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Boulevard Tree Failures During Wind Loading Events

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Abstract. Wind loading events vary in their intensity and degree of damage inflicted on urban infrastructure, both green and gray. Damage to urban trees can begin with wind speeds as low as 25 miles per hour, especially when those trees harbor defects that predispose them to structural failures. The tree damage triangle integrates the three main factors that influence tree failures during wind loading events, namely the site characteristics, the (wind) loading event and any defects of the trees in question. The degree of damage that trees experience is generally a function of these factors overlapping each other. For instance, when the potential damage from wind loading events is exacerbated by poor tree architecture and compromised site conditions, the likelihood of significant damage is realized. Two studies on the damage to urban trees and the predictability of damage are reviewed; one study is a long-term gathering of wind loading events and accompanying damage to trees while the other is a case study of one storm in one city on one day. Both studies revealed critical pre-existing conditions that left trees vulnerable to whole tree losses: large trees in limited boulevard widths and severed roots as a result of sidewalk repair.

Keywords. Construction Damage; Tree Architecture; Wind Loading Events.

INTRODUCTION

When winds and trees collide, sometimes some trees fail; rarely do all trees suffer failures. Failures may be catastrophic, where entire trees are uprooted or broken and cause significant damage or injury while other failures may border on insignificant, resulting in little to no damage to the tree or nearby targets. The range of damage can be explained to a great degree by the range of critical factors affecting failures and their degrees of impacts. An equilateral storm damage triangle (Figure 1) provides a model to visualize the integration of the three major factors or sides of the triangle, to wit: the loading event, site characteristics for where the tree is located, and any tree defects that predispose the tree to failures.

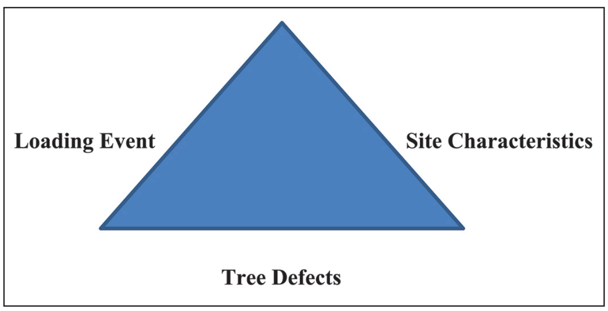

Figure 1. Components of the Storm Triangle.

These three impact factors have been identified together or separately before by other authors (Mitchell 1995; Lopes et al. 2008; Schindler et al. 2012), and in fact mirror the variables for assigning levels of risk to urban trees, namely "Site Factors," "Load Factors," and "Tree Defects and Conditions Affecting the Likelihood of Failure" (Smiley et al. 2011). Each variable on its own can account for the potential of tree or tree part failure, but when the storm triangle is used as a holistic approach to predicting wind loading damage to trees and the extent of said damage, it becomes a more valuable tool for managing trees in urban spaces.

Loading events, in this case wind loading events, are relative factors. The most commonly referenced wind loading scale relative to potential damage to trees is the Beaufort Wind Scale, conceptualized by Sir Francis Beaufort, U.K. Royal Navy in 1805 (Table 1). Based on wind speed, the scale describes impacts on trees assuming the trees are not structurally defective. When tree defects such as codominance, branch attachments with included bark, decay, stem-girdling roots or compromised root plates are factored in, the tree would then be considered structurally defective to some degree (Pokorny et al. 2003).

The direction of the wind loading event has also been shown to influence the extent of damage to urban trees (Lopes et al. 2008; Lopes and Fragoso 2009). Most wind loading events that cause tree damage occur during the

Table 1. Beaufort Wind Scale (abbreviated). National Weather Service—National Oceanic and Atmospheric Administration (NOAA). www.weather.gov/ilx/swopwindscale. The Wind Scale (Force numbers 0-12) was abbreviated to begin with wind speeds that were relevant to tree damage.

Beaufort #	Wind speed (mph)	Wind force description	Tree impacts
6	25-31	Strong breeze	Larger tree branches moving
7	32-38	Near gale force	Whole tree moves
8	39-46	Gale force	Twigs breaking off trees
9	47-54	Strong gale force	Slight structural damage occurs
10	55-63	Storm	Tree broken up or small trees uprooted; considerable structural damage
11	64-73	Violent storm	Moderate sized trees uprooted; large branches snapped off trees
12	74+	Hurricane	Large trees and branches downed

growing season and parallel the paths of the predominant growing season winds. For example, trees lining east-west (approximately) streets in a community are more likely to suffer damage during wind loading events that move in approximately the same direction. In urbanized areas, especially older urbanized areas with mature trees and extensive infrastructure, tree damage follows the direct lines of the prevailing winds despite the friction offered by buildings. For instance, in at least one study, the extent of street trees damaged parallel to the wind direction was essentially twice the damage to street trees perpendicular to the prevailing winds (Lopes and Fragoso 2009).

Site characteristics that can influence tree stability and resistance to failures include soil moisture, soil texture and structure, depth to water table, boulevard (the area between public sidewalks and street curbs) width and length, and friction (aka, frictional drag) (Wagar and Barker 1983; Mitchell 1995; Pokorny et al. 2003; Schindler et al. 2012). Friction or frictional drag is the effect that surface contact has on the speed and direction of (in this case) wind (WW2010 2010). The greater the surface areas that wind contacts, the greater the reduction of wind velocity. For instance, winds moving across a short-grass prairie or a parking lot experience some frictional drag, but not nearly as much as winds moving over and around large trees, forests, buildings or changes in topography.

Acknowledging the impact of frictional drag, there remain inconsistencies connecting some of the other site factors to frequency of failures, especially whole tree failures (partial or full wind throws). If soil conditions such as compaction, especially when combined with fine textures (e.g., clay) result in abnormally small root systems or poor fine root development (Rickman et al. 1965; Perry 1982; Costello et al. 1991; Nielson 2009), then it would follow that trees growing in those sites would be noticeably more vulnerable to full or partial windthrows (aka, tips). Disproportionate root systems resulting from varying degrees of soil compaction have been associated with higher frequencies of windthrows (Koisumi et al. 2007; Moore 2014), but to date, there is a dearth of research documenting the significance of compacted boulevard soil with the frequency of full or partial windthrows.

Soil moisture content has been associated with whole tree failures (Mitchell 1995; Ray and Nicoll 1998; Kamimura et al. 2009; Schindler et al. 2012). Tree roots are opportunistic and proliferate in rhizospheres where both soil moisture and oxygen meet balanced, optimum levels (Perry 1982). Poorly drained soil reduces the friction between the soil and tree roots, hence making it more difficult for roots to "hold on" to the rhizosphere. Sites with high water tables, in particular water tables within 24 inches of the soil surface, result in atypically shallow root systems, hence less stability (Harris et al. 2004). Poorly drained to saturated sites are deficient in soil oxygen and therefore do not provide the minimum depth considered essential for stable tree root systems (Perry 1982; Mitchell 1995; Harris et al. 2004). Combining these two phenomena, uncharacteristically shallow root systems with surface soils offering little friction to roots sliding through the soil, what results are trees that are more prone to whole tree failures.

Boulevard width is the least quantified factor in terms of a direct linkage to the frequency of tree failures. Although it seems intuitive that trees disproportionate in size compared to their boulevard foot print would be more vulnerable to whole tree failures, little evidence exists to substantiate that, although it has been observed that as distance between the trees and the infrastructure (sidewalks) increases, whole tree failures decrease (Randrup et al. 2001). There are linkages between boulevard width, tree size (trunk diameter measured at 4.5 feet [1.4 m] above ground, aka dbh), and whole tree failure rates; however that linkage combines two distinct storm damage factors (site characteristic and tree characteristic) rather than distinguishing the impacts of a single factor (Wagar and Barker 1983; Lopes et al. 2008).

The third factor is probably the most complicated since it includes both the biology and the structure of a living organism, the tree, as well as the location of the failure due to the wind loading event. Failures in the canopy are consistently linked to common defects and tree architecture in multiple assessment protocols (Pokorny et al. 2003; Harris et al. 2004; Smiley et al. 2011). Branch attachments, degrees of codominance and location of codominants, dead branches, presence and location of decay, live crown ratio (LCR), and canopy symmetry and density all play roles in a tree's vulnerability to wind loading events that result in damage to the canopy. Likewise, failures along the tree trunk line are generally associated with decay, cavities and open cavities, and more specifically, strength loss. Additionally, those factors that increase the probability of whole tree failures are associated with roots: dysfunctional root systems such as stem-girdling roots (SGRs), confined root systems, severed root plates, atypically shallow root systems, and deeply buried roots, all of which are exacerbated by trees with very dense or asymmetrical canopies, or excessive leans.

Tree Root Interactions with Infrastructure

Trees are not always innocent victims of tree vs. infrastructure conflicts. Damage to gray infrastructure (sidewalks, streets, curbs, buried utilities) by tree roots can range from moderate to significant in terms of repair costs (McPherson and Peper 1996; Stål and Rolf 1998). In at least one published seminal research article on the topic (McPherson and Peper 1996), sidewalks bore the brunt of the damage compared to the other utilities. Wang et al. (1988), documented street tree and sidewalk conflicts in Manchester, UK, noting that of the 2,232 street trees observed, 30% were causing unacceptable damage to paved surfaces.

The underlying causes for these conflicts, damage to paved sidewalks, and eventual repair to the infrastructure, go beyond a tree root vs. pavement scenario. Boulevard width has been documented as a factor, with boulevards narrower than (approximately) 10 feet (3 m) experiencing significantly more pavement damage than those 10 feet (3 m) or wider (Wagar and Barker 1983; Wang et al. 1988). Specific to tree trunk and root architecture, North et al. (2015) demonstrated that the trunk flare diameter at ground line was critical to predicting whether there would be tree and sidewalk conflicts. Using their formula for establishing a minimum boulevard width to accommodate a 20 inch (51 cm) dbh silver maple (*Acer saccharinum* L.), a width of 10 feet (3 m) would accommodate the trunk flare at ground line and leave an open space of (approximately) 4.0 feet (1.2 m) between the trunk flare and the parallel sidewalk and street curb. Additionally, tree species and size have also been revealed as damage to infrastructure factors (Wagar and Barker 1983; Wang et al. 1988; Nicoll and Armstrong 1998; North et al. 2015) although the relative rankings of examined trees were not always in agreement. What was agreed upon was that larger trees, especially faster growing larger trees, were often the main arboreal offenders.

The two studies detailed in this analysis of tree failures during wind loading events focused on street tree populations in multiple communities throughout the state of Minnesota. One study was a multiyear, multicommunity assessment of all types of damage to trees due to wind loading events, categorized as either damage confined to tree canopies, failures along tree trunks, or complete tree failures at or below the ground line. The second study closely detailed one day of wind loading events in one community that resulted in the full or partial windthrow of a significant number of street trees. The intent of both studies was to determine what if any pre-existing factors could be connected to the frequency and type of damage to street trees during wind loading events.

MATERIALS AND METHODS

Wind Loading Event Damage in Metropolitan Minnesota, 1995–2005

Due to the complexity of various types of wind loading events, this study addressed only those events that were not complicated by multi-directional wind forces (rotations) such as downbursts and derechos (NWS/NOAA 2018). Those wind loading events that were included were thunderstorms, straight-line winds, and gust fronts; these events comprise the majority of wind loading events that impact urban trees in North America.

Data collected on damage to urban trees following wind loading events was confined to communities in the 11 county metropolitan area of Minneapolis/Saint Paul, Minnesota. Immediately following a wind loading event, the storm type was confirmed with the National Weather Service Forecast Office—Twin Cities, Chanhassen, Minnesota. If the wind loading event was identified as one that included wind rotations, the sites were visited by the principle investigator from the University of Minnesota's Department of Forest Resources, and the path of the storm was located on a street map. All surveys of damaged trees were conducted beyond the borders of the rotation paths, extending to the points where damage to trees on public properties was no longer evident.

Collection of data was conducted by the principle investigator, research fellows in the Urban Forestry Outreach Research and Extension lab, graduate students in the Department of Forest Resources, and trained citizen scientists (Tree Care Advisors). All parties conducting the damage surveys were trained to observe and collect data in the same manner. Most data collection was conducted by teams of two to three trained personnel or citizen scientists. Training included an emphasis on the safety of the data collectors as well as avoiding any activities that would interrupt the storm recovery crews. Data collection forms had been made available to all trained personnel as part of the training workshops as well as made available online. They included the following: date of loading event, location (community, park name, street addresses), tree metrics (tree species, dbh), damage metrics (type of failure and location of failure, size of branch or trunk at failure), site location metrics (park, lawn, boulevard, right of way, sidewalk tree, dimensions of growing space if confined), pre-existing conditions (included bark, codominance, decay, cavities, dead wood, stem-girdling roots, lack of trunk flare at ground line), and a column for any notes not previously addressed in the spread sheet.

Since the data were largely being collected while emergency recovery activities were in process, not every tree was assessed immediately following the wind loading event. In those cases, damaged and undamaged trees in high risk areas were revisited after emergency operations had concluded and data were recorded at that time. All data collectors were instructed to not interpret or project, but to treat each tree as a snapshot. If there were any questions on tree identification or pre-existing conditions, they were instructed to take photographs and forward them to the principle investigator. All surveys submitted included the name(s) of the trained personnel or citizen scientists. Upon completion of the data collection, a tree species survey was conducted within the areas where the data were collected to add an element of perspective to the numbers and species suffering damage from the wind loading event. All data were reviewed and entered on a master spread sheet for each wind loading event and dated. At the conclusion of the 11-year study, the data were analyzed by the principle investigator.

Wind Loading Event in Minneapolis, Minnesota, June 21, 2013

Background

During the early evening hours of June 21, 2013, a violent thunderstorm swept through much of metropolitan Minneapolis/Saint Paul, Minnesota, wreaking significant damage to trees, utilities, and structures. This storm was characterized by two unusual phenomena. Earlier in the same day, a Beaufort Wind Scale force number 9 thunderstorm moved from the southwestern part of the state and through the metropolitan area, delivering rain and winds ranging from 45 to 50 miles per hour (mph)(National Weather Service Forecast Office [NWS], Chanhassen, MN, 6/21/13). Several hours after this storm caused minor damage to trees and infrastructure, a second wind storm with maximum wind speeds recorded at 61 mph (Beaufort Wind Scale force number 10) followed, accompanied by torrential rains of up to 2.5 inches in less than two hours (NWS, 6/21/13). Even though the earlier storms originated in the southwestern portion of the state, as the storms moved north and eastward toward Minneapolis, the path of both wind loading events altered their original paths and extended from the northwest corner (290°, NWS, 6/21/13) of Minneapolis and moved diagonally to the southeast corner. The neighborhoods that were hardest hit were those in the southern half of the city. Minneapolis lost many mature trees, including hundreds in the boulevards and parks, as well as a significant amount of structural damage to standing trees in public and residential landscapes.

The Minneapolis Park and Recreation Board (MPRB) Division of Forestry contracted with the University of Minnesota Department of Forest Resources Urban Forestry Outreach Research and Extension laboratory to conduct a detailed survey of tipped (aka, wind thrown or whole tree loss) or partially tipped trees, any associated pre-existing conditions that the trees were subjected to, and determine if there were any significant relationships between the noted variables (cause) and the tipped or partially tipped trees (effect). As per the agreement with MPRB, the stumps and root systems of affected trees were left in place until all tree failure data could be collected. All data collection began in August of 2013 and concluded by the end of December, which included the collection of information on sidewalk and street improvement activities (secondary data) with the cooperation of the Minneapolis Public Works Department.

The University of Minnesota's School of Statistics was contracted by the Urban Forestry Outreach Research and Extension lab to design the research sampling protocol and conduct the final data analysis. To that end, a study protocol was developed that included sampling both tipped and undamaged trees along the path of the storm. This path was a stratified path through the city boundaries that included block street segments (BSS) that contained at least two tree failures. A BSS was defined as both sides of a street that divided two paired blocks and included all of the trees in the boulevards on both sides of the street, damaged or not. Streets were selected that ran approximately north/south to roughly parallel with the path of the storms which would also experience the greatest force of the prevailing winds throughout the wind loading event.

To establish the number of BSS that would be included in the survey, a rapid visual assessment of tipped or partially tipped boulevard trees was conducted and mapped with GPS coordinates and street addresses (Figure 2). Consistent with the recorded path of the wind loading event, the majority of these trees occurred in a northwest to southeast pattern, with the greatest number of impacted trees in the southeast corner. Tipped trees were defined as those

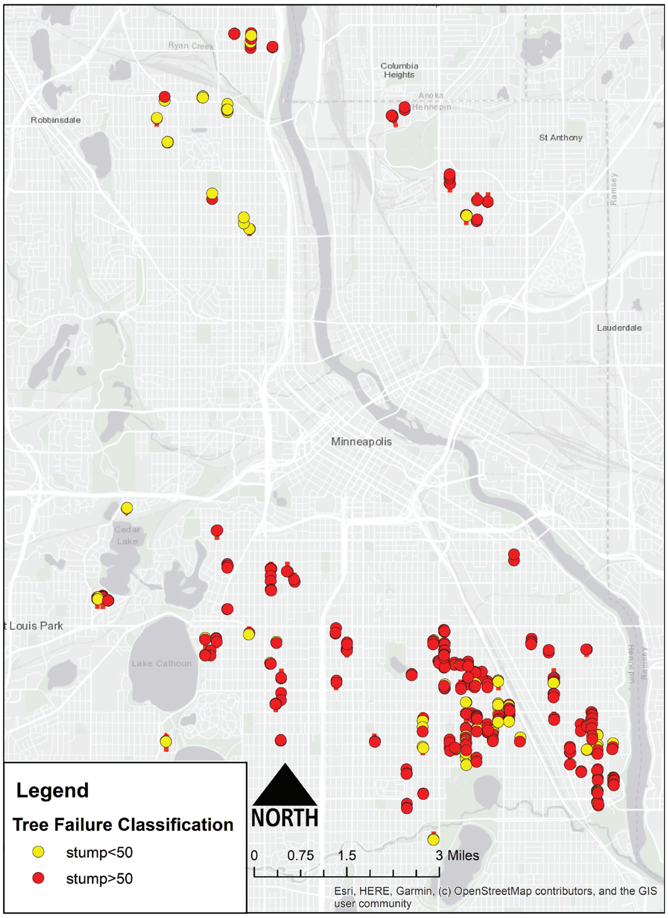

Figure 2. Location of boulevard trees that tipped (greater than 50% of root plate protruding above ground—red dots) or partially tipped (less than 50% of root plate protruding above ground—yellow dots) following the June 21, 2013 wind loading events in Minneapolis, Minnesota.

Figure 3. Example of a tipped tree with 50% or more of the root system protruding from the soil.

with 50% or more of their root plate protruding from the soil (Figure 3). Partially tipped trees were those that had experienced a partial root plate failure, but less than 50% of their root plates protruded from the soil (Figure 4). All were considered unacceptable root failures that warranted their removal.

Figure 4. A partially tipped tree with less than 50% of the root plate protruding from the soil.

Following the rapid visual assessment of the trees with root failures, block street segments (BSS) were selected within the areas where there were at least two tree failures in a BSS. In other stratified tree inventory samples, a block segment was defined as a residential or commercial block with four sides. Since the damage to trees for this study was confined to boulevard trees, and the goal was to minimize any unnecessary variables, the dividing blocks were selected as those that ran as close to north/south as possible, avoiding any east/west streets. Therefore, a BSS had only two sides rather than four, with each side paralleling the dividing street. This eliminated the variable of crosswinds affecting tree failures, which would dilute the accuracy of any statistical analysis. Figure 5 shows the stratified sampling points (BSS) throughout the city's political boundaries, again, heavily weighted in the area where most of the damage occurred—the southeast quarter of the city.

Tree Data

Within each BSS, all boulevards and boulevard trees were assessed, whether failed or not. A total of 3,076 trees were evaluated from a total of 122 BSS, of which 367 of the assessed trees were considered failures that warranted removal (tipped or partially tipped trees). Of the 3,076 trees encountered, each tree was identified to species. Each tree was measured as a function of trunk diameter at 4.5 feet above ground (aka, diameter at breast height or dbh).

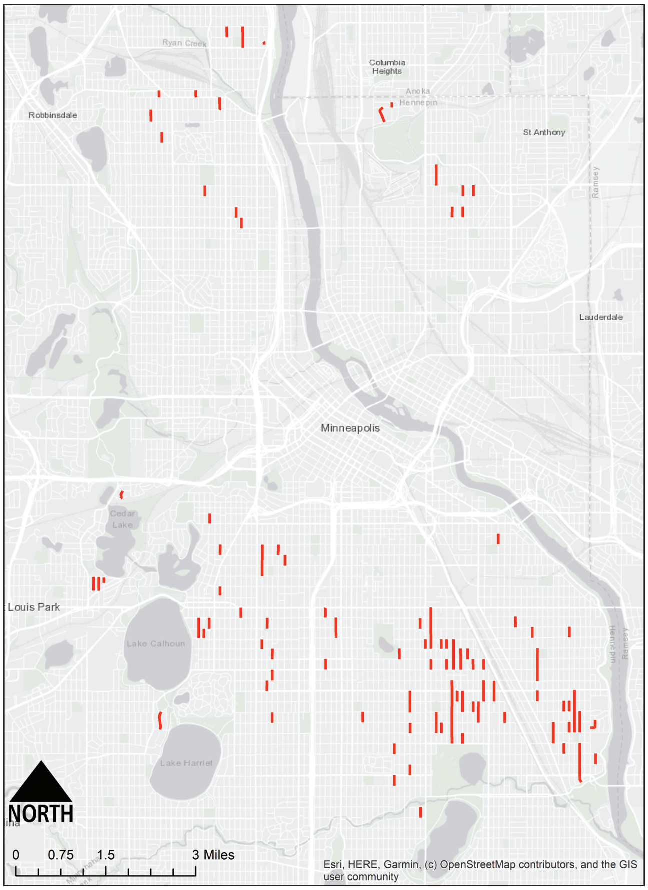

Figure 5. The stratified distribution of Block Street Segments (BSS) indicated as red bars, the sampling points for the study. Each BSS had a minimum of two tree failures.

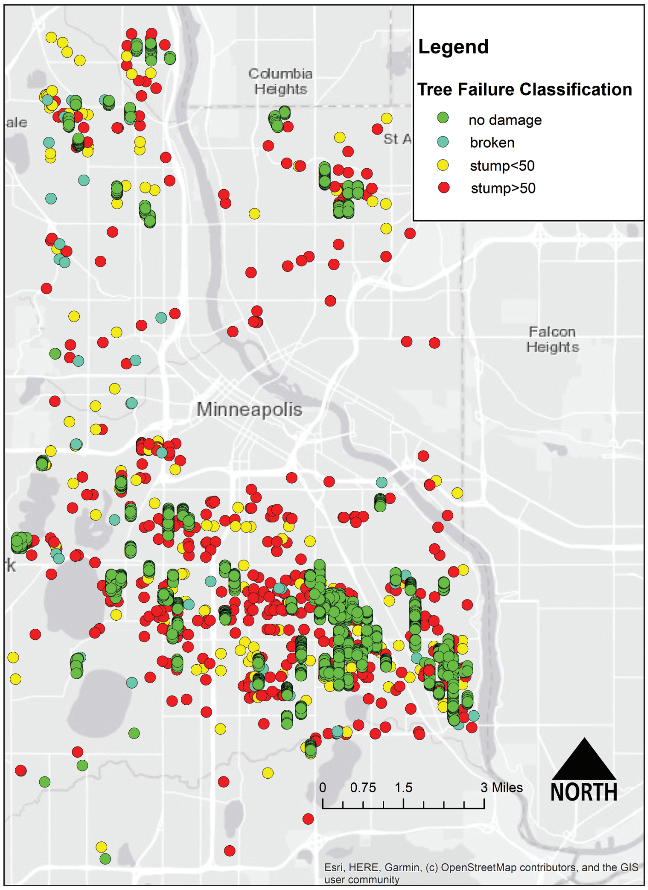

Figure 6. Trees inventoried and assessed within the 122 BSS sampling area.

Each tree was noted as tipped, partially tipped, or not. All trees assessed within the 122 BSS were then GPS and street address located and entered on a map (Figure 6).

Boulevard Data

Within each sampled BSS, the following data was collected in the field: boulevard width; distance from the curb and sidewalk to the inventoried tree trunk; length of the repaired or replaced sidewalk adjacent to the inventoried tree as applicable; and length of the curb repaired or replaced adjacent to the inventoried tree as applicable. Additionally, where applicable, the date stamp in the sidewalk that was repaired or replaced adjacent to the inventoried tree (Figure 7) was located and recorded. Since the extent, date, and nature of the infrastructure improvement was sometimes difficult to positively identify, records of infrastructure improvements were researched with the cooperation of Minneapolis' Department of Public Works. All records of infrastructure improvements were ground-truthed for accuracy. Soil structure (compaction) measured as resistance in foot pounds at 6 inch (15 cm) and 12 inch (30.5 cm) depths at a standard and typical boulevard point was recorded for each BSS. An Eijkelkamp, 1 meter, hand penetrometer was used in the field to measure compaction.

Soil Analysis

A total of 143 soil samples were analyzed by the University of Minnesota's Soils Lab. A one-pint soil sample was taken for each BSS at a depth of 8 inches (20 cm), beyond the depth of turf grass thatch and rooting depth, and submitted to the University of Minnesota's Soils Lab for laboratory analysis. Each sample was analyzed for texture by separating and analyzing the percentage of sand, silt, and clay. Soil reaction (pH)—a standard test—was determined as well as the percent of organic matter for each sample.

Data Analysis

All collected data were electronically entered and submitted to the University of Minnesota School of Statistics' Statistical Consulting Center for analysis. To investigate which variables were associated with root failure, generalized logistic mixed modeling was used, with root failure as the response and BSS as a random effect. Several models were fit to explore the various predictors, and the most

Figure 7. An example of a date stamp on sidewalk replacement/repair. Date is 07-30-12.

parsimonious model was chosen to explore further. First, the primary predictors—replacement work, boulevard width, dbh, and genera group—were considered, along with all two-way interactions. Nonsignificant terms were excluded, and the resulting model compared using AIC (Akaike information criterion) with the full model. Secondary predictors, including penetrometer readings (at both 6 and 12 inch [15 and 30.5 cm] depths), and percent organic matter, sand, silt, and clay, were then added to this model, along with interactions with genus group and replacement work done. For penetrometer readings at 12 inch (30.5 cm) depth, an additional binary variable was included to indicate if the reading was able to be made at all. Each variable was considered separately; only the two penetrometer reading terms were significant. Since they gave similar model fits and are known to be correlated, the penetrometer readings at 6 inch (15 cm) depth were chosen for inclusion, as then the additional binary variable was unneeded. The final model included replacement work and genera group, as well as boulevard width, dbh, the penetrometer reading at 6 inch (15 cm) depth, and their interactions with replacement work.

Analysis was focused on which variables (e.g., tree species, boulevard width, sidewalk improvement) were associated with root failure. A generalized logistics mixed modeling was used with root failure as the response and BSS as a random effect. All calculations were performed in R version 3.0.1 using the lme4 package.

RESULTS

Wind Loading Event Damage in Metropolitan Minnesota, 1995–2005

Only data relevant to the topic of this study, i.e., tipped or partially tipped trees in boulevard landscapes, is itemized for discussion. Of 1,584 sampled trees, 54% were categorized as whole tree losses. Of the whole tree losses, 24% occurred on boulevards, described as the space between the street curb and the public sidewalk. Of the whole tree losses on boulevards, 74% were categorized as tips or partial tips. Of the whole tree losses on boulevards, 74% were located on boulevards 4.0 feet (1.2 m) in width or less. Of the whole tree losses on boulevards, 42% were in the dbh ranges of 20 inches (51 cm) and greater; 29% were in the dbh range of 6 to 10 inches(15 to 25 cm). Of the whole tree losses on boulevards, the most common genera were *Tilia* (18%), *Fraxinus* (15%), and *Picea* (12%).

Wind Loading Event in Minneapolis, Minnesota, June 21, 2013

A total of 3,076 trees representing 18 genera and 27 species were surveyed, 367 (11.9%) of which were identified as tips or partial tips. Only genera were used in this evaluation, since each genera was often represented by a mix of species and cultivars. Only when these species and cultivars were grouped into their respective genera were there sufficient numbers to conduct statistical analyses. A total of eight genera had representative trees that tipped or partially tipped during the wind loading event, namely: *Abies, Acer, Celtis, Fraxinus, Picea, Quercus, Tilia,* and *Ulmus*.

The major finding is that having sidewalk replacement work done increased the odds of root failure by 2.24 times (95% CI: 1.77, 2.83; $P < 0.0001$). For illustration, when no replacement work was done, the average *Tilia* had a 10.6% chance of root failure, the precursor to tips or partial tips; this increased to 21.0% when replacement work was done. *Tilia* is used as the baseline genus for reference throughout this analysis because it was the most represented genus in the tipped/partially tipped damage category (52% of all damaged trees).

The genus of the tree was also significant ($P < 0.0001$), even after adjusting for the average dbh of each group. Compared with linden/basswood (*Tilia)*, ash (*Fraxinus*) had a decrease in odds of root failure of 0.94 times (95% CI: 0.73, 1.21); maple (*Acer*) of 0.47 (95% CI: 0.29, 0.77); elm (*Ulmus*) of 0.39 (95% CI: 0.22, 0.69); and "other genera" of 0.22 (95% CI: 0.11, 0.46). The influence of genera was most notable when considered in light of sidewalk replacement. For illustration, ash had a 10.0% chance of root failure when no replacement work was done, compared with a 20.0% chance when it was done; for maple these were 5.3% and 11.1%, respectively; for elm, 4.4% and 9.4%; and for other genera, 2.6% and 5.6%. It must be noted that *Tilia* and *Fraxinus* accounted for 89% of all surveyed genera (52% and 37%, respectively). Therefore, overinterpretation of the effects of other genera on root failures and subsequent tips or partial tips should be avoided.

Boulevard width was found to have a significant interaction with replacement work ($P = 0.011$). When work was done, an increase in boulevard width of 1.42 times (one standard deviation) reduced the odds of root failure by 0.64 (95% CI: 0.49, 0.84; $P = 0.001$). For illustration, two otherwise average *Tilia* on streets with widths of 4.0 feet (1.2 m) and 8.0 feet (2.4 m) have a 29.4% and 14.6% chance of failure, respectively, when work is done. However, when no replacement work was done, boulevard width was not significant ($P = 0.50$).

Dbh was also found to have a significant interaction with replacement work ($P = 0.008$). In this case, when no replacement work was done, an increase in dbh of 6.77 inches (17.19 cm) increased the odds of root failure by 1.27 times (95% CI: 1.08, 1.51; $P = 0.005$). So two otherwise average *Tilia* with dbh of 8.2 inches (20.8 cm) and 21.7 inches (55.1 cm) have 8.5% and 13.2% chance of tipping or partially tipping, respectively, when no work was done. When replacement work was done, dbh was not significant ($P = 0.29$).

Penetrometer measurements at 6.0 inches (15.2 cm) deep also had a significant interaction with replacement work ($P = 0.019$). So two otherwise average *Tilia* with penetrometer readings of 204 foot-pounds (low) and 516 foot-pounds (moderate to high) have a 9.7% and 11.6% chance of failure when no work was done, but a 24.1% and 18.3% chance of failure when work was done.

Percent organic matter ($P = 0.94$), percent sand ($P = 0.55$, and percent silt ($P = 0.38$) were not found to be significant variables for tipped or partially tipped tree incidences.

DISCUSSION

Several factors were found to be consistent with tree tips or partial tips in public landscapes, primarily boulevards during wind loading events. Based on these studies—one being a long-term collection of data from a variety of storms, wind speeds, and site factors, and the other an in-depth assessment of one storm on one day in one city—several common "storm damage triangle" factors were identified. The most common factors that were associated with tree failures were as follows.

Roots severed due to sidewalk repair was the most influential tree defect factor related to root failures ($P = 0.0001$) in the case of the 2013 Minneapolis case study. Regardless of genera, trees were 2.24 times more likely to tip or partially tip compared to those trees not exposed to root losses due to sidewalk repairs. This is consistent with data reported in a similar study in Australia (Moore 2014), where it was observed that root severance due to construction activities (among other activities) was highly coincident to windthrows of mature trees during wind loading events.

Trees in narrow boulevards (4 feet [1.2 m] wide compared to 8 feet [2.4 m] wide) were more likely to fail when sidewalk repair severed roots. In the 2013 Minneapolis case study, this relationship became significant ($P = 0.0001$) when combined with sidewalk repair activities that included root severance. Both studies revealed that wider boulevards (greater than 4 feet [1.2 m]) had lower frequencies of windthrows or whole tree failures (in the case of the 1995—2005 study).

Other variables such as tree size and soil compaction were inconsistently associated with tree failures. In the 1995—2005 study, size did matter, with the majority of the whole tree failures in boulevards, including windthrows, represented by trees with dbh values of 20 inches (50.8 cm) or greater (42% of the incidences). The relationship between size and failures with the June 21, 2013 study was weaker and only significant as a site factor when sidewalk repairs had not taken place. When sidewalk repairs and associated root losses had occurred, dbh was no longer a significant factor.

Soil compaction in the upper rhizosphere (top 6.0 in [15.2 cm]) was a factor in the frequency of windthrows only when combined with sidewalk replacement activities. As opposed to soil compaction, though, other soil properties such as organic matter percentage and soil texture were not influential site factors. Soil compaction alone has been noted in several research summaries as an inhibiting factor for "normal" root development, producing root systems that are abnormally shallow and theoretically more vulnerable to damage (Alberty et al. 1984; Gillman 1990; Day et al. 2000; Nielson et al. 2009; Day et al. 2010). However, there have been no similar studies that have shown boulevard soils or any urban soils to be homogenous and predictable in terms of compaction, soil texture, or organic matter. So as much as the literature has identified soil compaction as a "litmus test" for the extent of tree root systems, the reality of using compaction alone as a predictor or a site factor for tree failures during loading events is tenuous at best. The same caution can be extended to soil texture. Although it is logical and evidence suggests that soil textures do in fact correlate to tree stability (Koisumi et al. 2007), the heterogeneous nature of urbanized soils does not favor this as a predictable site factor.

In retrospect, there are three factors that could have either been modified or added to make this data and subsequent conclusions even more robust. First, tracking the infrastructure repair was arbitrarily set at any activities within five years of the storm failures. That may or may not have been an accurate or best practices decision. Perhaps a closer look at more frequent intervals would reveal other conclusions, or the same could be said for extending the interval to perhaps ten years.

The second factor is percolation rate: the rate that soil moisture drains vertically. There is good documentation that saturated soils leave trees more vulnerable to wind throws, either partial or full (Day 1950; Munishi and Chamshama 1994; Steil et al. 2009). In the case of the June 13, 2013 event study, it would have been most advantageous to have run the percolation tests immediately after the rain event that accompanied the winds. It is a time-consuming procedure but could reveal even more conclusions from events such as those that combine significant rainfalls with wind loading events.

The third factor is determining what other construction or reconstruction activities had taken place below the landscape surface and out of sight. As generous as the Department of Public Works was with this study, data for the timing and extent of buried utilities is overwhelming and complicated and not always readily available to assess. However, it is logical to assume that at least some of those activities took place within the five previous years before the storm struck and involved the loss of structural roots to some degree.

Alternatives to Falling Trees

As noted in the beginning of this manuscript, the value of collected and interpreted data in urban forestry research is to develop predictive management tools that will moderate losses during these events. To that end, there are some management recommendations that could be considered, based on this interpretation of these two studies.

Wider growing spaces are better. Larger trees provide more valuable canopy and require more substantial footprints for stability. For boulevards to successfully support those larger trees, a minimum width of 8 to 10 feet (2.4 to 3 m) should be provided.

Make better decisions on tree preservation during infrastructure repair projects. Not all trees deserve to be preserved, especially those that are large and will certainly suffer inevitable root loss during the repair of infrastructure, or those trees that are in poor condition and are already posing unacceptable levels of risk. Those trees are hazardous and further expose those sites with unacceptable levels of risk.

There are creative measures to resolve unacceptable infrastructure situations, such as lifted sidewalks that create tripping hazards, requiring the replacement of sidewalk panels. The problem is not the tree or the pavement; the problem is the trip hazard. Trip hazards can be remedied by ramping sidewalk panels with asphalt or other materials that eliminate the hazards that lifted sidewalks present. Panels can be lifted by hydraulic pressure to line up surfaces and the void can be filled with materials to support the panel or panels in place. Sidewalk shaving is a technique where irregularities in panel heights can be eliminated by grinding down the high points, thereby eliminating the trip hazards.

Redirect new sidewalk panels well away from tree roots or trunk flares at ground line. This may involve curving the sidewalk out several feet to avoid damaging structural roots, but most communities have sufficient rights-of-way areas where the sidewalks are located to use this as an alternative for preserving valuable, large trees.

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Résumé. Les aléas de vents violents varient dans leur intensité et dans le niveau de dommages qu'ils infligent aux infrastructures urbaines, qu'elles soient vertes ou grises. Les dommages sur les arbres urbains peuvent débuter dès que les vents atteignent 35 milles à l'heure (56 km/heure), particulièrement pour les arbres possédant des déficiences les prédisposant à des bris structuraux. Le triangle des dommages aux arbres intègre les trois principaux facteurs qui influencent les bris aux arbres durant les épisodes de vents violents, à savoir les caractéristiques du site, la charge éolienne causée par l'événement et toute déficience déjà présente dans les arbres concernés. Le niveau de dommage occasionné aux arbres est généralement fonction de ces facteurs se chevauchant ou interagissant les uns avec les autres. Par exemple, lorsque le dommage potentiel d'un épisode de vents violents est aggravé par une faible structure et des conditions de site compromettantes, la probabilité d'un dommage significatif est confirmée. Deux recherches portant sur les dommages aux arbres urbains et la prévisibilité de ceux-ci ont été examinées. La première recherche est une collecte menée à long terme d'aléas de vents violents en lien avec des dommages occasionnés aux arbres tandis que l'autre est une étude de cas pour un orage survenu dans une ville lors d'une journée. Les deux recherches démontrèrent des conditions préexistantes critiques—de grands arbres croissant dans des espaces réduits en largeur le long de boulevards et dont des racines avaient été sectionnées lors de travaux de réparation du trottoir—ce qui rendit les arbres vulnérables à une chute éventuelle.

Zusammenfassung. Windlastige Ereignisse variieren in ihrer Intensität und ihrer schädigenden Auswirkungen auf die urbane Infrastruktur, sowohl grün wie grau. Der Schaden an Stadtbäumen beginnt bei Windgeschwindigkeiten von 35 m/h, besonders wenn diese Bäume bereits Defekte haben, die sie einem strukturellen Versagen aussetzen. Das Baumschadendreieck integriert die drei Hauptfaktoren, die das Baumversagen während starker Windereignisse beeinflussen, insbesondere die Standortbedingungen, das Windereignis und vermeintliche Vorschäden des betroffenen Baumes. Der Schadensgrad, den die Bäume hier erfahren, ist meist eine Funktion aus der Überlappung dieser drei Faktoren. Zum Beispiel wenn der potentielle Schaden aus Windlasteintrag durch eine schlechte Kronenarchitektur begleitet wird und ungünstige Standortbedingungen herrschen, dann ist die Möglichkeit für potentiellen Baumschaden realisiert. Zwei Studien zum Schaden an urbanen Bäumen und der Vorhersagbarkeit von Schäden werden hier vorgestellt; eine Studie ist ein langfristiges Sammeln von Daten zu Starkwindereignissen und den dabei auftretenden Schäden, während die andere eine Fallstudie zu einem Sturm in einer Stadt an einem Tag ist. Beide Studien deckten kritische, vorher existierende Bedingungen auf—große Bäume in limitierten Straßenbreiten und mit beschädigten Wurzeln als Ergebnis von Gehwegarbeiten—welche Bäume in einem anfälligen Zustand bis zum totalen Baumverlust hinterließ.

Resumen. Los eventos de carga de viento varían en intensidad y grado de daño infligido a la infraestructura urbana, tanto verde como gris. El daño a los árboles urbanos puede comenzar con velocidades del viento tan bajas como 35 millas por hora, especialmente cuando esos árboles albergan defectos que los predisponen a fallas estructurales. El triángulo de daño de los árboles integra los tres factores principales que influyen en las fallas de los árboles durante los eventos de carga del viento, a saber, las características del sitio, el evento de carga (del viento) y cualquier defecto de los árboles en cuestión. El grado de daño que experimentan los árboles es generalmente una función de estos factores que se superponen entre sí. Por ejemplo, cuando el daño potencial de los eventos de carga del viento se ve agravado por la mala arquitectura de los árboles y las condiciones comprometidas del sitio, se da cuenta de la probabilidad de un daño significativo. Se revisaron dos estudios sobre el daño a los árboles urbanos y la previsibilidad del daño; un estudio es un conjunto a largo plazo de eventos de carga de viento y daños que acompañan a los árboles, mientras que el otro es un estudio de caso de una tormenta en una ciudad en un día. Ambos estudios revelaron condiciones preexistentes críticas (árboles grandes en bulevares limitados y raíces cortadas como resultado de la reparación de la acera) que dejaron a los árboles vulnerables a la pérdida total.