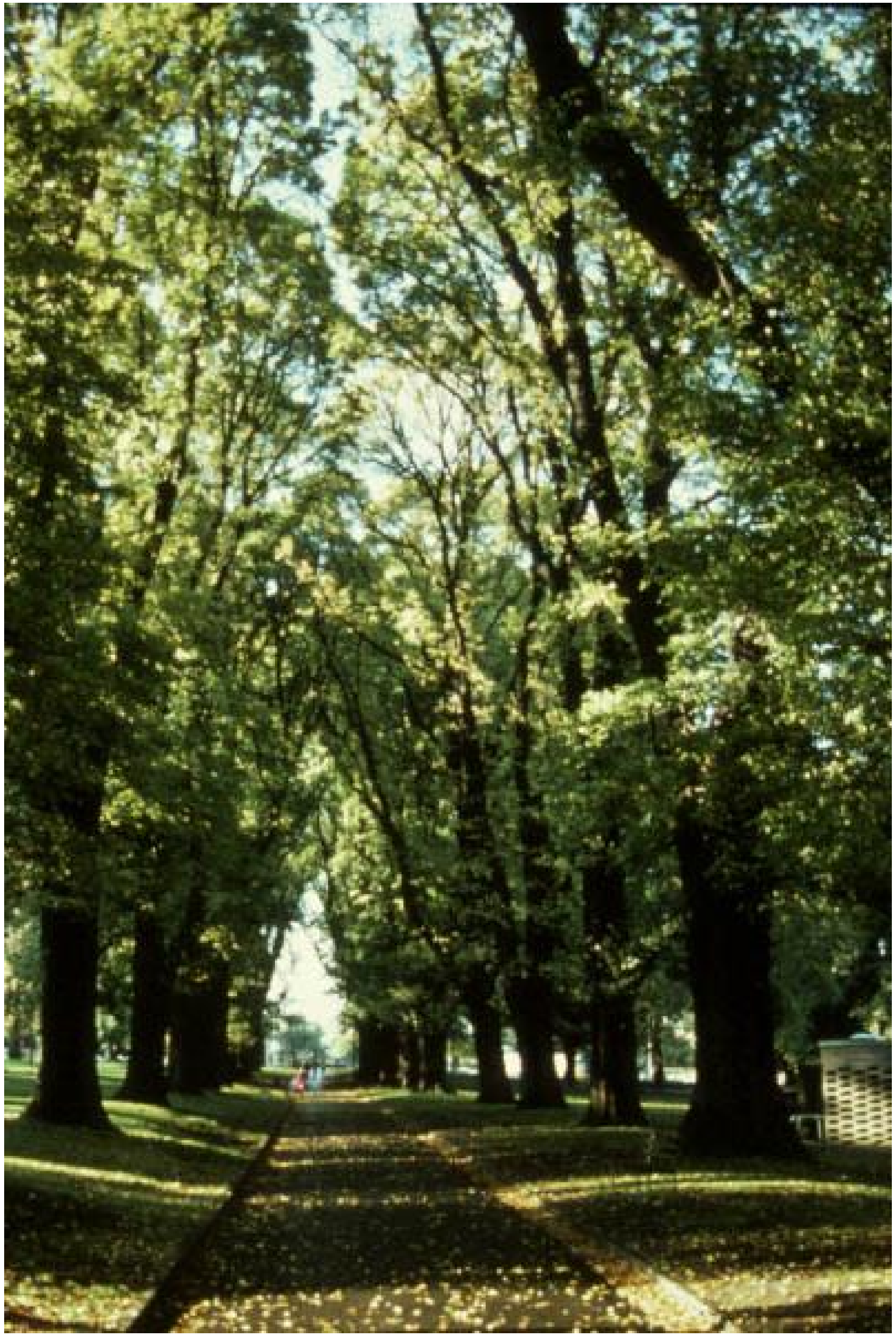

Windthrow of Trees: Storms or Management

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People often assume that trees fall over during severe storm events because of the stormôs strong winds and accompanying heavy rain.

However, many other and often larger trees withstand the force of the storm. The resilience of the many hundreds and thousands of trees that do not fall and which do not shed limbs is rarely remarked upon.

This situation raises the question,

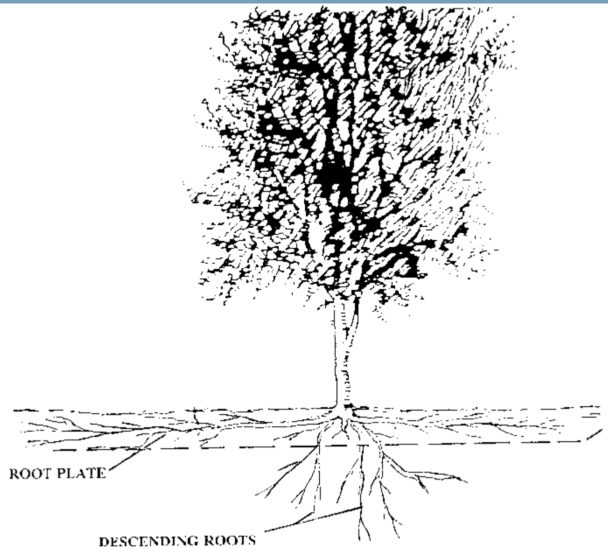
ñ**Why did a particular tree fail?”**

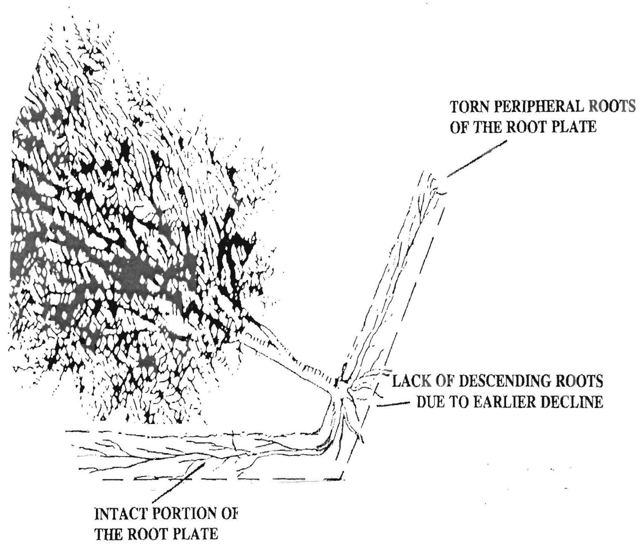
In this presentation:

Windthrow is defined as the uprooting 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.

A fallen poplar in a prominent Melbourne park with lack of descending roots, shallow root plate and lateral root damage in evidence.

Figure 2. Base of a fallen elm after 2005 storm showing in excess of 300mm fill around the trunk of the tree and growing very close to the footpath.





STABLE TREE	**WINDTHROWN TREE**
Direction of wind ←	Direction of wind ←
Wide and solid root plate	Wide and solid root plate
Descending roots intact	Loss or absence of descending roots
Windward roots intact	Windward roots pulled from soil, breaking in tension and snapping in sheer
Leeward roots intact	Leeward roots buckled and hinged in compression close to trunk
Healthy canopy by Visual Tree Assessment	Healthy canopy by Visual Tree Assessment

Most analyses of windthrow consider two components of tree structure.

Above ground: trunk, branches and foliage. Trees withstand physical loads from gravity and persistent winds, but the greatest loads come from occasional, sporadic wind gusts. Analyses often considered the forces as equivalent to those of a ships sail on its mast which may lead to breakage.

The root system: anchors the tree in the soil against the forces of the wind and which will be the focus of this presentation.

Many urban tree managers still focus attention on the size, health and canopy of the tree when assessing the risk of windthrow

Wind loads and the canopies of trees 1:

Above the ground, **forest trees** have a similar shape - a straight columnar trunk, little side branching and apical foliage and branches.

They have a **slenderness ratio (tree height (m) divided by trunk diameter at DBH (m))** of about 75 or above and respond to wind dynamically like a pole. In forest trees, **slenderness ratios above 100** are considered **unstable** and those **below 80** are described as **stable**.

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.

Wind loads and the canopies of trees 2:

Trees growing 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.

The development of large side branches contributes to and modifies their dynamic responses. Urban trees tend to exhibit significantly lower slenderness ratio than forest trees, because they tend to be shorter with higher trunk diameters.

Wind loads and the canopies of trees 3:

Analysis of windthrown trees shows tree size is significant. As they grow in height and canopy spread trees:

Åhave greater mass

Ådevelop greater self-loading and better anchorage

Åbut are exposed to higher wind speeds in taller canopies

Åwhich develop greater bending moments.

However, they are older and have had more time to adjust to the winds experienced in their environments so tend to be more stable than younger, establishing trees.

Wind loads and the canopies of trees 4:

Many static analyses of tree structure, responses to wind or mechanical pulling and wind tunnel experiments on canopies.

Åknown wind was not a static force and that trees responded to gusts of wind
Åbut to simplify analysis, wind loading was considered to be a static force
Åapproximated by pulling a tree with a rope at the equivalent force of an estimated wind

The approach to tree biomechanics by Mattheck and Breloer (1994) and their ñaxiom of uniform stressò is an example that has influenced arboricultural practice, but there was little dynamic analysis in these studies.

The treeõs resistive forces depended on factors such as stem characteristics, wood strength and root plate and soil interactions.

Static and dynamic loads on tree canopies:

ÅStatic pull tests were used to determine the mechanical resistance to overturning
Åthe strength parameters of a tree (including the strength of the trunk and the anchorage strength of the root plate and soil combination)
Åand to approximate the wind force acting on a tree and its responses.

Dynamic loads can be defined simply as time-varying and may vary with magnitude, direction and/or position with time. Tree leafy canopies are flexible

Åsurfaces realign themselves in high winds by reconfiguring their shape and reducing the total canopy area
Åthe whole canopy bends and changes shape and becomes more streamlined which reduces drag

Mass damping by branches and foliage

Damping, a dynamic parameter, estimates how much energy is absorbed or transferred (eg mass dampers in skyscrapers to reduce sway during earthquakes).

ÅMeasuring the effect of mass damping in trees is difficult.
ÅMost modelled the tree as a single degree of freedom system (pole/mast)
ÅTrees are multi-degree of freedom systems due to their branches and foliage
ÅEnergy from the wind may not be transferred to the tree but returned to the wind via small vortices at the scale of the leaves.

ÅThe work of James (2003; 2006) highlights the mass damping capacity of foliage and branches during storm events.

ÅRaises questions about the validity of the view that mature and bigger trees are more likely to fail simply because of their size and suggests that the failure of trees may have more to do with root systems than sail area.

The role of roots in tree stability under wind load:

Tree root development

A tree seed germinating in natural soil produces a radicle that develops as a tap root, which is often a juvenile characteristic of the treeõs early establishment phase.

The tap root often descends almost vertically reaching soils that are dense and low in oxygen and nutrients, which explains why 95% of the absorbing roots are close to the surface and why tap roots stop extending or die. The spreading lateral roots perform the roles of absorbing nutrients and water and of anchoring the tree.

In many urban trees, the propagation of trees from cuttings or growing seedlings in shallow seed trays and successively larger containers often means that there was no tap root even in young trees which can affect anchorage.

Mature root systems: the root plate, lateral and descending roots 1:

The root system of mature trees tends to be spreading and relatively shallow consisting of a relatively shallow, spreading root plate, consisting of the root crown, structural roots and the network of shallow, spreading, absorbing roots that are located close to the soil surface (300-60mm deep) and often spreading well beyond the dripline of the canopy

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 dripline of the tree and are often denser closer to the trunk. 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 3. The spread and depth of a typical tree root system. From (Watson and Neely, 1994).

Mature root systems: the importance of the root plate, lateral and descending roots:

Depending on the species, soil type and soil conditions, descending roots
Åmay be more or less prolific,
Åpossible that not all tree species develop them
Åor some species fail to develop them in certain soil conditions.

ÅDescending roots closer to the trunk tend to grow deeper in the soil than descending roots further from the trunk, which are smaller in diameter and shallower in their descent.
ÅDescending roots may grow to depths of 1000mm or more and persist for a number of years and at maturity may be 100-150mm in diameter before they die back and are replaced.

ÅBoth the root plate and the descending roots are important in tree stability.

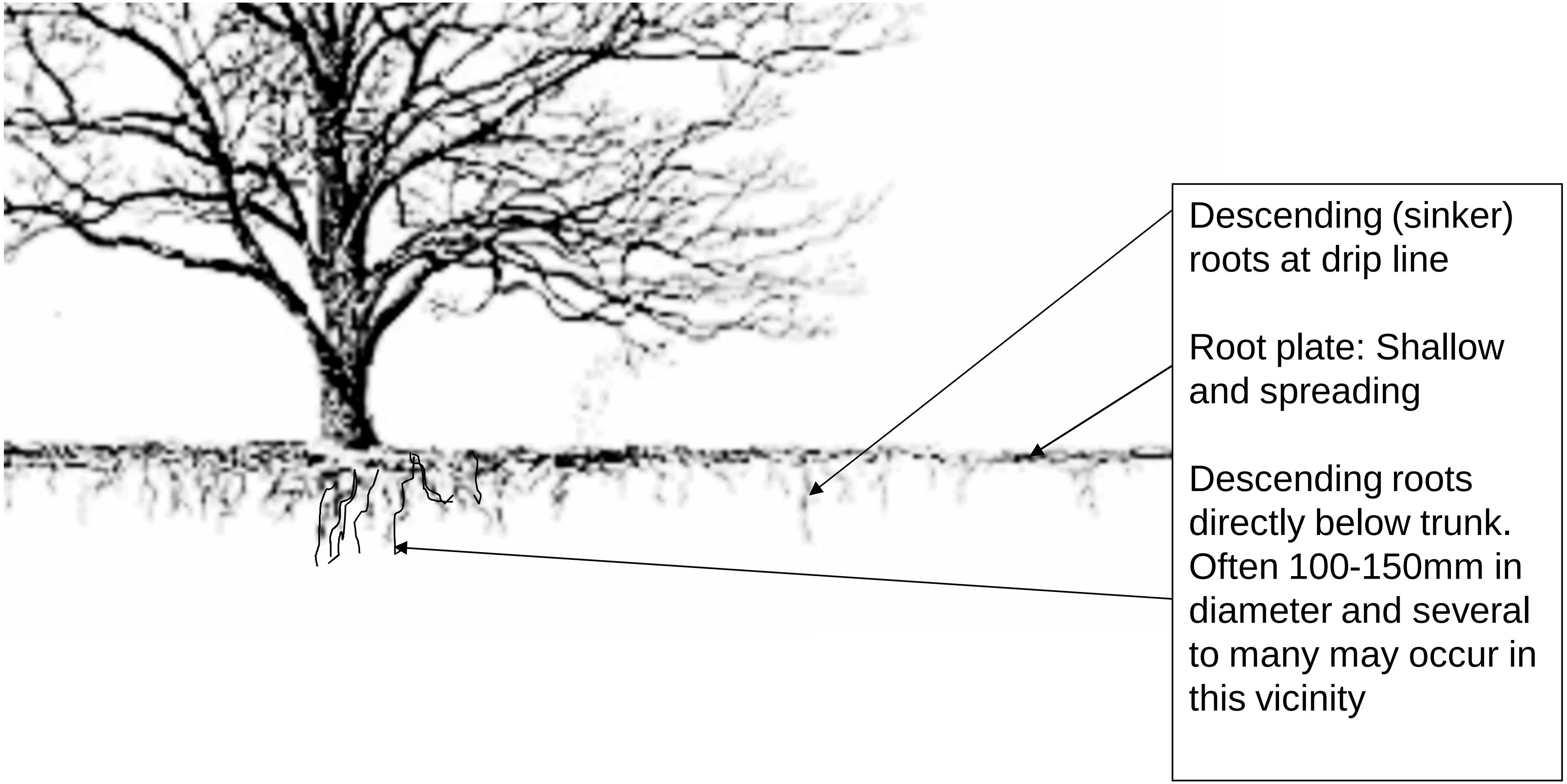


Figure 4. Descending or sinker roots typical of urban tree root systems (Modified from Watson and Neely, 1994)

Mature root systems: the importance of the root plate, lateral and descending roots 2:

ÅStructural roots are important for tree stability (tree protection regulations for development sites protect them as part of the critical root zone (CRZ).

ÅFine roots in large numbers and surface area contribute to tree anchorage binding closely to the soil, consolidating the root plate and increasing its mass.

ÅThe two major components of anchorage are the resistance of leeward roots to bending (25%) and the resistance of taproots/descending roots to uprooting (75%).

ÅAbout 92% of lateral roots have descending roots in close proximity (within 300mm) to the trunk.

ÅThe most important component of the root system in resisting windthrow is the windward side of the root system, which is pulled up during overturning.

Mature root systems: the importance of the root plate, lateral and descending roots 3:

Tree stability is enhanced when external loading forces are smoothly and rapidly dissipated which is best achieved by a large surface area with a high branching density to which branched descending roots contribute.

Tap roots are close to the centre of rotation in windthrown while descending roots are better orientated than horizontal windward roots to resist uprooting.

During a windthrow event:

Å the leeward lateral roots bend and eventually break often close to their base near the root crown,

Å the windward lateral roots are pulled from the soil, often with their descending roots, if present, intact

Å the tap root or one, or more, of the larger descending roots closest to the centre of the tree trunk rotate

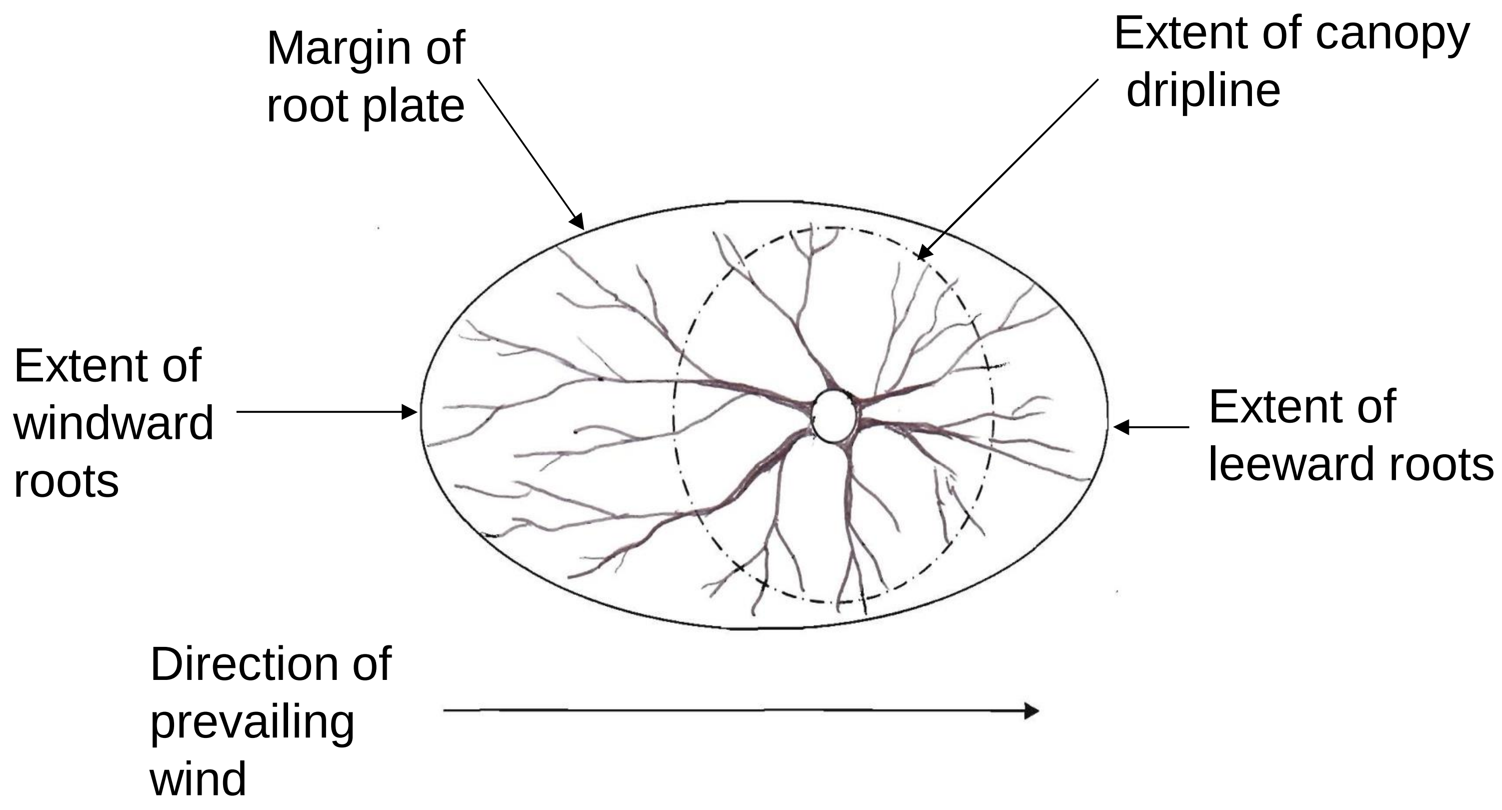
The pattern of windthrow is similar in dry and wet soils, but in the latter failure usually occurs closer to the trunk.

Mature root systems: the importance of the root plate, lateral and descending roots 5:

Size matters in the development of tree root systems Much of the root mass exists in the relatively few, large structural roots and these, along with the larger woody transport roots, stabilize the tree and under tension resist increasing wind speeds

There are many different models of root plate development - often depicted as being circular. However, root plates often have about 60% of their roots in the direction of the prevailing wind. Windward roots are smaller in diameter but longer and more branched at greater distances from the trunk while on the leeward side, the roots are shorter, thicker and tend to have more descending roots.

Thus the root plate is more likely to be elliptical but skewed to the windward side of the trunk.


Margin of root plate
Extent of canopy dripline
Extent of windward roots
Extent of leeward roots
Direction of prevailing wind

Major root failure patterns (sourced from Norris 2005, Coder 2010).

Windthrow tends to occur due to three basic root failure patterns.

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 a straight, 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 over time

Root depth, the root-soil interaction and waterlogging 1;

Trees can be windthrown in strong winds especially when heavy rain has saturated soils reducing soil strength.

Waterlogged soil may result in the windthrow of a tree, in which the windward root system is exposed more-or less intact with descending roots in place as they slip from the weakened soil.

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 roots are damaged/severed close to the trunk on the windward side of the tree.

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 above ground 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 which resists splitting

Root depth, the root-soil interaction and waterlogging 2:

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 negative affect on tree root systems.

Construction practices that compact lower soil horizons can restrict descending root penetration, diminishing the extent and mass of the root plate. Altered soil water flows creating waterlogged conditions restrict root development to < 200mm.

Tree protection on development and construction sites usually protects the structural root zone (SRZ), but the more extensive root protection zone (RPZ) protects not only the structural roots, but the lateral and descending roots further from the trunk.

Neither guarantee that the root system/plate will remain intact or the stability of the tree. Protection systems cannot deal with the nuances of every tree and the affects of soil type, soil conditions or the levels of environmental stress on the development of tree root systems

Data on site inspections of windthrown urban trees in Melbourne, Victoria 1:

Data on 80 large windthrown trees from eight different genera were collected from site inspections across Melbourneover 20 years.

The specimens were mature, but none had been characterised as senescent before they failed.

A set of seven criteria were developed to assess trees after failure that allowed data collection by rapid qualitative visual assessments.

The data include 30 windthrown specimens when Melbourne suffered a one in one hundred and fifty year storm event in February 2005.

Table 1: Criteria used in assessment of windthrown trees in Melbourne (modified from Moore, 2004)

1	Evidence of site or trenching works within 4m 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

Data on site inspections of windthrown urban trees in Melbourne, Victoria 2:

After a thirteen year dry period, 120mm of rain fell in 30 hours, most of it in a 10 hour period over night with very strong gusty winds. There was property and infrastructure damage and hundreds mature trees were windthrown in parks, gardens and on streets.

In most cases, there was evidence of major interference with the tree root systems from trenching, construction works, or from mowing practices. Such wounds may provide access for pests and diseases. While root damage was a common factor associated with the failure, there was also a strong correlation with changed soil/water conditions.

These changes were of two major types. The first was waterlogged soils with a pool of water at the base of the hole at the time of inspection. Waterlogged soils have a significant impact on descending roots, which often die back leaving a root plate with very few, if any, descending roots if the tree has been growing under such conditions for long enough.

Figure 6. A fallen elm in a prominent Melbourne park with lack of descending roots, shallow root plate and lateral root damage in evidence.

Assessment of eighty windthrown older trees against the selected criteria

GENUS	No	Crit 1	Crit 2	Crit 3	Crit 4	Crit 5	Crit 6	Crit 7
		Trench	Lateral root	Desc. Roots	Compa-ction	Fill	Water logging	Canopy dieback
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
Lophestemon	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 +ve criterion (%)		**58.8**	**87.5**	**88.8**	**65.0**	**37.5**	**56.3**	**32.5**

Data on site inspections of windthrown urban trees in Melbourne, Victoria 3:

A second condition arises when the patterns of soil water movement are altered by construction works, adding soil as fill or re-contouring of surfaces, all of which can inadvertently divert flows from the treeôs root system.

These water deficient trees were the only specimens that appeared to show symptoms of canopy dieback and significant amounts of deadwood. However, many windthrown 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.

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 mown.

Data on site inspections of windthrown urban trees in Melbourne, Victoria 4:

The finding that soils are compacted in heavily trafficked areas of a city park is to be anticipated. Compaction may be due to pedestrian or vehicular traffic, especially if there is active sporting activitywhen people congregate under the trees for shade.

More that one third of the windthrown trees had fill around their trunks which not only contributes to the waterlogging of soils around trees by interfering with natural drainage and contours but may also alter subterranean water flows. In the 2005 storm, without exception, trees that fell were growing beside roads or pathways.

In many situations there are multiple factors that contribute to root system failures which lead to trees falling. The strong wind may be the trigger that initiates windthrow, but there may also be other contributing factors to 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 did to the strength of the storm winds.

Figure 7. A fallen elm growing a long a pathway in a public garden in Melbourne after the major storm event of 2005.

Data on site inspections of windthrown urban trees in Melbourne, Victoria 5:

These 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:

Åtrees showing damaged or decayed lateral roots
Åloss of descending roots,
Åevidence of site or trenching works close to the trunk
Åwhether trees are growing in compacted soil
Åwhether trees are growing in waterlogged soil
Åthe presence of fill and canopy die back
Ådeadwood should also be noted.

Trees which are positive for a number of the criteria should then be subjected to further stability testing and regular monitoring to minimize the risks from failure

Comparing windthrown forest and urban trees:

Windthrow is not confined to urban trees, as forest trees may also be windthrown

The structure of forest trees is often different from urban trees as they tend to be taller with fewer branches along their trunks and have a different root architecture and are more likely to have a tap root and a number of descending roots than urban trees.

Site inspections of a small cohort (15 trees) of windthrown forest trees, using the criteria developed for urban trees, revealed that all lacked descending roots, 40% had lateral root damage and two thirds of them had been waterlogged (Table 5).

In contrast to the urban trees, most of these fallen forest trees (80%) showed signs of canopy die back and significant deadwood in the canopy. This suggests that the trees may have been stressed for some time

Comparison of assessment criteria for eighty fallen urban trees compared to fifteen windthrown 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
Site or trenching works within 4m of trunk	0	58.8
Presence of fill around base of tree	0	37.5
Canopy dieback and deadwood	80	32.5

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.

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.

Concluding Discussion:

If roots are severed on the prevailing windward side of the tree or significantly reduces roots mass then the risk of windthrow is heightened.

Under-root boring options are not only less likely to damage trees root systems, but also are often cheaper than trenching.

Damage which 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 some time after the damage has occurred when there is a subsequent storm event.

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