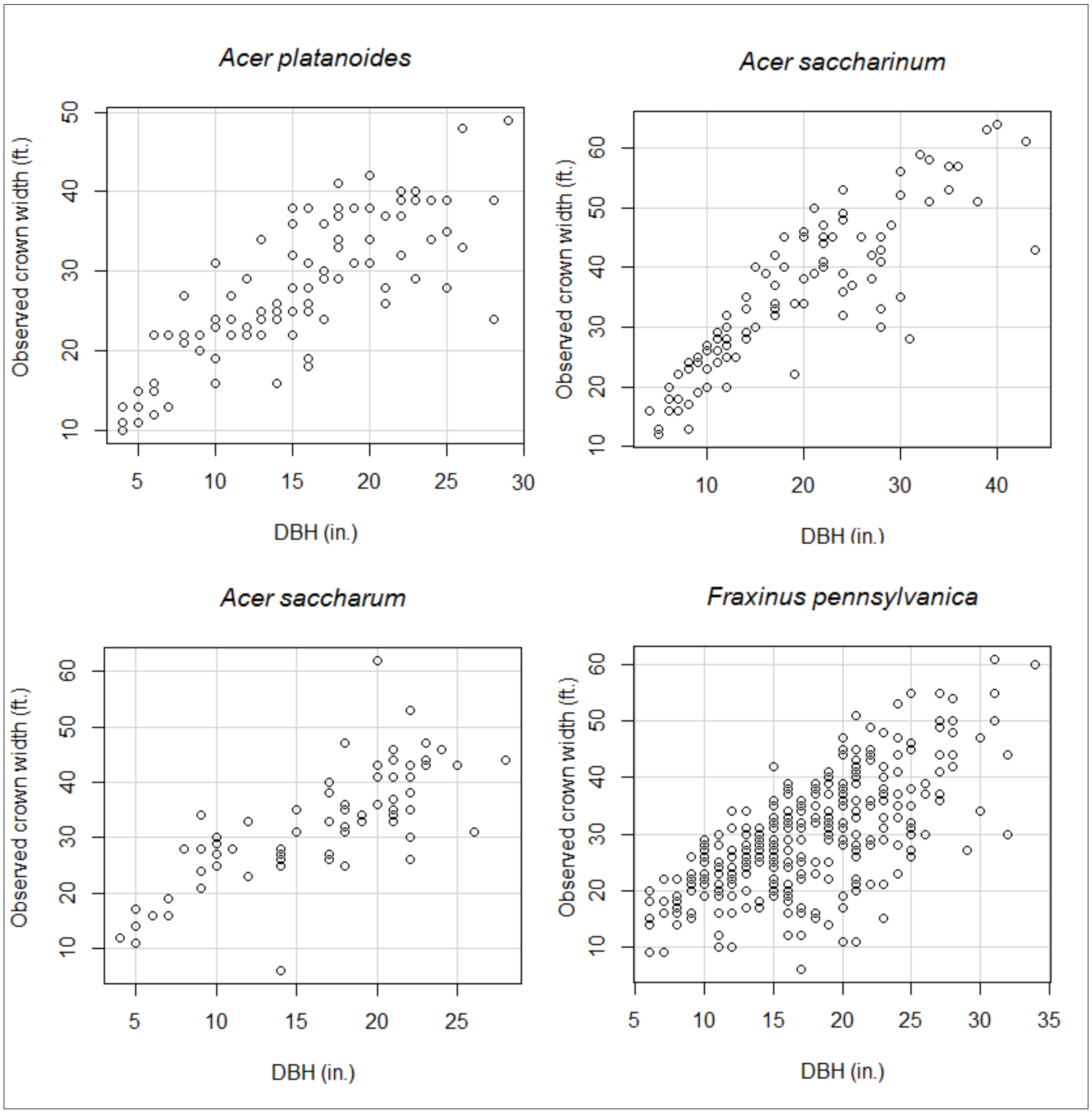

Figure 10. Plots of crown width on DBH by species.

Table 12. Model forms investigated for predictive value of crown width on DBH

Model	Model form	Authors
A	$CW=b_0+b_1DBH^{b_2}$	(Ek, 1974) & (Frelich, 1992)
B	$CW=EXP\{MSE/2+(b_0+b_1\log(\log(DBH+1)$	(Peper, McPherson, & Mori, 2001a)
C	$CW=b_0+b_1DBH+ b_2DBH^2+ b_3DBH^3$	(Semenzato, Cattaneo, & Dainese, 2011)
D	$CW=b_0+b_1DBH+ b_2DBH^2$	(Martin, Chappelka, Loewenstein, Keever, & Somers, 2012)

b_0 = intercept, b_n = regression coefficient, CW= Crown width, DBH=diameter at breast height, EXP= inverse of the natural log, MSE= means standard error, log= natural log

The final model form and coefficients are detailed in Table 13. The coefficient (b_1) was significant or highly significant for all species. The intercept (b_0) was not significant for *Acer platanoides* or *Acer saccharum* likely due to the lack of observations for small diameter trees. The low adjusted R^2 value for *Fraxinus pennsylvanica* may indicate a high degree of morphological variation within the species or use of specific varieties or cultivars.

Table 13. Crown width on DBH. Crown width (CW) predicted in feet.

Model form: $\widehat{CW}=b_0+b_1DBH+ b_2DBH^2$							
Species	**n**	**b_0**	**b_1**	**b_2**	**Adjusted R^2**	**Mean absolute deviation**	**RMSE**
Acer platanoides	94	2.907	2.383***	-0.043**	0.713	7.376	4.337
Acer saccharinum	93	7.031**	1.867***	-0.014**	0.850	14.642	4.937
Acer saccharum	66	3.706	2.370***	-0.033	0.639	7.508	6.442
Fraxinus pennsylvanica	324	12.128***	0.837*	0.009	0.479	7.341	6.905

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

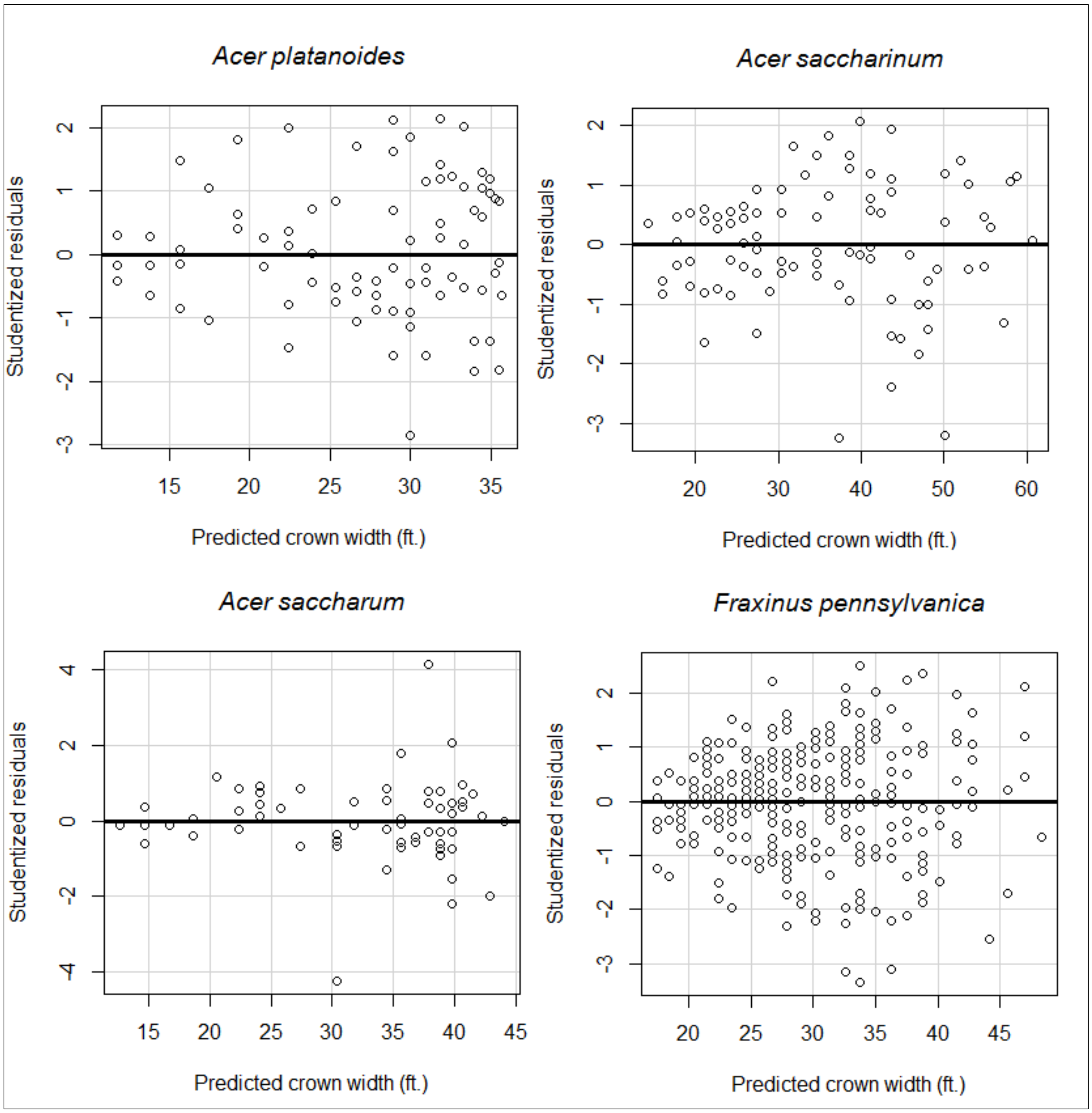

Figure 11. Plots of crown width residuals by species

Community data points were randomly dispersed in the all of the data plots and residual plots showed no pattern for individual communities. Residual plots (Figure 11) also showed only a slight increase in variation with increase in size. The predicted values of crown width plotted on the observed values are additional evidence of the model adequacy for prediction of crown width (Figure 12). Figure 13 shows the fitted values with the prediction intervals.

The model for *Fraxinus pennsylvanica* shows more overall variation in crown width and may require additional parameters to adequately predict crown width.

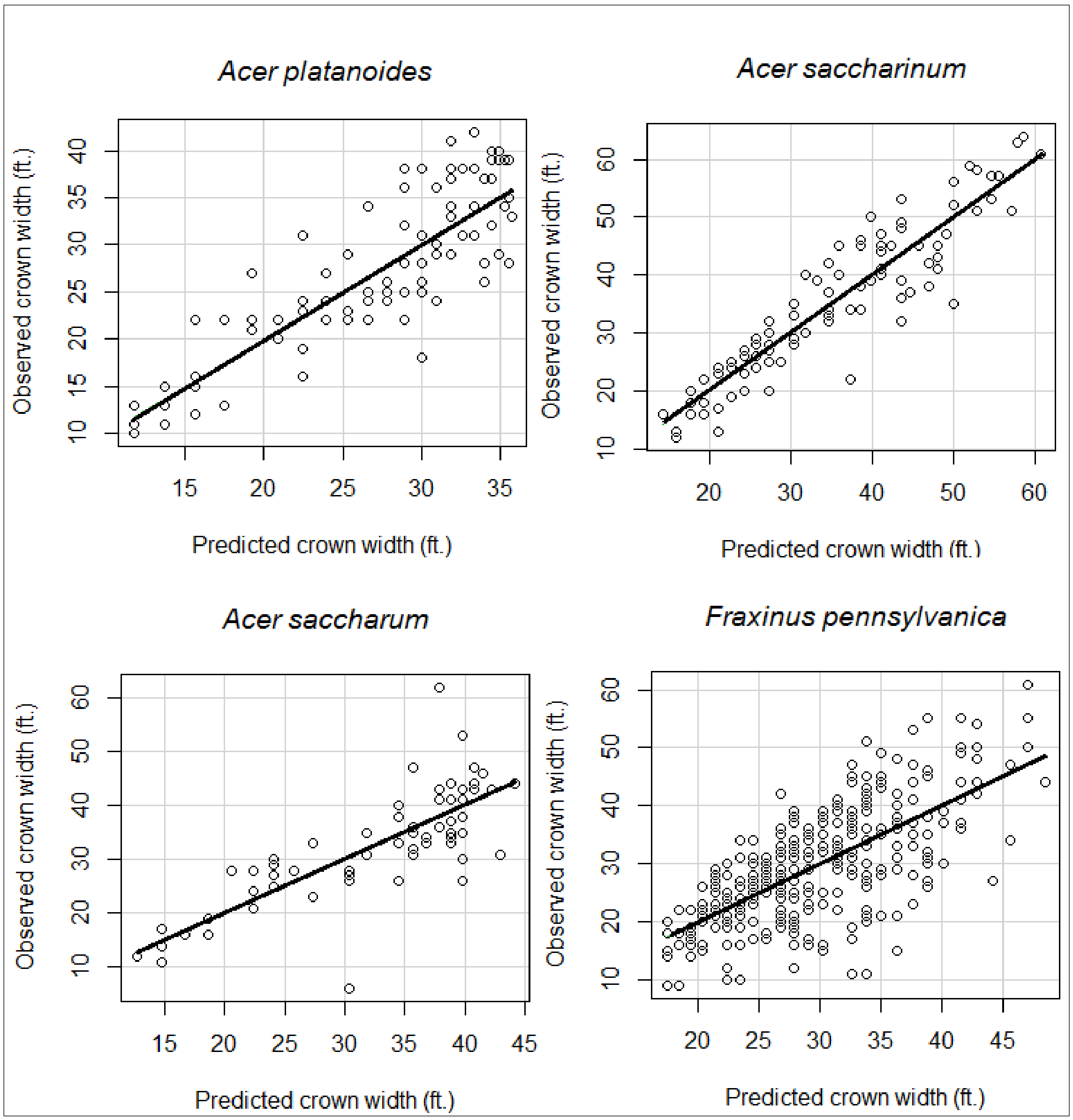

Figure 12. Observed crown width on predicted crown width by species.

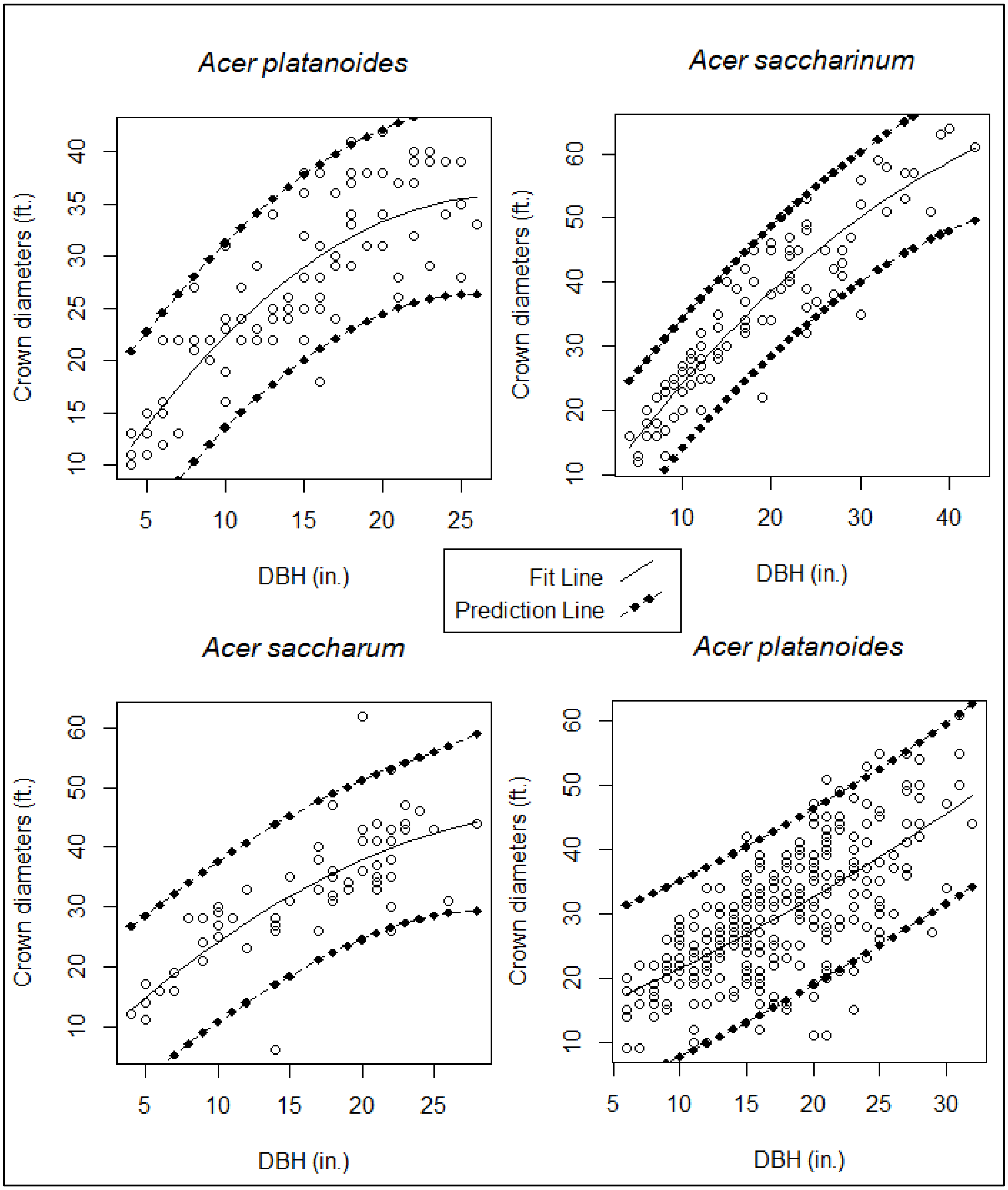

Figure 13. Model form $CW=b_0+b_1DBH+ b_2DBH^2$ with fit line, upper and lower prediction lines.

Discussion

Trunk flare diameter predictions

Predictive models are important tools not only for managers of urban street tree planting programs, but also for designers of urban infrastructure. Urban infrastructure often has elements that include restricted planting spaces, and ability to predict the TFD of a mature tree can assist urban planners and natural resource managers in designing appropriate sites or selecting appropriate trees.

Previous work on development of TFD predictions was accomplished through the use of TDR, in which researchers measured a variety of common street trees in urban areas of San Francisco, Palo Alto, and Redwood City, California. Trees measured were specifically selected to exclude trees in restricted growing spaces (e.g. street trees) or with any obvious defects such as mechanical damage or encircling roots. In order to calculate TDR, two measurements were taken: diameter at ground line (DGL) and diameter above flare or buttress (DAFB) (Costello & Jones, 2003). DAFB was not well defined which may lead to creation of ratios along differing sections of the trunk. Whereas the technique used in this study for development of models predicting TFD relies on DBH and trunk flare diameter at ground line measurements. The standardized DBH measurement is a common attribute recorded in tree inventories and allows for more consistent predictions of TFD.

The TFD measurement method developed in this study included only trees represented in the population of interest, specifically urban street. Urban trees are often grown in restricted planting spaces and may have variations in morphology that are not well represented by their open-grown counterparts. Potential variation in TFD, when representative of the population of interest, should be included in any analyses where the goal is to create predictive models. The approach used is this study can be replicated and applied to additional species and locations.

Trunk flare shape was determined visually as either circular, oval, or egg shaped; however, due to inconsistencies in determining egg shaped or oval shaped trunk flare, analysis was simplified to circular or non-circular. Models for the four species included in the study were tested with shape as a dummy variable; however, the differences between models that included a term for trunk flare shape and those that did not were not significant. The simpler model was chosen. Trunk flare shape for other species may prove to be of importance when creating additional models of TFD. When designing or selecting an appropriately sized planting space for a given species it is desirable to overestimate the TFD.

The slope (b_1) was highly significant for all species in the TFD model indicating DBH is a good predictor of TFD for the species included in the study. The intercepts (b_0) lacked significance in *Acer saccharinum* and *Acer saccharum* (Table 10). The lack of significance for the intercept is likely be attributable to the lack of trees with observed DBH near 0, indicating the intercept cannot be well estimated. Performance of the models at lower DBH should not be seen as an issue, as planners and managers are generally more concerned with mature tree size.

Acer saccharum had the highest percent of non-circular trunk flares (Table 7) which may result in predicted trunk flare diameters that are misrepresented in terms of size, either too small or too large depending on the orientation of the trunk. Species that commonly exhibit non-circular trunk flares may benefit from the inclusion of a trunk flare shape or orientation parameter to account for increased variation.

Applications and recommendations

Prediction of TFD has several potentially useful applications for urban planners and managers of urban street trees. First, TFD models can be used to better inform the design or allocation of planting spaces with regard to tree species. Previous research has shown that tree roots taper rapidly outward from the trunk and root injury should be avoided at a distance of 4 feet (or more) from the trunk to limit negative impacts to tree health and reduce the probably of conflicts between infrastructure and trees as roots increase in size (Hauer, Miller, & Ouimet, 1994). Site design and species selection goals should seek to maximize the distance between tree trunks and infrastructure for the life of the tree. Species-specific models of TFD can aid in site design and species selection where trees are concerned.

If *Fraxinus pennsylvanica* had a maximum DBH in a community of 24 inches, then using the model from Table 10, the predicted TFD would be approximately 33 inches. The minimum design space allowing for future trunk flare and root growth would be the TFD plus a four foot buffer on both the street side and the sidewalk side of the trunk flare resulting in a required planting space of approximately 10.75 feet for a 24 inch DBH *Fraxinus pennsylvanica* (Figure 12).

$$\text{Planting space width in feet} = \{ \left(\frac{\text{TFD}}{12}\right) + 8 \}$$

Figure 14. Calculation for recommended planting space width based on predicted TFD.

A second application of the TFD predictive model is to identify potential tree and sidewalk conflicts using existing inventory data. If managers of urban street trees have existing boulevard width information in combination with a street tree inventory that included species and DBH, then, using the models from Table 10 and the formula in Figure 12, a list of probable sidewalk and tree conflicts could be generated. The generated list could be used to prioritize onsite inspections of both sidewalk damage and potential tree work.

The third application of the TFD model is to generate a list of stump sizes for grinding. When urban street trees need to be removed, many cities work the tree in stages, with stump grinding frequently performed by a third party. Some cities currently generate a list of the number and size of stumps to be ground-out by completing an on-site measurement of stumps. Stump sizes at ground line could be pre-determined using the appropriate TFD model, saving money and staff resources. Money and time savings may be especially helpful following catastrophic losses due to storms strong enough to be declared state or federal disasters.

Limitations

The TFD models presented here are limited to the species *Acer platanoides, Acer saccharum, Acer saccharinum,* and *Fraxinus pennsylvanica* grown in Minnesota in restricted spaces and where management practices such as pruning or sidewalk repair are common. Models may not reliably predict TFD outside the range of DBH measurements used in the creation of the models. Trees with severe trunk damage or abnormal graft-unions may also not be accurately predicted.

Based on previous research the minimal distance from hardscape infrastructure to tree trunk at ground line is approximately 4 feet (Hamilton, 1988; Hauer, Miller, & Ouimet, 1994), which may exclude tree planting in many boulevard spaces. Where boulevard spaces are too small to adequately accommodate large shade tree growth and infrastructure, consideration should be given to planting smaller statured trees, programs that utilize land from adjacent property owners, or site design enhancements. Such programs may include green easements or enhancements such as suspended pavement systems.

The effects of management and restricted planting spaces on the development of TFD are not known. Additional TFD models should be created to include more species and account for differences in regional growth and management. Continued research comparing open-grown tree to trees grown in restricted space is needed to determine what differences, if any, exist in trunk flare development.

Crown width models

Measurements of crown width can be valuable in determining the ability of an urban forest to mitigate storm-water runoff and air pollution, and in estimating energy savings (Nowak, 1993; Peper, McPherson, & Mori, 2001b; Maco & McPherson, 2003; Martin, Chappelka, Loewenstein, Keever, & Somers, 2012). Urban planting space considerations should not be limited to the available ground space. Planting space considerations need to incorporate the above ground limitations in space for the expected growth of mature trees. Electrical lines, street signs, street lights, and buildings all represent potential infrastructure conflicts which may be avoided, in part, through proper species selections. Predictive crown width models can assist planners and managers in designing or selecting the right space for the right tree.

Models predicting crown width for forest trees, open-grown trees, and more recently urban street trees are not new. The attempt here was to add to the growing body of work through establishment of a new crown width measurement technique and, using that technique, create models predicting crown width for urban street trees throughout Minnesota.

Overall the crown width models for the species of *Acer* presented here explain between ~64% and ~85% of the variation seen in crown width. The model for *Fraxinus pennsylvanica* explains only around 47% of the observed variability. Variation in crown width is expected in urban environments where above ground conflicts, pruning of the crown, and defensive dieback of the tree crown after construction activities are not uncommon. Urban street tree pruning practices have common goals to raise the canopy a set distance from street and sidewalk surfaces and to reduce inference with above ground infrastructure (e.g. signs, electrical transmission lines, etc.).

The model for *Acer saccharinum* appears to be the most reliable model in terms of coefficient significance and variation explained by the model. The other species modeled have less total variation explained and several of the coefficients are not statistically significant indicating their values are not well estimated.

Some of the unexplained variation may be a result of varied pruning practices between communities; however, no community patterns emerged in the residual plots. There was no attempt made to identify species cultivars and much of the unexplained variation may be due to the variation in crown form that exists between cultivars (Table 14). *Acer saccharinum* has the fewest number of cultivars compared to the other species in the study. When creating models it may be beneficial to either analyze cultivars separately or include a cultivar parameter to account for the potential added variation in crown form.

Table 14. Species and their available cultivars (Dirr, 2009).

Species	Number of cultivars
Acer platanoides	38
Acer saccharinum	14
Acer saccharum	47
Fraxinus pennsylvanica	30

Application and recommendations

Using the models presented in Table 13 reasonable predictions can be made of the above ground planting space needed in order to accommodate the crown width of a tree at its mature size, allow for improve species selection when planting near above ground infrastructure. Improved species selection may lead to longer lived trees and a reduction in total management costs.

An analysis of the observed data led to an unexpected potential benefit of the crown width measurement data. The four measured crown radii can be utilized to provide a reasonable estimate of the canopy area. Total canopy area can be estimated from measurements of the four crown radii utilizing the formula for the area of a right triangle. Figure 13 depicts the four right triangles created from the measurement of the four crown radii. The individual areas of the right triangles can be summed to calculate an estimate of total canopy area. Increasing the number of measured crown radii at know angles, would result in additional triangle areas allowing for increased accuracy of estimate canopy area.

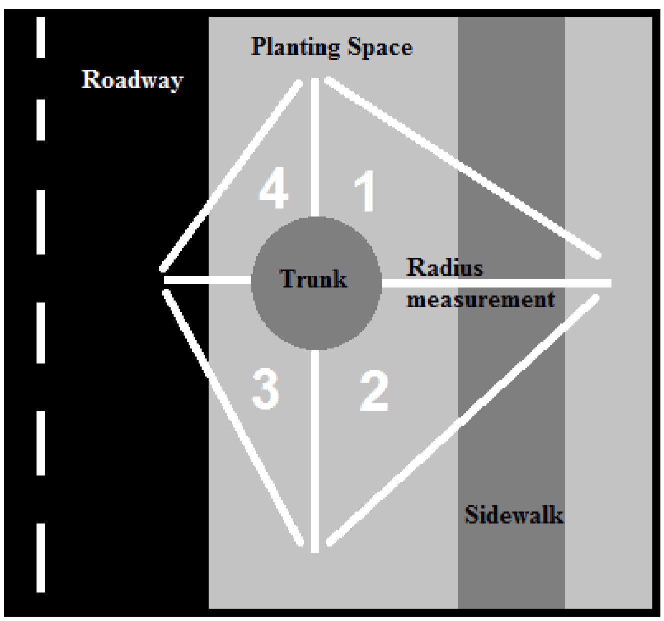

Figure 15. Illustration of the four triangles created from the measurements of four crown radii.

Urban forestry funding is often tied to data representing the current state of a community's urban forest and estimating canopy cover of a community may be vital in obtaining funding for urban forest initiatives or disaster relief. Inventory data or estimates of inventory data can be gathered quickly and inexpensively using rapid sampling techniques (Jaenson, Bassuk, Schwager, & Headley, 1992). Full or sample inventories can be used to estimate total canopy cover which may be a justification for increased urban forestry funding.

Limitations

The crown width models presented here are limited to the species *Acer platanoides, Acer saccharum, Acer saccharinum,* and *Fraxinus pennsylvanica* grown in Minnesota in restricted spaces and where management practices such as pruning or sidewalk repair are common. Models may not reliably predict crown width outside the range of DBH measurements used in the creation of the models. The models presented in Table 13 take into account variation that exists in Minnesota urban street tree populations; however, trees that have under-gone severe pruning or storm damage may not reliably conform to the models presented here.

Summary and conclusions

More countries are moving from rural population demographics to urban areas with high levels of development. Since 2007, more than half of the world's population is living in cities and using75% of available resources (Madlener & Sunak, 2011). As more people move into highly developed urban areas there will be an increased demand on all resources, including energy and green space. Development of livable urban infrastructures must address the challenges of increased use of limited natural resources as well as economic, engineering, and societal pressures (Sahley, Kennedy, & Adams, 2005). Management of urban trees to achieve more sustainable growth in urban areas is one facet that can help to reduce the consumption of energy as well as improve the lives of people living in cities by providing quality green space.

Human health is tied to the health of our environment and trees are significant organisms living in the urban environment. People need green spaces to maintain healthy and productive lives. Simply viewing trees, shrubs, and other plants combined with access to natural light have been attributed to helping reduce stress and increase overall human health (Jackson, 2003). Trees not only help make city life more pleasant, they also provide the benefits of filtering pollution, providing shade, and reducing noise (Dwyer, Nowak, Noble, & Sisinni, 2000; Brack, 2002). In order to provide the multitude of benefits and remain cost effective trees need to be managed to grow larger, and live longer and healthier (Scott & Betters, 2000; McPherson E. G., 2003; Nowak, Crane, & Stevens, 2006).

Currently there appears in the literature and among urban forest managers a conflict between the values of the built infrastructure and the natural infrastructure in urban environments. Abiotic infrastructure, such as sidewalks, roads, buildings, and electrical transmission lines, has many obvious benefits that most people living in developed areas use and appreciate. Pedestrian movement in cities helps to reduce energy consumption and pollution, as well as increases the health of a city's residents. Sidewalk design can increase or decrease use by pedestrians. Sidewalks along streets with slower traffic and large, healthy trees are preferred (Lee, Jang, Wang, & Namgung, 2009; Kim, Choi, & Kim, 2011). Greater use of sidewalks and streets lined with trees helps to reduce crime and increases property values (Sanders, Polasky, & Haight, 2010; Donovan & Prestemon, 2012).

Biotic infrastructure, the natural areas and street trees in our cities, also has many benefits and costs previously described. In order for the urban environments to be accessible, healthy, efficient, and cost effective places to live, a paradigm shift is needed in the management of urban infrastructure. A more useful approach for development of urban areas would be to consider abiotic infrastructure and biotic infrastructure as simply urban infrastructure.

The false divide between abiotic and biotic infrastructure leads to sidewalks that are replaced at the expense of longer lived, healthier, and more stable trees. Tree species, such as *Ulmus americana* and *Quercus ellipsoidalis*, are often described by professionals and researchers as species that do well in small boulevards. However, when considering what species do well in a given planting space more attention needs to be paid to the infrastructure that already exists. *Ulmus americana* and *Quercus ellipsoidalis* do not do particularly well in small boulevard spaces if you consider their impacts to the adjacent sidewalks or when those sidewalks are repaired at the expensive of tree roots. The economics of tree and infrastructure conflicts should not be ignored. Root and trunk damage leads to higher replacement rates and costs for urban infrastructure (Coder, 1998).

Root severance near the trunk can lead to unstable, large trees lining streets (Hamilton, 1988). The City of Los Angeles' General Plan Framework of the 1980's included trees as major components of urban infrastructure. While initially lagging in enforcement, the plan has since been improved to help deal with conflicts between sidewalks and trees helping to preserve street trees and plant additional trees (Gonzalez, 2006).

Expanded creation and use of models for the biotic components of urban infrastructure can assist urban planners and managers create and maintain multiuse spaces in growing urban environments. While models are simplified representations of complex systems or organisms, well-constructed models should be viewed as reasonable estimates capable of aiding the management of urban forests. The models presented here offer a basis for urban planners and urban forest managers to better integrate biotic infrastructure with abiotic infrastructure. Urban infrastructure projects should be assessed for their total impacts including abiotic and biotic components, as often a fix to biotic infrastructure directly impacts an abiotic portion of the infrastructure. Cooperation between abiotic infrastructure experts and biotic infrastructure experts is crucial to providing long-term, cost effective management of urban infrastructure.

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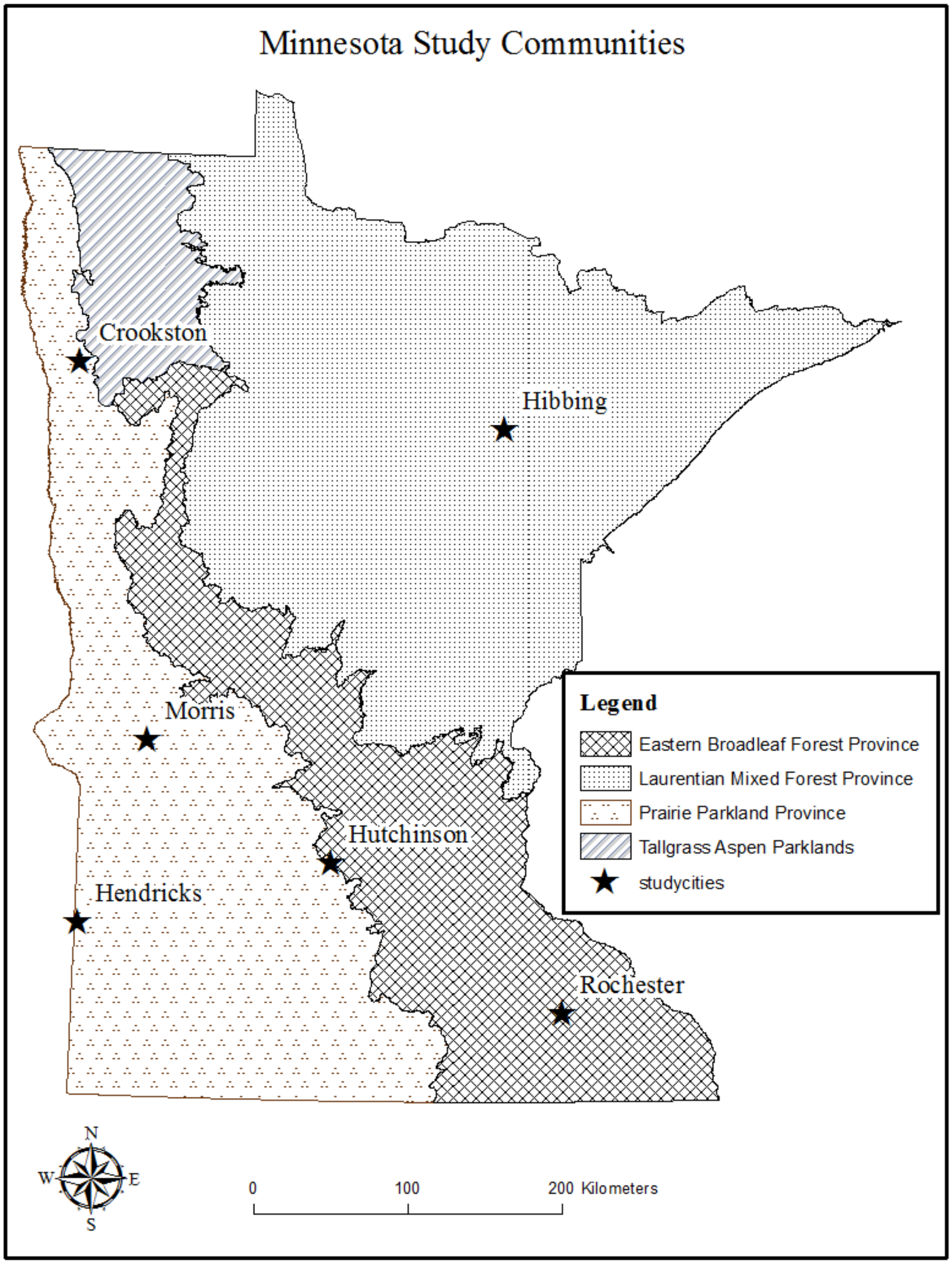
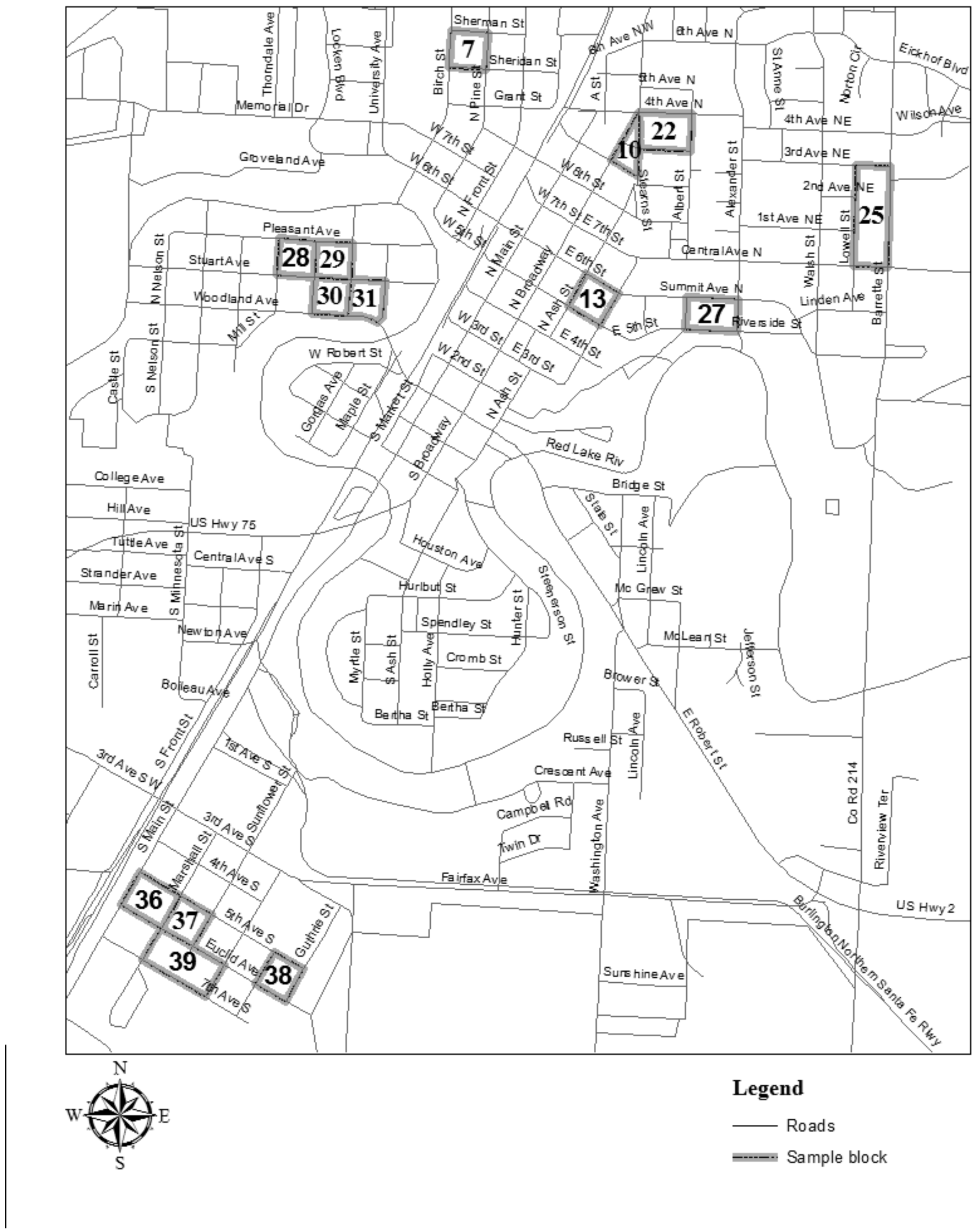
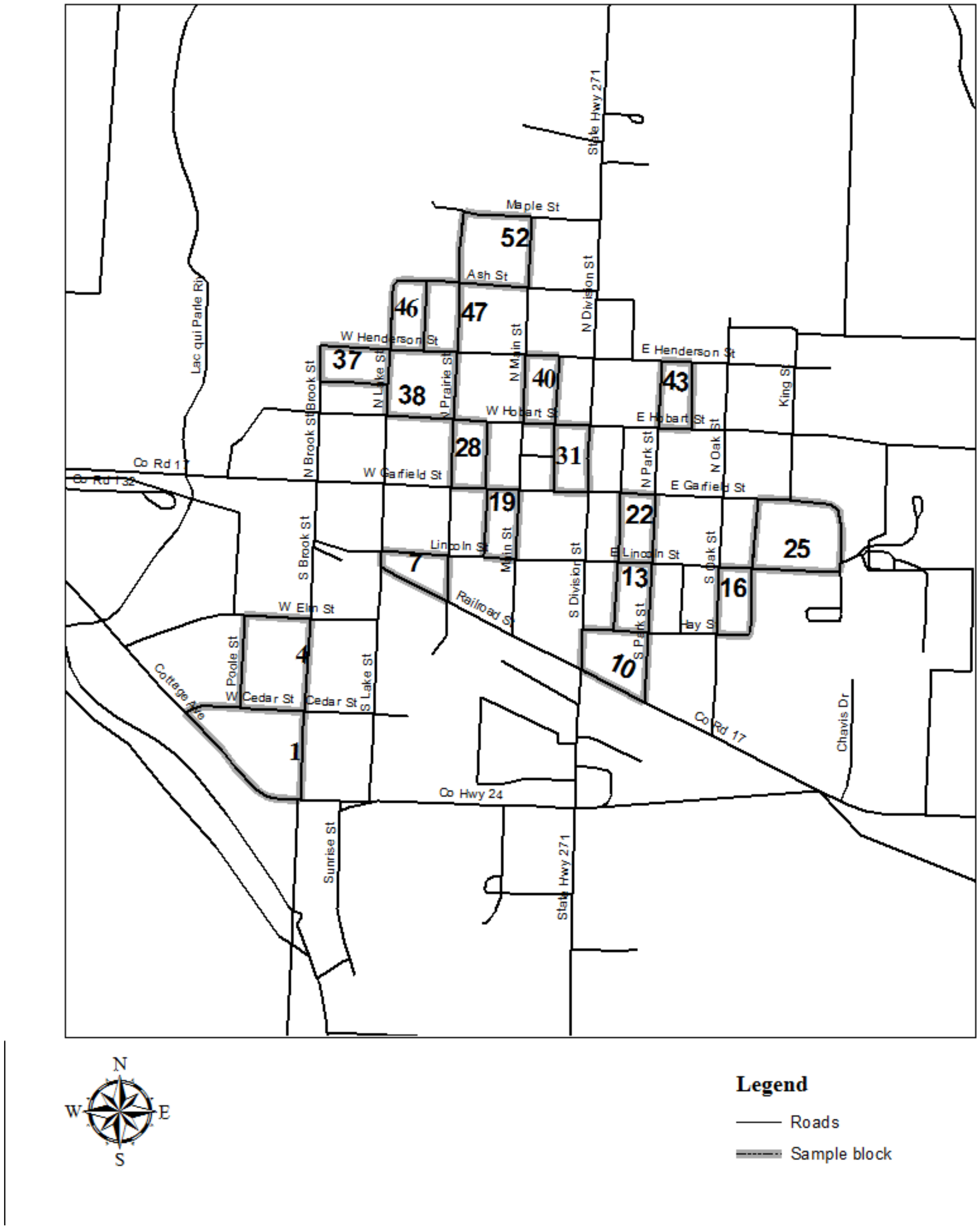
Appendix A: Study Maps



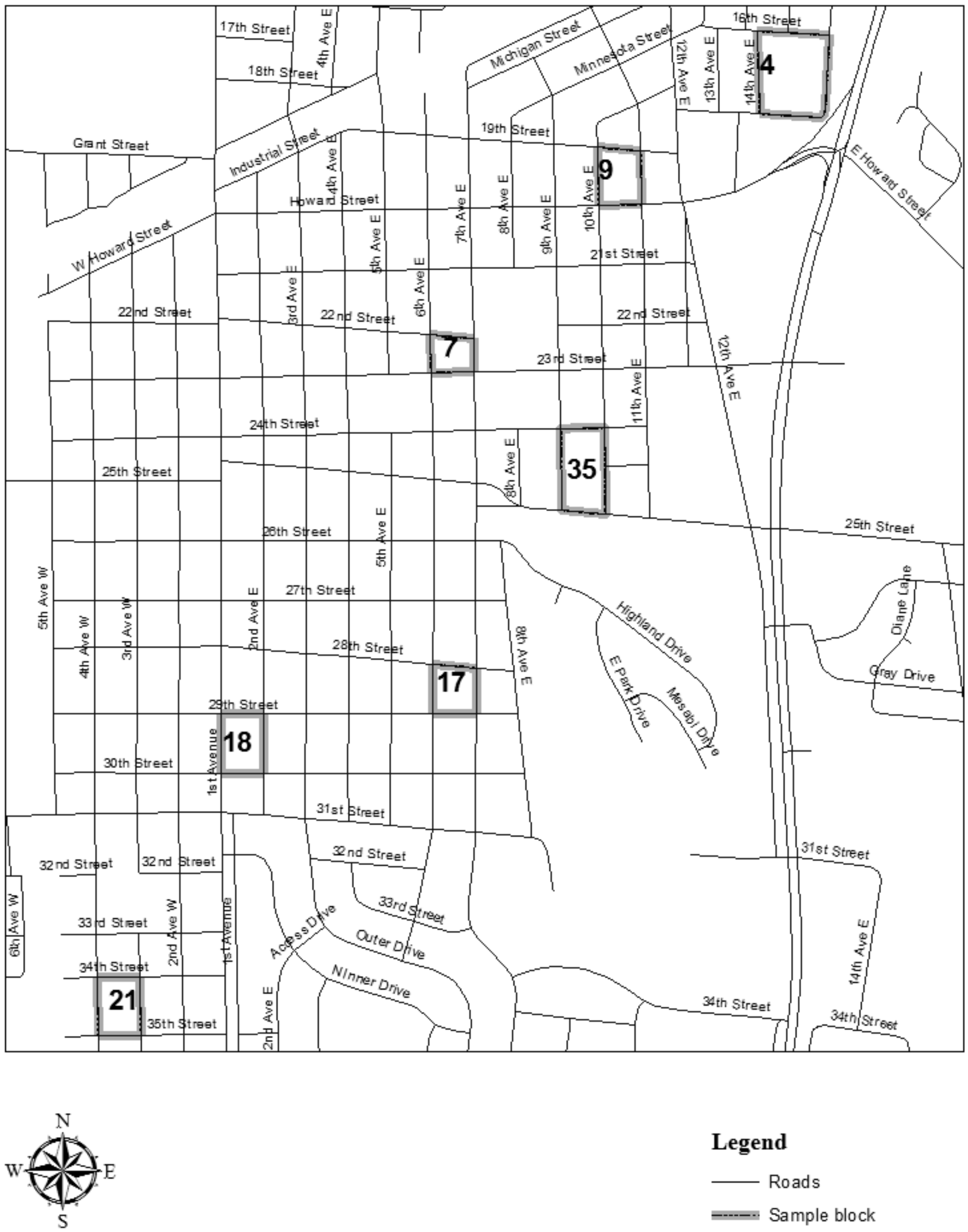
Crookston, Minnesota sample blocks



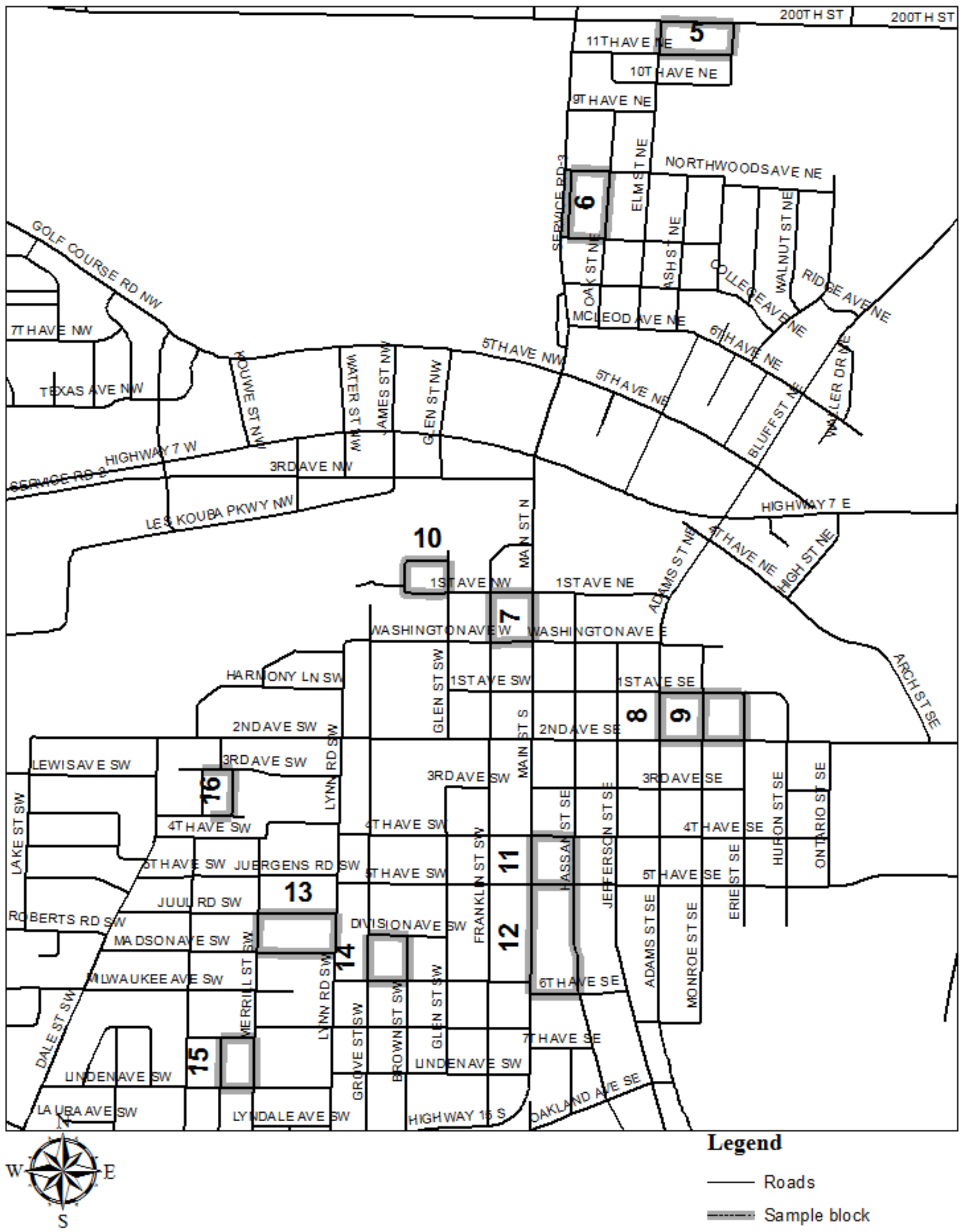
Hendricks, Minnesota sample blocks



Hibbing, Minnesota sample blocks

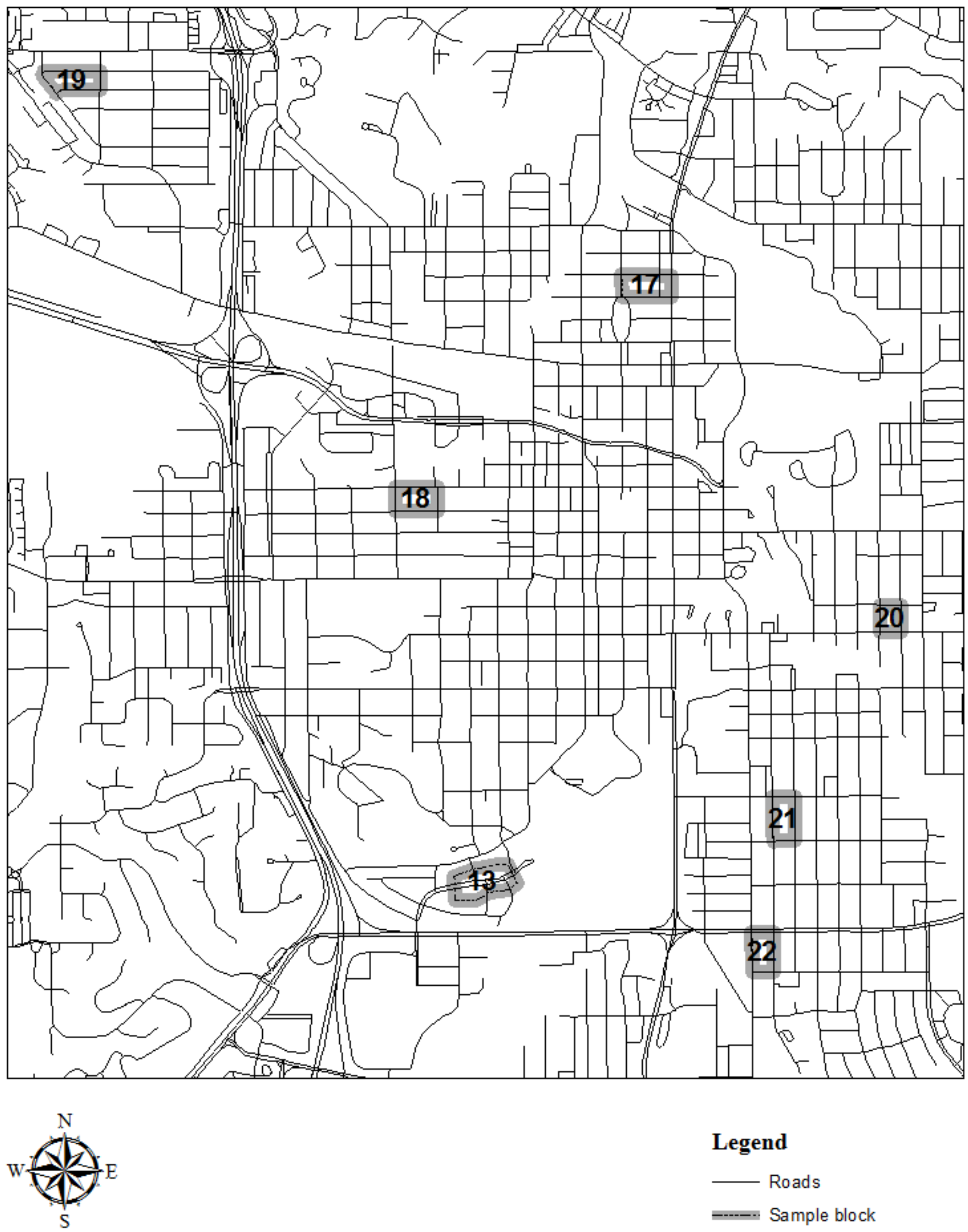


Hutchinson, Minnesota sample blocks



Morris, Minnesota sample blocks

Rochester, Minnesota sample blocks



Appendix B: Data collection form

City:					Crown width Parallel to sidewalk		Crown wdith perpendicular side			Sidewalk Damage	Stem Girdling Roots	Trunk Flare Shape
tree #	Block #	Species	DBH	Trunk Flare (inch)	CR1 (feet)	CR2 (feet)	CR 3 (feet)	CR 4 (feet)	BLVD (feet)	Sidwalk: N=none; L=lift; R=repair/replace	N=No EN=encircle Y= yes	circle oval egg
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
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