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Wind-Thrown Trees: Storms or Management?

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Abstract. Images of wind-thrown trees make for dramatic news coverage. The implied message in most coverage is that strong winds and heavy rain are the cause of the tree failure. However, is the storm the only cause of the tree falling? Many other, and often bigger, trees did not fall. This feature article reviews some of the current literature relating to windthrow of trees. The size and characteristics of tree canopies have a profound influence of the forces that winds exert on tree trunks and roots systems, while the characteristics of tree root systems often determine whether trees fail during storms. The results of a site inspection suggest that there may be other factors, such as the history of the tree and the history of management practices to which the tree has been exposed, which may contribute to its failure during a storm.

Site inspections of 80 wind-thrown trees from eight different genera were conducted over a period of 20 years. The inspections revealed that damage to exposed lateral roots (87.5%), the loss of descending roots (88.8%), and evidence of soil compaction at the base of the tree (65%) were often coincident with windthrow. Evidence of trenching near the trunk of the tree (58.8%) and waterlogging of the soil around the base of the tree (56.3%) were also common correlates. The literature surveyed and the results presented not only suggest where aspects of urban tree management might be improved, but may also prove helpful to arborists assessing tree hazards related to possible windthrow. Inspection protocol criteria should include damaged or decayed lateral roots, the loss of descending roots, evidence of site or trenching work close to the trunk, and whether trees are growing in compacted and waterlogged soil.

Keywords. Descending Roots; Root Damage; Tree Root Systems; Tree Management; Trees and Storm Damage; Urban Trees; Windthrow.

One of the images from the media coverage of Super Storm Sandy, a weather event that contacted the eastern United States in 2012, which received worldwide media attention, was the failure or windthrow of a tree growing in a suburban New York backyard. The photo was shown repeatedly on news bulletins around the world and appeared every hour on the news channels—a large tree growing in a green lawn, a wave-like ripple moving across the turf, and the tree falling (CNN 2012).

The message implied was that the tree fell over because of the storm's strong winds that were accompanied by very heavy rain. However, was the storm the only cause? Many other and larger trees withstood the force of the storm, which raises the question, "Why did this particular tree fail?" This then raises issues as to why trees fail during storms, whether there are management issues that contribute to failure, and what lessons might be learned by arborists from such failures.

WHOLE-TREE FAILURE DURING STORM EVENTS

Depending on the species and the severity of the level of environmental stress encountered as they grow, many trees can grow to large stature at maturity. So it is not surprising that the forces acting upon them can be large and the consequences of whole-tree or major-limb failure can be profound. The allometry of tree height to trunk diameter changes as trees grow (Niklas 1994), and so older, larger trees are structurally different from younger, smaller trees and they respond to winds differently from younger, smaller trees. There is also a limitation on tree height and size due to the properties of wood, first identified by Galilei in 1638. He noted that, "An oak tree two hundred cubits high would not be able to sustain its own branches if they were distributed as in a tree of ordinary size." The cellulose and other material that makeup cell walls of the wood have their own limits of

strength, and trees cannot grow in size and maintain structural integrity beyond these limits.

The interest in how trees change as they grow has seen various attempts to model both their form and function. One of the more widely used models focused on the tree as a continuously branching hierarchical network, with a system of ratios that scale constantly across the order of segments, such as the trunk, branches and leaves, or the branched system of roots that makeup the plant (Meinzer et al. 2011). The system developed by West, Brown, and Enquist (1999), often referred to as the WBE model, has proved particularly useful for the analyses of vascular transport modeling, fluid flows, and the distribution of nutrients and other resources within the tree (Nygren and Pallardy 2008). However, there have been a number of instances where the scaling and the ratios do not accurately apply even to these aspects of tree form and function (Mencuccini 2002; Coomes and Allen 2007; White et al. 2007; Nygren and Pallardy 2008; Veiga 2008; Capes 2009; Meinzer et al. 2011). Often, these failures occur as interspecific differences within species when individuals are growing in less than ideal conditions or where there are specific adaptations to stressful environments (Nygren and Pallardy 2008), perhaps because the model does not recognize the importance of competition for resources and its effects on tree growth (Coomes and Allen 2007; Capes 2009).

While the WBE model has a clear application to aspects of vascular transport modeling, despite its deficiencies, it also has implications for the overall mass and surface area distributions of a tree (West et al. 1999). For example, the model provided insight to the extent and surface area of a tree's root system in relation to the size of its canopy, and the notion that there was as much, if not more, of a tree below the ground as above it (West et al. 1999; Meinzer et al. 2011). The model serves a useful purpose in reminding arborists that there has to be sufficient root mass and surface area to supply the aboveground parts of the tree with water and nutrients, and that the anchorage of the tree depends on all of the components of the root system. However, the work of Peltola (1996), which suggested that no tree species cansurvive storm events without damage when mean wind speeds, over a period of 10 minutes exceed 30 ms^{-1} near the top of the canopy, is still a useful guide.

Figure 1. Wind-thrown trees in Kew Gardens (UK) after the 1987 storm. Note the closeness of the tree to the pathway and infrastructure.

In this paper, windthrow is taken to mean the failure of a whole tree at the interface of the trunk with the soil, which may involve the lifting of roots, the snapping of roots, or the failure of the trunk at the soil surface (Figure 1). In forestry, the term is often used to refer to trees that have trunks fail at or above ground level, or branches broken during storms, as well as whole-tree failure, but this aboveground breakage is sometimes, and probably better, referred to as wind snap (Allen 1992).

Significant economic losses in timber forests and plantations due to windthrow and trunk failure have been widely reported (Peltola 1996; Quine and Gardiner 1998; Peltola et al. 1999; Cucchi and Bert 2003; Grace 2003; Zeng et al. 2007). Forest tree failure due to strong wind has led to significant research into the structural properties of trees and their ability to endure the forces of wind. In cities, tree failure can result in injury and property loss and errors in tree assessment by arborists may lead to costly litigation, especially in the United States (Mortimer and Kane 2004; Barrell 2013). The reliance of arborists on visual tree assessment (Mattheck and Breloer 1994) and the issues of liability and court action have led to conservative tree assessments and likely recommendations of tree removal, which in turn have led to many unnecessary removals of trees with the potential for longer, useful lives.

In considering windthrow of trees, most analyses consider two components of tree structure. The first is the aboveground component of trunk, branches, and foliage, which experience the force of the wind

and have often been considered as equivalent to the forces that the sail area of a ship exert upon its mast which may lead to breakage under load. The second component is the root system that anchors the tree in the soil against the forces of the wind.

THE INTERACTION OF TREE CANOPIES AND WIND

Wind Loads and the Canopies of Trees

Trees withstand physical loads from gravity and persistent winds throughout their lives, but for most trees, the greatest loads that they will experience will come from occasional and sporadic wind gusts, which can be the strongest of natural forces affecting individual or stands of trees (Jacobs 1936; Vogel 1989). These loads are exerted on the canopies of trees and so it was to be expected that the early focus of research into windthrow was on the size and characteristics of the canopy and the analogies with sail area and levers. Some urban tree managers still focus their attention on the size and health and canopy of the tree when assessing the risk of windthrow, even though research reveals a more sophisticated relationship between tree canopy and root systems and the loads and forces generated by strong winds.

Above the ground, forest trees tend to have a similar shape, consisting of a straight central columnar trunk with little side branching until there is a tuft of foliage and branches at the apex. These trees have a slenderness ratio [tree height (m) divided by trunk diameter at DBH (m)] of about 75 or above and will respond to wind dynamically, like a pole (Kerzenmacher and Gardiner 1998). Forestry researchers also use slenderness coefficient [tree height (m) divided by trunk diameter at DBH (cm)] (Rudnicki et al. 2001), where a slenderness ratio of 75 gives a slenderness coefficient of 0.75. In forest trees, slenderness ratios above 100 are considered unstable and those below 80 are described as stable (Slodicak and Novak 2006), while in urban trees, a ratio of above 50 has been described as unstable by Mattheck et al. (2003) due to the risk of the trunk bending and the tree being pulled down by the weight of its canopy.

Trees growing on the edges of forests and plantations and in urban areas develop large numbers of large side branches and tend to have greater trunk diameters, which makes them more stable than typical forest trees. While urban trees may be either excurrent or decurrent (Harris et al. 2004), the development of large side branches contributes to and modifies their dynamic responses (James 2010). Urban trees tend to exhibit significantly lower difference in slenderness ratio between specimens than forest trees because they tend to be shorter with higher trunk diameters. Forest trees are usually taller and possess slender trunks due to competition for space with neighboring trees. Furthermore, they face different wind loads as urban trees face considerable side loads, while in forests, apart from trees on the forest edge, the load is experienced only on the top of the canopy.

Windthrow was often considered to be more likely in taller trees as larger trees had a greater sail area (Jacobs 1955; Mattheck and Breloer 1994). The early estimates of sail area were based on estimations of the total surface area of the foliage (James 2010), but it was known that treating the canopy of a tree like a full sail overestimated the forces exerted on the tree (Niklas 1992; Rudnicki et al. 2004). The canopy was more like a perforated sieve than a sail (Niklas 1992). However, in the past, recommendations were made to reduce the size of trees with large canopies or trees were removed on the basis of calculations of wind generated forces using the overestimates.

Analysis of windthrown trees has shown tree size to be a significant variable (Lundstrom et al. 2008). As trees grow in height and canopy spread, they have greater mass and develop greater self-loading and better anchorage, but they are also exposed to higher wind speeds in their taller canopies, which develop greater bending moments (Niklas and Spatz 2000). However, since they are older they have also had more time to adjust to the winds experienced in their environments, they tend to be more stable than younger, establishing trees.

Niklas (1992) summarized the history of plant biomechanical research and described the basic structural engineering theory that has been applied to the study of trees. There have been many static analyses of tree structure (Sugden 1962; Fraser and Gardiner 1967; Mayhead 1973; Oliver and Mayhead 1974; Blackburn et al. 1988; Bell et al. 1991; Lilly and Davis Sydnor 1995; Rodgers et al. 1995; Neild and Wood 1999; Bruchert et al. 2000; England et al. 2000; Silins et al. 2000; Moore 2000; Peltola et al. 2000; Brudi 2002; Cucchi 2003;

Vidal et al. 2003; Cucchi et al. 2004; Peltola 2006), responses to wind or mechanical pulling (Petty and Swain 1985; Milne 1988; Peltola et al. 1993; Baker 1997; Saunderson et al. 1999), and wind tunnel experiments on canopies (Gardiner 1994; Wood 1995; Gardiner et al. 1997; Gardiner et al. 2005; Vollsinger et al. 2005). The approach to tree biomechanics by Mattheck and Breloer (1994) and their "axiom of uniform stress" is an example that has influenced arboricultural practice, but there was little, if any, dynamic analysis in these studies.

Historically, while it was recognized that wind was not a static force and that trees responded to gusts of wind, to simplify the analysis, wind loading was often considered to be a static force with different values assigned to cope with varying wind forces. Later work approximated wind forces by pulling a tree with a rope at the equivalent force of an estimated wind force, and evaluating the stability of the tree (Brudi 2002). The forces applied to the trees depended on factors modelled, such as wind speed, upwind conditions, and tree characteristics, such as size, shape, and mass. The tree's resistive forces depended on factors such as stem characteristics, wood strength, and root plate and soil interactions. The resistance to overturning and breakage is based on empirical relationships developed from tree pulling tests and timber strength tests.

Static and Dynamic Loads on Tree Canopies

Static pull tests were used to determine the mechanical resistance to overturning (Moore 2000; Cucchi et al. 2004), the strength parameters of a tree (including the strength of the trunk and the anchorage strength of the root plate and soil combination) (Silins 2000), and to approximate the wind force acting on a tree and its responses. Other studies used the static pull test to assess tree strength and stability (Smith et al. 1987; Gardiner 1995; Hedden et al. 1995; Papesch et al. 1997; Flesch and Wilson 1999; Stokes 1999; Achim et al. 2003; Cucchi et al. 2004; Lundstrom et al. 2008), but trees failed or snapped at wind speeds considerably lower than those predicted by the tests on calm days (Fraser and Gardiner 1967; Oliver and Mayhead 1974; Gardiner 1995; Hassinen et al. 1998), probably because the static analyses failed to consider the dynamic forces affecting trees (Mayhead 1973).

Dynamic loads can be defined simply as time-varying (Clough and Penzien 1993) and may vary with magnitude, direction, and/or position with time. The responses of tree structures also vary with time (Coutts and Grace 1995). Trees and their leafy canopies are flexible, and their surfaces realign themselves in high winds by reconfiguring their shape and reducing the total canopy area (Vogel 1989) as the whole canopy bends and changes shape, becoming more streamlined, which reduces drag (Rudnicki et al. 2004).

Mass Damping by Branches and Foliage

Damping is a dynamic parameter that estimates how much energy is absorbed or transferred. Perhaps the best known examples of mass damping are the mass dampers that are placed in skyscraper buildings to reduce sway during earthquakes. Measuring the effect of mass damping in a tree is difficult because there are complex transfers of energy from the wind to the tree. The tree absorbs energy at its natural frequencies, with most energy absorbed at the tree's first natural frequency (Holbo et al. 1980; Mayer 1987; Peltola 1996), which is the frequency of oscillation of a system under free vibration when no external force is applied (James 2010). Most modeling has considered the tree as a single degree of freedom system, like a pole or a ship's mast. However, trees are multi-degree of freedom systems due to their branches and foliage, so the natural frequency is the frequency of the first mode of vibration. Furthermore, in dealing with trees, energy from the wind may not be transferred to the tree but returned back to the wind via small vortices at the scale of the leaves (James 2010).

The work of James et al. (2003; 2006) highlights the mass damping capacity of foliage and branches during storm events. This raises questions about the validity of the view that mature and bigger trees are more likely to fail (Jacobs 1955; Mattheck and Breloer 1994) simply because of their size and suggests that the failure of senescent trees may have more to do with root systems than sail area (Coder 2010). The capacity for mass damping by smaller branches and foliage is an important arboricultural consideration, as a large tree with a full canopy and many branches not only has a bigger canopy area, which may be exposed to strong wind gusts, but it also has the capacity to dissipate much of this force. Without data, it is not clear that

crown reduction to reduce the exposed canopy area will necessarily reduce the load that wind places on a tree, because depending on which branches are removed, the capacity for mass damping may also be diminished (Milne 1991; Moore and Maguire 2005; Moore and Maguire 2008; James 2010). There is a need to determine whether canopy reduction is efficacious in reducing the risk of windthrow.

Trees also fail in different places and in various ways due to the presence of fungal diseases, columns of decay, or hollows (Smiley et al. 1998; Mattheck et al. 2003; Mattheck et al. 2006), which are often undetectable until failure occurs. The probability of failure increased in hollow trees, trees with a high slenderness ratio, and trees with cracks, but trunks can be up to 70% hollow before the probability of failure suddenly increases (Mattheck et al. 2003; Kane and Ryan 2004). In current arboricultural practices, the aim of using pull tests is to provide data for a diagnosis of probable tree stability while the focus of dynamic analysis is to explain the loads and forces involved in whole-tree failure.

THE ROLE OF ROOTS IN TREE STABILITY UNDER WIND LOAD

Tree Root Development

When a tree seed germinates in undisturbed natural soils, the radicle emerges and usually develops into a tap root (Esau 1965). In many species, it is not uncommon to find a seedling of 20 mm height with a primary root of 150–200 mm in length, which develops as a tap root, anchoring the young tree, providing a reservoir of carbohydrate and the necessary water and nutrients to facilitate seedling growth. The tap root provides the framework from which lateral roots develop. In most trees species, however, the tap root could be considered a juvenile characteristic that persists for the early establishment phase of the tree's life cycle (Moore 2013). The tap root, which often descends almost vertically, soon reaches soils that are dense and low in oxygen (Peltola 2006) and nutrients. Furthermore, the nutrients in the rhizosphere surrounding the tap root are soon exhausted. Oxygen levels in soils decrease rapidly with depth, which explains why 95% of the absorbing roots are so close to the surface and why tap roots stop extending or die. Often, the tap root has then served its purpose and dies leaving the spreading lateral roots to perform the roles of absorbing nutrients and water and of anchoring the tree. In many urban trees, the propagation techniques of growing trees from cuttings or growing seedlings in shallow seed trays, and then through successively larger containers, often means that there is no tap root, even in young trees, which can affect their anchorage (Khuder et al. 2007; Gilman 2013).

MATURE ROOT SYSTEMS: THE ROOT PLATE, LATERAL AND DESCENDING ROOTS

The root system of mature trees tends to consist of a relatively shallow, spreading root plate (Figure 2), as opposed to a root ball. The root plate consists of the root crown, structural roots and the network of shallow, spreading, absorbing roots that are located close to the soil surface (300–600 mm deep) and often spreading well beyond the drip line of the canopy (Perry 1982). The root plate of lateral, spreading roots is complemented by the presence of descending (or vertical, sinker, or oblique) roots, which tend to occur within the drip line of the tree and are often denser closer to the trunk (Figure 3) but can occur anywhere oxygen is more readily available and where nutrients and organic matter are being actively recycled (Coile 1937; Perry 1982; Nielsen 2009). Descending roots occur across the root plate, but there tends to be more of them concentrated around the base of the trunk where they are often confused for tap roots, but they are morphologically and anatomically distinct from tap roots (Esau 1965; Moore 2008). The descending roots tend to become more important to trees as they mature, particularly in the development of a heavier root plate (Nielsen 2009).

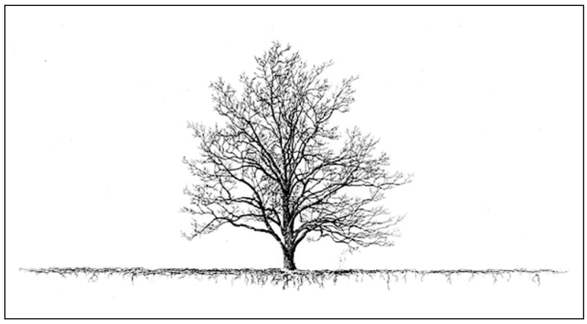

Figure 2. The spread and depth of a typical tree root system (Watson and Neely 1994).

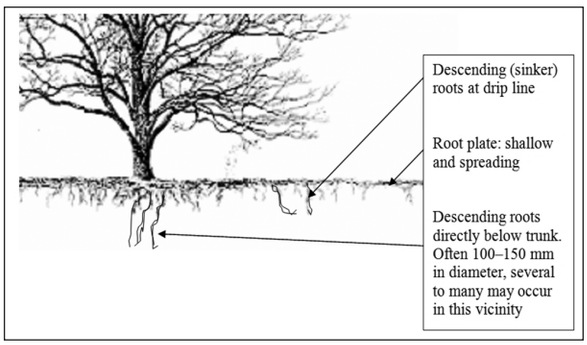

Figure 3. Descending or sinker roots typical of urban tree root systems (modified from Watson and Neely 1994).

Depending on the species, soil type, and soil conditions, descending roots may be more, or less prolific, and it is possible that not all tree species develop them or that some species fail to develop them in certain soil conditions (Nielsen 2009). Descending roots closer to the trunk also have a tendency to grow to greater depths in the soil than descending roots farther from the trunk that are smaller in diameter and shallower in their descent. While the lateral roots are often within 200–300 mm of the soil surface, descending roots may grow to depths of 1000 mm or more (Jacobs 1955; Kozlowski 1971). They persist for a number of years and at maturity may be 100–150 mm in diameter before they die back and are replaced (Moore 1995; Smith and Moore 1997). Both the root plate and the descending roots appear to be important in tree stability (Moore 2008).

Nielsen (2009) notes that arborists and foresters describe root systems differently, and so do botanists. Esau (1965) considers that most trees develop a tap root from which lateral roots branch, and consistent with Tobin et al. (2007), the tap root can be considered the first of a number of orders of roots, with the main lateral roots often being second-order roots that then persist for the life of the tree and can be described as structural roots when they become woody (Tobin et al. 2007; Nielsen 2009). Arborists often describe roots as coarse and fine, which is often associated with their assumed functions of fine roots absorbing and coarse roots providing a mechanical role in transport and anchorage (Tobin et al. 2007). Structural roots are important to tree stability, and it is one of the aims of tree protection regulation for development sites to protect them as part of the critical root zone (Matheny and Clark 1998: Anonymous 2009). However, fine roots, because of their large numbers and surface area, still contribute substantially to tree anchorage, as they bind closely to the soil and consolidate the root plate, increasing its mass (Tobin et al. 2007)

While it is clear that all components of a tree's root system contribute to its stability (Tobin et al. 2007), the two major components of the root system that contributed to anchorage are the resistance of leeward roots to bending (25%) and the resistance of tap roots and descending roots to uprooting (75%) (Crook and Ennos 1996). About 92% of lateral roots have descending roots in close proximity (within 300 mm) to the trunk, and the depth to which these penetrate depends on soil conditions, but on average they were still about 35 mm in diameter at depths of 230 mm in sandy soils (Crook and Ennos 1996). The most important component of the root system in resisting windthrow is the windward side of the root system, which is pulled upwards during overturning (Coutts 1982; Coutts 1986; Stokes and Mattheck 1996). Tree stability is enhanced when external loading forces are smoothly and rapidly dissipated (Stokes and Mattheck 1996), which is best achieved by a large surface area with a higher branching density to which branched descending roots contribute. Tap roots are close to the center of rotation when a tree is wind thrown, while descending roots are better orientated than horizontal windward roots to resist uprooting (Crook and Ennos 1996).

During a windthrow event, the leeward lateral roots bend and eventually break, often close to their base near the root crown; the windward lateral roots are pulled from the soil, often with their descending roots, if present, intact and the tap root or one, or more, of the larger descending roots closest to the center of the tree trunk rotate (Crook and Ennos 1996). If the leeward lateral roots break farther out from the root crown, then the longer fulcrum means that an even greater force has been applied. When inspecting wind-thrown trees, the lack of descending roots on the exposed windward side of the root system is often an indication that they have not been present (Table 1), which may be important in diagnosing the causes of the failure. The pattern of windthrow is similar in dry and wet soils, but in the latter, failure usually occurs closer to the trunk (Figure 4). Other professions have noted the importance of descending roots in stabilizing slopes, with deeper rooted trees stabilizing slopes only to the depth to which descending roots can penetrate (Gray and Sotir 1996).

Table 1. Major root failure patterns (Norris 2005; Coder 2010).

Failure pattern	Effect on root system	Consequence
Type 1	A straight root is pulled directly from the soil	Sudden failure as frictional forces between soil and tapered root are exceeded
Type 2	A lateral root with many small lateral roots pulled	Slower failure as there is a gradual failure after a major force is applied as small lateral roots progressively break
Type 3	Major branched roots are pulled	Failure occurs in abrupt steps as major root components break

As with studies of tree canopies, size also matters in the development of tree root systems (Coder 2010). Much of the root mass is located in the relatively few, large structural roots that are typical of most trees, and these, along with the larger woody transport roots, stabilize the tree, and under tension resist increasing wind speeds (Kalliokoski et al. 2008). There are many different models of root plate development (Koisumi et al. 2007; Achim and Nicholl 2009; Coder 2010). Often, they are depicted as being circular; however, this is a simplified approximation, as root plates of two *Pinus* species have about 60% of their roots in the direction of the prevailing wind (Figure 5). This suggests that models based on an elliptical root plate may be better approximations to real root systems (Tobin et al. 2007).

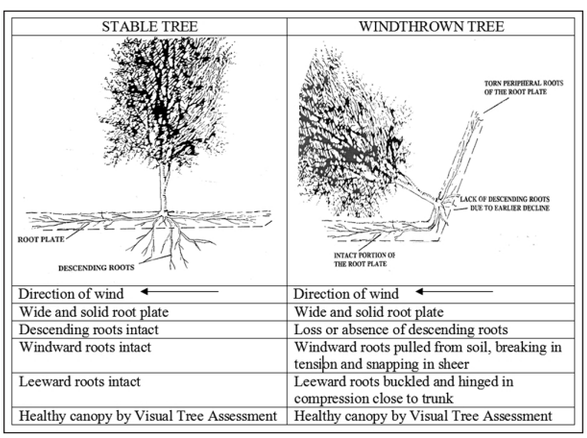

Figure 4. Windthrow due to the failure of windward roots and the buckling of leeward roots.

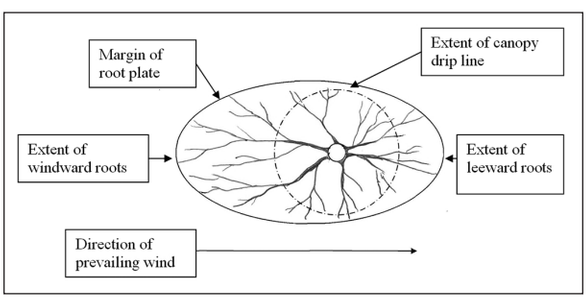

Figure 5. Skewed, elliptical root plate in response to prevailing wind.

Furthermore, trees subject to directional winds usually have windward roots that are smaller in diameter but longer and more branched at greater distances from the trunk than leeward roots. On the leeward side, the roots are shorter, thicker, and tend to have more descending roots (Tobin et al. 2007). Thus, the root plate is more likely to be elliptical, but skewed to the windward side of the trunk (Figure 5). Damage to roots anchoring the tree on the windward side, by trenching or construction, is more likely to lead to a windthrow event where the root plate tilts (Figure 4).

There is also great variation in the depth of root plate models (Coder 2010), but in urban soils, the roots do not typically descend to great depths (Tobin et al. 2007; Moore 2008). Some studies have reported that the depth of the root plate is not significant in anchorage or in tree failure (Koisumi et al. 2007). However, in many urban environments, the capacity of roots to penetrate the soil is limited by site and construction activities that have altered and compacted the soil profile (Nielsen 2009), and so roots often are limited in their depth to no more than 750–1000 mm.

Windthrow usually occurs due to three basic root failure patterns (Table 1): 1) a straight, tapered root may be pulled directly from the soil when the frictional forces between it and the soil fail to hold the root in position and there is sudden failure; 2) a root with many small lateral roots can be pulled gradually from the soil, as the strong forces applied by the wind result in a progressive breaking of many small roots (Table 2); and 3) roots may fail in distinct stages as major roots break over time (Norris 2005; Coder 2010).

Root-Soil Interaction and Waterlogging

The depth to which descending roots can grow varies depending on species and soil conditions (Stone and Kalisz 1991; Stokes and Mattheck 1996; Tobin et al. 2007). Jacobs (1955) described eucalypt descending roots growing to depths of 900–1000 mm,

Table 2. Major factors affecting tree stability (after Coder 2010).

Factor	Attributes to resist windthrow
Soil	Soil must resist fracture and remain dryer than its plastic limit
Windward roots	Longest 2–3 major windward roots must resist pulling out and breaking in tension; they must resist snapping in sheer
Mass of tree	Weight of the tree, including both aboveground mass and root plate mass, must be sufficiently great
Leeward roots	Leeward roots must resist buckling or hinging in compression and snapping in sheer
Root plate	Stem base and large roots must provide a wide stiff supporting platform that resists splitting

Kozlowski (1971) described *Camellia thea* as having most of its feeding roots in the top 900 mm, but with deep roots that ramified through a larger volume of soil. The roots of Jarrah, *Eucalyptus marginata*, penetrate through a layer of bauxite often 5–8 m thick, but in some instances up to 15 m deep (Stone and Kalisz 1991) and then develop a spreading, lateral root system below the bauxite.

Eucalypt roots have been observed at depths of 45–60 m (Stone and Kalisz 1991), coming through the ceilings of caves, especially in limestone-based soils. In *Banksia prionotes*, the typical pattern of root development consists of a persistent and dominant sinker root that penetrates 2–3 m into the sandy soil to extract water, a series of lateral roots that are usually in the top 700 mm of the soil, and fine roots that are dimorphic in both anatomy and function with proteoid roots absorbing nutrients while other fine roots absorb water (Jeschke and Pate 1995). In more typical, natural soil profiles, descending roots penetrate to depths of 1.5–3 m (Stone and Kalisz 1991).

Trees can be wind-thrown in very strong winds (Table 2), especially when heavy rain has saturated soils, reducing soil strength (Harris 1992; Smiley et al. 1998) (Figure 6). Waterlogged soil may result in the wind throw of a tree, in which the windward root system is exposed more or less intact (Table 1) with descending roots in place as they slip from the weakened soil (Crook and Ennos 1996). Such a situation may see a tree wind thrown even without heavy rain, because the soil in the vicinity of the base of the tree has lost strength due to excess water pooling due to poor drainage or altered subterranean water flows. The combination of heavy rain that saturates soil (reducing the strength of the connection between soil and tree roots) that is followed by strong winds may see trees fail in both urban and forestry situations (Coder 2010). However, even then the wind-thrown tree is usually the exception rather than the rule.

In the urban context, both tap and descending root development can be restricted by plant propagation techniques that horizontally cut roots when seedlings are removed from germination trays or pricked out and potted on (Moore 1985; Nielsen 2009). As they mature, such trees may never develop a tap root, and the number of descending roots that these trees develop may be lower than those on forest trees of the same species (Nielsen 2009). Urban landscape management practices, which damage lateral roots, particularly on the windward side of the tree, could leave a tree vulnerable to windthrow, especially if the roots are damaged or severed close to the trunk, which could affect the number of descending roots on the windward side of the tree (Coutts 1982; Coutts 1986; Stokes and Mattheck 1996).

Figure 6. A fallen elm (*Ulmus* spp.) in a prominent Melbourne park with waterlogging, lack of descending roots, shallow root plate, lateral root damage, and paved surface in evidence.

Table 3. Criteria used in assessment of wind-thrown trees in Melbourne (modified from Moore 2004).

	Criteria
1	Evidence of site or trenching works within four meters of trunk
2	Significant damage and/or decay to exposed lateral roots
3	Evidence of the loss of descending (sinker or vertical) roots
4	Evidence of soil compaction in immediate vicinity of the trunk
5	Presence of fill around base of tree
6	Indicators of waterlogging in immediate vicinity of the trunk
7	Canopy dieback and deadwood

Urban construction activities that compact or deposit fill around the base of trees can alter soil aeration, organic matter content, nutrient availability, and water penetration, all of which can have a profound negative affect on tree root systems (Day 1999). Other construction practices that compact the lower soil horizons can make descending root penetration difficult and diminish both the extent and mass of the root plate. Furthermore management practices that alter soil water flows, thereby creating waterlogged conditions, can restrict root development to depths below 200 mm (Coutts 1982; Coutts 1986; Nielsen 2009). The loss of soil strength from greatly increased soil moisture levels further increases the risks of windthrow.

Tree protection on development and construction sites often has the protection of the structural root zone as an aim, but the more extensive root protection zone protects not only the structural roots, but the lateral and descending roots farther from the trunk (Matheny and Clark 1998: Anonymous 2009). However, while these are admirable attempts at protection they do not guarantee that the root system and root plate will remain intact or retain the stability of the tree. Furthermore, standard protection systems cannot deal with the nuances of every tree and the root systems that develop in response to particular environments. Many attempts have been made to generalize classification systems describinroot system architecture, but the effects of soil type, soil conditions, and the levels of environmental stress on the development of tree root systems mean that generalizations rarely apply to trees growing in stressful urban sites (Stone and Kalisz 1991; Tobin et al. 2007; Nielsen 2009).

DATA FROM SITE INSPECTIONS OF WIND-THROWN URBAN TREES

Storm events, especially those involving heavy rain and strong winds, often prove to be very busy times for arborists, with the cleanup of wind-thrown and damaged trees. There is also an increase in service calls for routine maintenance and other arboricultural interventions, as public awareness of the trees in their cities rises in the aftermath of a storm event. These occasions also provide opportunities to observe wind-thrown trees that have been growing in different locations and soil types, to record information relevant to the trees and the sites, and to discern patterns that might be common to the fallen specimens.

Data on 80 large wind-thrown trees from eight different genera were collected from site inspections across the City of Melbourne, Victoria, Australia, over 20 years. Most of the specimens were mature, but none had been characterized as senescent before they failed (Moore 1998; Moore 2004). A set of seven criteria were developed to assess trees after failure (Table 3) that allowed for data collection by rapid qualitative visual assessments. The data include 30 windthrown specimens when Melbourne suffered a 1 in 150-year storm event in February 2005.

After a thirteen-year period of below-average rainfall, 120 mm of rain fell in less than 30 hours, most of it in a 10-hour period overnight with very strong, gusty winds. There was significant property and infrastructure damage, and several hundred mature trees were wind thrown in parks, gardens, and along streets across the city (Figure 7; Figure 8). The media coverage—radio, TV, and newspaper—was quick to report that the significant loss of trees was due to an act of God (insurance companies accepted claims on that basis) or the fury of Nature. The heavy rain had reduced soil strength and the winds were strong; however, the pattern of wind-thrown trees across the city suggested that other factors contributed to the failure of these trees.

Figure 7. A fallen elm with a shallow root plate growing near a pathway; windward roots pulled from the soil, lack of descending roots, and a pool of water under the base of the tree two days after the major storm event of 2005. The tree has hinged close to the trunk on the leeward side.

Figure 8. Some of the many fallen elms growing along pathways in a public garden in Melbourne, Australia, after a major storm event in 2005. Both trees proved to be positive for criteria 1–6, and both have hinged close to the trunk on the leeward side.

In almost all cases, there was evidence of major interference with the tree root systems (Table 4). This interference may have been from trenching and other construction work, or from mowing practices, which repeatedly damaged the roots that had come to the soil surface through secondary growth. Such wounds may provide access for pests and diseases. While root damage was a common factor associated with the failure of many of these specimens, there was also a strong correlation of failure with changed soil/water conditions (Figure 7).

These changes to soil/water conditions were of two major types. The first was the existence of waterlogged soils. In many instances, the soil under the trunk of the fallen tree was so wet that there was a pool of water at the base of the hole at the time of inspection. Over time, waterlogged soils have a significant impact on descending roots, which often die back and leave a root plate with very few, if any, descending roots if the tree has been growing under such conditions for long enough. In most cases, the pungent odor of the exposed soil after the tree had been wind thrown, the large number of smaller blackened roots, and the sogginess of the soil suggested that there had been problems with waterlogging over a longer period.

A second condition arises when the patterns of soil water movement are altered by construction work, adding soil as fill, or re-contouring surfaces, all of which can inadvertently divert flows from the tree's root system. The trees often benefitted from these subterranean flows for decades and then face a sudden imposition of a water deficit. Under these circumstances, the trees show the effects of wilting and are often significantly stressed. These water-deficient trees were the only specimens that appeared to show symptoms of canopy dieback and significant amounts of deadwood. In one case, a tree was wind thown the day after an inspection recommended its removal due to canopy dieback and a lack of stability of the root plate. In these situations, the canopy dieback may well be an indication of stress that has affected the health and integrity of the root system, which may increase the risk of windthrow. However, many wind-thrown trees had intact and healthy canopies, and trees with significant canopy dieback and deadwood remained standing, which suggests caution when using these canopy characteristics in the visual assessment of the risk of windthrow.

Compaction was assessed using a narrow screwdriver with a 300 mm blade, which was pushed into the wet soil within 24 hours of the trees being wind thrown. In some cases, around the bases of fallen trees, it was not possible to penetrate the soil at all, and in others, penetration was only to a depth of 10–30 mm. In undisturbed soil, the blade could be pushed into the soil up to its handle (Table 4). Soil was described as compacted if the blade did not penetrate 30 mm into the soil. The

Table 4. Assessment of eighty wind-thrown trees against the criteria listed in Table 3.

Genus	No.	Crit 1	Crit 2	Crit 3	Crit 4	Crit 5	Crit 6	Crit 7
Eucalyptus	18	7	14	16	11	4	9	10
Ulmus	30	28	29	29	25	21	23	10
Acacia	15	2	11	10	3	0	4	2
Cupressus	5	2	5	5	3	0	1	0
Melaleuca	4	0	3	3	2	0	2	0
Lophastemon	2	2	2	2	2	0	1	1
Populus	4	4	4	4	4	3	3	3
Ficus	2	2	2	2	2	2	2	0
Total	80	47	70	71	52	30	45	26
Trees positive for criterion (%)		58.8	87.5	88.8	65.0	37.5	56.3	32.5

30 mm mark was then confirmed as a reasonable indicator of compacted soil by comparison with a penetrometer. This, however, remains no more an indicator of likely compaction, as while soils were close to saturated as evidenced by pooling, soil moisture was not quantified.

The large number of trees found with damaged lateral roots and evidence of the loss of descending roots may not be surprising for urban trees growing in parks, where trees are growing in lawns that are regularly mowed. The mowing regularly shaves parts from the exposed lateral roots and these roots are repeatedly wounded and re-wounded, which may afford entry points for disease- and decay-causing organisms (Ruehle 1973; Shigo 1986). The exposed lateral roots are often part of the structural root system, and so if a number of them start to decay, then not only is the tree deprived of significant root absorptive surface area, but also may be more prone to windthrow.

The finding that soils are compacted in heavily trafficked areas of a city park is also to be anticipated. Compaction may be due to pedestrian or vehicular traffic, especially if there is active sporting activity, particularly in the summer months, when people congregate under the trees for shade. In parks, compaction occurs when people walk along sight lines, but also when walkers and joggers run on turfed and mulched areas of the park, rather than on the harder paved surfaces, to reduce the effects of hard surfaces on ankle and knee joints. Compaction impacts descending and lateral roots by reducing aeration and water penetration. Compaction also increases soil strength, which affects root tip growth. This can lead to reduced root extension and the loss of descending roots, which can affect tree stability.

That more than one-third of the wind-thrown trees had fill around their trunks (Table 4) needs further explanation, especially as most of the trees were growing in major metropolitan parks. All of the fallen trees were near footpaths through the parks, and these paths, often due to tree root damage to the footpaths, were regularly replaced or maintained for pedestrian safety. The simplest and cheapest way of doing so is to raise the paths and then fill is placed around the tree to maintain site levels. Over the past 100–125 years, Melbourne City Council maintenance records reveal that paths have been replaced up to six times, with fill levels exceeding 300–500 mm in some instances. These works not only contribute to the waterlogging of soils around trees, by interfering with natural drainage and contours, but they may also alter subterranean water flows.

In the storm of 2005, without exception, trees that fell were growing beside roads or pathways in parks and gardens (Figure 8). When the trees were inspected after the storm, every tree that fell showed evidence of site works, lateral root damage, fill around the base of the tree and loss of descending roots (Figure 9). Most (above 90%) showed evidence of compaction and waterlogging, but few showed evidence of canopy dieback or excessive deadwood. Trees growing in the same parks and along the same streets but without root damage or interference may have suffered loss of branches during the storm, but none were wind-thrown. In the parks, many trees of the same species that were growing in garden beds or undisturbed turf remained standing while those growing along paths and near buildings fell.

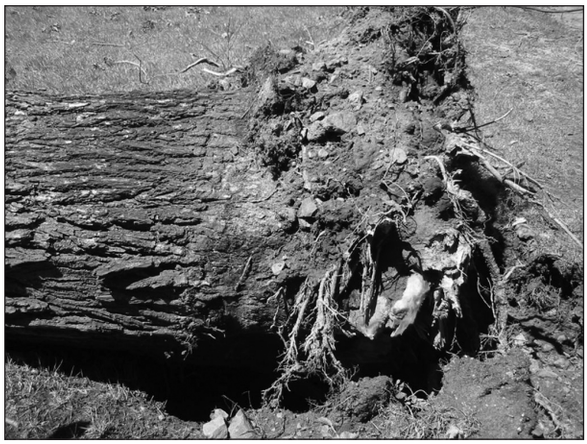

Figure 9. Close-up of the base of one of the fallen elms after the 2005 storm, showing in excess of 300 mm fill around the trunk of the tree.

In many situations, there are multiple factors that contribute to root system failures that lead to trees falling (Table 4). The strong wind may be the trigger that initiates windthrow, but there may be other contributing factors to whole-tree failure. It would seem that the failure of trees ascribed to windthrow has as much to do with their history and the management practices to which they had been exposed as it does the strength of the storm winds. This raises questions about the role of tree

management in tree failure due to windthrow and suggests there may be root management practices that would not only minimize the risks of tree failure during storms, but also maximize tree life expectancies. It is worth investigating the pattern of tree failure due to windthrow after storms, as the majority of failures occur where there has been a history of significant root system interference.

In the interpretation of site inspection data, there is no capacity for comparison with trees that did not fail, and caution must also be exercised as it looks only for the correlation of factors with windthrow but not its causes. The data collected did not address situations where there was whole-tree failure that was not associated with storm events and high winds. There is evidence of trees failing on calm days after storm events. Such failures are sometimes ascribed to root fatigue, which is believed to be due to many events contributing to root breakages and loss of root mass over a longer period (Hale et al. 2010). This cumulative root damage and loss may lead to tree instability, which then results in a tree failing days to a few weeks after a storm event.

However, the data may be used by arborists as indicators of the likelihood of a tree failing due to windthrow. When assessing trees at risk of windthrow, arborists should include as part of their inspection protocols, trees showing damaged or decayed lateral roots and the loss of descending roots, evidence of site or trenching work close to the trunk, and whether trees are growing in compacted and waterlogged soil. The presence of fill and canopy dieback or deadwood should also be noted. Trees that are positive for a number of the criteria could then be subjected to further stability testing and regular monitoring to minimize the risks from failure.

COMPARING WIND-THROWN FOREST AND URBAN TREES

Wind throw is certainly not confined to urban trees, as forest trees may also be wind thrown (Figure 10). The structure of forest trees is often different from urban trees as they tend to be taller and with fewer branches along their trunks with the central column model being a better approximation for their responses (James et al. 2006). They also have different root architecture and are more likely to have a tap root and a number of descending roots than urban trees (Nielsen 2009). For trees growing within the forest, roots systems can also naturally graft and overlap, adding to both root mass and tree stability, while trees on the edge of forests and plantations usually behave more like urban trees.

Figure 10. A fallen eucalypt in a forest roadside reserve. Note the waterlogged soils in a site where roadwork had altered drainage, as well as the lack of descending roots.

Furthermore, the natural frequencies of forest trees are better and more easily approximated by a pull test than is the case for urban trees, as forest trees more closely approximate the tree as a single degree of freedom system (James 2010). It is of interest that in the few studies that have compared natural frequencies before and after branch removal, oscillating frequencies were greater after branch removal (Milne 1991; Moore and Maguire 2005; James 2010). This emphasizes the importance of considering branch and foliage involvement in tree responses to strong winds. The differences in some of the characteristics of urban and forest trees means that while there are similarities between the two types of tree in windthrow events there are differences as well.

Human interference with root systems, which occurs in the windthrow of many urban trees, can often be excluded as a contributor to windthrow in forests, but it may be a contributor to failures near roads, firebreaks, trails, or where drainage has been altered (Figure 10). There is also a management contribution to forest tree failure after forest clearing and thinning operations, which has been well researched because of the economic losses that result (Gardiner and Stacey 1996; Peltola 1996; Cucchi et al. 2004).

In forests, trees that are wind-thrown tend to be taller and senescent, but they also fall when heavy rain has reduced soil strength and there

Table 5. Comparison of assessment criteria for eighty fallen urban trees compared to fifteen wind-thrown forest trees.

Criterion	Forest trees positive for criterion (%)	Urban trees positive for criterion (%)
Evidence of the loss of descending (sinker or vertical) roots	100	88.8
Significant damage and/or decay to exposed lateral roots	40	87.5
Evidence of soil compaction in immediate vicinity of the trunk	0	65.0
Indicators of waterlogging in immediate vicinity of the trunk	66.6	56.3
Evidence of site or trenching works within four meters of trunk	0	58.8
Presence of fill around base of tree	0	37.5
Canopy dieback and deadwood	80	32.5

are accompanying strong winds. Site inspections of a small cohort (15 trees) of wind-thrown forest trees, using the criteria developed for urban trees, revealed that all specimens lacked descending roots, 40% had lateral root damage, and two-thirds of them had been waterlogged (Table 5). In Australian forests, damage to the lateral surface roots is often associated with previous forest fires and all of the inspection sites had been burnt at least once in the past 30 years. Changes to drainage leading to waterlogging in these sites may have been the result of the construction of access or fire tracks, but none were closer than 100 m to fallen trees. None of the trees surveyed were close to roads or fire tracks or on the edge of stands of forest trees.

In contrast to the urban trees, most of these fallen forest trees (80%) showed signs of dieback and significant deadwood in the canopy. This suggests that the trees may have been stressed for some time and that their root systems may also have been in decline, and that there had been a loss of root mass. When the forest trees fell they tended to leave a relative small lens shaped depression in the ground that was rarely deeper than 500 mm; much the same as for urban trees. This pattern is also consistent with the root plate models discussed earlier, where the leeward roots bend and snap, the windward laterals are pulled from the ground, more or less intact, and the base of the trunk has rotated in the ground (Crook and Ennos 1996; Stokes and Mattheck 1996).

CONCLUDING DISCUSSION

Management practices have a profound influence on the health of aged trees growing under environmental stress. Trees that are growing in ideal locations, where they are not subject to invasive management practices that impact either their root systems or canopies remain healthy and vigorous as they age and are capable of dealing with many of the pests, diseases, and stresses that might otherwise affect them (Andrews et al. 2010).

Trees in urban areas that have had their root systems interfered with are more likely to be stressed and prematurely senescent. They are also more likely to suffer windthrow. Even if the canopies of tree appear to be healthy and intact, root systems may be stressed and their structures compromised. If roots are severed on the prevailing windward side of the tree, then a significant reduction of root mass will indicate that the risk of windthrow is heightened. In many instances, older urban trees will have been subjected to major root damage from construction, road and infrastructure works. Trenching is often implemented without thought of the effects of open trenching on tree root systems, or consideration of the options of tunneling under the trees that modern boring technologies provide.

Under-root boring options are not only less likely to damage trees root systems, but also are often cheaper than trenching. However, the misconception that trees have tap roots or a large root mass under their trunks persists, and so too often alternatives to trenching are not even considered. Trenching practices add significantly to the stress levels that older trees endure and the consequences can take many years to emerge. Damage that cuts the major roots on the windward side of the tree or increases the likelihood of root buckling on the leeward side are of particular concern, as trees can be left prone to windthrow for some time after the damage has occurred.

Finally, what of the tree that fell during Super Storm Sandy? The footage showed a relatively small and very shallow root plate with no descending roots apparent. A longer version of the same video (Telegraph 2012) showed a pool of water under the trunk region of the fallen tree and a different soil substrate below the turf. The lack of roots

in the turfed level of the soil suggests that fill had been added to even the contours of the backyard and facilitate the growth and mowing of the turf. It would seem that a number of the correlated criteria applied to the tree. Once again, it raises questions as to whether the storm was the final trigger in a lengthy chain of events leading to windthrow and whole-tree failure. Many of these events relate to tree management and need to be given greater consideration by gardeners and arborists.

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Zusammenfassung. Bilder von windgeworfenen Bäumen machen einen dramatischen Aufhänger in der Berichterstattung. Die implizierte Botschaft in den meisten Berichterstattungen ist, dass starke Winde und schwerer Regen die Ursachen für das Baumversagen sind. Dennoch, ist der Sturm der einzige Grund für das Baumversagen? Viele andere und auch größere Bäume fallen nicht. Dieser Bericht gibt einen Überblick zur gegenwärtigen Literatur in Beziehung zu Windwurf von Bäumen. Die Größe und Charakteristika von Baumkronen haben einen profunden Einfluss auf die Kräfte, die der Wind auf den Stamm und das Wurzelsystem ausübt, während die Charakteristika des Wurzelsystems oft bestimmen, ob ein Baum während des Sturms versagt. Die Ergebnisse einer Standortüberprüfung zeigten, dass es auch andere Faktoren, wie zum Beispiel die Historie des Baumes und die Historie der durchgeführten Baumpflege, die zum Baumversagen beitragen können.

Standortinspektionen von 80 windgeworfenen Bäumen aus acht verschiedenen Gattungen wurden über eine Periode von 20 Jahren durchgeführt. Die Inspektionen ergaben, dass der Schaden an entblößten lateralen Wurzeln (87,5%), die Verlust an absteigenden Wurzeln (88,8%) und der Beweis für Bodenverdichtung an der Stammbasis (655) oft mit Windwurf assoziiert war. Das Vorkommen von Gräben in der Stammbasisnähe (58,8%) und Wassersättigung des Bodens um die Stammbasis (56,3%) waren ebenfalls häufig korreliert. Die untersuchte Literatur und die gezeigten Ergebnisse verdeutlichen nicht nur, welche Aspekte der urbanen Baumpflege verbessert werden können, sondern liefern auch hilfreiche Hinweise an Arboristen, die Gefahren für drohenden Windwurf zu untersuchen. Die Kriterien für Inspektionsprotokolle sollten Beschädigte oder eingefaulte laterale Wurzeln, Verlust von absteigenden Wurzeln, Anzeichen für Schachtungsarbeiten im Traufbereich und ob Bäume in verdichteten oder nassen Böden stehen, enthalten.

Resumen. Las imágenes de árboles impactados por el viento hacen difíciles las nuevas coberturas. El mensaje implícito es que los vientos fuertes y las lluvias intensas son la causa de la falla del árbol. Sin embargo, ¿son las tormentas la única causa de la falla del árbol? Muchos otros árboles, y a menudo muy grandes, no caen. En este artículo se revisa la literatura actual en relación con algunas características de los árboles volcados por el viento. El tamaño y las características de la copa tienen una profunda influencia en las fuerzas que ejercen los vientos en los troncos de los árboles y en los sistemas de raíces, mientras que las características de estos sistemas de raíces a menudo determinan si los árboles no fallan durante las tormentas. Los resultados de una inspección in situ sugieren que puede haber otros factores, como la historia del árbol y las prácticas de gestión a los cuales el árbol ha sido expuesto, que pueden contribuir a su fracaso durante una tormenta.

Se realizaron inspecciones de los emplazamientos de 80 árboles impactados por el viento de ocho géneros diferentes durante un período de 20 años. Las inspecciones revelaron que los daños en las raíces laterales expuestas (87,5 %), la pérdida de las raíces descendentes (88,8 %), y la evidencia de la compactación del suelo en la base del árbol (65 %) eran a menudo coincidentes con la acción del viento. La evidencia de apertura de zanjas cerca del tronco del árbol (58,8 %) y el anegamiento del suelo alrededor de la base del árbol (56,3 %) estuvo también comúnmente correlacionada. La revisión de literatura y los resultados sugieren no solamente dónde se podrían mejorar los aspectos de la gestión de los árboles urbanos, sino también puede ser útil para la evaluación por los arboristas de los riesgos relacionados con la posible acción del viento. Los criterios del protocolo de inspección deben incluir las raíces laterales dañadas o descompuestas, la pérdida de raíces descendentes, la evidencia en el sitio de trabajos de apertura de zanjas cerca del tronco y si los árboles están creciendo en suelos compactados y encharcados.