Arboriculture & Urban Forestry 2022. 48(4):242–257
https://doi.org/10.48044/jauf.2022.018

Likelihood of Failure of Trees Along Electrical Utility Rights-of-Way: A Literature Review

By Mathew Walker and Gregory A. Dahle

Abstract. Utility vegetation managers need tools to predict tree-related risks and knowledge of the necessary management prescriptions to reduce the risk of windthrow damage to utilities' electrical infrastructure. This review focuses on key studies involving the likelihood of failure of trees, beginning with a description and discussion of failure in trees, followed by an examination of methodologies that have been used to assess tree failure, before concluding with a review of factors which have been found to influence tree failure. Ultimately, a better understanding of the likelihood of failure of individual trees and the relationships governing tree failure and vegetation-related outages may allow for significant advances in the risk management of utility infrastructure.

Keywords. Likelihood of Failure; Urban Forestry; Utility Forestry; Utility Tree Risk Assessment; Utility Vegetation Management.

INTRODUCTION

Trees cause electric service interruptions primarily through 2 methods: first, by failing structurally such that the tree strikes electrical infrastructure (mechanical failure); and second, by providing the electrical conductor an unintended ground or fault pathway to another conductor (electrical failure)(Appelt and Goodfellow 2004). Tree-related conflicts with electrical infrastructure have also been classified into 2 groups by whether the conflict is attributable to growth, "grow-ins," or failure, "fall-ins" (Guggenmoos 2003). While "grow-ins" are limited to causing electric service interruptions via the providing of an unintended ground, these types of interruptions are not common at distribution-level voltages (Guggenmoos 2003; Appelt and Goodfellow 2004). Yet, most vegetation-related electrical outages are attributed to trees which exist outside of the right-of-way (ROW) and possess the height necessary for all or part of the tree to fall into or through the electrical conductor. These trees are known as "fall-ins" (Figure 1)(Guggenmoos 2003, 2011; Guggenmoos and Sullivan 2009).

Many trees fail along the stem or at the soil-root plate due to wind loading, since it is the most prevalent force plants must deal with within the terrestrial environment (Niklas 1992; Guggenmoos 2003, 2011; Guggenmoos and Sullivan 2009). We refer to the process of wind-induced stem breakage or uprooting as "windthrow."

To differentiate stem breakage and uprooting as 2 different types of windthrow, we will refer to these as different "modes" of failure. Furthermore, material properties can influence the mode of failure of a tree, which has implications for assessing the likelihood of failure, particularly in branches (Dahle et al. 2006; Dahle and Grabosky 2010). In earlier windthrow literature, it was customary to limit the concept of "wind damage risk" to the likelihood of a particular percentage of trees experiencing uprooting or breakage (Gardiner et al. 2008). Gardiner et al. (2008) suggested a more appropriate term might be "wind damage probability modelling." More recent research has explored the possibility of predicting the probability of windthrow for individual trees (Ciftci et al. 2014a; Kamimura et al. 2016).

Currently, utility vegetation managers need tools for predicting windthrow risks and knowledge of the necessary management prescriptions to reduce the risk of windthrow damage to utilities' electrical infrastructure. Risk accounts for both the likelihood of an

Figure 1. Tree failure from outside the distribution ROW.

event and the consequences caused by that event (Smiley et al. 2017). Qualitative assessments are commonly used by decision makers to assess windthrow risks (Miller et al. 1987; Mitchell 1998; Gardiner et al. 2008). Empirical models have been developed to assess the probability of windthrow of individual trees or the probability of an expected proportion of stand damage based on tree and stand attributes in forest stands, plantations, and seaside shelterwoods (Peltola et al. 1999; Gardiner et al. 2008; Suzuki et al. 2016). A difference to note between forestry and utility vegetation management are the consequences of tree failure. In the former, losses of a number of trees are acceptable and expected, whereas in the latter, even a single tree may contact a conductor and cause a wildfire. Thus, a better understanding of the likelihood of failure of individual trees and the relationships governing tree failure and vegetation-related outages would allow for significant advances in the risk management of electric distribution lines (Appelt and Goodfellow 2004).

Participating researchers at the 2010 Tree Biomechanics Summit at The Morton Arboretum identified 5 areas of focus for future research of tree biomechanics, the first of which was "assessing the likelihood of failure in trees" (Dahle et al. 2014). This review will focus on key studies involving the likelihood of failure of trees. We will begin with a description and discussion of failure in trees, followed by an examination of methodologies that have been used to assess tree failure and a review of factors which influence tree failure.

Defining Likelihood of Failure

Current tree-risk-assessment methods generally utilize a professional arborist's qualitative assessment of the likelihood of failure of a given tree within a defined duration of time (Smiley et al. 2017). While quantitative assessments of the likelihood of failure of trees have been completed, the process is computationally intensive, and the effects of the contributing factors are difficult to evaluate (Ciftci et al. 2014a;

James et al. 2014). Simply stated, the theoretical likelihood of failure of a tree can be determined by the moment capacity of the tree, the anticipated loads the tree will experience, and the anticipated weather-related phenomena which the tree will experience (Dahle et al. 2017). Yet, there is sparse information available for the load-bearing capacity of trees, the anticipated load trees intercept, and the site and environmental factors that affect failure (Dahle et al. 2014; James et al. 2014; Dahle et al. 2017).

The inspection of vegetation in and along electric ROWs for utility vegetation management (UVM) is difficult, as trees with elevated likelihood of failure, such as those with significant internal decay or structural issues, may not be observable or obvious from a foot patrol's visual inspection (Dahle et al. 2006; Most and Weissman 2012; Goodfellow 2020). The International Society of Arboriculture (ISA) recently published a new Best Management Practices (BMP) for *Utility Tree Risk Assessment* (UTRA) to provide arborists, urban and utility foresters, and their associated industries with tree work–related guidance and research-based recommendations (Goodfellow 2020). The UTRA is specifically intended to aid utility foresters and the UVM industry in assessing tree-related risks to utility infrastructures. The application of tree-risk-assessment practices for UVM differs in scale from other users of tree-risk-assessment frameworks. Whereas a commercial tree-risk assessor and a utility forester may both conduct a tree-risk assessment on a singular tree, the risk being managed by the utility forester is managed across a widespread population of trees in proximity to the utility infrastructure, also known as the utility forest. Additionally, UTRA differs from general arboricultural tree-risk assessment in that both direct (damage to the infrastructure) and indirect consequences (power outages, fines, public safety, etc.) are considered (Goodfellow 2020).

Due to the scope and spread of the utility systems, utility foresters may not be able to assess each tree individually, either because of time constraints or lack of access to the location. Trees can experience a localized failure (e.g., broken branches or cracks in the branches or stem) without incurring full structural failure and tree fall (or "final failure")(Dunster et al. 2017). Thus, assessing the number of trees that have experienced final failure and have fallen within a specified time period will be easier than attempting to assess the number of trees which have experienced localized failures. This is particularly true of remotely sensed data, where the presence or absence of a given tree over a time series of images or scans may be detectable. However, there do not currently exist methods to remotely assess whether a given tree has experienced a localized failure.

Furthermore, the UVM industry stands to benefit from change-detection techniques and remote-sensing technologies, such as LiDAR data and temporal-image differencing or ratioing (Lillesand et al. 2007; Matikainen et al. 2016). With successive scans of the same area, one should be able to visualize vegetation differences along ROWs. In particular, the presence of new vegetation or absence of previously present vegetation should be obvious. Change-detection methodologies would also aid in calculating vegetation growth rates, perhaps down to the individual tree or stem. Additionally, remote sensing and change detection could provide a robust set of tools to help monitor a large number of trees over time, which would potentially be useful in the calculation of the likelihood of failure of trees. However, due to the limitations of current remote-sensing technologies, the likelihood of tree failure derived from a change-detection study would be limited to the detection of tree fall, and thus, final failure.

METHODOLOGIES

Several techniques have been proposed in the literature to assess the likelihood of windthrow of trees (Baker 1995; Peltola et al. 1999; Ciftci et al. 2014a; Kamimura et al. 2016; Suzuki et al. 2016; Virot et al. 2016; Yan et al. 2016; Kamimura et al. 2017). Kabir et al. (2018) separate these research techniques into 3 key methodological groups: explanatory approaches, mechanistic approaches, and statistical approaches, and our review will follow this grouping. In the following section we will discuss each of the 3 methodological approaches, including an in-depth discussion of different methodologies within mechanistic approaches. Furthermore, each of the biomechanical methodologies mentioned have benefits and drawbacks, and all have aided in augmenting the existing knowledge base.

Explanatory Approaches

Explanatory approaches assess the relationship of tree failure and a variety of physical or geographical parameters, such as tree species, diameter at breast height (DBH), soil characteristics, or mode of failure (Kabir et al. 2018). The primary methodology within explanatory approaches is referred to as a "post-storm study," where, after a storm event, standing and failed trees are examined to discern patterns in measurable physical properties or geographic characteristics.

Francis and Gillespie (1993) related wind-gust speed to tree damage, where the maximum-damage category was uprooting. They found their uprooting category to be independent of both DBH and gust speed, while stem breakage decreased with increasing diameter and was also independent of wind-gust speed (Francis and Gillespie 1993). Additionally, they concluded that large trees are at greater risk than small trees, which supports Reilly (1991).

Peterson (2007) observed consistent influence of tree diameter and species on tree failure due to tornado blowdowns. He observed that windthrow occurrence increased with tree diameter, and that uprooting was more common among trees of smaller size classes (Peterson 2007).

Kane (2008) examined tree failure after a windstorm in Brewster, MA. He too found that the likelihood of failure increased with trees of greater DBH and height. Yet, the different failure rates were not able to explain variation among species (Kane 2008).

Furthermore, Kane (2008) states that the study did not factor in exposure, which is a known predictor of damage (Gardiner et al. 2008).

Lastly, explanatory studies are limited in that they typically utilize parametric analyses, such as logistic or linear regression, and/or use *R*-squared as an indicator of predictive accuracy, thus leading to over-fitting (Kabir et al. 2018).

Mechanistic Approaches

The fundamental premises of tree biomechanics are: trees cannot violate the laws of physics, trees are mechanical objects, and tree size and shape are limited by biomechanical constraints (Niklas 1992; Spatz and Brüchert 2000; de Langre 2008; James et al. 2014; James et al. 2018). Therefore, engineering and physical methods are reasonable methodologies to attempt to understand the structural properties of trees and how they interact with the environment (James et al. 2014). Dependent upon the line of action of a force, trees will experience stress in the forms of tension, compression, and shear when subjected to bending and torsion loading (Dahle et al. 2017).

A tree's material properties are factors which affect its load-bearing capacity (Dahle et al. 2017). The 2 most commonly reported material properties are the elasticity modulus (*E*) and the modulus of rupture (MOR). These are used to describe a material's stiffness and maximum load-bearing capacity, respectively (Burgert 2006; Dahle et al. 2017). Additionally, material properties can influence the mode of failure of a tree (Dahle et al. 2017). There is a large body of literature describing such wood properties (Kollmann and Côté 1968; Kollmann et al. 1975; Panshin and de Zeeuw 1980; Bodig and Jayne 1982; Haygreen and Bowyer 1982; Dahle et al. 2017). Despite this, the application of measured wood properties to living trees may not accurately estimate a given individual tree's material properties due to the large variability of material properties of wood with age, growing conditions, genetics, moisture content, and location in an individual (Zobel and van Buijtenen 1989; Clair et al. 2003; Dahle and Grabosky 2010; Kretschmann 2010; Dahle et al. 2017).

In addition, the values of *E* and MOR vary longitudinally, tangentially, and radially within an individual tree, often decreasing axially with trunk height and/or branch length (Niklas 1992; Lundström et al. 2008; Dahle and Grabosky 2010; Kretschmann 2010; Dahle et al. 2017). Juvenile wood often has lower values of *E* and MOR than mature wood, and the proportion of juvenile wood to mature wood can influence *E* and MOR (Lundström et al. 2008; Dahle and Grabosky 2010; Dahle et al. 2017). This generally allows for younger, more flexible, distal parts of the tree crown to reconfigure in the wind, and more mature, rigid, proximal tree parts, such as the stem, structural branches, and structural roots, to resist increased loading from self-weight and wind-induced bending and torsional moments (Niklas 2002; Clair et al. 2003; Lundström et al. 2008; Dahle and Grabosky 2010; Dahle et al. 2017).

In an attempt to better represent these real-world loading schemes, researchers have utilized dynamic analysis methods. Three different approaches are commonly used to assess the dynamic behavior of trees (Clough and Penzien 1993; James et al. 2014; James et al. 2018). The first is the lumped-mass procedure, where mass is assumed to be concentrated at a discrete point (James et al. 2014). The second utilizes generalized displacements for a uniformly distributed mass, with the trunk treated as a beam (James et al. 2014). Lastly, the Finite Element Method (FEM) utilizes complex computer modeling (James et al. 2014).

The lumped-mass procedure, which assumes the mass is concentrated at a discrete point as it oscillates dynamically, is a simplification of the actual dynamic process of windthrow, since inertial forces only develop at the mass points (James et al. 2014). Even so, this method has been used to develop spring-mass-damper models for trees as a single mass or as a complex system of coupled masses that represent the trunk and branches (Milne 1991; Miller 2005; James et al. 2014).

The uniformly distributed mass method considers a tree as a beam or column, with its mass uniformly distributed along its length. A fourth-order partial differential equation has been used to study the oscillations and damping of woody and nonwoody plants (Gardiner et al. 2000; Spatz 2000; Moore and Maguire 2008; James et al. 2014; James et al. 2018).

The FEM combines features of both the lumped-mass and uniformly distributed mass procedures (Sellier et al. 2006; Moore and Maguire 2008; Theckes et al. 2011; Ciftci et al. 2014a; James et al. 2014). FEM divides a structure, in this case a tree, into an appropriate number of elements: beams, whose sizes may vary, and the ends of which, nodes, become the generalized coordinate points. An advantage of FEM is that complex wind-loading scenarios can be modeled (James et al. 2014). Yet, FEM's reliability is limited by its requirements of multiple accurate, empirical measurements peculiar to the individual tree and its loading conditions (James et al. 2014).

All models used for dynamic analysis of trees make assumptions and may not accurately represent the complex dynamics of trees (Moore and Maguire 2004). Models must account for the damping and dynamic contribution of branches (de Langre 2008; Rodriguez et al. 2008; James et al. 2014; James et al. 2018). Additionally, trees require multi-degrees of freedom, or multimodal analysis, to model dynamic interactions between the branches and trunk, and literature is lacking on how these interactions take place (Sellier et al. 2006; de Langre 2008; Rodriguez et al. 2008; James et al. 2014).

Damping dissipates energy and thus reduces the amplitude of oscillation through the frictional forces of aerodynamic drag and collisions as well as internal, viscoelastic forces (Milne 1991; James et al. 2006; James et al. 2014). Damping forces are considered velocity dependent and are most effective around the natural frequency, while having little effect at lower and higher frequencies where the inertia of a tree's mass is the dominant effect (James et al. 2014). Furthermore, damping is usually not well understood in vibrating structures or in nature (Clough and Penzien 1993; James et al. 2014). The effect of damping may be nonlinear, thus it may potentially result in a higher level of complexity than seen in most dynamic models to this point (James et al. 2014).

Multimodal response in branched structures occurs when several coupled masses (branches) oscillate in a complex manner, with in-phase and out-of-phase responses such that several modal swap responses are possible (Rodriguez et al. 2008; James et al. 2014).

Furthermore, where multimodal response occurs, a damping effect known as "mass damping" may also occur (James et al. 2014). Mass damping was described by Den Hartog (1956) and has been defined for trees (James et al. 2006). Mass damping occurs when the branches sway together or against each other, in-phase and out-of-phase, respectively (de Langre 2008; Theckes et al. 2011; James et al. 2014). Mass damping allows for the dissipation of forces exerted by wind on tree crowns in a nondestructive fashion. Additionally, trees may also dissipate wind energy through a mechanism called "multiple resonance damping" (Spatz et al. 2007), "multiple mass damping" (James et al. 2006), or "branch damping" (Spatz and Theckes 2013; James et al. 2014).

Gardiner et al. (2008) published a review of predictive, mechanistic models of wind damage to forests. These models attempt to capture the physical processes involved in tree uprooting or failure typically through a 2-step process. The initial stage is to calculate the above-canopy "critical wind speed" (CWS) required to cause windthrow within a forest (Gardiner et al. 2008). The second stage is to use some assessment of the local wind climatology to calculate the probability of such a wind speed occurring at the geographic location of the trees (Gardiner et al. 2008). They termed this probability of damage the "risk of damage" (Gardiner et al. 2008). The approaches used to calculate the CWS and the local wind climate may vary between the different predictive models (Gardiner et al. 2008).

These predictive mechanistic models attempt to approximate the CWS of trees based on the anticipated wind-related forces and the counteracting and combined resistive forces of their roots and stem (Gardiner et al. 2008). When predicting the CWS, the resistance to overturning is based upon correlations between the bending moment required to cause windthrow and stem weight or root-soil plate weight (Gardiner et al. 2008). The resistance to breakage of a tree is related to the diameter of the stem and the tree species and must be greater than the bending moment required to exceed the MOR or stem failure will occur (Gardiner et al. 2008). "These relations can be simplified to state that the stem volume best predicts the resistance to uprooting, whereas dbh^3 best predicts resistance to stem breakage" (Quine and Gardiner 2007; Gardiner et al. 2008).

The second stage of the mechanistic modeling of windthrow risk to trees is predicting the probability of the CWS being exceeded (Gardiner et al. 2008). The primary method to predict the local wind climate is to use the airflow model, Wind Atlas Analysis and Application Program (WAsP)(Mortensen et al. 2005; Gardiner et al. 2008). Although in settings with more complex terrain or wind climates the use of Weibull parameters from highly accurate weather forecast data may be required for accurate airflow modeling (Gardiner et al. 2008; Mitchell et al. 2008).

The GALES model utilizes tree height, diameter, current tree spacing, soil type, cultivation, drainage, and tree species to determine the CWS (Gardiner et al. 2008). GALES was originally designed to calculate the CWS at 10 m above the zero-plane displacement height for even-aged conifer monocultures. To consider mixed-species stands, the simulation must be run for each species in turn and all trees in the stand must be considered to be of that species (Gardiner et al. 2008). GALES can be utilized to calculate the risk at any distance from a newly created edge and for any size of upwind gap (Gardiner et al. 2008). For existing edges, the risk is considered constant from the edge due to the effects of adaptive growth by trees (Telewski 1995; Gardiner et al. 2008). Additionally, GALES requires tree-pulling data, MOR for the green timber of the tree species of interest, and descriptive measures of the crown characteristics (Gardiner et al. 2008). When using GALES, it has been found that an increase of the predicted CWS by an additional fixed value of 1 m/s improves the accuracy of the model's predictions (Gardiner et al. 2008).

The HWIND model was developed by Peltola et al. (1999) for the description of the mechanistic behavior of monocultures of Scots pine, Norway spruce, and birch under wind and snow loading (Peltola et al. 1999; Gardiner et al. 2008). While originally designed for calculations of the CWS of trees at newly created edges of stands, HWIND has now been adapted for the calculation of CWS at different distances from the upwind gap and for different sizes of upwind gap (Gardiner et al. 2008). HWIND predicts the mean CWS over a 10-minute time period at 10 m above ground level (Gardiner et al. 2008). This model requires knowledge of tree species, tree height, DBH, stand density, distance to the stand edge, and gap size (Gardiner et al. 2008). HWIND, like GALES, is sensitive to any inaccuracies of the inputs, especially DBH, which determines the amount of wind load a tree can experience before failure and the expected amount of wind load a tree will experience (Gardiner et al. 2008). Thus, any inaccuracy can have a significant influence on the predicted CWS (Gardiner et al. 2008). The FOREOLE model developed by Ancelin et al. (2004) was the first attempt to contend with complex stand structure within predictive mechanistic models (Gardiner et al. 2008). FOREOLE assumes an empirical wind profile within the canopy and calculates the horizontal wind loading on each individual tree (Gardiner et al. 2008). Reasonable agreement between the predictions made by GALES, HWIND, and FOREOLE have been noted when compared (Gardiner et al. 2008). While FOREOLE has yet to be entirely validated, its predicted CWSs have aligned with the wind speeds required to cause damage to trees (Gardiner et al. 2008).

To quantify wind loading, GALES may use either a "roughness method," where a wind-induced stress distribution of trees in a forest is calculated, or a predicted wind profile within or at the forest front (Gardiner et al. 2008). In contrast, HWIND and FOREOLE both utilize only the latter method (Gardiner et al. 2008). An early limitation of CWS-based models was that they were originally built to represent the risk to a "mean tree" within a stand, not to consider the risk posed to individual trees (Gardiner et al. 2008). However, recently Suzuki et al. (2016) determined CWS for individual trees as well as demonstrated a quantitative risk-management evaluation for individual trees (Suzuki et al. 2016).

Most of these CWS-based models are limited because they do not account for variations in wind from different directions (Gardiner et al. 2008). While Ancelin et al. (2004) demonstrated a first attempt to deal with complex stand structure, their approach has not yet been validated against data from complex stand structures (Gardiner et al. 2008). Additionally, Wellpott et al. (2006) suggested that the approach used in Ancelin et al. (2004) is not a realistic representation of wind loading on individual trees (Gardiner et al. 2008). A possible alternative approach to modeling wind risk of individual trees is to make use of the competition indices developed for predicting growth conditions of individual trees within stands, which Achim et al. (2007) demonstrated are extremely well correlated to the wind loading of individual trees within a mature Sitka spruce plantation (Gardiner et al. 2008).

To become more than research tools, these predictive mechanistic models must be incorporated into forest-management systems in ways that are useful and practical (Gardiner et al. 2008). Yet currently, due to the need of numerous, precisely measured parameters, these models are not practical in many cases. While these tools have not been widely utilized in practice, Gardiner et al. (2008) suggest that, first, their operation must be simple and interpretation of the results routine (Gardiner et al. 2008). Future research into predictive mechanistic models should integrate decision-support tools to simplify each model's operation, such that the requirements are a hierarchical set of questions on the characteristics of the trees and site, and outputs are different levels of risk, low to high (Gardiner et al. 2008; Kamimura et al. 2008). Moreover, the integration of other remote-sensing data and additional geographic information system (GIS) layers to enhance location-specific conditions may be useful for the prediction of tree failure along utility ROWs.

Statistical Approaches

Statistical approaches, much like explanatory approaches, utilize geographic characteristics and physical properties of trees as variables to aid in the prediction of windthrow (Kabir et al. 2018). However, instead of utilizing a single statistical tool, such as linear regression, statistical approaches examine the relationships of the measured properties through the lens of multiple statistical tools to see which tool best predicts windthrow (Kabir et al. 2018). Examples of such properties include Generalized Linear Models (GLMs), Monte Carlo simulation (MC), classification and regression trees (CART), Random Forests (RF), and Artificial Neural Networks (ANN).

Ciftci et al. (2014a) utilized a Monte Carlo–based methodology for the prediction of individual tree failure. Their study attempted to quantify the probability of failure of 2 maple trees in Massachusetts. Although one of the first and more novel methods for the prediction of likelihood of failure of individual trees, this study is limited in that it was computationally intensive and not well-suited for the large data sets that would be associated with trees along electric distribution ROWs (Ciftci et al. 2014a).

Kamimura et al. (2016) developed a logistic regression model and utilized a GALES-based model for individual tree failure from 1 storm at an Aquitaine forest in southwestern France, then validated the model against the next storm at that location. Their results suggested that GALES was capable of predicting wind-damage risk of trees on certain soils, while their statistical models were not able to be generalized to other locations or storm events (Kamimura et al. 2016).

Kabir et al. (2018) used the covariates location, height, DBH, existence of severe defects, whether or not a tree had been pruned, and whether or not a tree had been removed in the immediate proximity of the tree in question to demonstrate that tree failure can be statistically estimated. Kabir et al. (2018) utilized several statistical tools, including a GLM with a Bernoulli response, CART, a multivariate adaptive regression spline (MARS), ANN, Naïve-Bayes Classifier, boosting, RF, and an ensemble model of RF and boosting. The ensemble model yielded the best prediction accuracy for estimating the failure probability of trees for their data set (Kabir et al. 2018). This was a novel approach to predicting windthrow of individual trees and contributed to the literature, primarily by demonstrating the potential predictability of tree failure using statistical models. However, the results of this study cannot be used to estimate tree-failure probabilities for either other storms at the study site or at other locations because the models implemented included data from only 1 storm, at the 1 study site (Kabir et al. 2018).

Thus far in likelihood-of-failure research, most statistical analyses have limited their statistical tools to linear or logistic regression (Kabir et al. 2018). Nevertheless, Ciftci et al. (2014a) and Kabir et al. (2018) have demonstrated the utility of other statistical tools. Additionally, most studies are not able to be generalized as the models developed only apply to 1 location or 1 storm due to the lack of validation in subsequent locations or storms. Yet, Kamimura et al. (2016) developed models, both statistical- and GALES-based, in 1 storm and validated them against a second storm, at the same location. Furthermore, studies utilizing more sophisticated statistical tools and multiple storms or multiple location model validation methodologies are needed.

Factors Which Influence Failure

Across all methodologies, certain factors which contribute to tree failure have been illuminated. In this section we will discuss the factors that have been related to tree failure across all methodological approaches, including: tree stems, tree crowns and branches, root systems, soil type and properties, precipitation, and wind (Figure 2).

Stems

Post-storm study literature has suggested failures are more likely as tree size and wind speed increase (Duryea et al. 2007). Kane (2008) observed an increase in likelihood of failure of trees with a greater diameter as well as taller trees. Peterson (2007) also observed that as tree diameter increased so did the risk of tree failure. Additionally, Kabir et al. (2018) found that the probability of failure for a tree increased for tall trees, though the height used to determine "tall" was not provided. The model used by Kabir et al. (2018) found that trees with smaller DBH were more likely to experience failure, which is incongruent with most current literature (Kabir et al. 2018). Kabir et al. (2018) also found that height and DBH had large influences on a model's predictions, whereas the removal of nearby trees had a relatively small effect on the model's prediction (Kabir et al. 2018).

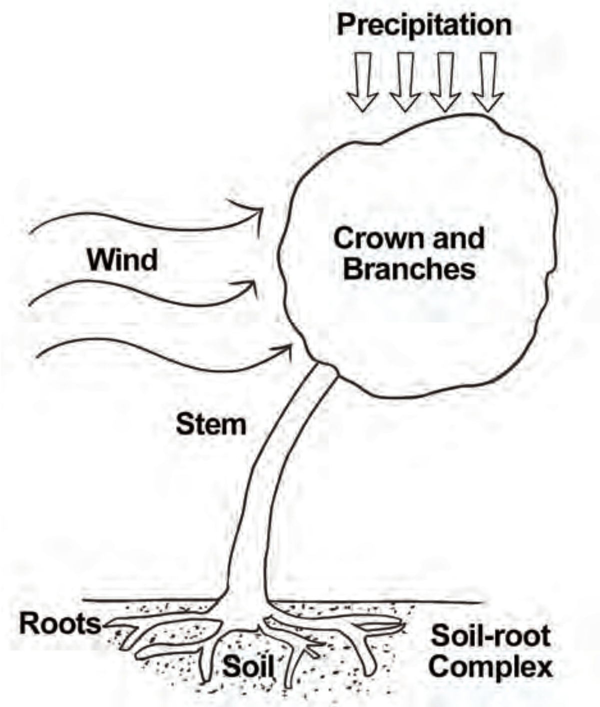

Figure 2. Common factors in studies that investigated tree failures.

Despite the general correlation of increased tree size and increased likelihood of failure, multiple studies have found that tree size and wind-gust speeds by themselves cannot explain the variation in failure rates for different tree species (Francis and Gillespie 1993; Kane 2008). Yet, despite the unexplained variation within species, simplified methods for estimation of uprooting and stem breakage have been described (Gardiner et al. 2008; Kane 2008). In addition, Lundström et al. (2007) found that 75% of the variation of the turning moment in the soil-root plate was explained by tree mass, trunk mass, trunk diameter, or tree height, either alone or in combination, during static loading.

Decay is a major component of the likelihood of failure of a given tree (Smiley et al. 2017). Decay causes moment capacity loss in tree branches and stems (Dahle et al. 2006; Ciftci et al. 2014b), and the severity and location of decay are the factors which determine the effect of decay on likelihood of failure (Luley et al. 2009). The study by Kane (2008) found that most trunk failures (76%) involved a defect and that about half (56%) of the trunk failures were visible prior to failure. However, currently, the detection of decay through remote-sensing means does not appear to be feasible, and as such the full relationship of decay and likelihood of failure will not be reviewed here. Instead, see Dahle et al. (2014), Ciftci et al. (2014b), or Kane (2008) for a more complete review.

Crown and Branches

Crown size and shape has been generally found to play a significant role in how trees resist wind, snow, and ice loads (Niklas and Spatz 2000; Gaffrey and Kniemeyer 2002). Furthermore, stem taper, canopy shape, and canopy size have a more significant effect on wind-induced stem-stress intensities than the shape of the wind-speed profile (Niklas and Spatz 2000). Gaffrey and Kniemeyer (2002) found that a crown-volume reduction of 50% reduced sail area by 18%, which caused a stress reduction of 15% to 24% (Gaffrey and Kniemeyer 2002). Yet, in the same study, an asymmetric crown (Figure 3) reduction resulted in a mid-crown increase in stress of up to 25%, which may have implications for UVM

Figure 3. An asymmetrical crown resulting from line-clearance operations.

ground-to-sky trimming techniques (Gaffrey and Kniemeyer 2002). Furthermore, Kane (2008) found that pruning did not reduce a tree's overall likelihood of failure.

The literature does suggest that the time of year or season can account for up to a 40% difference in probability of failure, particularly in deciduous trees, due to differences of leaf-off and leaf-on wind, snow, and ice-load interception (Ciftci et al. 2014a). Additionally, thinning of an individual tree may help prevent snow and/or ice damage to that tree, but in turn may change wind regimens and make wind-induced failure of neighboring trees more likely (Peltola et al. 1999; Kane 2008; Peterson and Claassen 2013).

Root Systems

Tree stability depends upon a tree's root spread, root architecture, and root-plate development (Dahle et al. 2017). Yet the most important region of a tree's root system, in regard to tree failure, appears to be the soil-root plate (Ji et al. 2006; Dupuy et al. 2007; Tobin et al. 2007; Ghani et al. 2009). Smiley (2008) found that trenching at a distance less than twice the trunk diameter reduced anchorage strength by more than 15%, and if lateral roots were severed at the trunk base, the anchorage strength was reduced by roughly 35%. Furthermore, during static pull tests, trees were observed to not return to upright if inclined past 1° to 2.5° at the tree's base (Sinn 1990), and afterwards the stiffness of the root-soil plate was found to be decreased (Rodgers et al. 1995; Vanomsen 2006; Lundström et al. 2009).

The soil-root plate of younger trees was found to have a greater degree of rotation at maximum resistance, and the degree of rotation at maximum resistance is expected to vary with tree-age class, root architecture, and soil structure (Crook and Ennos 1996; Stokes 1999). As trees grow, their root-system strength increases, and root shape may be altered in response to loading (Stokes et al. 1998; Stokes 1999). This adaptive growth may decrease the likelihood of overturning (Dahle et al. 2017). When trees do uproot, a consistent relationship between tree diameter and the size or volume of the root pits and mounds has been observed (Peterson 2007). Root failures were observed to be more likely at sites where nearby trees had been removed prior to storms (Kane 2008). Yet, it is difficult to determine how the interactions of neighboring tree removal, the associated wind regimen change, hypothesized elevated stress levels at the soil-root plate of the remaining tree, soil properties at that location and time, and likelihood of tree failure relate to one another.

Multiple findings have suggested greater vulnerability of conifers and early successional species, but the support is weak (Peterson 2007; Kabir et al. 2018). When a species tends to possess traits for both deep rooting and strong wood, they are generally resistant to windthrow: for example, *Acer saccharum* (Peterson 2007). In addition, wood strength was observed to have some influence on the risk of final failure and the mode of failure but was generally not significant on its own (Putz et al. 1983; Asner and Goldstein 1997; Gardiner et al. 2000; Peterson 2007). Furthermore, wood strength seems more indicative of the mode of failure, where trees with stronger wood are more likely to experience uprooting and trees with weaker wood are more likely to experience stem breakage (Peterson 2007). This relationship could explain how a variable for "tree species" may partially capture that particular species' general wood properties, while partially confounding the results due to the effect of that individual tree's crown and root architecture.

In conclusion, a tree's biophysical properties, including stem, crown, and root characteristics, have been found to dictate how trees resist loads, whether from self-weight or wind, snow, or ice loads (Niklas 2000; Niklas and Spatz 2000; Peterson and Claassen 2013). These biophysical properties have a more significant effect on wind-induced stem-stress intensities than the shape of the wind-speed profile (Niklas and Spatz 2000). Furthermore, the literature has suggested failures are more likely as tree size increases (Reilly 1991; Duryea et al. 2007; Peterson 2007; Kane 2008). Root systems also play a vital role in tree stability, and decay is a major component of the likelihood of failure of a given tree (Smiley et al. 2017).

Soil Type and Properties

Soil type and soil conditions are factors which affect the load-bearing capacity of a tree's root system (Moore 2000; Dupuy et al. 2005; Ji et al. 2006; Ow et al. 2010). The most crucial region appears to be the soil-root plate, and its depth is particularly important in sandy or clay soils (Ji et al. 2006; Dupuy et al. 2007). In the trenching study by Smiley (2008), the side of the tree where the roots were cut had an influence when soil was water saturated, but not under dry conditions. This demonstrates the importance of soil conditions (e.g., type, texture, and moisture content) in the process of windthrow and how soil plays an integral role in the soil-root plate and tree stability.

Precipitation

Saturated soils exacerbate wind-caused failure rates (Peterson 2007). Thinning (pruning) of an individual tree helps prevent snow and/or ice damage but may have repercussions related to wind regimens and the wind exposure of neighboring trees (Peltola et al. 1999; Kane 2008; Peterson and Claassen 2013). Snow and ice loads cause the static loading of trees and may help explain the vast difference in likelihood of failure of deciduous trees, due to phenological differences of leaf-on load interception and leaf-off load interception (Ciftci et al. 2014a; James et al. 2014; Dahle et al. 2017). When snow or ice loads are intercepted in tandem with wind loading, elevated likelihoods of failure are to be expected. Research has incorporated both wind and snow/ice loads into their models, but there is little empirical evidence detailing the relationship of combined wind and snow/ice loads (Peltola et al. 1999; Niklas and Spatz 2000; Gaffrey and Kniemeyer 2002; Luley and Bond 2006; Ciftci et al. 2014a).

Wind

The literature has suggested failures are more likely as tree size and wind speed increase (Duryea et al. 2007). Niklas (2000) suggested that wind is likely the most common causal factor of tree failure, and wind was described as the most prevalent dynamic force on trees in the terrestrial environment (Niklas 1992). Wind gusts may initiate more failures than a constant wind speed, since gusts cause additional crown displacement (Milne 1988). Additionally, changes in the local wind regimen, through the removal or failure of neighboring trees in the stand, will result in higher likelihood of failure of remaining trees due to increased exposure to wind forces (Peltola et al. 1999; Kane 2008; Peterson and Claassen 2013). Furthermore, stem taper, canopy shape, and canopy size also possess a more significant effect on wind-induced stem-stress intensities than the shape of the wind-speed profile (Niklas and Spatz 2000).

The fluid pressure of wind increases with the square of wind velocity (Francis and Gillespie 1993). Thus, the severity of wind damage to trees can be explained by relatively small increases in wind speed (Francis and Gillespie 1993). Instantaneous wind speeds are rarely available and average wind speed may be calculated over either 10-minute or 1-hour intervals (James et al. 2014). Wind-gust speed is described as an average wind speed, though taken over a 3-second interval (Holmes 2007). The lack of consistent reporting methods and measures of wind can be an obstacle to disseminating knowledge for practical tree-risk management (Cullen 2002).

Predictive mechanistic modeling studies have shown the CWS for a vast number of tree species to exist between 36 and 234 km/h, with many species failing by roughly 180 km/h (Suzuki et al. 2016; Virot et al. 2016). Francis and Gillespie (1993) observed that wind-induced tree damage was not present below about 60 km/h, damage increased rapidly as gust speeds increased from 60 to 130 km/h, and beyond 130 km/h variability in damage increased dramatically. The wind speed necessary to cause tree failure will vary depending on tree species, growth pattern, and location (James et al. 2014). Yet, trees generally cannot weather violent storms with mean wind speeds exceeding 108 km/h at the top of the canopy, for a period of 10 minutes, without sustaining some amount of damage (Peltola 1996). Canham and Loucks (1984) postulated that as the severity of damage increases, the differences between species, size, and other factors diminish, until a threshold at which most trees over a certain diameter fail is reached. This idea is one with which Francis and Gillespie (1993) unknowingly concurred, positing their own idea of "storm build-up." Storm build-up describes a process where there exists a wind speed at which any tree will shed its crown or will be windthrown. The authors go on to describe how time, too, has a role, such that storms with a slow build-up to their maximum wind speed should cause less windthrow because of the increased time for trees to defoliate and thus decrease wind-load interception (Francis and Gillespie 1993). Likewise, storms with a fast build-up should see more windthrow due to the decreased time to defoliate and thus increased wind-load interception (Francis and Gillespie 1993). Furthermore, the complete dynamic process of windthrow has never been verified in field experiments, and the assumption that the maximum wind load produced by a particular event is the key factor in whether damage to trees occurs has never been confirmed (Hale et al. 2012; James et al. 2014).

In summary, the removal of a tree will eliminate the risk associated with that tree but may increase the risk of windthrow of neighboring trees due to changes in the wind regime and exposure (Kane 2008). While tree properties and wind are likely the 2-largest factors contributing to windthrow, the 2 combined do not explain all observed variation in the windthrow of trees (Francis and Gillespie 1993; Kane 2008). Moreover, understanding how to manage the interaction of wind and trees is as crucial to utility vegetation management as it is to society during times of inclement weather when the population is most dependent upon the electrical grid.

CONCLUDING REMARKS

Each of the reviewed methodologies aided in building our collective knowledge about the nature of tree failure. Explanatory approaches have helped illuminate the key factors which influence failures and their relations (Peterson 2007; Kane 2008). Mechanistic studies have revealed monotonous response to soil-root plate inclination and the existence of damping responses in trees, and have even predicted individual tree failures as a function of location, the critical wind speed for the tree to fail, and the likelihood of that location experiencing a wind speed greater than or equal to the critical wind speed (Peltola et al. 1999; Ancelin et al. 2004; Gardiner et al. 2008; Lundström et al. 2009; James et al. 2014). Statistical methods have demonstrated that tree failure may be somewhat predictable given the correct method and variables (Kabir et al. 2018). Yet, despite each of these contributions to our body of knowledge, none are perfectly suited to UVM.

Even so, GIS-implemented predictive mechanistic models such as GALES, HWIND, and FOREOLE may prove to be adaptable to UVM, particularly if these models can refine their tree-based inputs (i.e., species, height, DBH, etc.), such that they are better suited to and integrated with modern remote-sensing technologies. Vegetation managers can then utilize remotely sensed imagery of a ROW or service area to inform a predictive mechanistic model. Moreover, these models may prove useful during storm hardening efforts and major storm-response planning by modeling where tree failures would be likely given 10-, 50-, and 100-year storm wind speeds.

Furthermore, the use of remote sensing to inventory the utility forest and monitor individual trees and stands may have applications in tree contractor work auditing and work planning. As an additional benefit to the field of arboriculture overall, the development of a baseline likelihood of tree failure may be possible through successive imaging and change-detection techniques of electric ROWs.

Suggestions for future work include incorporating inputs from remotely sensed products into predictive mechanistic models of tree failure and the continued validation of predictive mechanistic models such as GALES, HWIND, FOREOLE, and their derivatives. The use of more advanced statistical techniques within the study of likelihood of tree failure may be required to make accurate conclusions about the relationships between the factors which influence failure, as well as how to predict failure on the whole. Furthermore, the standardization of vegetation-related distribution interruption and outage-reporting methods and codes would be beneficial for the study of UVM generally and would be useful for the identification of the regionality and phenology of vegetation-related conflicts with distribution systems.

Our current standard, the ISA's UTRA BMP, has proven to be a powerful tool in an adept arborist's hands. Yet, the UTRA is limited by physical access to rugged ROW locations and by the time constraints that are necessary to inspect the many miles of lines that need to be assessed on a rotational basis (Goodfellow 2020). Remote sensing, change-detection techniques, predictive mechanistic models, and more advanced statistical techniques may be able to provide us with a broader view of the utility forest and a more complete set of tools to manage the risks associated with it.

Even while the study of the likelihood of failure of trees remains a hot topic within the arboricultural world, wise management practices should recognize that the vast majority of trees will stand throughout the duration of a human lifetime, and that once cut, a tree may take many years to replace. With regards to UVM this means understanding that many of the trees that stand along ROWs are healthy and do not pose elevated risk by themselves, as it is the combination of the likelihood of failure with the likelihood of impact and the consequences of failure which ultimately comprise risk. For example, of the 1,259 trees surveyed by Kane (2008), only 12.8% experienced failure. Put another way, 87.2% of trees survived.

Electric utilities, their customers, and the vegetation management industry all stand to benefit from a greater number of more varied and targeted approaches to tree-risk identification. As such, new techniques and technologies should be assessed, validated, and, when applicable, utilized by vegetation managers, for these methods may allow for some combination of decreased expenditure of financial resources, decreased vegetation-related outages, and increased safety of utility arborists, foresters, and the communities serviced, all the while leaving more trees standing and healthy.

LITERATURE CITED

Achim A, Wellpott A, Gardiner B. 2007. Competition indices as a measure of wind loading on individual trees. “Wind and Trees” Conference; 2007 August 5–9; Vancouver, Canada. Vancouver (Canada): University of British Columbia. https://www.researchgate.net/publication/266886250_Competition_indices_as_a_measure_of_wind_loading_on_individual_trees_Competition_indices_as_a_measure_of_wind_loading_on_individual_trees

Ancelin P, Courbaud B, Fourcaud T. 2004. Development of an individual tree-based mechanical model to predict wind damage within forest stands. *Forest Ecology and Management*. 203(1-3):101-121. https://doi.org/10.1016/j.foreco.2004.07.067

Appelt PJ, Goodfellow JW. 2004. Research on how trees cause interruptions—Applications to vegetation management. In: *Rural electric power conference, 2004.* 48th Annual Conference; 2004 May 25; Scottsdale, AZ, USA. Piscataway (NJ, USA): Institute of Electrical and Electronics Engineers, Inc. p. C6-1. https://doi.org/10.1109/REPCON.2004.1307064

Asner GP, Goldstein G. 1997. Correlating stem biomechanical properties of Hawaiian canopy trees with hurricane wind damage. *Biotropica.* 29(2):145-150. https://doi.org/10.1111/j.1744-7429.1997.tb00018.x

Baker CJ. 1995. The development of a theoretical model for the windthrow of plants. *Journal of Theoretical Biology*. 175(3): 355-372. https://doi.org/10.1006/jtbi.1995.0147

Bodig J, Jayne BA. 1982. *Mechanics of wood and wood composites*. New York (NY, USA): Van Nostrand Reinhold Company. 736 p.

Burgert I. 2006. Exploring the micromechanical design of plant cell walls. *American Journal of Botany*. 93(1):1391-1401. https://doi.org/10.3732/ajb.93.10.1391

Canham CD, Loucks OL. 1984. Catastrophic windthrow in the presettlement forests of Wisconsin. *Ecology*. 65(3):803-809. https://doi.org/10.2307/1938053

Ciftci C, Arwade SR, Kane B, Brena SF. 2014a. Analysis of the probability of failure for open-grown trees during windstorms. *Probabilistic Engineering Mechanics*. 37:41-50. https://doi.org/10.1016/j.probengmech.2014.04.002

Ciftci C, Kane B, Brena SF, Arwade SR. 2014b. Loss in moment capacity of tree stems induced by decay. *Trees*. 28:517-529. https://doi.org/10.1007/s00468-013-0968-8

Clair B, Fournier M, Prevost MF, Beauchene J, Bardet S. 2003. Biomechanics of buttressed trees: Bending strains and stresses. *American Journal of Botany*. 90(9):1349-1356. https://doi.org/10.3732/ajb.90.9.1349

Clough RW, Penzien J. 1993. *Dynamics of structures*. New York (NY, USA): McGraw-Hill. 738 p.

Crook MJ, Ennos AR. 1996. The anchorage mechanics of deep rooted larch, *Larix europea* × *L. japonica*. *Journal of Experimental Botany*. 47(10):1509-1517. https://doi.org/10.1093/jxb/47.10.1509

Cullen S. 2002. Trees and wind: Wind scales and speeds. *Journal of Arboriculture*. 28(5):237-242. https://doi.org/10.48044/jauf.2002.036

Dahle G, Grabosky J, Kane B, Miesbauer J, Peterson W, Telewski FW, Koeser A, Watson GW. 2014. Tree biomechanics: A white paper from the 2010 international meeting and research summit at The Morton Arboretum (Lisle, Illinois, U.S.). *Arboriculture & Urban Forestry*. 40(6):309-318. https://doi.org/10.48044/jauf.2014.029

Dahle GA, Grabosky JC. 2010. Variation in modulus of elasticity (*E*) along *Acer platanoides* L. (Aceraceae) branches. *Urban Forestry & Urban Greening*. 9(3):227-233.

Dahle GA, Holt HH, Chaney WR, Whalen TM, Cassens DL, Gazo R, McKenzie RL. 2006. Branch strength loss implications for silver maple (*Acer saccharinum*) converted from round-over to V-trim. *Arboriculture & Urban Forestry*. 32(4):148-154. https://doi.org/10.48044/jauf.2006.020

Dahle GA, James KR, Kane B, Grabosky JC, Detter A. 2017. A review of factors that affect the static load-bearing capacity of urban trees. *Arboriculture & Urban Forestry*. 43(3):89-106. https://doi.org/10.48044/jauf.2017.009

de Langre E. 2008. Effects of wind on plants. *Annual Review of Fluid Mechanics*. 40:141-168. https://doi.org/10.1146/annurev.fluid.40.111406.102135

Den Hartog JP. 1956. *Mechanical vibrations*. 4th Ed. New York (NY, USA): McGraw-Hill. 436 p.

Dunster JA, Smiley ET, Matheny N, Lilly S. 2017. *Tree risk assessment manual*. 2nd Ed. Champaign (IL, USA): International Society of Arboriculture. 194 p.

Dupuy L, Fourcaud T, Stokes A. 2005. A numerical investigation into the influence of soil type and root architecture on tree anchorage. *Plant and Soil*. 278:119-134. https://doi.org/10.1007/s11104-005-7577-2

Dupuy LX, Fourcaud T, Lac P, Stokes A. 2007. A generic 3D finite element model of tree anchorage integrating soil mechanics and real root system architecture. *American Journal of Botany*. 94(9):1506-1514. https://doi.org/10.3732/ajb.94.9.1506

Duryea ML, Kampf E, Littell RC. 2007. Hurricanes and the urban forest: I. Effects on southeastern United States coastal plain tree species. *Arboriculture & Urban Forestry*. 33(2):83-97. https://doi.org/10.48044/jauf.2007.010

Francis JK, Gillespie AJR. 1993. Relating gust speed to tree damage in Hurricane Hugo, 1989. *Journal of Arboriculture*. 19(6):369-373.

Gaffrey D, Kniemeyer O. 2002. The elasto-mechanical behaviour of Douglas fir, its sensitivity to tree-specific properties, wind and snow loads, and implications for stability—A simulation study. *Journal of Forest Science*. 48(2):49-69. https://doi.org/10.17221/11856-JFS

Gardiner B, Byrne K, Hale S, Kamimura K, Mitchell SJ, Peltola H, Ruel JC. 2008. A review of mechanistic modelling of wind damage risk to forests. *Forestry*. 81(3):447-463. https://doi.org/10.1093/forestry/cpn022

Gardiner B, Peltola H, Kellomäki S. 2000. Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modeling*. 129(1):1-23. https://doi.org/10.1016/S0304-3800(00)00220-9

Ghani MA, Stokes A, Fourcaud T. 2009. The effect of root architecture and root loss through trenching on the anchorage of tropical urban trees (*Eugenia grandis* Wight). *Trees*. 23:197-209. https://doi.org/10.1007/s00468-008-0269-9

Goodfellow JW. 2020. *Best management practices—Utility tree risk assessment*. Atlanta (GA, USA): International Society of Arboriculture. 95 p.

Guggenmoos S. 2003. Effects of tree mortality on power line security. *Journal of Arboriculture*. 29(4):181-196. https://doi.org/10.48044/jauf.2003.022

Guggenmoos S. 2011. Tree-related electric outages due to wind loading. *Arboriculture & Urban Forestry*. 37(4):147-151. https://doi.org/10.48044/jauf.2011.019

Guggenmoos S, Sullivan TE. 2009. Outside right-of-way tree risk along electrical transmission lines. In: Evans JM, Goodrich-Mahoney JW, Mutrie D, Reinemann J, editors. *9th international symposium: Environmental concerns in rights-of-way management*; 2009 September 27–30; Portland, Oregon, USA. Champaign (IL, USA): International Society of Arboriculture. p. 55-61. https://www.experts.com/content/articles/sguggenmoos1.pdf

Hale SE, Gardiner BA, Wellpott A, Nicoll BC, Achim A. 2012. Wind loading of trees: Influence of tree size and competition. *European Journal of Forest Research*. 131:203-217. https://doi.org/10.1007/s10342-010-0448-2

Haygreen JG, Bowyer JL. 1982. *Forest products and wood science: An introduction*. Ames (IA, USA): Iowa State University Press. 495 p.

Holmes JD. 2007. *Wind loading on structures*. 2nd Ed. London (UK): CRC Press. 392 p. https://doi.org/10.4324/9780203964286

James KR, Dahle GA, Grabosky J, Kane B, Detter A. 2014. Tree biomechanics literature review: Dynamics. *Arboriculture & Urban Forestry*. 40(1):1-15. https://doi.org/10.48044/jauf.2014.001

James KR, Haritos N, Ades PK. 2006. Mechanical stability of trees under dynamic loads. *American Journal of Botany*. 93(10):1522-1530. https://doi.org/10.3732/ajb.93.10.1522

James KR, Moore JR, Slater D, Dahle GA. 2018. Tree biomechanics. *CABI Reviews*. 12(38):1-11. https://doi.org/10.1079/PAVSNNR201712038

Ji J, Fourcaud T, Zhang Z. 2006. Towards simulating the biomechanical acclimation of tree roots using numerical analyses. 2006 Second International Symposium on Plant Growth Modeling and Applications; 2006 November 13–17; Beijing, China. Piscataway (NJ, USA): Institute of Electrical and Electronics Engineers, Inc. p. 78-84. https://doi.org/10.1109/PMA.2006.43

Kabir E, Guikema S, Kane B. 2018. Statistical modeling of tree failures during storms. *Reliability Engineering & System Safety*. 177:68-79. https://doi.org/10.1016/j.ress.2018.04.026

Kamimura K, Gardiner B, Dupont S, Guyon D, Meredieu C. 2016. Mechanistic and statistical approaches to predicting wind damage to individual maritime pine (*Pinus pinaster*) trees in forests. *Canadian Journal of Forest Resources*. 46(1):88-100. https://doi.org/10.1139/cjfr-2015-0237

Kamimura K, Gardiner B, Kato A, Hiroshima T, Shiraishi N. 2008. Developing a decision support approach to reduce wind damage risk—A case study on sugi (*Cryptomeria japonica* (L.f.) D.Don) forests in Japan. *Forestry*. 81(3):429-445. https://doi.org/10.1093/forestry/cpn029

Kamimura K, Gardiner BA, Koga S. 2017. Observations and predictions of wind damage to *Larix kaempferi* trees following thinning at an early growth stage. *Forestry*. 90(4):530-540. https://doi.org/10.1093/forestry/cpx006

Kane B. 2008. Tree failure following a windstorm in Brewster, Massachusetts, USA. *Urban Forestry & Urban Greening*. 7(1):15-23. https://doi.org/10.1016/j.ufug.2007.11.001

Kollmann FFP, Côté WA Jr. 1968. *Principles of wood science and technology: I Solid wood*. Berlin (Germany): Springer. 592 p.

Kollmann FFP, Kuenzi EW, Stamm AJ. 1975. *Principles of wood science and technology: II Wood based materials*. Heidelberg (Germany): Springer. 703 p.

Kretschmann DE. 2010. Mechanical properties of wood. In: *Wood handbook: Wood as an engineering material*. Centennial Ed. Madison (WI, USA): US Department of Agriculture, Forest Service, Forest Products Laboratory. General Technical Report FPL-GTR-190. p. 5.1-5.46.

Lillesand TM, Kiefer RW, Chipman JW. 2007. *Remote sensing and image interpretation*. 6th Ed. Hoboken (NJ, USA): John Wiley & Sons, Inc. 804 p.

Luley CJ, Bond J. 2006. Evaluation of the fate of ice storm-damaged urban maple (*Acer*) trees. *Arboriculture & Urban Forestry*. 32(5):214-220. https://doi.org/10.48044/jauf.2006.027

Luley CJ, Nowak DJ, Greenfield EJ. 2009. Frequency and severity of trunk decay in street tree maples in four New York cities. *Arboriculture & Urban Forestry*. 35(2):94-99. https://doi.org/10.48044/jauf.2009.017

Lundström T, Jonsson M, Volkwein A, Stoffel M. 2009. Reactions and energy absorption of trees subjected to rockfall: A detailed assessment using a new experimental method. *Tree Physiology*. 29(3):345-359. https://doi.org/10.1093/treephys/tpn030

Lundström T, Stoffel M, Stöckli V. 2008. Fresh-stem bending of silver fir and Norway spruce. *Tree Physiology*. 28(3):355-366. https://doi.org/10.1093/treephys/28.3.355

Matikainen L, Lehtomäki M, Ahokas E, Hyyppä J, Karjalainen M, Jaakkola A, Kukko A, Heinonen T. 2016. Remote sensing methods for power line corridor surveys. *ISPRS Journal of Photogrammetry and Remote Sensing*. 119:10-31. https://doi.org/10.1016/j.isprsjprs.2016.04.011

Miller KF, Quine CP, Hunt J. 1987. The assessment of wind exposure for forestry in upland Britain. *Forestry*. 60(2):179-192. https://doi.org/10.1093/forestry/60.2.179

Miller LA. 2005. Structural dynamics and resonance in plants with nonlinear stiffness. *Journal of Theoretical Biology*. 234(4):511-524. https://doi.org/10.1016/j.jtbi.2004.12.004

Milne R. 1988. The dynamics of swaying trees. *New Scientist*. 21:46.

Milne R. 1991. Dynamics of swaying of *Picea sitchensis*. *Tree Physiology*. 9(3):383-399. https://doi.org/10.1093/treephys/9.3.383

Mitchell SJ. 1998. A diagnostic framework for windthrow risk estimation. *The Forestry Chronicle*. 74(1):100-105. https://doi.org/10.5558/tfc74100-1

Mitchell SJ, Lanquaye-Opoku N, Modzelewski H, Shen Y, Stull R, Jackson P, Murphy B, Ruel JC. 2008. Comparison of wind speeds obtained using numerical weather prediction models and topographic exposure indices for predicting windthrow in mountainous terrain. *Forest Ecology and Management*. 254(2):193-204. https://doi.org/10.1016/j.foreco.2007.07.037

Moore JR. 2000. Differences in maximum resistive bending moments of *Pinus radiata* trees grown on a range of soil types. *Forest Ecology and Management*. 135(1-3):63-71. https://doi.org/10.1016/S0378-1127(00)00298-X

Moore JR, Maguire DA. 2004. Natural sway frequencies and damping ratios of trees: Concepts, review and synthesis of previous studies. *Trees*. 18:195-203. https://doi.org/10.1007/s00468-003-0295-6

Moore JR, Maguire DA. 2008. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. *Tree Physiology*. 28(1):75-83. https://doi.org/10.1093/treephys/28.1.75

Mortensen NG, Heathfield DN, Myllerup L, Landberg L, Rathmann O. 2005. *Wind atlas analysis and application program: WAsP 8 help facility* (online). Roskilde (Denmark): Risø National Laboratory. 242 p.

Most WB, Weissman S. 2012. Trees and power lines: Minimizing conflicts between electric power infrastructure and the urban forest [issue brief]. Berkeley (CA, USA): Center for Law, Energy & the Environment; Berkeley Law, University of California, Berkeley. 26 p. https://www.law.berkeley.edu/files/Trees_and_Power_Lines_March_2012.pdf

Niklas KJ. 1992. *Plant biomechanics: An engineering approach to plant form and function*. Chicago (IL, USA): The University of Chicago Press. 622 p.

Niklas KJ. 2000. Computing factors of safety against wind-induced tree stem damage. *Journal of Experimental Botany*. 51(345): 797-806. https://doi.org/10.1093/jexbot/51.345.797

Niklas KJ. 2002. Wind, size, and tree safety. *Journal of Arboriculture*. 28(2):84-93. https://doi.org/10.48044/jauf.2002.011

Niklas KJ, Spatz HC. 2000. Wind-induced stresses in cherry trees: Evidence against the hypothesis of constant stress levels. *Trees*. 14:230-237. https://doi.org/10.1007/s004680050008

Ow LF, Harnas FR, Indrawan IGB, Sahadewa A, Sim EK, Rahardjo H, Leong EC, Fong YK, Tan PY. 2010. Tree-pulling experiment: An analysis into the mechanical stability of rain trees. *Trees*. 24:1007-1015. https://doi.org/10.1007/s00468-010-0470-5

Panshin AJ, de Zeeuw C. 1980. *Textbook of wood technology: Structure, identification, properties, and uses of the commercial woods of the United States and Canada*. Subsequent Ed. New York (NY, USA): McGraw-Hill. 736 p.

Peltola H. 1996. Model computations on wind flow and turning moment by wind for Scots pines along the margins of clear-cut areas. *Forest Ecology and Management*. 83(3):203-215. https://doi.org/10.1016/0378-1127(96)03717-6

Peltola H, Kellomäki S, Väisänen H, Ikonen VP. 1999. A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce, and birch. *Canadian Journal of Forest Resources*. 29(6):647-661. https://doi.org/10.1139/x99-029

Peterson CJ. 2007. Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns. *Forest Ecology and Management*. 250(1-2):96-108. https://doi.org/10.1016/j.foreco.2007.03.013

Peterson CJ, Claassen V. 2013. An evaluation of the stability of *Quercus lobata* and *Populus fremontii* on river levees assessed using static winching tests. *Forestry*. 86(2):201-209. https://doi.org/10.1093/forestry/cps080

Putz FE, Coley PD, Lu K, Montalvo A, Aiello A. 1983. Uprooting and snapping of trees: Structural determinants and ecological consequences. *Canadian Journal of Forest Research*. 13(5):1011-1020. https://doi.org/10.1139/x83-133

Quine CP, Gardiner BA. 2007. Understanding how the interaction of wind and trees results in windthrow, stem breakage and canopy gap formation. In: Johnson EA, Miyanishi K, editors. *Plant disturbance ecology*. Burlington (MA, USA): Academic Press. p. 103-155.

Reilly AE. 1991. The effects of Hurricane Hugo in three tropical forests in the U.S. Virgin Islands. *Biotropica*. 23(4):414-419. https://doi.org/10.2307/2388260

Rodgers M, Casey A, McMenamin C, Hendrick E. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. In: Coutts MP, Grace J, editors. *Wind and trees*. Cambridge (UK): Cambridge University Press. p. 204-219. https://doi.org/10.1017/CBO9780511600425.012

Rodriguez M, de Langre E, Moulia B. 2008. A scaling law for the effects of architecture and allometry on tree vibration modes suggests a biological tuning to modal compartmentalization. *American Journal of Botany*. 95(12):1523-1537. https://doi.org/10.3732/ajb.0800161

Sellier D, Fourcaud T, Lac P. 2006. A finite element model for investigating effects of aerial architecture on tree oscillations. *Tree Physiology*. 26(6):799-806. https://doi.org/10.1093/treephys/26.6.799

Sinn G. 1990. *Untersuchungen zur kippursache von eichen im Riederwald Frankfurt/Main*. Zurich (Switzerland): Verlag SKV AG.

Smiley ET. 2008. Root pruning and stability of young willow oak. *Arboriculture & Urban Forestry*. 34(2):123-128. https://doi.org/10.48044/jauf.2008.016

Smiley ET, Matheny N, Lilly S. 2017. *Best management practices—Tree risk assessment*. 2nd Ed. Champaign (IL, USA): International Society of Arboriculture. 86 p.

Spatz HC. 2000. Greenhill's formula for the critical Euler buckling length revisited. In: Spatz HC, Speck T, editors. *Proceedings of the 3rd plant biomechanics conference*; 2000 August 27–September 2; Freiburg-Badenweiler, Germany. Stuttgart, Baden-Württemerg (Germany): Georg Thieme Verlag.

Spatz HC, Brüchert F. 2000. Basic biomechanics of self-supporting plants: Wind loads and gravitational loads on a Norway spruce tree. *Forest Ecology Management*. 135(1-3):33-44. https://doi.org/10.1016/S0378-1127(00)00296-6

Spatz HC, Brüchert F, Pfisterer J. 2007. Multiple resonance damping or how do trees escape dangerously large oscillations? *American Journal of Botany*. 94(10):1603-1611. https://doi.org/10.3732/ajb.94.10.1603

Spatz HC, Theckes B. 2013. Oscillation damping in trees. *Plant Science*. 207:66-71. https://doi.org/10.1016/j.plantsci.2013.02.015

Stokes A. 1999. Strain distribution during anchorage failure of *Pinus pinaster* Ait. at different ages and tree growth response to wind-induced root movement. *Plant and Soil*. 217:17-27. https://doi.org/10.1023/A:1004613126353

Stokes A, Berthier S, Sacriste S, Martin F. 1998. Variations in maturation strains and root shape in root systems of Maritime pine (*Pinus pinaster* Ait.). *Trees*. 12:334-339. https://doi.org/10.1007/PL00009720

Suzuki S, Sakamoto T, Noguchi H. 2016. Wind damage risk estimation for strip cutting under current and future wind conditions based on moment observations in a coastal forest in Japan. *Journal of Forest Research*. 21(5):223-234. https://doi.org/10.1007/s10310-016-0539-0

Telewski FW. 1995. Wind-induced physiological and developmental response in trees. In: Coutts MP, Grace J, editors. *Wind and trees*. Cambridge (UK): Cambridge University Press. p. 237-263.

Theckes B, de Langre E, Boutillon X. 2011. Damping by branching: A bioinspiration from trees. *Bioinspiration & Biomimetics*. 6(4):046010. https://doi.org/10.1088/1748-3182/6/4/046010

Tobin B, Čermák J, Chiatante D, Danjon F, Di Iorio A, Dupuy L, Eshel A, Jourdan C, Kalliokoski T, Laiho R, Nadezhdina N, Nicoll B, Pagès L, Silva J, Spanos I. 2007. Towards developmental modeling of tree root systems. *Plant Biosystems*. 141(3):481-501. https://doi.org/10.1080/11263500701626283

Vanomsen P. 2006. Der einfluss der durchforstung auf die verankerung der fichte hinsichtlich ihrer sturmresistenz [doctoral thesis]. Zurich (Switzerland): ETH. https://doi.org/10.3929/ethz-a-005195897

Virot E, Ponomarenko A, Dehandschoewercker É, Quéré D, Clanet C. 2016. Critical wind speed at which trees break. *Physical Review E*. 93:02300. https://doi.org/10.1103/PhysRevE.93.023001

Wellpott A, Gardiner B, Salmén L. 2006. Wind loading on trees in a mature Sitka spruce forest. In: *Proceedings of the 5th plant biomechanics conference*; 2006 August 28–September 1; Stockholm, Sweden. Stockholm (Sweden): STFI-Packforsk. p. 323-328.

Yan WM, Zhang L, Leung FTY, Yuen KV. 2016. Prediction of the root anchorage of native young plants using Bayesian inference. *Urban Forestry & Urban Greening*. 19:237-252. https://doi.org/10.1016/j.ufug.2016.06.027

Zobel BJ, van Buijtenen JP. 1989. *Wood variation: Its causes and control*. Berlin (Germany): Springer Verlag. 363 p.

ACKNOWLEDGMENTS

We would like to thank Drs. Michael Strager, Timothy Warner, Aaron Maxwell, and Paul Kinder for assistance during the preparation of this literature review. Financial support was received in part from the following sources: NIFA McIntire-Stennis Grant (WVA00819), TREE Fund UARF Grant #19-UAA-01, WVU Energy Institute Obrien Energy Research Funds Grant, and the WVU West Virginia Agriculture and Forestry Experiment Station (scientific article #3425). Figure 2 was drawn by Lucille Dahle.

Mathew Walker (corresponding author)
Davis College, Division of Forestry and Natural Resources
West Virginia University
Morgantown, WV, USA
mwalke18@mix.wvu.edu

Gregory A. Dahle
Davis College, Division of Forestry and Natural Resources
West Virginia University
Morgantown, WV, USA

Conflicts of Interest:
The authors reported no conflicts of interest.

Résumé. Les gestionnaires du contrôle de la végétation aux abords des services publics ont besoin d'outils afin de prévoir les risques liés aux arbres et connaître les prescriptions d'intervention nécessaires pour réduire les risques de dommages causés par les chablis aux réseaux électriques aériens. Cette revue de littérature se concentre sur les études fondamentales concernant la probabilité de défaillance des arbres, en débutant par une description et une discussion des défaillances chez les arbres, suivie d'une analyse des méthodologies utilisées pour estimer les défaillances des arbres, avant de conclure par une revue des facteurs considérés comme influençant la défaillance des arbres. En définitive, une meilleure compréhension de la probabilité de défaillance des arbres individuels et des relations régissant la défaillance des arbres et les pannes du fait de la végétation, peut permettre des avancées significatives dans la gestion des risques posées aux infrastructures de services publics.

Zusammenfassung. Vegetationsmanager von Versorgungsunternehmen benötigen Instrumente zur Vorhersage baumbezogener Risiken und Kenntnisse über die notwendigen Bewirtschaftungsvorschriften, um das Risiko von Windwurfschäden an der elektrischen Infrastruktur von Versorgungsunternehmen zu verringern. Dieser Bericht konzentriert sich auf die wichtigsten Studien über die Wahrscheinlichkeit des Versagens von Bäumen, beginnend mit einer Beschreibung und Diskussion des Versagens von Bäumen, gefolgt von einer Untersuchung der Methoden, die zur Bewertung des Versagens von Bäumen verwendet wurden, bevor er mit einer Überprüfung der Faktoren abschließt, die nachweislich das Versagen von Bäumen beeinflussen. Letztlich kann ein besseres Verständnis der Wahrscheinlichkeit des Versagens einzelner Bäume und der Zusammenhänge zwischen Baumversagen und vegetationsbedingten Ausfällen zu bedeutenden Fortschritten beim Risikomanagement der Versorgungsinfrastruktur führen.

Resumen. Los administradores de servicios públicos de la vegetación necesitan herramientas para predecir los riesgos relacionados con los árboles y el conocimiento de las prescripciones de gestión necesarias para reducir el riesgo de daños por viento a la infraestructura eléctrica de las empresas de servicios públicos. Esta revisión se centra en estudios clave que involucran la probabilidad de falla de los árboles, comenzando con una descripción y discusión de la falla en los árboles, seguida de un examen de las metodologías que se han utilizado para evaluar la falla, antes de concluir con una revisión de los factores que se ha encontrado que influyen en dicha falla. En última instancia, una mejor comprensión de la probabilidad de falla de árboles individuales y las relaciones que rigen la falla de los árboles y las interrupciones relacionadas con la vegetación puede permitir avances significativos en la gestión de riesgos de la infraestructura de servicios públicos.

Arboriculture & Urban Forestry Quiz Questions

To complete this quiz, go to the ISA website, log into your MyISA account, and make your way to the page for *Arboriculture & Urban Forestry* CEU Quizzes (www.isa-arbor.com/store/ceuquizzes/113).

Add the quiz to your cart, proceed through checkout, and look for the content to appear on your personal dashboard under the header, "My Quizzes." If you need a username and password, send us an e-mail (isa@isa-arbor.com).

A passing score for this quiz requires sixteen correct answers. Quiz results will display immediately upon quiz completion. CEU(s) are processed immediately. You may take the quiz as often as is necessary to pass.