

Tree Mechanics and Wind Loading



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Abstract The response of trees to applied wind loads ranges from minor movement of leaves, branches and stems through to catastrophic failure in the form of stem breakage and uprooting. Catastrophic wind damage is a major source of economic loss in managed forests but is also an important ecological process in natural forests. Exposure to chronic wind stress results in a number of thigmomorphogenic responses including changes in tree shape and internal wood properties. In order to better understand the impacts of wind on trees, knowledge is required on wind loading of trees and their response to these loads. In this chapter, we provide an overview of the mechanics of wind loading of trees, starting with the drag force acting on trees for a given wind speed and how this wind speed varies within forest canopies. We then discuss how this load is resisted by the stem and root system, including tree dynamic response to fluctuating wind loads. Throughout the chapter, we focus on advances in instrumentation and modelling techniques that have aided our understanding of this complex phenomenon. We also highlight some of the key gaps in our knowledge and suggest future directions where research advances could be made. An improved knowledge of the mechanics of wind loading on trees aids the better management of the risk of damage to forests and a better understanding of the thigmomorphogenic responses of trees to wind stress and the biomechanical benefits these confer. It can also aid our understanding of the effects of wind exposure on wood properties and the potential consequences for the wood products sector.

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Introduction

Wind is a persistent force in the natural environment which is primarily generated by differential heating of the Earth's surface by the sun (Stull 1988). Regional differences in wind direction and the distribution of wind speeds are primarily due to latitude and differences in meteorological conditions, but are also the result of differences in topography and surface roughness. Wind imposes a stress on trees to which their response can range from relatively minor leaf flutter within canopies to mild wind sway of limbs and trunks well within the elastic limits of the wood material to physical damage manifesting as micro-failures internally within the trunk branches and roots, and in the most extreme cases to catastrophic failure of branches, stems and roots (Fig. 1) (Grace 1977; de Langre 2008; Gardiner et al. 2016).

Catastrophic wind damage in the form of uprooting and breakage of individual trees through to whole stands is a major disturbance in both managed and natural forests in many regions of the world (Foster and Boose 1995; Everham and Brokaw 1996; Martin and Ogden 2006; Gardiner et al. 2011; Mitchell 2012). In forests managed for timber production, wind damage can result in significant financial losses due to reduced revenues and the increased cost of salvaging trees (Manley and Wakelin 1989). It can also result in substantial disruption to regional wood supply, particularly when the amount of wind damaged timber is a substantial proportion of the annual harvest levels (Hanewinkel and Peyron 2013). While the effects of wind are generally considered to be negative for managed forests, wind is an important disturbance agent in natural forests that is responsible for ecological succession and soil mixing (Schaetzel et al. 1989; Ennos 1997; Ulanova 2000). A better understanding of the catastrophic effects of wind on trees is needed as forests represent the major terrestrial sink for carbon and are a key component in the global carbon cycle (Grace et al. 2013) and an increased frequency of disturbances (including wind damage) under projected future climate change may result in reduced carbon storage by forests (Aber et al. 2001; Bonan 2008). Catastrophic wind damage can also have a large impact on trees in the urban environment (Duryea and Kampf 2007; Lopes et al. 2009). Broken and uprooted trees can pose a hazard to infrastructure and the human population, with partial or complete tree failures being one of the main causes of injury and death during strong wind events.

Exposure to chronic wind loading can result in a number of morphological changes in trees—a phenomenon known as thigmomorphogenesis—as well as affect their physiology (Telewski and Jaffe 1986; Telewski 1995, 2012; Bonnesoeur et al. 2016; Gardiner et al. 2016). In extreme cases, where trees are exposed to persistent strong winds they exhibit highly deformed growth which has terms such as 'krummholz' or 'elfin' associated with it (Lawton 1982; Grace 1989). In natural forests, these responses are important for understanding forest structure and species distribution, while in managed forests they can have important, and often adverse, impacts on log quality which in turn has implications for the forest products sector (Telewski and Moore 2016).



Fig. 1 Examples of wind effects on trees in the form of catastrophic damage (top) and flag form growth (bottom). Photographs from John Moore and Scion photo collection

Because of the economic and ecological importance associated with wind impacts on trees, there have been a large number of studies that have addressed this issue. These studies have often sought to understand and quantify the response of trees to different levels of wind loading and the contribution that different factors (i.e. tree size and shape, stand structure, soil type, etc.) have on this response. This is particularly true for catastrophic wind damage where researchers have attempted to better understand the underlying risk factors. One approach has been to use data collected from catastrophic events to identify empirical relationships between the probability of wind damage and various tree, stand and site factors (Quine 1995; Mitchell et al. 2001; Schmidt et al. 2010; Albrecht et al. 2012). However, two of the challenges with this empirical approach are that the scope of inference is limited to the same underlying population that was used to develop the models, and they do not necessarily identify underlying causal mechanisms (Quine 1995; Lanquaye-Opoku and Mitchell 2005). As a result, there has been an increasing focus on developing hybrid models (i.e. containing both mechanistic and empirical elements) to predict the probability of wind damage to individual trees and stands (see Gardiner et al. 2008 for a summary of models). These models combine plant biomechanics and wind engineering to calculate the critical wind speed at which trees will either uproot or break. However, a biomechanical approach has also enabled a better understanding of the non-catastrophic effects of wind on trees, including the impacts of tree thigmomorphogenic responses to chronic wind stress that improve the resistance of trees to applied loading (Nicoll et al. 2008; Fournier et al. 2013; Gardiner et al. 2016).

In this chapter, we review recent progress in understanding and quantifying wind–tree interactions. We particularly focus on the development of new measurement and modelling approaches that have facilitated a greater understanding of these interactions, highlight where gaps exist in our current knowledge and identify future directions for research. The chapter starts with an overview of tree responses to wind, including a summary of thigmomorphogenic responses and the biomechanical benefits these confer. We then describe the interaction between wind and trees and how advances in instrumentation and modelling techniques have enabled data to be more readily collected in the field and more realistic simulations of the response of trees to fluctuating wind loads. Finally, we discuss some of the gaps in our understanding of wind–tree interactions, which are often manifest as simplifications in simulation models, and provide some perspectives on future directions for research.

Tree Responses to Applied Wind Loading

Wind induces a variety of responses in trees which depend on the magnitude, duration and frequency of loading. The mechanical stability of trees subjected to strong winds depends on the magnitude of the applied force from the wind acting on the crown and the relative capacity of the stem and root–soil system to resist this applied loading (Fig. 2) (Wood 1995; Peltola 2006; Gardiner et al. 2008; Peltola et al. 2013). The threshold (or critical) wind speed required to cause uprooting or stem failure can then

be defined as the wind speed required to produce an applied bending moment equal to the maximum resistive moment that can be provided by either the stem or the root–soil system. This is the fundamental basis for mechanistic models, such as GALES and HWIND that have been developed to predict the risk of wind damage to forests (Gardiner et al. 2008). The magnitude of both the applied loads and resistive forces depends on a number of site, tree and stand factors, including (but not limited to) wind climate, tree species, tree height and diameter, wood stiffness and strength, stand density (inter-tree spacing), soil type and rooting depth. Many of these factors are able to be manipulated by forest managers through the selection of sites for establishing forests, choice of species and stand structure (Ruel 1995), and mechanistic models provide a useful basis for evaluating the impacts of different factors on the risk of wind damage (Gardiner and Quine 2000).

There are a variety of growth responses of trees to chronic wind exposure and these are described in more detail in recent reviews (de Langre 2008; Badel et al. 2015; Telewski 2016; Gardiner et al. 2016). It is hypothesised that these thigmomorphogenic responses increase the ability of a tree to withstand wind stress. The earliest observations of these responses were made around 300 B.C. (Telewski 2012) and the first experiments examining the effects of restricting trees from swaying were conducted over 200 years ago (Knight 1803). Within the linear elastic range of material behaviour, thigmomorphogenic responses are characterised by an increase in stem taper, mostly resulting from a reduction in the rate of height growth (Telewski 1995), increase in branch diameter and a reduction in the rate of branch extension (Watt et al. 2005), the formation of flexure wood with a lower modulus of elasticity but higher strength (Telewski 2016), increased radial growth of roots (Urban et al. 1994) and changes in the cross-sectional shape of structural roots (Nicoll and Ray 1996). Wind stress has also been proposed as a significant factor influencing the shape of tree stems (Metzger 1893; Larson 1963, 1965). Under this theory, the cambium is hypothesised to produce new wood in order to equalise the distribution of stresses along the outer surface of the stem (Morgan and Cannell 1994). This theory is known as the mechanical theory of uniform stress and has been the subject of considerable debate in the scientific literature (Mattheck 2000; Niklas and Spatz 2000a, b).

Exposure to higher magnitude chronic wind stress can result in plastic deformation of the stem, branches and wood cells (Telewski 1995, 2012, 2016). Examples of woody tissues responses to plastic deformation include the formation of ‘Wulstholz’ in response to fibre buckling near the cambium (Koch et al. 2000), resin pockets and shake (Moore et al. 2014). The most obvious and striking whole-tree response to strong prevailing winds is the windswept growth form in which branches and in some cases stems curve away from the wind (Fig. 1) (Telewski 2012). Where wind stress causes the stem to be displaced for a period of time much longer than the presentation time for gravitropism, reaction wood will form in order to help the tree recover an upright position (Fournier et al. 2014).

The thigmomorphogenic responses of trees to chronic wind stress increase the resistance of trees to wind stress by reducing the wind forces acting on the tree for a given wind speed and increasing the mechanical strength of the stem and root–soil system. The degree to which this acclimation to chronic wind stress can affect the

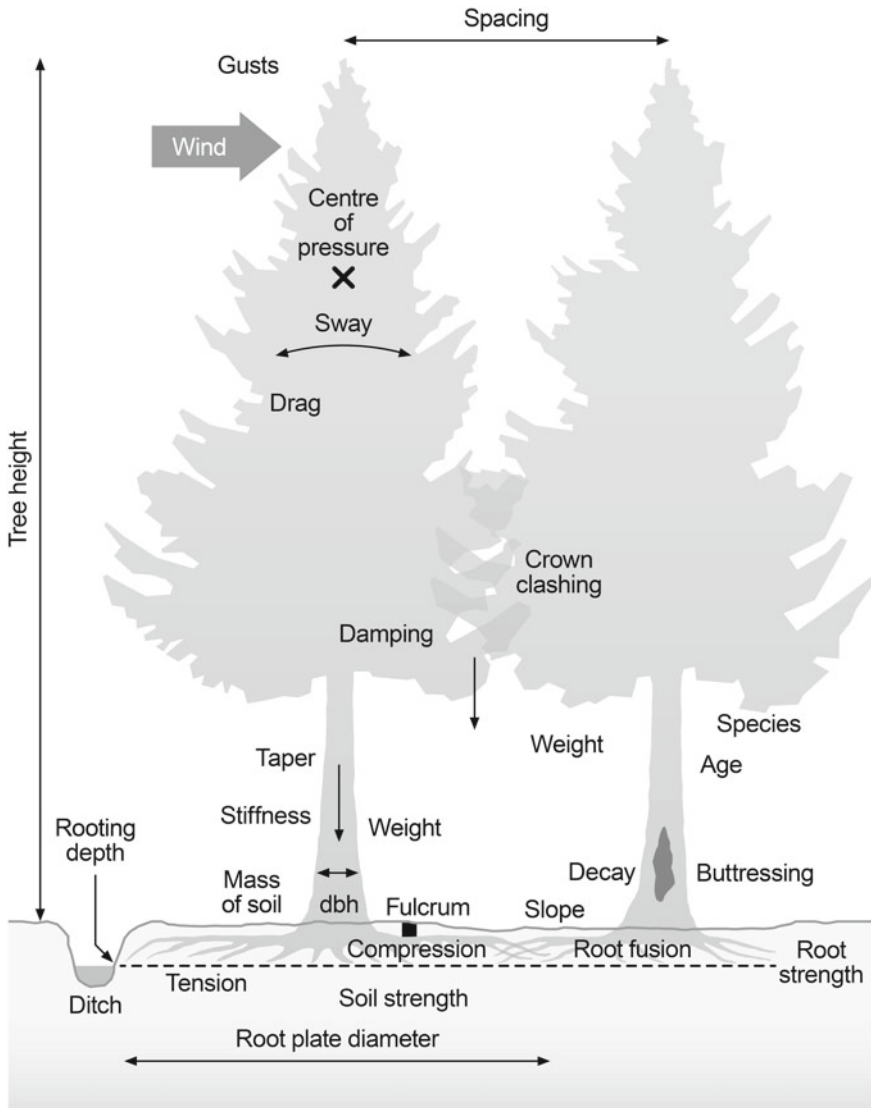


Fig. 2 Factors affecting the mechanical stability of a single tree subjected to wind loading (after Quine et al. (1995) © Crown Copyright Forestry Commission. Used with permission

mechanical stability of trees under strong wind conditions can be determined through analysis of the mechanics of wind loading on trees. This type of analysis is also a key component of understanding how the tree acclimation responses to wind stress are actually produced (Telewski 2006; Coutand 2010; Moulia et al. 2015) and can

potentially be used by tree breeders to select for traits that confer greater wind firmness (Telewski and Moore 2016).

The Mechanics of Wind Loading on Trees

Wind Forces Acting on the Tree

The wind force acting on a tree is due to a combination of viscous drag and pressure drag (Patton and Finnigan 2012). Viscous drag (or skin friction) is the friction of the air flowing over the surfaces of the stem, branches and needles. At the interface between these surfaces and the air, the velocity of the air is zero and thus the viscosity of the air imparts a drag force on the tree. The second component of drag is pressure drag (or form drag) which is due to the pressure difference that occurs between the front and back of the elements (i.e. stem, branches and foliage) of the tree as the flow moves around these elements. As the wind speed increases, the flow becomes more turbulent and the pressure drag dominates. The wind force (F) acting on a tree for a given wind speed (u) can be determined through empirical approaches in which wind speed data and the tree response data are collected simultaneously (e.g. Hale et al. 2012; Butler et al. 2012) or by using the drag equation:

$$F = \frac{1}{2} C_D \rho A u^2 \quad (1)$$

where C_D is a non-dimensional drag coefficient, A is the projected crown frontal area and ρ is the mass density of air (1.226 kg m^{-3} at standard atmospheric pressure and temperature). This equation requires information on the drag coefficient of tree crowns, which can be obtained from wind tunnel tests. However, one of the challenges is that the working section of most wind tunnels only allows small sections of tree crowns to be tested (Ennos 1999). Wind tunnel tests on larger trees (diameter at breast height = 10–15 cm, height = 6–8 m) were undertaken by the British Forestry Commission in the 1960 and 1970s to determine the drag force acting on different species as a function of wind speed and to calculate the drag coefficients for the species tested (Raymer 1962; Mayhead 1973). Reanalysis of data from these wind tunnel tests showed that wind drag was not proportional to the square of wind speed, but to the power of between 1.24 and 1.41 (Fig. 3). As a result, the drag coefficients calculated from these tests decreased with increasing wind speed as the crown frontal area measured under still air conditions was applied in Eq. (1). Because tree crowns are flexible structures and as the wind speed acting on them increases as the foliage and branches move into alignment with the direction of the applied wind loading (Fig. 4). This process of streamlining acts to reduce the crown frontal area and more recent wind tunnel experiments found that the crown frontal area of trees decreased by between 20 and 54% at a wind speed of 20 ms^{-1} depending on the species (Rudnicki et al. 2004; Vollsinger et al. 2005).

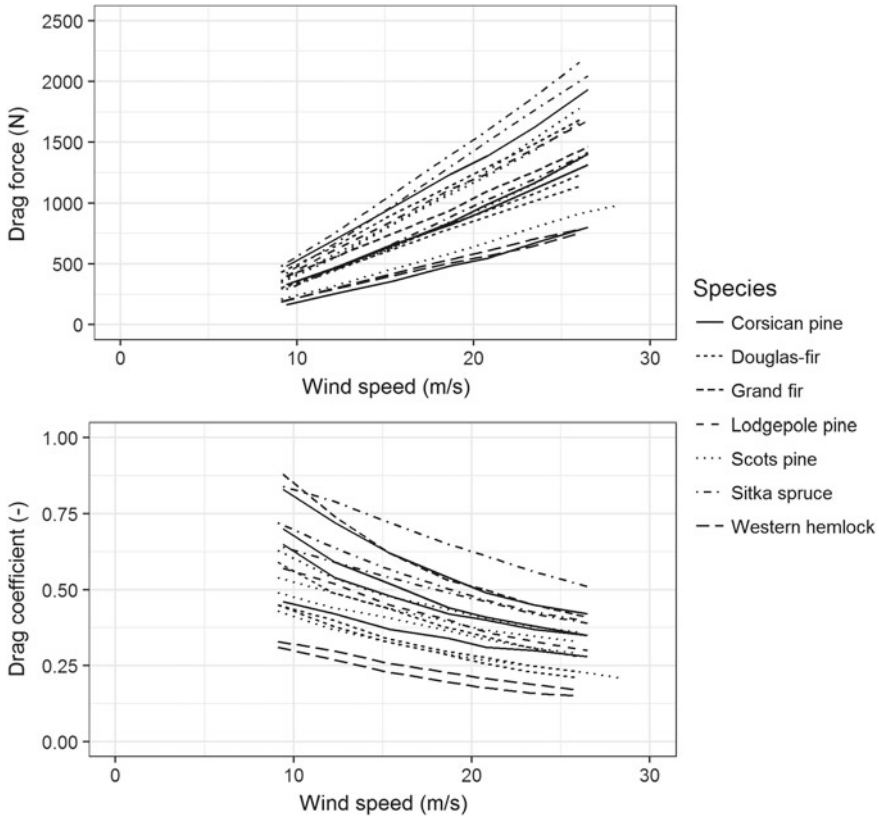


Fig. 3 Relationship between drag force and wind speed based on wind tunnel testing of conifer trees. The bottom panel shows the dependence of drag coefficient on wind speed. Relationships are based on data presented in Raymer (1962) and Mayhead (1973)

The degree of reconfiguration of the crown in high winds can be quantified through the value of E , which is calculated through the following equation (Vogel 1994):

$$\frac{F}{u^2} \propto u^E \tag{2}$$

Based on the data from wind tunnel studies undertaken by the British Forestry Commission, the average value of E across all trees tested was -0.65 .

The total mean wind-induced force, F , acting on the tree is the sum of the wind forces acting at each point on the stem and crown, i.e. $F = \sum_{z=0}^h F(z)$. To calculate the wind load acting at height z on a tree, the drag equation can be used in combination with an equation to represent the vertical profile of mean horizontal wind speed, i.e.



Fig. 4 Reconfiguration of the crown of a Sitka spruce tree in the Royal Aircraft Establishment wind tunnel at a constant wind speed of 24.9 m/s. Photograph from Graham Mayhead © Crown Copyright Forestry Commission. Used with permission. For details of tests see Mayhead (1973)

$$F(z) = \frac{1}{2} C_D \rho A(z) u(z)^2 \quad (3)$$

Over open ground containing a few isolated trees, the vertical profile of mean horizontal wind speed can be represented by a logarithmic function of the following form (Stull 1988):

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z}{z_0}\right) \quad (4)$$

where u_* is the friction velocity (ms^{-1}), k is von Karman's constant (0.4), z is the height above ground (m) and z_0 is the roughness length (m). As the density of trees increases, trees are sheltered by other trees and the wind speed u at height z is no longer linearly related to $\ln(z)$ but instead is linearly related to $\ln(z - d)$ where d is the zero-plane displacement (m). The wind speed profile **above** the forest canopy is described by the following equation:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z - d}{z_0}\right) \quad (5)$$

The zero-plane displacement is the height at which zero wind speed occurs due to the presence of a tree canopy and is also considered to be the mean level of momentum absorption by the tree canopy (Thom 1971). Theoretical equations for predicting z_0 and d based on tree dimensions and inter-tree spacing have been developed by Raupach (1992, 1994), although approximate values are given by

$$d = 0.78 h \quad (6a)$$

$$z_0 = 0.075 h \quad (6b)$$

where h is the height to the top of the canopy (Jones 1992). Within a forest canopy, the wind speed profile can be approximated by an exponential function of the following form:

$$\frac{u(z)}{u_h} = e^{-v_e(1-z/h)} \quad (7)$$

where v_e is an extinction coefficient that is dependent on leaf area density. The canopy-top wind speed u_h can be obtained from Eq. 5 with $z = h$.

The wind force acting on trees within a forest canopy can also be calculated by partitioning the shear stress acting on the canopy among the trees within the forest. The shear stress on the surface of the canopy is given by

$$\tau = \rho u_*^2 \quad (8)$$

The shear stress is the drag per unit area imposed on the canopy surface by the wind. If D represents the average spacing between trees within the forest then τD^2 is the average drag force acting on each tree. Both the ‘profile’ method (Eqs. 3, 5 and 7) and the ‘roughness’ method (Eq. 8) are used within the GALES model to calculate wind loading on trees (Gardiner et al. 2000, 2008). Using the roughness method, the mean bending moment BM_{mean} acting at any height z on the stem below the zero-plane displacement height is given by $(d - z) \tau D^2$ or as a function of the canopy-top wind speed u_h as

$$BM_{mean}(z) = (d - z) \rho \left(\frac{Du_h k}{\ln\left(\frac{h-d}{z_0}\right)} \right)^2 \quad (9)$$

There is also an additional moment exerted on the tree due to the offset mass of stem and crown from the wind-induced stem bending and this is discussed in a subsequent section.

Effects of Canopy Structure and Forest Layout on Wind Loads Acting on Trees

Wind flow in and above forests is highly turbulent and hence the wind loading on trees is not simply a function of the mean wind speed. A detailed description of canopy turbulence is beyond the scope of this chapter (for reviews see Finnigan 2000; Patton and Finnigan 2012) and the following is a brief and simplified overview of what is a complex process. There is strong wind shear (change in wind speed with height) at the canopy top with an associated inflection point in the vertical profile of mean horizontal wind speed. This inflection point is an instability that leads to the formation of Kelvin–Helmholtz waves that quickly become transformed into across-wind vortices. These vortices are unstable and begin to distort to produce coherent gusts at the top of the canopy. Each gust consists of a rapid increase in horizontal wind speed together with downward movement of air into the canopy (Finnigan 2000). These sweep events are responsible for much of the momentum transfer into the canopy and the strongest gusts can exert forces on trees that are up to ten times larger than those due to the mean wind speed (Gardiner et al. 1997). There are relatively few experimental studies of the influence of canopy morphology and forest structure on turbulent statistical fields and coherent structures because of the difficulties in implementing such experiments, although new techniques such as LiDAR anemometry offer new possibilities to obtain measurements of the three-dimensional wind field at multiple heights above the ground without the alignment errors that can affect sonic anemometers (Dellwik et al. 2010; Boudreault et al. 2016). However, considerable insight into turbulence in and above forest canopies has been gained through both wind tunnel studies (e.g. Stacey et al. 1994; Gardiner et al. 1997;

Harman et al. 2016; Poëtte et al. 2017) and large eddy simulation (LES) techniques (Yang et al. 2006a, b; Dupont and Brunet 2008, 2009; Dupont et al. 2008). One of the challenges in these studies is realistically representing the forest structure, although LiDAR provides a means for rapidly capturing information on forest structure that can be used in numerical simulations (Boudreault et al. 2015).

In forests, particularly those managed for timber production, there may be a mosaic of forest edges created by differences in age (and thus height) between adjacent stands and also by harvesting activities. Wind tunnel studies on model trees have been used to determine the relative wind load acting on a tree as a function of the distance downwind from the stand edge (X) and the relative spacing of trees (D/h) in the stand (Gardiner et al. 1997, 2005). These experiments were also used to determine the ratio of maximum loading to mean loading as a function of these two variables (Fig. 5). These studies have shown that while the mean wind load acting on a tree is much higher at the stand edge than inside the forest, the ratio of maximum load to mean load increases with distance back from the edge. These two factors can be added to Eq. 9 in order to estimate the maximum bending moment acting on a tree at a known distance downwind from the stand edge, i.e.

$$BM_{max}(z) = BM_{mean}(z) G f_{edge} \quad (10)$$

where G is the ratio of the maximum bending moment to the mean bending moment as a function of relative spacing and distance downwind from the stand edge and f_{edge} is the ratio of the mean bending at a known distance downwind from the forest edge relative to the mean bending moment well inside the stand (normally taken as a distance of $9h$ downwind from the edge). The use of this empirical gust factor is a major simplifying assumption in mechanistic wind damage models and understanding the relationship between peak loading and mean loading under actual forest conditions is a key area for future research (see section on Gaps in knowledge and suggestions for future research).

Bending of the Stem Caused by Applied Wind Loads

The wind force acting on the stem creates an applied bending moment which causes the stem to bend. Euler–Bernoulli beam theory can be used to determine the deflection of the stem under applied loading as well as the stress distribution in the outer fibres in the stem. For an initially straight beam or beam section, Euler–Bernoulli beam theory states that

$$\frac{1}{R} = \frac{M}{EI} \quad (11)$$

where R is the radius of curvature of the beam, M is the bending moment acting on the beam, E is modulus of elasticity and I is the second area moment of inertia.

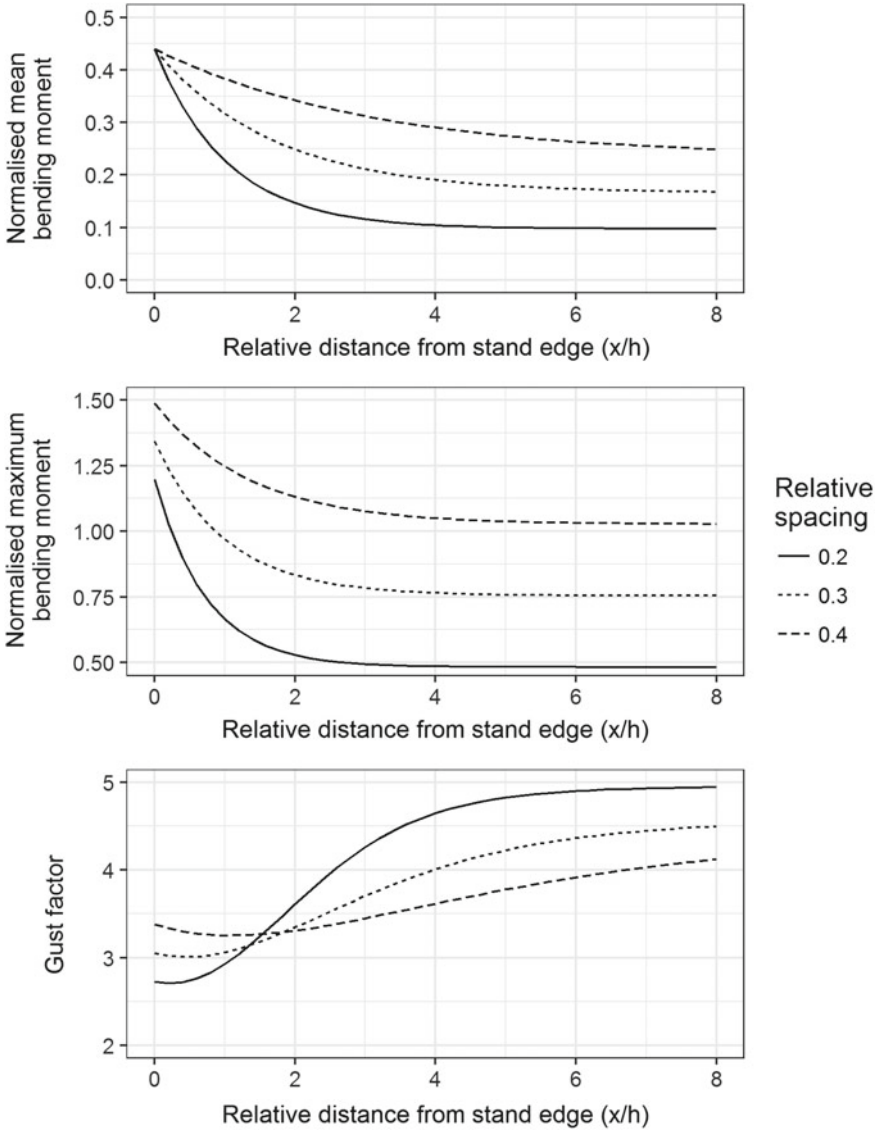


Fig. 5 Change in mean and maximum bending moment and gust factor with relative distance (normalised by tree height) from the windward stand edge. Based on the equations presented in Gardiner et al. (2000)

If a tree is assumed to have a circular cross section then $I = \frac{\pi d^4}{64}$ where d is the diameter of the stem, taken as constant over length. Various analytical approaches have been developed to calculate stem deflection that account for the taper of the stem (Petty and Worrell 1981; Petty and Swain 1985; Blackburn et al. 1988; Gardiner

1992), variation in E along the stem (Wood 1995), the relative flexibility of the stem and root system (Neild and Wood 1999), and bending through large deflections (Morgan and Cannell 1987). Predictions from these equations have generally been in good agreement with deflection measurements made on trees in the field that have been bent through the application of artificial loads (Milne and Blackburn 1989; Neild and Wood 1999). If the bending stress in the tree is in the linear elastic region, then the tensile or compressive stress σ in a section of the tree as a result of a bending moment M will vary with distance y from the neutral axis, i.e.

$$\sigma = \pm \frac{My}{I} \quad (12)$$

An additional compressive stress will occur because of the self-weight of the tree, but this stress is small compared with the bending stress in a deflected tree. The maximum tensile and compressive stresses occur in the fibres at the surface of the stem (where $y=d/2$). Substitution of $I = \frac{\pi d^4}{64}$ into Eq. 12 gives

$$\sigma = \pm \frac{32M}{\pi d^3} \quad (13)$$

Failure of the stem is assumed to occur when the stress in the outer fibres exceeds the strength of the wood. Therefore, by calculating the vertical profile of maximum outer fibre stress due to wind-induced bending and comparing this with the modulus of rupture of green wood, the wind speed required to break the stem can be calculated (Gardiner et al. 2000). Values for the strength of green wood often come from tests made on small defect-free samples (Lavers 1983; USDA 1999) and need to be adjusted to account for the presence of strength reducing defects such as knots and decay. Studies that have measured the modulus of rupture on whole sections taken from living trees have found that values are between 80 and 100% of values obtained from tests on small defect-free specimens (Ruel et al. 2010).

In addition to determining the wind speed required to cause the stem to break, quantifying the distribution of the stresses and strains along the stem is important for understanding the thigmomorphogenic responses of trees to wind loading. Models based on the Finite Element Method (FEM) (Zienkiewicz et al. 2014) have more realistic descriptions of stem geometry and internal wood properties and have been used to simulate the static behaviour under wind and snow loads (Gaffrey and Kniemeyer 2002) and growth mechanics (Fourcaud et al. 2003). These models have particular utility for quantifying the wind-induced displacement and stresses in trees whose shape is not readily approximated by a single tapered cantilever beam.

Mechanics of Root Anchorage

Root anchorage strength is dependent on root system topology as well as the structure and characteristics of the soil that the tree is growing in. Tree winching studies in which a simulated wind load is applied to the stem have been used to assess the root anchorage strength of a wide range of tree species growing on different soil types (Fraser 1962; Fraser and Gardiner 1967; Fredericksen et al. 1993; Moore 2000; Peltola et al. 2000; Cucchi et al. 2004; Achim et al. 2005; Nicoll et al. 2006; Byrne and Mitchell 2007). In these studies, root anchorage strength was found to positively scale with some measure of tree size, e.g. tree height, diameter at breast height, stem volume or stem mass (see summary table in Peltola 2006). These empirical relationships between root anchorage strength and tree size are used in mechanistic wind damage models to calculate the critical wind speed required to uproot a tree (Gardiner et al. 2008).

While these relationships are useful for predicting the overall root anchorage strength, they do not explain how root system and soil characteristics affect anchorage. Several winching studies have been undertaken to identify the contribution of different root types to the overall anchorage strength (Coutts 1983; Crook and Ennos 1996; Stokes 1999; Stokes et al. 2005). In shallowly rooted Sitka spruce (*Picea sitchensis* (Bong.) Carr) trees without a tap root, Coutts (1983) found that the windward lateral roots held in tension were the most important component of root anchorage. However, on free draining soils that afforded deeper rooting, Crook and Ennos (1996) found that approximately 75% of the root anchorage strength was provided by the taproot and the windward sinker roots and Stokes et al. (2005) found that the most resistant species to overturning were those possessing a ‘heart’ root system, i.e. with many branched, oblique, horizontal and lateral roots.

One of the challenges of studying the factors affecting root anchorage is describing root system topology. Root systems are complex, they are located underground and are difficult to extract without damaging them. Three-dimensional digitisation techniques have been used to study excavated root systems and to identify some of the key features that contribute to anchorage (Danjon et al. 2005). Other non-invasive techniques such as ground penetrating radar may offer the possibility of capturing information on the root system topology without the need to excavate trees. However, further development of these systems is needed in order to be able to provide accurate information in a wide range of conditions (Barton and Montagu 2004). The complex topology of root systems also presents challenges for modelling their behaviour under applied load. Since the first mechanistic anchorage model developed by Blackwell et al. (1990), most models of root system behaviour have been based on the FEM (Dupuy et al. 2005, 2007; Fourcaud et al. 2008; Yang et al. 2014). The development of these models has involved increasingly refined descriptions of the root system topology, soil mechanics and the inclusion of progressive root breakage under increasing loads and they are able to produce results that are in close agreement with those obtained from tree-pulling tests.

Dynamic Response of Trees to Fluctuating Loads

By fluctuating over time the wind exerts a dynamic force on trees and sets them in motion. Under such conditions, the magnitude of a tree's response depends on both the magnitude of the applied wind load and also the frequency of loading, with the greatest response occurring when the frequency of applied loading coincides with the natural frequency of the tree (Holbo et al. 1980; Mayer 1987; Gardiner 1992). Structural dynamics approaches have been used to study the behaviour of trees subject to dynamic loads by considering them as a damped harmonic oscillator. The response of a damped harmonic oscillator depends on the natural frequency and damping ratio and a number of field studies have measured these properties on a range of species (for a summary see Moore and Maguire 2004; James et al. 2006). Such studies have often involved pull-and-release tests in which the tree returns to its rest position under damped free vibration. A number of different sensors including stopwatches, displacement transducers, accelerometers, tilt sensors, strain gauges and lasers have been used to collect data on the frequency and magnitude of tree oscillations in these tests. For trees with simple architecture (i.e. conifer species with a single stem), the natural frequency is strongly and linearly related to the ratio of diameter at breast height (DBH—typically measured at 1.3–1.4 m above ground) to total tree height (H) squared (i.e. DBH/H^2) in accordance with theory for the oscillation of a beam with circular cross section. Damping of tree oscillations is due to a number of factors including: aerodynamic drag on foliage; collisions between neighbouring trees; internal friction; and structural damping (Milne 1991; Spatz et al. 2007; Spatz and Theckes 2013). Published values of damping ratios from free vibration tests on conifer trees range from 0.05 up to 0.23 (Moore and Maguire 2004). Few studies have attempted to model damping due to a lack of knowledge about the energy loss mechanisms involved although recent field experiments and numerical simulations have provided considerable additional insight into these mechanisms, particularly structural damping due to the multiple oscillation frequencies of different parts of a tree (Theckes et al. 2011; Spatz and Theckes 2013; Theckes et al. 2015) and the effects of crown clashing between adjacent trees (Schindler et al. 2011; Webb et al. 2013).

Several theoretical models of tree dynamics have been developed based on the equations of motion for a harmonic oscillator. In these models, many representations of a tree as a dynamical system are possible. It can be represented by a simple oscillator or inverted pendulum (Flesch and Wilson 1999), a system of masses coupled by spring-dashpot connectors (James 2003), a rigid body system (Kerzenmacher and Gardiner 1998; Murphy and Rudnicki 2012), and a vertical cantilever beam (Papesch 1974; Mayer 1987; Saunderson et al. 1999; England et al. 2000). Independently of the representation, a set of equations must be written to describe mechanical equilibrium between inertia, elastic and applied forces. Tree motion is predicted by solving those equations which, for systems with distributed properties, can be achieved using numerical methods (Saunderson et al. 1999).

In the most detailed representations of tree structure, the system is modelled by coupled cantilevered beams oriented in three-dimensional space. Typically, the mechanical behaviour of the system is predicted using the FEM (Zienkiewicz et al. 2014). The FEM relies on a division of the geometric domain into elements with finite properties and a weak formulation of mechanical equilibrium equations for which the displacement field (i.e. the solution) can be numerically approximated. It has been designed to simulate large and complex problems.

The first FEM model of tree dynamic behaviour was developed to investigate the vibration modes in two tree species, *Pinus pinaster* and *Hevea brasiliensis*, with distinct architectural forms (Fournier et al. 1993). The model was instrumental in documenting branch deformation and mode shapes in the crown for higher frequency modes. FEM models were later developed to simulate the free sways of real trees (Sellier et al. 2006) as well as wind-induced ones (Moore and Maguire 2008; Sellier et al. 2008). Including branch motion improved the accuracy of predicted displacements if compared to models with the branches described as lumped masses (Kerzenmacher and Gardiner 1998). In angiosperm trees, especially open-grown individuals with a decurrent form, the architecture plays an even more prominent role in tree sways. A FEM-based approach is valuable to understand the complex interplay of branch dynamics for these trees (Ciftci et al. 2013). Building detailed geometrical models of real trees is an expensive task. However, access to remote sensing technologies such as terrestrial LiDAR makes it now possible to digitise tree geometry (Dassot et al. 2012) and to predict the response to wind using FEM with a semi-automated approach (Jackson et al. 2015). FEM modelling is not limited to characterising real structures. It has also become a de facto investigation tool to test hypotheses and isolate mechanisms relative to the branched system and its theoretical organisation. For example, it has been used to research evidence for branching scaling laws and mode compartmentation (Rodriguez et al. 2008), irreversible crown reconfiguration in high winds (Lopez et al. 2011), or branch function in dissipating kinetic energy (Theckes et al. 2011, 2015).

Most FEM models predict tree vibrations by modal analysis using linearised equations of motion. This approach is valid while structural displacements remain small, which is reasonable under chronic wind loads but less so under acute ones. Nonlinear analyses, suitable for large displacements, can be performed using a direct integration technique such as a modified Newton–Raphson algorithm (Sellier and Fourcaud 2009). In that case, the drag forces are calculated for the deformed crown shape, and by doing so account for the reduction in crown area during loading, i.e. streamlining. If a stress–strain analysis is not required, rigid body dynamics provides an alternative to FEM as a less computationally intensive numerical method (Murphy and Rudnicki 2012).

Gaps in Knowledge and Suggestions for Future Work

There have been considerable advances in our understanding of the interactions between wind and trees, particularly the mechanical stability of trees subjected to strong winds, over the past 20 years. These advances have come about through a combination of factors, including: improvements in instrumentation that have enabled better data on the mechanical behaviour of real trees to be collected; improved models of the turbulence processes within and above forest canopies; improved models of the wind-induced responses of trees to dynamic loading that include more realistic representations of above- and below-ground tree architecture; and the tremendous increase in computing power that has enabled complex simulations of different components of wind and tree interactions to be performed.

Understanding and modelling turbulent wind flow over complex forested terrain remains one of the key challenges for better understanding the damaging effects of strong winds. In many empirical studies examining patterns of wind damage across the landscape, information on the spatial variation in wind speed across the landscape is often missing. In the absence of such information, surrogate parameters such as topographic exposure are often used in an attempt to explain this variation (Quine 2000; Quine and White 1994). Recently, however, there has been a marked improvement in our ability to model airflow across forested landscapes (Blennow and Sallnäs 2004; Lopes da Costa et al. 2006; Belcher et al. 2012) but continued improvement in predicting airflow at the landscape level is still an important area for further research.

Despite improvements in instrumentation, we are not aware of any situations in which an instrumented tree has failed under extreme wind loading. All our empirical knowledge about the maximum resistance of trees to applied loads comes from simulated loads (generally point loads applied by a winch and cable system). The manner in which these simulated loads are applied differs from that of actual wind loads as the simulated loads are concentrated while the actual ones are non-uniformly distributed over the length of the crown. This may result in different stress profiles along the stem (Wood 1995). Having instrumented trees loaded to failure would also provide important insight into their dynamic behaviour under extreme wind loading. Anecdotal evidence from video footage of trees that have failed suggests that that failure occurs due to quasi-static loading rather than resonant oscillations (i.e. incremental failure due to a series of strong gusts rather than due to an increasing magnitude of oscillation) but empirical evidence is required to confirm this.

The FEM has resulted in models of the mechanical behaviour of trees in response to wind loading that better represent the architecture of trees and have offered new insights into structural effects such as the coupling of branch and stem oscillations. These models rely on the beam theory in which the wood properties are elastic, isotropic and homogeneous. A better representation of internal stresses and strains is likely to be obtained by using more elaborate material models (Schwager et al. 2013). In materials, failure is often evaluated on the basis of criteria combining all components of the stress tensor. While orthotropic elastic constants are still relatively

scarce for green wood (Davies et al. 2016), including orthotropic material behaviour in models would represent a significant improvement in the characterisation of the process of stem failure, in particular to anticipate non-catastrophic damage such as wind-induced compression failures (Hocking 1949; Arnold and Steiger 2006). Wood is also a prestressed material; internal growth stresses are progressively generated during the tree growth. Growth stresses can be modelled using an incremental formulation of mechanical equilibrium (Fourcaud and Lac 2003; Ormarsson et al. 2010). As growth stresses can be quite large (c. 5 MPa), accounting for them may be a significant advance for evaluating the point at which stem breakage occurs and also to better comprehend the role played by physical forces in the developmental processes of wood formation (mechanobiology). Accounting for the radial and longitudinal variations of wood properties that exists within tree stems is another aspect that mechanical models of trees could benefit from. Better material models are an overarching priority to better understand the mechanical design of trees (Fournier et al. 2013). In particular, these models would enable us to better understand the various thigmomorphogenic responses to wind as they would show where regions of high stress and strain occur under wind loading (Mouliia et al. 2015) and can also help us to understand the benefits from acclimation. Using highly simplified assumptions about stem shape and wood properties in mechanistic models of tree behaviour can result in their inability to discern key differences between species and individuals within a species (Virot et al. 2016; Albrecht et al. 2016).

The FEM has also facilitated a greater understanding of the mechanics of root anchorage. However, there are still a number of gaps in our knowledge, particularly around the effects of soil moisture on root anchorage, the adhesion between roots and soil (i.e. root resistance to sliding through the soil) and the response of root systems to repeated cyclic loading. These gaps could be addressed through field measurements, e.g. tree-pulling experiments on wet and dry soils, and monitoring of root system behaviour under cyclic loading (O'Sullivan and Ritchie 1993; Kamimura et al. 2011).

Mechanistic wind damage models such as GALES have provided useful insights into the effect of different factors on the risk of wind damage. One of the key gaps in these models is the acclimation of trees to wind, particularly following abrupt changes in conditions such as the creation of a new edge by harvesting an adjacent stand or by thinning. It is assumed that trees acclimate to these new conditions and that stand stability recovers over time (Mitchell 2000). However, the rate to which trees acclimate to these new conditions is not known, nor is the impact of this acclimation on tree stability. Mechanistic models such as GALES were originally developed to predict the critical wind speed required to damage the mean tree within a stand and, therefore, a better understanding of the effects of variability in tree dimensions and relative wind loading on the critical wind speed for damage is needed. The work of Hale et al. (2012) is an important step in this direction but more research is needed across a wider variety of species and stand conditions (e.g. Kamimura et al. 2016, 2017). This improved understanding of the variation in critical wind speeds within a stand will also lead to a better understanding of the relationship between wind speed and the proportion of a stand that is damaged. Dupont et al. (2015) have linked a LES model and a simple mechanistic model to explore damage propagation in uniform

stands and Byrne and Mitchell (2012) provide an example of how mechanistic models can be applied to heterogeneous stands in order to model the progression of wind damage. Such models allow us to estimate the effect of forest structure, wind speed intensity and storm duration on the overall level of damage.

One of the key factors affecting the predictions of critical wind speed from the GALES model is the empirical gust factor, which relates the maximum loading to the mean loading. This is an attempt to represent the dynamic response to trees to fluctuating wind loads. Ultimately, a coupled wind flow and tree response model would alleviate the need for this gust factor. Progress towards this goal has been made with the development of a tree sway model that is suitable for use in large eddy simulations (Pivato et al. 2014) and more recently Dupont (2016) has used large eddy simulations to develop a stochastic model to predict extreme wind speeds and wind loading in forest canopies.

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