Arboriculture & Urban Forestry 2019. 45(6):279–288

Stability Recovery in London Plane Trees Eight Years After Primary Anchorage Failure

By Andreas Detter, Philip J. E. van Wassenaer, and Steffen Rust

Abstract. As the intensity and frequency of strong storms increase, the potential for damage to urban trees also increases. So far, the risk of ultimate failure for partially uprooted trees and how they may recover their stability is not well understood. This study sets out to explore if and to what extent trees can regain anchoring strength after their root systems have been overloaded. In 2010, ten London Plane (*Platanus* × *acerifolia*) trees were subjected to destructive winching tests. Two trees were pulled to the ground while eight were loaded until primary anchorage failure occurred and were left standing with inclined stems. In 2013, two trees had failed and six were re-tested nondestructively. By 2018, another tree had failed, and we tested the remaining five again. Rotational stiffness was derived for all trials and served as a nondestructive proxy for anchoring strength ($R^2 = 0.91$). After eight years, one tree had regained its original strength, while four had reached between 71 and 82% of their initial rotational stiffness. However, three trees failed during the observation period. The results indicate that partially uprooted trees may re-establish stability over time, but some will not and may fail. In our small data set, it was not possible to identify visual criteria that could provide a reliable indication of tree stability recovery, but our data support the assumption that nondestructive pulling tests can be successfully employed to determine good vigorous candidates for retention after partial uprooting.
Keywords. Partial Uprooting; Pulling Test Method; Restabilization; Storm Damage; Tree Biomechanics.

INTRODUCTION

The failure of trees with root systems compromised by decay, storm damage, or construction-related damage can pose risk to significant targets and human beings in an urban setting (cf. Smiley 2008; Bergeron et al. 2009; Schmidlin 2009; Smiley et al. 2014; Dahle et al. 2017) and may also pose a risk to those involved in climbing or dismantling trees (Detter et al. 2008). Assessing this structural characteristic of a tree is very difficult. In many cases, when a tree is observed to have significant root issues, the recommendation is to remove the tree. This mitigates risk but also removes the stream of valuable social, environmental, and economic benefits that a tree provides (Price 2007; Roloff 2016; Kim and Jin 2018). It also prevents arborists and researchers from studying whether such compromised trees can recover and regain stability over time.

Root systems are complex subterranean structures that direct a major portion of the wind load collected by the crown into the ground. Below-ground damage to structural roots can often occur due to root decay or root severance and may also be caused by overloading during storm events, by snow loads, or even by heavy impacts (e.g., during road accidents or avalanches).

As the effects of climate change are felt, many predictions indicate that the world will experience more variable and more extreme weather. For example, Cheng et al. (2013) predicted that Canada could receive significantly more wind gusts later in this century and that the magnitude of those gusts would increase. The effect will be stronger for wind gusts over 70 and 90 km/h, and we can expect that more trees will be damaged or destroyed in high wind events. However, not all trees affected by winds experience ultimate failure. It is quite common that after such wind events, some trees are left standing with a lean. While historically many of these trees are removed, there may be alternative management options. Preserving some of these trees may become more important as we strive to increase canopy cover in urban areas for the sake of the benefits provided to those who live among or in close proximity to trees.

Static load tests, as introduced by Sinn and Wessolly (1989), can be effectively utilized to inform tree risk assessments on trees with compromised rooting stability (Smiley et al. 2011; Sani et al. 2012). A tree's rooting characteristics can be assessed by applying a moderate nondestructive load with a winch, measuring the tree's reactions with a high-precision inclinometer, and extrapolating those data to determine the minimum strength of the root system (Wessolly 1996; Detter and Rust 2013; Buza and Divós 2016). Estimations of resistance to uprooting are based on comparing this load capacity of the root system with modelled wind loading scenarios for a tree at its actual location, as informed by statistical wind data and local wind conditions (Brudi and van Wassenaer 2002; van Wassenaer and Richardson 2009; Wessolly and Erb 2016; Esche et al. 2018).

The anchorage of trees has been studied in many scientific experiments (cf. for an overview Dahle et al. 2017) and was modelled by several authors (e.g., Dupuy et al. 2005; Rahardjo et al. 2014). Tree uprooting is often described as a progressive failure process that occurs in different stages (O'Sullivan and Ritchie 1993), where a number of components play different roles (Coutts 1983; Blackwell et al. 1990; Nielsen 1991). When the change in stem base inclination does not exceed 0.5° during pulling tests, the process is reversible and nondestructive (Coutts 1983; James et al. 2013). As the stem base inclination increases, the maximum resistance of the root system will be overcome at angles between roughly 2° and 7°; after that point the load applied during the pulling test will decrease as the root-soil matrix progressively fails (e.g., Coutts 1983; Wessolly 1996; England et al. 2000; Jonsson et al. 2006; Vanomsen 2006; Lundström et al. 2007).

Such excessive root plate tilt is likely to cause damage by bending and breaking roots on the leeward side close to the stem and by lifting the windward side of the rootplate, causing horizontal and vertical cracks in the soil as well as bending and ultimately the breaking of roots in tension (Crook and Ennos 1996). When a severe storm partially uproots a vigorous tree, some roots may still be able to retain their water transport function (Ueda and Shibata 2004). Since living wood is weaker in compression, bending failure is initiated by fibre buckling on the compression side (Niklas and Spatz 2014). This fibre buckling may eventually interrupt water transport. However, the fibres on the tension side of mechanically compromised roots and roots less stressed during such catastrophic events may fully retain their water conductivity.

If such a tree is left leaning after the primary anchorage failure, it will usually adapt the orientation of its terminal shoots (Du and Yamamotu 2007) through the formation of tension or compression wood (Archer 1987; Archer 1989). Significant changes in the curvature of the shoot by extension or contraction of the wood tissues has only been observed on stems up to 10 cm in diameter (Berthier and Stokes 2006; Yamashita et al. 2007). It is unlikely that significant changes in shoot curvature will occur on stems much larger than that due to the rapid rise in flexural stiffness with increasing diameter (Fobo and Blum 1985; Coutand et al. 2007).

Furthermore, trees typically respond to a lean by initiating strong increment growth on the side of the stem base in compression from the gravitational loads, which is usually referred to as *supporting wood* (Götz 2000; Mattheck et al. 2003; Detter and Rust 2018). During wind-induced uprooting, the greatest strains will also occur in the area under compression on the leeward stem base (Stokes 1999). Trees are able to increase increment growth in areas with greater strains (Müller et al. 2006; Larjavaara and Muller-Landau 2010). Finite elements modelling has shown that the addition of wood volume on the compression side of the stem base can be most effective at increasing stability (Yang et al. 2017). The formation of *supporting wood* at the stem base may be, among others, one mechanism of stability recovery.

Adaptive increment growth is stimulated by a change in the loads that trees experience (Bonnesoeur et al. 2016). For example, healthy forest trees have been found to regain their former stability after a thinning cut within five to eight years (Mitchell 2000). Similarly, after the transplant of both small and large trees, the original root system size could be restored within five to thirteen years (Watson 1985) or sooner (Watson 2005). The effect of root severance on tree stability depends on the distance of the damage from the stem (Smiley et al. 2014), but young trees can recover their anchoring strength as soon as four years after the root severance occurs (Fini et al. 2012).

Our assumption is that trees can recover their anchoring strength within eight to ten years after primary anchorage failure. Experimental data and quantification of stability recovery following overloading of the root system are lacking in the literature. The study presented here provides such data. The degree of root stability recovery after partial uprooting was quantified over a period of eight years.

MATERIAL AND METHODS

All of the research trials described in this paper were undertaken at the Davey Tree research site in Shalersville Township, Ohio, U.S.A., in a plot with London Plane (*Platanus* × *acerifolia*) trees. The trees were planted between 1968 and 1970 on Ravenna silt loam. The trials were undertaken in three separate field seasons in 2010, 2013, and 2018. Table 1 summarizes the trees used in the three test series and Table 2 lists their average diameter and height.

The initial research trial was undertaken in 2010. Ten trees with similar diameters at 1 m height, crown shape, and wind exposure were selected for the trial and were pulled until primary anchorage failure occurred. For this project, primary anchorage failure was described as the point during load application (i.e., winching) where the inclination would continue increasing without any further increase in the applied force. This trial could be described as a destructive test since the winching force was applied

Table 1. Summary of trees used in treatments and as controls in 2010, 2013, and 2018.

	2010	2013	2018
Treatment group 1	2 trees pulled first to primary anchorage failure and then to ultimate failure (uprooted)		
Treatment group 2	8 trees pulled to primary anchorage failure and left standing with a lean	2 trees failed in the meantime, 6 pulled non-destructively to 0.25°	1 tree failed in the meantime, 5 pulled non-destructively to 0.25°
Control group 1	10 trees first pulled non-destructively to 0.25°, then to ultimate failure (2 trees uprooted, 8 stems broke)		
Control group 2		6 trees first pulled non-destructively to 0.25°, then pulled to ultimate failure	
Control group 3			5 trees pulled non-destructively to 0.25°

until the resistance of the root system was overcome (treatment groups). Once these original destructive pulling tests were completed, two of the trial trees were subsequently pulled to ultimate failure, i.e., until the trees uprooted completely and fell to the ground (treatment group 1). Eight trees were left standing on the site (treatment group 2).

At the same time, in a separate experiment on the same site with the same tree species, a second set of ten trees was pulled nondestructively to 0.25° of inclination at the root plate before they were pulled to ultimate failure. The force and inclination data gathered from the nondestructive portion of those trials (at 0.25° of inclination) was used as a control reference for the rotational stiffness of trees on the site that did not experience primary anchorage failure in 2010 (control group 1).

The second field season was in 2013 at the same site. The six remaining trees were subjected to a nondestructive pulling test with the same configuration as the previous trials. The trees were pulled to 0.25° of inclination in the same direction and to the same anchor points. In 2013, another trial was also undertaken on the same London Plane plot. Six new trees were pulled nondestructively to 0.25° of inclination at the root plate before they were pulled to ultimate failure. The force and inclination data gathered from the nondestructive portion of those trials (at 0.25° of inclination) was used as a control reference for the 2013 pull tests of trees from treatment group 2.

In 2018 the site was revisited for a third time. The remaining five trees were retested nondestructively and pulled in the same direction to the same anchor points. Five other London Plane trees that were in the same plot and had not been winch-loaded in any of the previous trials were selected as controls for the 2018 trial. These trees were all pulled nondestructively to a maximum of 0.25° of inclination using the same protocols as the previous trials (control group 3).

While the winching tests were underway, the applied load was measured continuously with a forcemeter (load cell) in the pulling line, and the resulting root plate rotation was measured with two bi-axial inclinometers (one at the side of the stem base, one at the back). The instruments used are part of the TreeQinetic system (Argus Electronic GmbH, Germany). Inclinometers had a resolution of 0.001° (accuracy 0.002°) and the forcemeter had a resolution of 0.1 kN (accuracy 0.3 kN). The rope angle from the horizontal was measured by using a digital level (Digipass, United Kingdom) with an accuracy of 0.2°.

The test was configured according to the Static Integrated Method or Pulling Test Method (Sinn and Wessolly 1989; Brudi and van Wassenaer 2002). The applied force was converted into its lateral component by the cosine of the rope angle. The bending moment was determined as the product of the lateral force component (in kN) and the lever arm length as the vertical distance from the stem base to the anchor point of the rope (in m).

Rotational stiffness at the stem base was calculated for all trees in our data set as the bending moment at 0.25° of basal inclination and served as a nondestructive proxy for anchorage strength. Anchorage strength was defined as the maximum bending moment that occurred during the winching tests. It was only measured for trees that we pulled to primary anchorage failure. In order to account for differences in tree size, rotational stiffness was scaled by tree size (height × diameter^2) when different groups were compared with each other. Data were analysed with a random slope and intercept linear mixed effects model (Pinheiro and Bates 2000) adjusting for variance between years using the statistical analysis software R (R Core Team 2018).

RESULTS AND DISCUSSION

In our data set, measured rotational stiffness proved to be a good indicator for a tree's anchorage strength (Figure 1). This is consistent with the findings in earlier experiments (e.g., Wessolly and Erb 1998; Brudi and van Wassenaer 2002; Jonsson 2007; Smiley 2008; Detter and Rust 2013). The correlation is very strong in our specific data set (R^2 = 0.91), presumably because all of the pulling tests were undertaken on the same plot of land, and because we used trees of the same species as well as of similar age and size (cf. Table 2). Limitations to this approach could result from drastic changes in the soil water content (Kamimura et al. 2011) which we avoided in the present study. Minor changes in the soil moisture content will not considerably affect the rotational stiffness (Rust et al. 2013). Therefore, it was possible to determine the current anchorage strength of trees in our data set using data on their rotational stiffness that was gathered during nondestructive tests. This allowed for the assessment of anchorage strength recovery among the remaining trees from treatment group 2 without pulling the subject trees to failure a second time.

The data for the study trees showed similar load vs. inclination curves to those observed in earlier uprooting experiments (e.g., Coutts 1983; Wessolly 1996; Lundström 2007; Detter and Rust 2013; Buza and Divós 2016). After primary anchorage failure during the first treatment in 2010, the trees remained leaning by more than 2°, except for #277, the only tree that was not loaded beyond 1.2° in the initial winching test (Figure 2).

Table 2. Mean height and diameter of trees used in treatments and as controls in 2010, 2013, and 2018

Year	Height, m	sd(Height), m	Diameter, m	sd(Diameter), m
Treatment groups				
2010	18.04	1.68	0.27	0.03
2013	17.40	1.76	0.28	0.04
2018	19.20	1.03	0.29	0.04
Control groups				
2010	18.03	1.80	0.32	0.05
2013	18.90	1.23	0.29	0.06
2018	18.72	1.21	0.24	0.05

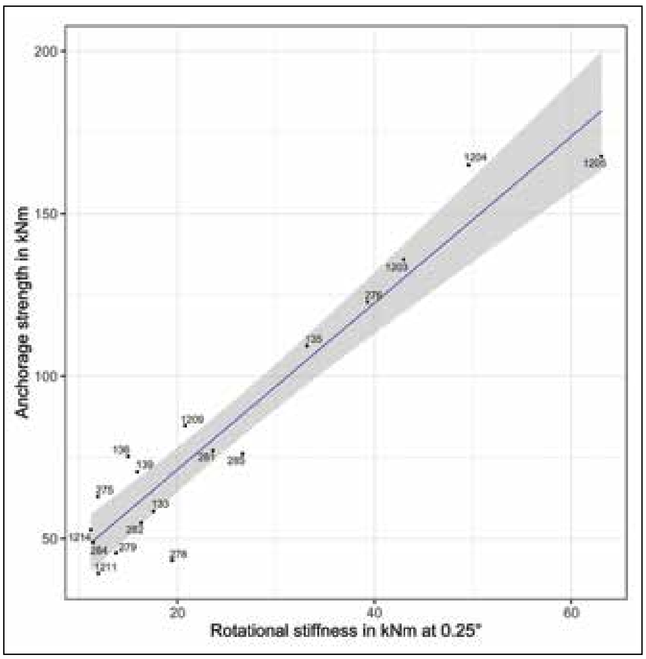

Figure 1. Rotational stiffness indicates anchorage strength (adjusted R^2: 0.91). This figure contains all the trees from this study that were pulled beyond primary anchorage failure.

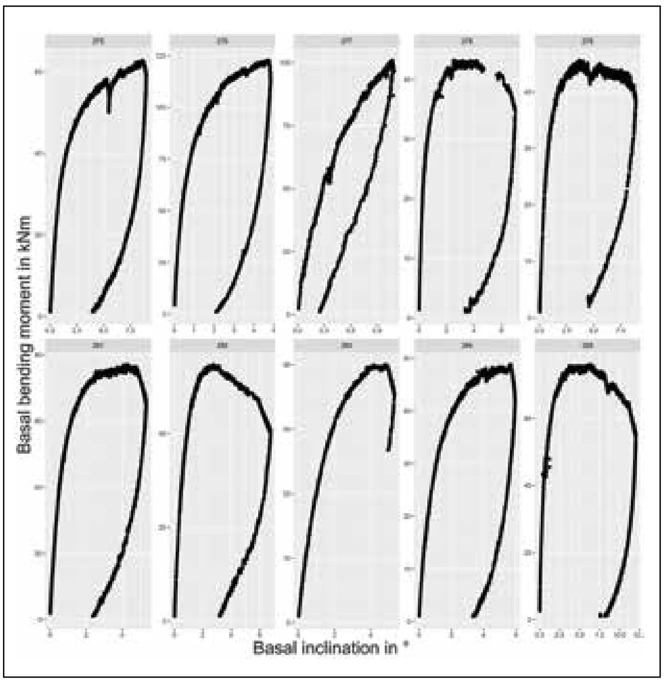

Figure 2. Load vs. inclination diagrams for both treatment groups in 2010.

The two trees in treatment group 1 (#284 and 285) showed a reduction in rotational stiffness of 44 and 56% respectively between the first test undertaken to primary anchorage failure and the second winching test directly after the first. Once the load at which the first test was terminated was exceeded in the second test, the load vs. inclination curve continued almost as if the tree had been pulled to ultimate failure all at once (Figure 3). We suspect that the root system was damaged by the first winching test, but the damage was restricted to a certain level since the uprooting process was interrupted. As winching was continued beyond this point in the second test, the root system may have resumed the progressive failure process until the tree was on the ground. This observation was the subject of further studies undertaken by the authors during the Tree Biomechanics Research Week in 2013, but those studies are beyond the scope of this paper.

For treatment group 2, two trees had failed in the three years since the original trial, and six trees remained standing in 2013. Out of those six trees, one more had failed in the subsequent five years, leaving five of the original trial trees standing in 2018. The load vs. inclination data for different years is shown in Figure 4. A linear mixed effects model statistical evaluation gives $P = 0.0016$ for the difference between 2010 and 2013, and $P = 0.0815$ for the difference between 2010 and 2018. The pronounced difference between rotational stiffness in 2013 vs. the first treatment in 2010 indicates that the initial winching had significantly damaged the root system. However, after eight years, the load response of all remaining trees was not significantly different from their predamaged responses in 2010.

The rotational stiffness was derived from the original data shown in Figure 4. Changes in rotational stiffness between years are shown in Figure 5. After three years, the rotational stiffness of four trees ranged between 44 and 66% of the rotational stiffness found when the trees were undamaged in 2010. After eight years, the rotational stiffness of those four trees was still less than the rotational stiffness found in the 2010 tests (71 to 82%). None of those trees reached their original rotational stiffness within the observation period, but none of them failed during that eight year period either.

A fifth tree (#278) failed somewhere between 2013 and 2018. This tree had lost two thirds of its original rotational stiffness by 2013, indicating that it never recovered after the initial damage in 2010. At the same time, the rotational stiffness of

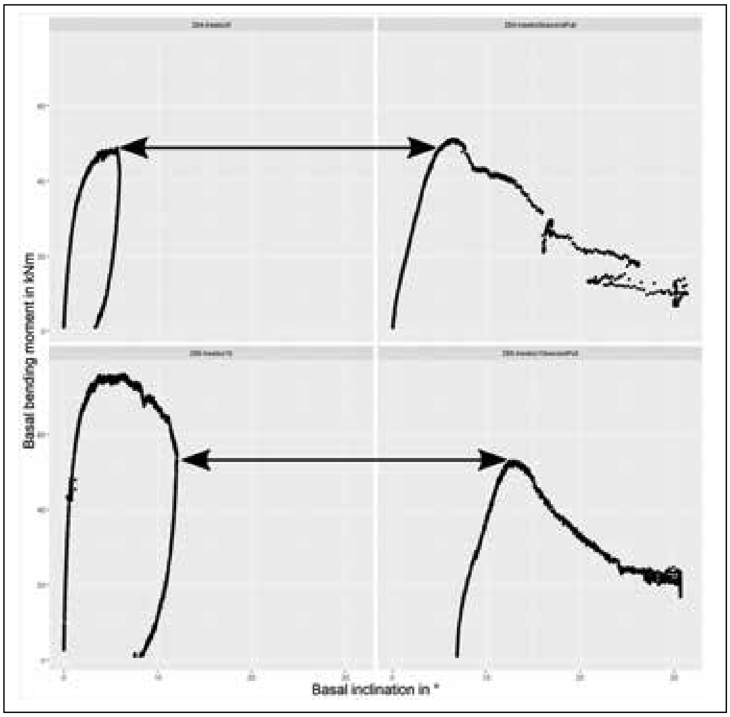

Figure 3. Load vs. inclination diagrams of treatment group 1. The first winching test to primary anchorage failure is shown on the left, and the second test to complete uprooting is shown on the right. The horizontal lines mark the load at which winching terminated in the first test and where the progressive failure was resumed in the second. Data recording was automatically terminated at roughly 30°.

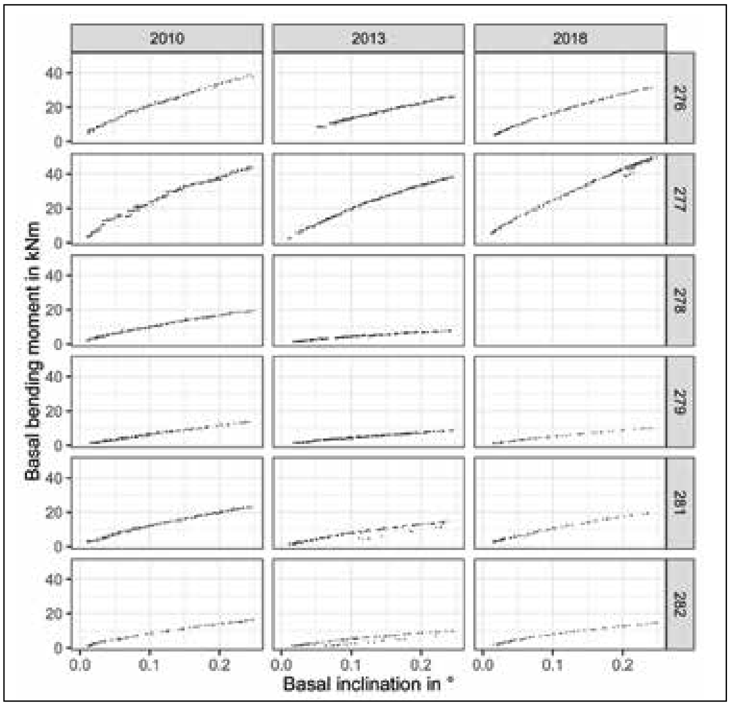

Figure 4. Load vs. inclination data from treatment group 2. From the winching test in 2010 (left), only the nondestructive part up to 0.25° is displayed. For 2013 (middle) and 2018 (right), the first loading cycle up to 0.25° inclination is displayed.

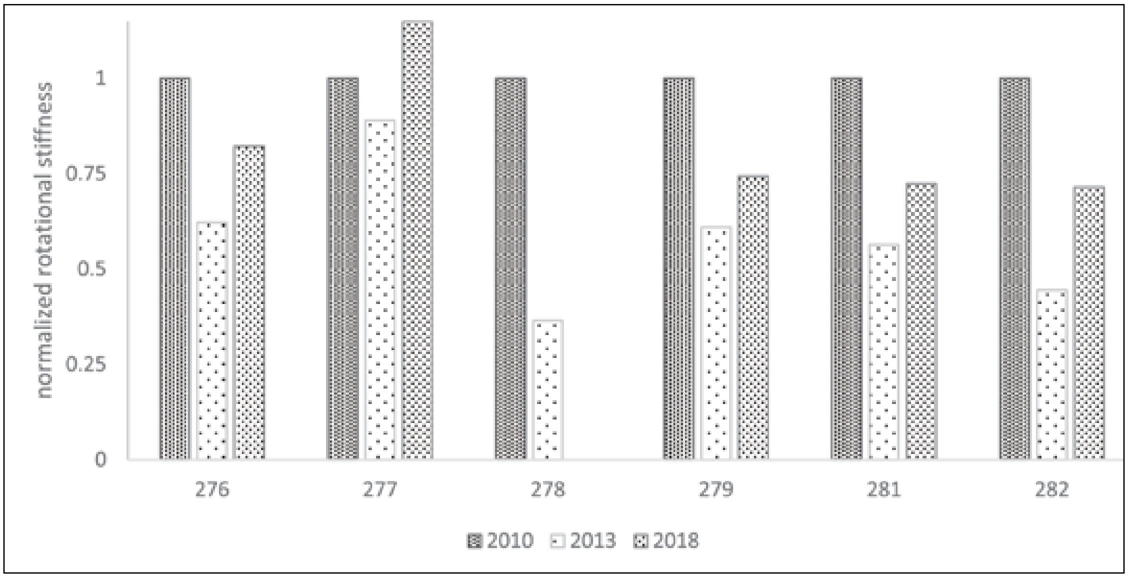

Figure 5. Rotational stiffness in years 2010 (left column), 2013 (middle column), and 2018 (right column) among the trees in treatment group 2, standardized to the initial winching test in 2010.

the sixth tree (#277) was only reduced by roughly 10% in 2013, and by 2018 its rotational stiffness was higher than the value recorded prior to the 2010 treatment. This result can likely be explained by the fact that the anchorage of tree #277 had not been compromised as seriously as other trees during the initial winching treatment of 2010.

In the control groups, different trees were tested each year. In order to enable meaningful observations, we scaled the measured rotational stiffness by tree size (Figure 6). It is not surprising that there are obvious differences between the rotational stiffness of the control trees in different years, because these were different trees. Nevertheless, the range of values was similar for treatment groups and control groups in 2010 and 2018, respectively. Only in 2013, the rotational stiffness of treated trees (treatment group 2) fell drastically below that of the control trees (control group 2).

The rotational stiffness of the trees in treatment group 2 clearly shows a decrease from 2010 to 2013 and an increase from 2013 to 2018. The former may be the consequence of the damages generated from the destructive winching tests, while the latter can demonstrate the subsequent recovery of the strength of the trees' anchoring systems and confirms our hypothesis. Since Figure 6 shows no such trend for the control groups, we are confident that the observed effect within treatment group 2 did not occur due to either climatic or seasonal effects, nor is it likely the consequence of generic circumstances that would have affected all trees on the test site.

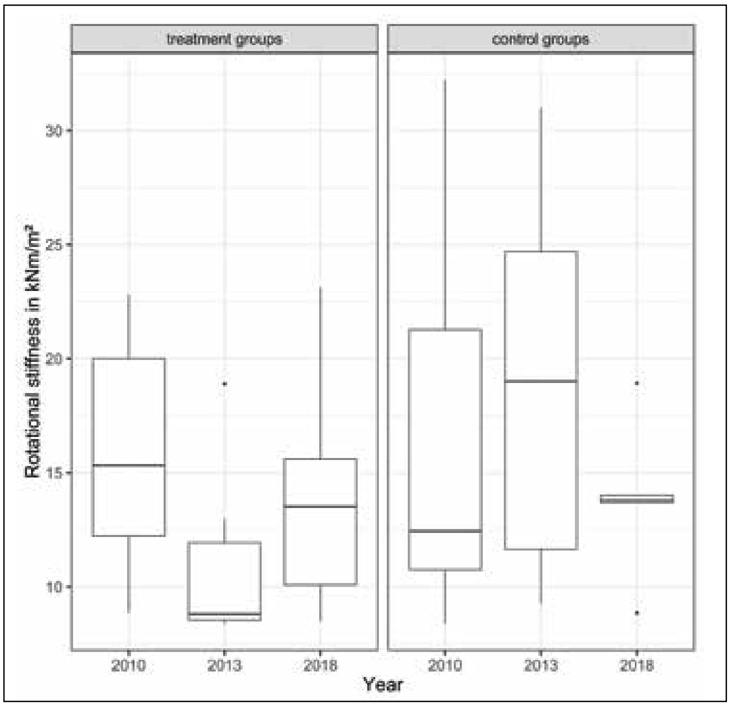

Figure 6. Boxplot of rotational stiffness scaled by tree size. In the treatment groups (left), the same trees were tested, but the control groups (right) consisted of different trees each year. In both cases, the sample size fell from *N* = 10 in 2010, to *N* = 6 in 2013, and *N* = 5 in 2018.

It is likely that only healthy trees will be capable of making the adaptations required to regain their anchorage strength after significant damages have occurred. The vitality (assessed visually) of the trees tested in this experiment was generally good and did not vary over time. The number of trees in this study was very limited, and only one species was studied. The findings may differ for trees with lower vitality, trees growing under adverse conditions, larger or smaller trees, or trees of other species. Therefore, additional studies are required to enlarge the empirical basis for quantifying anchorage strength recovery after primary anchorage failure.

When arborists visually inspect trees with increased leans, they should be able to recognize symptoms of root failure after significant storms and also draw conclusions from signs of growth adaptation in response to earlier events (Dunster et al. 2013; Smiley et al. 2017). The results of this study indicate that some trees are capable of recovering their stability over time after primary anchorage failure has occurred. Therefore, some insights into the current stability of leaning trees can be made by assessing current tree vitality, a tree's self-correcting response, and the formation of supporting wood (Detter and Rust 2018). Since the likelihood of ultimate failure is generally higher for partially uprooted trees in urban situations, visual assessments alone may not be sufficient to identify which trees are good candidates for retention.

Three out of eight trees in this study that were left standing after the initial winching tests subsequently failed within eight years, while five others recovered most of their original stability during this period of time. Tree pulling tests can be used to effectively determine a conservative estimate of a tree's ability to withstand strong wind events. The pulling test results for tree #278 in 2013 showed an exceptionally high loss of rotational stiffness. This loss of stability could have been detected with a pulling test during a level three tree risk assessment (Smiley et al. 2011) and mitigation could have been prescribed if a target would be affected by a failure. Since this tree failed between 2013 and 2018, the nondestructive pulling test had correctly identified its weakness.

Finally, the study shows that some trees can survive partial uprooting, presumably by correcting their growth direction, formation of supporting wood, regrowing roots, and thus eventually restabilizing after a period of time. The pulling test method can help to measure and quantify this effect nondestructively and could be used in conjunction with preventive guying to help identify and preserve some partially uprooted trees rather than removing them. The remaining trees from treatment group 2 may be retested at a later date and eventually harvested to study the strategies of morphological adaptation within their stems and the actual mechanisms involved in the recovery of anchorage strength.

LITERATURE CITED

Archer, R.R. 1987. On the origin of growth stresses in trees part 1: Micro mechanics of the developing cambial cell wall. *Wood Science and Technology* 21(2): 139-154.

Archer, R.R. 1989. On the origin of growth stresses in trees part 2: Stresses generated in a tissue of developing cells. *Wood Science and Technology* 23(4): 311-322.

Bergeron, C., J.C. Ruel, J.G. Élie, and S.J. Mitchell. 2009. Root anchorage and stem strength of black spruce (*Picea mariana*) trees in regular and irregular stands. *Forestry* 82(1): 29-56.

Berthier, S., and A. Stokes. 2006. Righting response of artificially inclined maritime pine (*Pinus pinaster*) saplings to wind loading. *Tree Physiology* 26(1): 73-9.

Blackwell, P.G., K. Rennolls, and M. Coutts. 1990. A root anchorage model for shallowly rooted Sitka spruce. *Forestry* 63: 73-91.

Bonnesoeur, V., T. Constant, B. Moulia, and M. Fournier. 2016. Forest trees filter chronic wind-signals to acclimate to high winds. *The New Phytologist* 210(3): 850-860.

Brudi, E., and P.J.E. van Wassenaer. 2002. Trees and statics: Nondestructive failure analysis. pp. 53-70. In: *Tree Structure and Mechanics Conference Proceedings: How Trees Stand Up and Fall Down*. International Society of Arboriculture, Champaign, Illinois, U.S.A.

Buza, Á.K., F. Divós. 2016. Root stability evaluation with nondestructive techniques. *Acta Silvatica et Lignaria Hungarica* 12(2): 125-134.

Cheng, C. S., E. Lopes., C. Fu, and Z. Huang. 2013. Possible impacts of climate change on wind gusts under downscaled future climate conditions: Updated for Canada. *Journal of Climate* 27(3): 1255-1270.

Coutand, C., M. Fournier, and B. Moulia. 2007. The gravitropic response of poplar trunks: Key roles of prestressed wood regulation and the relative kinetics of cambial growth versus wood maturation. *Plant Physiology* 144(2): 1166-80.

Coutts, M.P. 1983. Root architecture and tree stability. *Plant and Soil* 71: 171-188.

Crook, M.J., and A.R. Ennos. 1996. The anchorage mechanics of deep rooted larch, *Larix europea* × *Larix japonica*. *Journal of Experimental Botany* 47(303): 1509-1517.

Dahle, G., K. James, B. Kane, J. Grabosky, and A. Detter. 2017. A review of factors that affect the static load-bearing capacity of urban trees. *Arboriculture & Urban Forestry* 43(3): 89-106.

Detter, A., and S. Rust. 2013. Aktuelle untersuchungsergebnisse zu zugversuchen. pp. 87-100. In: Dujesiefken (Ed.). *Jahrbuch der Baumpflege*. Braunschweig, Haymarket Media GmbH & Co. KG.

Detter, A., and S. Rust. 2018. Grundlagen und kriterien zur visuellen beurteilung der standsicherheit von bäumen. pp. 145-160 In: Dujesiefken (Ed.). *Jahrbuch der Baumpflege*. Braunschweig, Haymarket Media GmbH & Co. KG.

Detter, A., C. Cowell, L. McKeown, and P. Howard. 2008. Evaluation of Current Rigging and Dismantling Practices Used in Arboriculture (Research Report No. RR668). Norwich, United Kingdom. 361 pp.

Du, S., and F. Yamamoto. 2007. An overview of the biology of reaction wood formation. *J. Integr.Plant Biol*. 49:131-143

Dunster, J.A., E.T. Smiley, N.P. Matheny, S. Lilly, and International Society of Arboriculture. 2013. Tree Risk Assessment Manual. International Society of Arboriculture, Champaign, Illinois, U.S.A.

Dupuy, L., T, Fourcaud, and A. Stokes. 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil* 278(1): 119-134.

England, A.H., C.J. Baker, and S.E. Saunderson. 2000. A dynamic analysis of windthrow of trees. *Forestry* 73(3): 225-237.

Esche, D., P. Schumacher, A. Detter, and S. Rust. 2018. Experimentelle überprüfung der windlastanalyse für statische zugversuche. In: Dujesiefken (Ed.) *Jahrbuch der Baumpflege*. Braunschweig, Haymarket Media GmbH & Co. KG.

Fini, A., F. Ferrini, P. Frangi, R. Piatti, and G. Amoroso. 2012. Effects of root severance by excavation on growth, physiology and uprooting resistance of two urban tree species. pp. 487-494. In: *II International Symposium on Woody Ornamentals of the Temperate Zone.* ISHS Acta Horticulturae 990, Gent, Belgium.

Fobo, W., and R. Blum. 1985. Über die mechanik des druckholzes. *Arcus* (4).

Götz, K. 2000. Die innere optimierung der bäume als vorbild für technische faserverbünde Doctoral thesis, Faculty for Maschinenbau, University Karlsruhe (TH). Scientific Report FZKA 6552, Institut für Materialforschung, Forschungszentrum Karlsruhe GmbH, Karlsruhe. 124 pp.

James, K., C. Hallam, and C. Spencer. 2013. Measuring tilt of tree structural root zones under static and wind loading. *Agricultural and Forest Meteorology* 168: 160-167.

Jonsson, M.J.O. 2007. Energy absorption of trees in a rockfall protection forest. Doctoral thesis, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland.

Jonsson, M.J., A. Foetzki, M. Kalberer, T. Lundström, W. Ammann, and V. Stöckli. 2006. Root-soil rotation stiffness of Norway spruce (*Picea abies* [L.] Karst) growing on subalpine forested slopes. *Plant and Soil* 285 (1-2): 267-277.

Kamimura, K., K. Kitagawa, S. Saito, and H. Mizunaga. 2011. Root anchorage of hinoki (*Chamaecyparis obtuse* [Sieb. Et Zucc.] Endl.) under the combined loading of wind and rapidly supplied water on soil: Analyses based on tree-pulling experiments. *European Journal of Forest Research* 131: 219-227.

Kim, D., and J. Jin. 2018. Does happiness data say urban parks are worth it? *Landscape and Urban Planning* 178: 1-11.

Larjavaara, M., and H.C. Muller-Landau. 2010. Rethinking the value of high wood density. *Functional Ecology* 24(4): 701-705.

Lundström, T., T. Jonas, V. Stöckli, and W. Ammann. 2007. Anchorage of mature conifers: Resistive turning moment, root-soil plate geometry and root growth orientation. *Tree Physiology* 27(9): 1217-1227.

Mattheck, C., K. Bethge, R. Kappel, P. Müller, and I. Tesari. 2003. Failure modes for trees and related criteria. pp. 219-230. In: B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, and G. Wilhelm (Eds.). *Wind Effects on Trees*. Universität Karlsruhe, Karlsruhe, Germany.

Mitchell, S. 2000. Stem growth responses in Douglas-fir and Sitka spruce following thinning: Implications for assessing windfirmness. *Forest Ecology and Management*. 135: 105-114.

Müller, U., W. Gindl, and G. Jeronimidis. 2006. Biomechanics of a branch-stem junction in softwood. *Trees—Structure and Function* (20): 643-648.

Nielsen, C.C.N. 1991. Zur verankerungsökologie der Fichte: Ökologische und waldbauliche einflüsse auf die verankerungskomponenten und den verankerungslösungsprozess. *Forst und Holz* 46: 178-182.

Niklas, K.J., and H.C. Spatz. 2014. *Plant Physics*. University of Chicago Press, Chicago, Illinois, U.S.A.

O'Sullivan, M.F., and R.M. Ritchie. 1993. Tree stability in relation to cyclic loading. *Forestry: An International Journal of Forest Research* 66(1): 69-82.

Pinheiro, J.C., and D.M. Bates. 2000. *Mixed-Effects Models in S and S-PLUS*. Springer-Verlag, New York, New York, U.S.A.

Price, C. 2007. Putting a value on trees: An economist's perspective. *Arboricultural Journal* 30(1): 7-19.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org>

Rahardjo, H., F.R. Harnas, I.G.B. Indrawan, E.C. Leong, P.Y. Tan, Y.K. Fong, and L.F. Ow. 2014. Understanding the stability of *Samanea saman* trees through tree pulling, analytical calculations and numerical models. *Urban Forestry & Urban Greening* 13: 355-364.

Roloff, A. 2016. *Urban Tree Management: For the Sustainable Development of Green Cities*. John Wiley & Sons, Hoboken, New Jersey, U.S.A.

Rust, S., A. Detter, C. Fuchs, and B. Schirutschke. 2013. Einfluss der witterung auf die ergebnisse statischer zugversuche. pp. 296-300. In Dujesiefken (Ed.). *Jahrbuch der Baumpflege*. Braunschweig, Haymarket Media GmbH & Co. KG.

Sani, L., R. Lisci, M. Moschi, D. Sarri, M. Rimediotti, M. Vieri, and S. Tofanelli. 2012. Preliminary experiments and verification of controlled pulling tests for tree stability assessments in Mediterranean urban areas. *Biosystems Engineering* 112(3): 218-226.

Schmidlin, T.W. 2009. Human fatalities from wind-related tree failures in the United States, 1995–2007. *Natural Hazards* 50(1): 13-25.

Sinn, G., and L. Wessolly. 1989. A Contribution to the proper assessment of the strength and stability of trees. *Arboricultural Journal* 13: 45-65.

Smiley, E.T. 2008. Root pruning and stability of young willow oak. *Arboriculture & Urban Forestry* 34(2): 123-128.

Smiley, E.T., L. Holmes, and B.R. Fraedrich. 2014. Pruning of buttress roots and
stability changes of Red Maple (*Acer rubrum*). *Arboriculture & Urban Forestry* 40(4): 230-236.

Smiley, E.T., N.P. Matheny, S. Lilly, and International Society of Arboriculture. 2011. *Tree Risk Assessment*. International Society of Arboriculture, Champaign, Illinois, U.S.A.

Smiley, E.T., N.P. Matheny, and S. Lilly. 2017. Tree risk assessment. Managing urban forests and urban trees. pp. 478-488 In: *Routledge Handbook of Urban Forestry*. Routledge, Abingdon, United Kingdom.

Stokes, A. 199. Strain distribution during anchorage failure of *Pinus pinaster* Ait. at different ages and tree growth response to wind-induced root movement. *Plant and Soil* 217: 17-27.

Ueda, M., and E. Shibata. 2004. Why do trees decline or dieback after a strong wind? Water status of Hinoki cypress standing after a typhoon. *Tree Physiology* 24: 701-706.

Vanomsen, P. 2006. Der einfluss der durchforstung auf die verankerung der Fichte hinsichtlich ihrer sturmresistenz. Doctoral thesis, Swiss Federal Institute of Technology Zürich, Zürich, Switzerland.
van Wassenaer, P., and M. Richardson. 2009. A review of tree risk assessment using minimally invasive technologies and two case studies. *Arboricultural Journal* 32: 275-292.
Watson, G.W. 1985. Tree size affects root regeneration and top growth after transplanting. *Journal of Biomechanics* 11(2): 37-40.
Watson, W.T. 2005. Influence of tree size on transplant establishment and growth. *HortTechnology* 15(1): 118-122.
Wessolly, L. 1996. Standsicherheit von bäumen. Der kippvorgang ist geklärt. *Stadt und Grün* 4: 268-272.
Wessolly, L., and M. Erb. 2016. *Manual of Tree Statics and Tree Inspection*. Patzer-Verlag GmbH & Co. KG.
Yamashita, S., M. Yoshida, S. Takayama, and T. Okuyama. 2007. Stem-righting mechanism in gymnosperm trees deduced from limitations in compression wood development. *Annals of Botany* 99(3): 487-493.
Yang, M., P. Défossez, F. Danjon, S. Dupont, and T. Fourcaud. (2017). Which root architectural elements contribute the best to anchorage of *Pinus* species? Insights from in silico experiments. *Plant and Soil* 411(1-2): 275-291.

ACKNOWLEDGEMENTS

The authors would like to thank the ISA, the TREE Fund, Davey Tree, and all the volunteers for their generous contributions to make Tree Biomechanics Week a success and for their logistical support of this research. The research could never have succeeded without the amazing contributions of following field technicians: Alex Satel, Matt Follett, Will Koomjian, Mike Neuheimer, Josh Galiley, Taylor Hamel, Chris Cowell, Benedikt Morbach, and Ryan Lewis. We also would like to thank Alex Satel for reviewing an earlier version of this paper and providing helpful suggestions. Furthermore, Gary Watson and Jake Miesbauer provided comments and helped to improve the paper. Part of this work was funded by the German Ministry of Education and Research (research grant 17021X11).

Andreas Detter
Brudi & Partner TreeConsult
Berengariastr. 9, Gauting
Germany

Philip J.E. van Wassenaer (corresponding author)
Urban Forest Innovations Inc.
1331 Northaven Drive
Mississauga, ON
Canada
L5G 4E8
905-274-1022
pwassenaer1022@rogers.com

Steffen Rust
University of Applied Science and Art
Faculty of Resource Management
Büsgenweg 1a, Göttingen
Germany

Résumé. Alors que l'intensité et la fréquence d'orages violents augmente, le potentiel de dommages aux arbres urbains s'accroît en conséquence. Jusqu'à maintenant, le risque d'une défaillance totale pour des arbres partiellement déracinés et la manière dont ils peuvent rétablir leur stabilité ne sont pas bien comprises. Cette étude entreprend d'explorer d'abord la possibilité, puis la mesure dans laquelle les arbres peuvent rétablir une solidité d'ancrage suite à une sollicitation en surcharge de leur système racinaire. En 2010, dix platanes (*Platanus* × *acerifolia*) furent soumis à des essais destructifs de treuillage. Deux arbres furent tirés jusqu'au sol tandis que huit autres furent tirés jusqu'à ce que le bris d'une racine principale d'ancrage se produise. Ces arbres au tronc désormais incliné furent laissés ainsi. En 2013, deux arbres avaient échoué et six furent testés de nouveau de manière non-destructive. En 2018, un autre arbre avait échoué et les cinq arbres résiduels furent testés de nouveau. La rigidité rotationnelle fut mesurée pour tous les essais et servit en tant qu'intermédiaire non-destructif pour établir la résistance de l'ancrage (R^2 = 0.91). Après huit années, un arbre avait récupéré sa solidité initiale tandis que quatre autres avaient atteint entre 71 et 82% de leur rigidité rotationnelle initiale. Cependant, trois arbres échouèrent durant la période d'observation. Les résultats montrèrent que les arbres partiellement déracinés pouvaient rétablir leur stabilité avec le temps mais que certains autres ne réussiraient pas. Avec un si petit nombre de données, il n'était pas possible d'identifier les critères visuels qui auraient pu fournir des indices fiables du rétablissement de la stabilité des arbres, mais nos données corroborent cependant l'hypothèse que les tests non-destructifs de treuillage peuvent être utilisés avec succès afin de déterminer les bons et vigoureux candidats à conserver suite à leur déracinement partiel.

Zusammenfassung. Mit einem Anstieg der Intensität und Frequenz der starken Stürme steigt das Potential für die Schäden an urbanen Bäumen. Bislang ist das Risiko von totalem Versagen von teilweise entwurzelten Bäumen und wie sie möglicherweise ihre Stabilität wieder gewinnen, noch nicht verstanden. Diese Studie möchte erkunden, ob und in welchem Ausmaß sie ihre Verankerungskraft zurück gewinnen können, nachdem ihr Wurzelsystem überlastet wurde. In 2010 wurden an zehn Platanen Experimente mit der Seilwinde durchgeführt. Zwei Bäume wurden bis zum Boden gezogen, während acht Bäume solange belastet wurden, bis die ersten Verankerungsschäden auftraten und die Bäume dann in diesem Zustand stehen gelassen. In 2013 hatten zwei Bäume versagt und sechs wurden auf nicht-destruktive Weise erneut getestet. In 2018 versagte ein weiterer Baum und die verbliebenen wurden erneut getestet. Für alle Tests wurde eine rotationale Steifheit hergeleitet, die als nicht-destruktiver Proxy für die Verankerungskräfte (R^2 = 0.91) diente. Nach acht Jahren hatte ein Baum seine Originalstärke zurück gewonnen, während vier Bäume zwischen 71 und 82% ihrer ursprünglichen rotationale Steifheit erreicht hatten. Dennoch versagten drei Bäume während der Observationsperiode. Die Ergebnisse zeigten, dass partiell entwurzelte Bäume über die Zeit sich restabilisieren können, aber einige es nicht schaffen und versagen. In unserem kleinen Datenpaket war es nicht möglich, visuelle Kriterien zu identifizieren, die eine verlässliche Indikation für die Rückgewinnung von der Baumstabilität zeigen, aber unsere Daten unterstützen die Annahme, dass nicht-destruktive

Zugversuche erfolgreich verwendet werden können, um gute vitale Kandidaten für eine Nachspannung nach partieller Entwurzelung zu bestimmen.

Resumen. A medida que aumenta la intensidad y la frecuencia de las tormentas fuertes, también aumenta el potencial de daños a los árboles urbanos. Hasta ahora, el riesgo de falla final para los árboles parcialmente desarraigados y cómo pueden recuperar su estabilidad no se conoce bien. En este estudio se propone explorar si los árboles pueden recuperar y hasta qué punto la fuerza de anclaje después de que sus sistemas de raíces se hayan sobrecargado. En 2010, diez árboles de plátano (*Platanus* × *acerifolia*) fueron sometidos a pruebas destructivas de arrastre. Dos árboles fueron arrastrados mientras que ocho fueron jalados hasta que ocurrió la falla de anclaje primario y quedaron en pie con tallos inclinados. En 2013, dos árboles habían fallado y seis se volvieron a probar de forma no destructiva. Para 2018, otro árbol había fallado y los cinco restantes fueron probados nuevamente. La rigidez rotacional se obtuvo para todas las pruebas y sirvió como un aproximado no destructivo para la resistencia de anclaje ($R^2 = 0.91$). Después de ocho años, un árbol había recuperado su resistencia original, mientras que cuatro habían alcanzado entre el 71 y el 82% de su rigidez rotacional inicial. Sin embargo, tres árboles fallaron durante el período de observación. Los resultados indican que los árboles parcialmente desarraigados pueden restablecer la estabilidad con el tiempo, pero algunos no lo harán y pueden fallar. En nuestro pequeño conjunto de datos, no fue posible identificar criterios visuales que pudieran proporcionar una indicación confiable de la recuperación de la estabilidad del árbol, pero nuestros datos respaldan el supuesto de que las pruebas de tracción no destructivas pueden emplearse con éxito para determinar candidatos buenos y vigorosos para la retención y desarraigo parcial.