Chapter 2
Modeling Windthrow at Stand and Landscape Scales

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Contents

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2.1 Introduction

Wind damage to trees and stands has ecological and management implications. The spectrum of damage can range from creation of canopy gaps and development of multi-cohort (uneven-aged) stands, to whole-stand replacement and initiation of single-cohort (even-aged) stands (e.g., Kramer et al. 2001; Busby et al. 2008; Bouchard et al. 2009). Individual trees can be broken or uprooted. Soil inversion by overturned rootwads leads to complex microtopography, improves soil fertility (Schaetzl et al. 1989; Kramer et al. 2004), and creates a regeneration niche for many tree and understory plant species (Ulanova 2000). On steep slopes, the disturbance contributes to downslope movement of soil (Gallaway et al. 2009). In managed forests, as well as rural and urban landscapes, windthrow damages crop and amenity trees, affects conservation and recreation values, and poses a threat to human life and built structures (Fig. 2.1a; Schmidlin 2009). Rather than being viewed as individual catastrophic events, windthrow is more realistically viewed as a recurrent disturbance process, with an inverse relationship between event frequency and severity. At a given location, the likelihood and severity result from

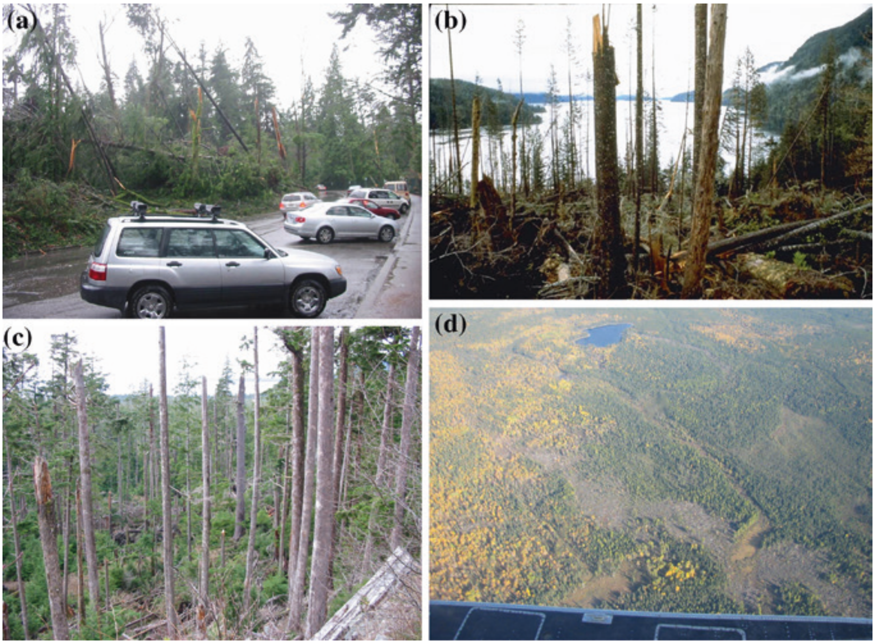

Fig. 2.1 **a** Aftermath of the December 15, 2006 windstorm in Stanley Park, Vancouver, British Columbia, Canada (photo credit S.J. Mitchell). **b** Stand-replacing windthrow from an extra-tropical cyclone in coastal British Columbia, Canada (photo credit S.J. Mitchell). **c** Partial-windthrow from an extra-tropical cyclone, coastal British Columbia, Canada (photo credit S.J. Mitchell). **d** Stand-replacing windthrow from a convective downburst—boreal forest in Ontario, Canada (photo credit A. Perera)

interactions among regional wind climate and local terrain, vegetation, and management regime (Mitchell 2013). Scientists use models to improve their understanding of the processes underlying forest disturbances and to integrate results of empirical, biomechanical, and numerical investigations. Ideally, the models or the results of modeling are presented in the form of decision support tools (e.g., Hanewinkel et al. 2011) that can be used by resource and conservation managers as well as those responsible for public utilities to evaluate windthrow risk and develop mitigative responses in a wide range of forest conditions.

In this chapter, we review the factors that contribute to windthrow frequency and severity within stands and across landscapes, summarize current approaches used to model windthrow, identify and discuss the gaps in existing modeling approaches, and outline strategies to improve modeling and application of windthrow models for decision support.

2.2 Overview of Factors that Contribute to Windthrow

A turning moment is the tendency of a force to rotate an object around its axis, and is calculated by multiplying the force by the length of the lever arm. Windthrow results when wind-induced turning moments exceed root anchorage or stem strength and trees uproot or break. The level of damage in forest stands ranges from partial to stand-replacing, depending on wind speed and the susceptibility of trees that make up the stand (Fig. 2.1 b, c). In temperate climates, most windthrow occurs during extreme weather associated with extra-tropical cyclones or remnant tropical cyclones. These systems produce sustained high winds over wide areas and are often accompanied by heavy rainfall that reduces anchorage. Regional-scale airflow is modified by local terrain, leading to areas of higher or lower topographic exposure to wind (Ruel et al. 2002). Downbursts or tornados associated with convective storms cause severe, localized windthrow along the track of the storm (Fig. 2.1d; Peterson 2007). In tropical climates, windthrow is caused by cyclones (e.g., Lugo 2008) and convective downbursts (Garstang et al. 1998).

The mechanical stability of individual trees reflects their long-term exposure to wind and the effects of inter-tree competition. Open-grown trees maintain long live crowns, and acclimate to local wind regimes by developing thick stems and structural roots. In locations with prevailing winds, their crowns are often wind-shaped or flagged, and stems and roots thicken asymmetrically (Telewski 1995; Fig. 2.2). Stand-grown trees are partially sheltered by neighboring trees, and compete with them for light and soil resources. Here, height growth, maintenance of sun exposed foliage, and fine root production take priority over stem and root thickening, leading to slender trees with lower mechanical stability (Mitchell 2000). Dense, uniform stands can grow into a condition where the whole stand becomes unstable as it reaches some critical height. This phenomenon has been reported for single-cohort stands in temperate forests around the world, and

Fig. 2.2 Wind shaped tree crowns in an area of strong prevailing winds (photo credit J.-C. Ruel)

motivated the original windthrow hazard classification system developed for the United Kingdom (Miller 1985). Management activities such as patch cutting, heavy thinning, or retaining isolated stems within harvested areas, which produce sudden increases in wind exposure, can lead to windthrow during routine winds. In contrast, planting trees at wide spacing, or gradually thinning stands, can lead to trees that are well acclimated to the local wind climate and therefore less susceptible to windthrow (Albrecht et al. 2012).

The influence of soils on tree and stand stability is complex. Open-grown trees may form stable anchorage on a wide variety of soils. Shallow or poorly drained soils can restrict anchorage; however, landscape-scale studies of windthrow often reveal that stands on deep soils are more susceptible (Dobbertin 2002; Bouchard et al. 2009). This apparent paradox may be explained by the fact that stands grow taller and trees compete more for light on sites with deeper, more fertile soils, making them more susceptible to windthrow.

Observations of the recurrent nature of wind damage and the role of component factors, have informed the development of classification schemes based on local expert knowledge (e.g., Miller 1985; Mitchell 1998; Wood et al. 2008), and have led to two broad approaches to windthrow modeling: empirical and hybrid empirical-mechanistic.

2.3 Empirical Modeling

2.3.1 Approaches to Empirical Modeling

The aims of empirical windthrow modeling are diagnostic, i.e., to identify the factors associated with windthrow, and predictive, i.e., to improve our capacity to predict where and how much damage is likely within forested landscapes.

Empirical modeling can be undertaken at spatial scales ranging from national through regional to local, and incorporate landscape-, stand-, and tree-scale data. Temporally, models can address damage from a single event or class of similar events, or cumulative damage that occurs over a fixed time interval. Wind damage estimates can be obtained via classification of aerial or satellite images (Ruel and Benoit 1999; Mitchell et al. 2001), establishment of temporary plots (Scott and Mitchell 2005), or from periodic re-measurement of permanent sample plots (Valinger and Fridman 1999). Predictor variables can be obtained via field measurement or from spatial data layers (e.g., topography, vegetation, soils, and management history maps). Wind exposure is often represented using topographic exposure indices but potential sources of wind data are many, including local climate stations, broad-scale regional wind atlases, and mesoscale modeling (Ruel et al. 1997, 2002).

In empirical modeling, local outcomes can be examined at the stand (plot) or individual tree scale. At stand scale, the response variable can be the percentage of stems or canopy area affected, but since it is common for the majority of plots or trees in a given study area not to be affected, the outcome is often represented as binary, i.e., above or below some damage threshold. Classification and Regression Trees (CART) can be used to identify damage thresholds and predictor variables (e.g., Kamimura et al. 2008). Tree-scale outcomes are dichotomous (trees fail, meaning they break or uproot, or remain standing), so logistic regression models are typically used to predict the probability of individual tree failure, and can also be used to determine the probability of damage within plots exceeding some threshold level of damage severity (Table 2.1).

Table 2.1 Examples of empirical windthrow models

Author	Location	Temporal scale	Spatial scale	Sample point	Other information sources	Analytical approach
Albrecht et al. (2012)	Germany	Multiple events	Tree and stand	Permanent sample plots	Tree, stand, site, management	GLMM
Dobbertin (2002)	Europe	Two events	Stand	Permanent sample plots	Stand, site	CART
Kamimura et al. (2008)	Japan	Multiple events	Stand	Temporary sample plots	Site, management	CART
Lavoie et al. (2012)	Canada (Québec)	Multiple events	Tree and stand	Temporary sample plots	Site, management	Logistic regression, mixed models
Mitchell and Lanquaye-Opoku (2005)	Canada (British Columbia)	Multiple events	Stand	Cutblock edge segments	Stand, site, management	Logistic regression
Moore et al. (2013)	New Zealand	Multiple events	National and regional	Regional summaries of area damaged	Wind speed	Generalized Pareto distribution
Scott and Mitchell (2005)	Canada (British Columbia)	Multiple events	Tree	Temporary sample plots	Tree, stand, site, management	Logistic regression
Valinger and Fridman (2011)	Sweden	Single event	Stand	Permanent sample plots	Stand, management	Logistic regression

One of the considerations in the use of logistic regression for developing windthrow prediction models is the potential for lack of spatial independence between observations used for model fitting. Spatial independence will differ among tree-, stand-, and landscape-scale variables, and will depend on the extent of the study area. Spatial independence can be tested using semivariance techniques (Carr 1995). The spatial independence of topographic and wind variables will depend on topographic heterogeneity and the grid resolution at which these variables are characterized. Another way to account for the lack of spatial independence at different scales is through the use of mixed models. For instance, random effects can be associated with plots and with harvest blocks to account for the fact that trees within a given plot and plots within the same harvest block are not independent (e.g., Lavoie et al. 2012).

In addition to ensuring adequate distances between sample points to reduce spatial correlation, it is good practice to reserve a portion of the data set for model testing. The portability of empirical models in space or time can be examined by testing their goodness-of-fit for observations collected in different locations, and over different time periods. Mitchell and Lanquaye-Opoku (2005) found consistency in variables among models fit for coastal and continental regions in British Columbia, Canada, and that models from one region gave good predictions of relative windthrow likelihood in other regions.

In their review of natural hazards modeling, Hanewinkel et al. (2011) identify as problematic the relatively high rates of misclassification for individual cases when the number of observations differs substantially between categories, as is often the case for wind damaged versus undamaged trees and stands. They provide examples of some alternative approaches including the generalized additive mixed model (GAMM) used by Schmidt et al. (2010) to explore damage caused by Storm Lothar, which affected Europe in 1999. Albrecht et al. (2012) used generalized linear mixed modeling (GLMM) to explore factors contributing to winter storm damage in southwest Germany. Described as very powerful tools, GLMMs are challenging to use even for statisticians, which can lead to inappropriate applications (Bolker et al. 2008). For nonspatial national or regional analyses of area damaged, extreme value approaches are useful. Moore et al. (2013) used generalized Pareto distributions to (i) examine the probability that the total area wind damaged in any year exceeded a threshold level, and (ii) predict the level of damage associated with a given return period, both for forested areas of New Zealand.

The results of empirical modeling have been incorporated into decision support tools. Kamimura et al. (2008) used the CART approach to create a decision support tool for windthrow in sugi (*Cryptomeria japonica*) forests in Japan. Regional stand-level logistic regression models have been incorporated into the growth and yield model TIPSY in British Columbia, Canada (Di Lucca et al. 2006). Where attributes such as stand, soil, topographic, or wind variables derived from existing spatial inventories are used for model fitting, the data sets can be compiled using geographic information system (GIS) software, with custom scripts for characterizing topographic exposure, drainage, and land management variables. The resulting predictive models can be entered into map-calculators (tools with a

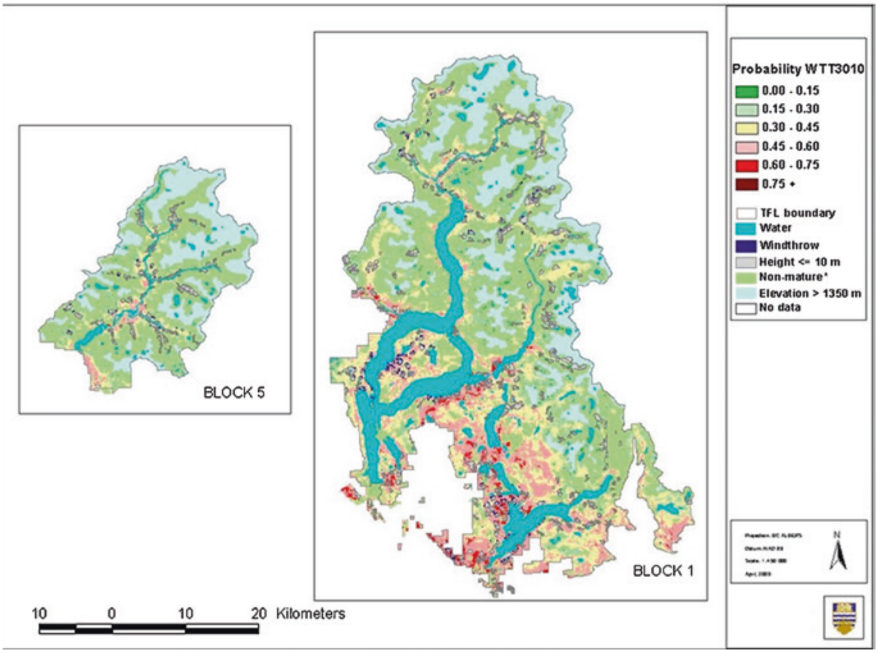

Fig. 2.3 Local windthrow probability maps produced using an empirical model with stand-level data, coastal British Columbia, Canada. *Shading* indicates probability of wind damage to forested edges of new, windward-facing clearcut boundaries due to routine winter winds (photo credit S.J. Mitchell)

GIS that enable users to combine values from different map layers via algebraic or logical expressions) to produce maps of stand vulnerability across the landscape (Fig. 2.3). These maps promote understanding of wind disturbance regimes and assist with the location and design of harvesting/thinning areas in order to reduce windthrow losses, or to better emulate natural disturbance patterns (e.g., Mitchell et al. 2001).

2.3.2 Advantages and Disadvantages of Empirical Models

Although they may have some shortcomings, empirical windthrow models have several advantages over existing mechanistic models. The full range of current ecological and management complexity can be accounted for in the data sets used for model fitting, including representation of multi-species, multi-aged stands with senescing and partially decayed trees. Harvest designs ranging from simple geometric clear-cuts to complex selection or variable retention harvests can be sampled and represented. While empirical models may not provide direct evidence of the mechanisms that lead to windthrow, they can be used to identify key factors to be evaluated in field-level diagnosis of its likelihood (e.g., Mitchell 1998). They also provide insights into how to represent climatic, geographic, and stand variables in mechanistic models. Furthermore, the data sets needed for empirical models can be assembled rapidly, particularly when windthrow is mapped via remote sensing, and are useful for testing and validating mechanistic models.

Regardless of the analytical framework or model form, empirical models are based on past or current outcomes. Changes in storm, temperature, or precipitation regimes, whether due to short-term climate cycles or longer-term climate change, and changes in the composition and arrangement of stands as land use and management practices change will influence the validity of these models. Other disadvantages of empirical models of windthrow include the typically coarse resolution of topographic (spatial) and wind (spatial and temporal) variables, and the difficulty in identifying the underlying biological or mechanical processes from the resulting models.

2.4 Hybrid-Mechanistic-Empirical Models

2.4.1 Windthrow Mechanics as Represented in Hybrid-Mechanistic Models

Windthrow mechanics are reviewed by Mayer (1989) and Wood (1995), both of whom identify static and dynamic aspects of wind loading and tree response. Windthrow occurs when the turning moments produced by wind acting on the crown of a tree exceed the capacity of the stem to resist the bending stresses—leading to stem breakage, or the capacity of the root-soil system to resist overturning. In purely mechanistic windthrow modeling, it would be possible to link a series of calculations of the applied and resistive moments for an individual tree at a given above-canopy wind speed, estimate the critical above-canopy wind speed at which the tree will fail, and apply these calculations to all of the trees that make up a given stand, while accounting for the dynamic aspects of tree motion and wind turbulence (e.g., Wood 1995). In reality, trees and stands are mechanically and architecturally complex and heterogeneous, as are wind patterns during wind storms, terrain and soil properties. In developing windthrow process models, researchers make several conceptual simplifications, including applying expert judgement about the value or range of key parameters and incorporating empirically-derived equations to simplify model construction (Fig. 2.4). The resulting products are best described as hybrid mechanistic–empirical models. The ultimate motivation for developing these models is to improve prediction of potential damage, and allow users to explore how different ecological and management scenarios would affect the likelihood and severity of damage. Development and validation of these models also focuses attention on the key component processes and relationships that drive this complex natural phenomenon. The following summary introduces key terminology, approaches, and information sources used in the major windthrow models, wherein windthrow is treated primarily as a static problem (e.g., Peltola 2006).

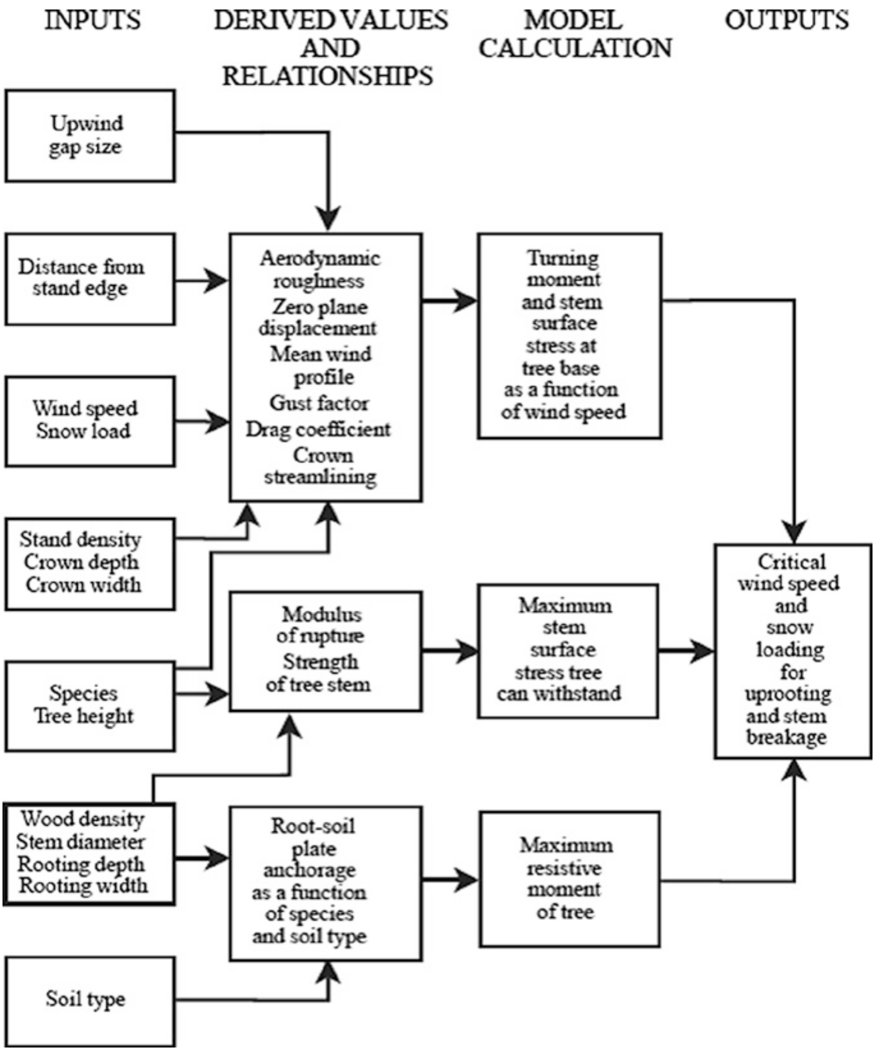

Fig. 2.4 The key inputs, relationships, calculations and outputs of the hybrid-mechanistic windthrow risk model HWIND (from Peltola et al. 1999)

In the simplest models, the stand is assumed to comprise identical trees, and when the representative tree fails, so does the entire stand. With this simplification, it is possible to estimate wind loading on trees within the stand using the "roughness" approach. In this approach, the shear stress that develops across the forest canopy as a function of the above-canopy wind speed and the canopy surface roughness is evenly distributed among the trees within a given area and is assumed to act at approximately two-thirds of the stand height (Gardiner et al. 2000, 2008).

The resulting equations for critical above-canopy wind speed that would lead to breakage (Uh_{break}) or uprooting (Uh_{over}) become (Table 2.2):

$$Uh_{break} = \frac{1}{kD}\left[\frac{\pi MOR \times d.b.h.^3}{32\rho\, G(d-1.3)}\right]^{\frac{1}{2}}\left[\frac{f_{knot}}{f_{edge} f_{CW}}\right]^{\frac{1}{2}} \ln\left(\frac{h-d}{z_0}\right) \quad (2.1)$$

$$Uh_{over} = \frac{1}{kD}\left[\frac{C_{reg} SW}{\rho\, Gd}\right]^{\frac{1}{2}}\left[\frac{1}{f_{edge} f_{CW}}\right]^{\frac{1}{2}} \ln\left(\frac{h-d}{z_0}\right) \quad (2.2)$$

The modulus of rupture (MOR) for sound green wood obtained from standard wood properties tables (e.g., Alden 1997) is modified to represent living tree stems by including a reduction in strength due to knots *(*f_{knot}*)* obtained from three-point bending tests with recently harvested logs. Ruel et al. (2010) demonstrated this process for balsam fir (*Abies balsamea* (L) Mill.) and expanded it by estimating the decay factor for logs with heart rot (Fig. 2.5).

Trees may be windthrown as a result of stem or root system failure. Critical resistance to uprooting is tested experimentally via tree-pulling (Fig. 2.6). This technique has been standardized, and very strong linear relationships are typically found between critical turning moment and stem mass (C_{reg}, SW) in conifers (Nicoll et al. 2006). These regressions are applicable across fairly large geographic regions (Bergeron et al. 2009). However, when wind climate varies across a region, regressions may need to be adjusted to reflect acclimation to the local climate (Nicoll et al. 2008). Stem and crown attributes are typically estimated from tree diameter and height via dendrometric (or biomass) equations developed via destructive analysis of felled or pulled trees. During tree-pulling studies, most

Table 2.2 Description of terms used in Eqs. 2.1 and 2.2

Symbol	Description	Units
k	von Karman's constant	Dimensionless
d	Zero plane displacement	m
$z0$	Aerodynamic roughness	m
D	Average spacing between trees	m
G	Gust factor	Dimensionless
h	Mean tree height	m
ρ	Air density	kg/m^3
d.b.h.	Diameter at breast height (1.3 m above ground)	m
f_{knot}	Knot factor—reduction of wood strength due to knots	Dimensionless
f_{edge}	Increase in load due to proximity of tree to forest edge	Dimensionless
f_{cw}	Increase in load due to stem and crown displacement under wind load	Dimensionless
MOR	Modulus of rupture for sound green wood	Pa
SW	Stem mass	kg
C_{reg}	Regression constant that relates critical turning moment to stem mass	Dimensionless

Fig. 2.5 Three-point bending tests of stem with heart rot (photo credit J.-C. Ruel)

Fig. 2.6 Static tree-pulling with motorized winch to determine critical turning moment (photo credit J.-C. Ruel)

trees uproot, but a proportion of sound trees experience stem failure. In some studies, critical moments for stem-failed trees were comparable to those of uprooted trees of similar size (e.g., Achim et al. 2005; Byrne and Mitchell 2007), while in other studies stem failure occurred at higher bending moments than uprooting (e.g., Moore 2000; Bergeron et al. 2009).

While it is the standard approach for measuring tree resistance to wind loads, tree-pulling has limitations. Any structure is most likely to fail at the weakest point, and while trees may not universally do so, they can theoretically maintain optimum stability while remaining competitive with other trees by allocating photosynthate in the most structurally efficient manner. This is known as the uniform stress hypothesis (e.g., Morgan and Cannell 1994). In the standard tree-pulling technique, cables are often attached below the crown for practical and safety reasons, and this is lower than would be required to generate a uniform stress in the outer stem fibers (e.g., Wood 1995). Furthermore, pulling is "static", i.e., is a straight pull with gradually increasing cable tension) and does not emulate tree motion during storms and the potential for gradual loss of root-soil cohesion.

The roughness method of calculating critical wind speed applies to conditions well downwind of any gaps or stand edges. The effect of the width of an opening on wind loading at the stand edge and with distance into the downwind stand has been tested empirically in wind tunnel studies with turbulent airflow and model stands made up of flexible "trees" (Gardiner et al. 1997). The ratio of peak to mean applied moments at the base of individual trees is referred to as the gust factor (G), while the effect of upwind gaps, referred to as fetch, is accounted for with a gap factor and distance from stand edge. An alternate method of estimating wind loading, which is better suited to stand edges, is the "profile" method (e.g., Smith et al. 1987; Peltola et al. 1999). The latter method is also more suitable for evaluating loads on individual trees in nonuniform and mixed species stands. In the profile method, the wind load on an individual tree is calculated from the within-canopy wind speed profile, the crown frontal area, and the drag coefficient, using the classical drag equation (Eq. 2.3):

$$F_d = 0.5\,\rho * C_d * A * U^2 \qquad (2.3)$$

where F_d is the drag force acting on the tree crown, ρ is air density, C_d is the drag coefficient, A is the frontal area of the tree crown in still air and U is the horizontal wind speed. In reality, tree branches and foliage are not rigid. Branches taper toward the tip, similar to fishing rods, leading to increasing flexibility at the periphery of the crown. Branches and foliage reconfigure and realign as wind speeds increase (Fig. 2.7), streamlining drag elements and reducing frontal area. Where the classical drag equation is used with a fixed drag coefficient, it is necessary to adjust the crown frontal area measured in still air (A_s) using a streamlining coefficient (S):

$$S = c * U^{-n} \qquad (2.4)$$

where the parameters c and n are species specific and represent the rate of crown frontal area reduction with increasing wind speed. Drag and streamlining coefficients have been determined experimentally for several conifer and broadleaf species, by placing the crowns of small trees in wind tunnels (Mayhead 1973;

Fig. 2.7 Side view of western redcedar (*Thuja plicata* Donn ex D. Don) tree crown in a wind tunnel in horizontal airflow (photo credit S.J. Mitchell)

Rudnicki et al. 2004; Vollsinger et al. 2005) or by mounting them on vehicles that are driven at a succession of higher wind speeds through calm air (e.g., Kane et al. 2008). However, experimentally determined drag coefficients are not available for many species, and whether the behavior of small crowns is representative of large tree crowns remains an open question.

Combining Eqs. 2.3 and 2.4 leads to:

$$F_d = 0.5\,\rho * S * C_d * A_s * U^2 \tag{2.5}$$

Drag can be calculated for whole crowns and applied at the height of center of pressure to calculate applied turning moment, or it can be calculated for successive vertical segments of the crown. When vertical segmenting is used, differing vertical wind profiles can be applied at stand edges and within the stand. The attenuation of the wind profile within forest canopies depends on canopy density (e.g., Cionco 1972; Shaw et al. 1988).

Horizontal wind loads deflect the tree stem from vertical, and an additional applied moment is created from the displaced stem and crown mass. This additional bending moment is estimated by assuming that the tree stem behaves like a tapered cantilever beam, anchored at the base, and is normally calculated iteratively since the displaced mass leads to further displacement until the resistive moment balances the applied and self-loading moments.

Once the critical wind speed has been estimated using either the roughness or profile methods, the probability of a wind of this speed occurring at a given site can be estimated. Since long-term weather stations tend to be concentrated near urbanized areas rather than distributed through forested landscapes, a variety of approaches are used. The UK Forestry Commission used tatter flags located across open moorland as a direct measure of wind exposure, and related this to a variety of indices of topographic exposure to wind and to regional windiness (Hannah et al. 1995). The underlying assumption in these approaches is that a relationship exists between general windiness at a location and the recurrence of extreme winds. Physical airflow models and numerical weather prediction models can be used to represent the effect of complex terrain on local wind speed and direction (Ruel et al. 1997). Numerical weather prediction models have the advantage of allowing for reconstruction of specific weather events, and can be used to predict wind, temperature, and precipitation. As well, they can be used to produce gridded maps of mean and extreme wind and precipitation conditions (e.g., Guthrie et al. 2010). Goodrick and Stanturf (2010) refer to this as “event risk”, and describe a process for producing gridded maps from climatological models.

2.4.2 Overview of Hybrid-Mechanistic Models

Several hybrid-mechanistic windthrow models incorporate some or all of the components described above (Table 2.3). The most broadly applied model, ForestGALES, was initially developed by the UK Forestry Commission to predict

Table 2.3 Examples of hybrid-mechanistic models for predicting windthrow

Author	Origin	Base model	Adaptations
Gardiner et al. (2000, 2006)	United Kingdom	ForestGALES	France Cucchi et al. (2005), New Zealand Moore and Quine (2000), Japan Kamimura et al. (2008), Canada—Québec Ruel et al. (2000), British Columbia Byrne and Mitchell (2013)
Peltola et al. (1999)	Finland	HWIND	Sweden Blennow and Sallnäs (2004), The Netherlands Schelhaas et al. (2007)
Ancelin et al. (2004)	France	FOREOLE	–

failure of Sitka spruce (*Picea sitchensis*) plantations in Britain (Gardiner et al. 2006). It can be run using either the roughness or profile method to calculate critical wind speeds (however, the profile method is not included in the public version), and can be used to simulate outcomes for even-aged plantations of major commercial conifer species for uniform thinning or strip cutting scenarios. Regional windiness is modified via a topographic exposure score to estimate the probability of a critical wind speed occurring at the target location. Topographic exposure accounts for elevation, local topography, the direction of prevailing winds, and the funneling effect of valleys (Quine and White 1993). In the public version, the stand is treated as completely uniform and if the critical wind speed for the representative tree is exceeded the entire stand will fail. The effects of upwind gaps and uniform thinning can be evaluated. Soil type and drainage are used to modify critical turning moments using adjustment factors derived from tree-pulling studies on a range of soil types. The model has been coupled with data from growth and yield tables to project the age at which stands will reach critical height. The ForestGALES model has been adapted by research groups in New Zealand (Moore and Quine 2000), France (Cucchi et al. 2005), Japan (Kamimura et al. 2008), and Canada (Québec—Ruel et al. 2000; British Columbia—Byrne and Mitchell 2013) by adding tree-pulling and dendrometric data for local species (primarily conifers), use of local wind climate data, and local stand growth models.

The model HWIND was developed in Finland to predict the risk of wind or snow damage via uprooting or stem breakage along recently exposed stand edges (Peltola et al. 1999), and incorporates the profile method to calculate critical wind speed. Stands are assumed to be uniform and edge trees will fail if the critical wind speed is reached at a newly exposed edge. The model includes the effect of distance from the stand edge and it is possible to calculate critical wind speeds separately at one, two, or more tree heights from the edge. Wind loading, deflection, and resistance are calculated for representative trees for successive vertical stem/crown sections. The other major difference between HWIND and ForestGALES is that the critical moment for uprooting is calculated from root system dimensions (root system mass) rather than estimated based on stem mass using empirical relationships from tree-pulling studies. Schelhaas et al. (2007) have adapted HWIND in their model ForGEM-W to include spatial mapping of trees and tree-to-tree shelter and collision effects.

Ancelin et al. (2004) developed FOREOLE, an individual tree model in which the profile method is used to calculate wind loading and resistance for successive vertical stem/crown sections. Loads are calculated assuming static loading and are adjusted for turbulent wind effects using a gust factor. The principle departure from ForestGALES in the wind loading and resistance calculations is in the improved representation of stem taper and the use of the transfer matrix method for stepwise calculation of loads, displacement, and resistance within stem segments. This model has been linked with an individual-tree-based growth and yield model (Courbaud et al. 2001) within the Computer Aided Projection of Strategies in Silviculture (CAPSIS) platform (e.g., Dufour-Kowalski et al. 2012) and allows windthrow to be simulated for populations of trees at any point in the growth of uniform or nonuniform stands. While CAPSIS allows for the spatial representation of modeled trees, Ancelin et al. (2004) did not incorporate iterative processing in FOREOLE to account for the effect of damage propagation during a given wind event.

ForestGALES_BC/WindFIRM extends the capacity of ForestGALES to model damage propagation in nonuniform, mixed species stands under complex partial harvesting scenarios (Byrne and Mitchell 2013). The model has two modules. The first, WindFIRM, assembles spatial information from input GIS layers and spatially explicit tree lists, calculates stand attributes for 25 m × 25 m grid cells, and passes the stand- and tree-scale data to the second, ForestGALES_BC, for calculation of the critical and applied wind speeds for each tree in the area under investigation. Rather than using a representative tree, the model uses an input table that lists each tree in the stand, with its species, diameter at breast height, height, and location (*x*, *y* coordinate). These "tree lists" can be derived from field measurements, growth and yield models, or other sources, including LIDAR. Using the spatially explicit tree list, the critical wind speed for each tree in the stand is calculated using the profile method. The within-canopy wind profile acting on each tree is calculated by modifying the user-specified above-canopy wind speed based on the canopy density in upwind grid cells. To better represent damage propagation, any trees that would fail for the user-specified above-canopy wind speed are deleted from the tree list. The resulting tree list is passed from the ForestGALES_BC module back to the WindFIRM module for recalculation of stand attributes within each 25 m × 25 m grid cell, and then passed back to ForestGALES_BC to recalculate tree-level wind loading for the remaining trees. These calculations are repeated until no additional trees in the stand would fail for the user-specified above-canopy wind speed (Fig. 2.8).

2.4.3 Integration of Hybrid-Mechanistic Models into Spatial Decision Support Models

Both ForestGALES and HWIND have been integrated with other models and information layers within GIS to expand their capacity for decision support at stand and landscape scales. For example, HWIND has been integrated with the European Wind Atlas Analysis and Application Program (WASP) within a GIS

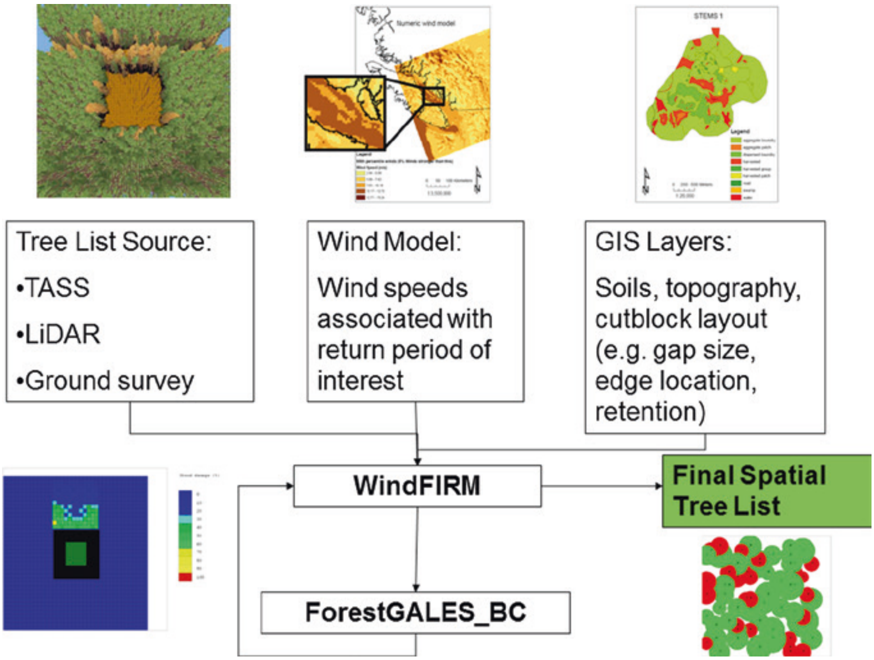

Fig. 2.8 Integration of ForestGALES_BC and WindFIRM, spatial decision support system for windthrow likelihood modeling (from Gardiner et al. 2008)

in the predictive framework WINDA to examine the probability of wind damage across landscapes where stand edges are exposed following forest harvesting (Blennow and Sallnäs 2004). It has also been integrated with forest growth models and forest cover data to examine windthrow potential across landscapes under various growth and management regimes (Zeng et al. 2007a, b), and with current and future wind climate simulations to explore the implications of climate change (Blennow et al. 2010; Peltola et al. 2010).

2.4.4 Advantages and Disadvantages of Hybrid-Mechanistic Modeling

Researchers have examined and characterized several of the biological, ecological, and physical processes that contribute to windthrow at individual tree to landscape scales (Mitchell 2013). Hybrid-mechanistic windthrow models provide conceptual and computational vehicles to link knowledge on component processes, allow input information to be scaled appropriately, and produce tabular or graphical outputs. Representing the process of windthrow via a series of linked algorithms helps researchers to generate hypotheses and identify knowledge gaps. Model predictions can be tested for individual components or the whole model, using independent data. As forest management decision support tools, hybrid mechanistic models are useful for examining and contrasting management scenarios, albeit with full regard for the inherent limitations in how these models represent reality. Ideally, prior to their application in a new location, models are adapted to include parameters for local conditions, and model outputs are compared to local observations. In contrast to empirical models, hybrid-mechanistic models allow exploration of management or climate scenarios that have not yet occurred or are not documented in observational data sets of wind damage. In these simulations however, it is important to keep in mind that these models contain empirical components.

The empirical equations included in the calculation of applied and resistive moments are based on a limited number of tree-pulling and wind tunnel studies. For example, in the base ForestGALES, FOREOLE, and HWIND models, the drag coefficients are estimated based on the work of Mayhead (1973) who tested small numbers of sapling-sized specimens of commercial conifers in the United Kingdom, at speeds under 30 m s^{-1}. Additional studies have been conducted in recent years (e.g., Rudnicki et al. 2004; Vollsinger et al. 2005; Kane et al. 2008) and new parameters could easily be added to the models. Similarly, in each of these models, the gust factors are derived from the wind tunnel work of Gardiner et al. (1997, 2000) with model trees, but could be updated with results from field studies and numerical simulations. The representation of stands by an average or typical tree is clearly a simplification, even for the most uniform plantations. Using the profile method to calculate wind loading provides the potential to incorporate tree lists and simulate outcomes for mixed species, multi-storied, and partially harvested stands. However, to properly represent the windthrow process for stands in which tree stability varies, it is necessary to represent the process of damage propagation during storm events. At this point, only ForestGALES_BC/WindFIRM is designed to account for progressive loss of upwind trees and damage propagation (Byrne and Mitchell 2013). The iterative approach used in this model is computationally intensive, which limits the speed at which a user can compare scenarios if the area under study extends beyond a few tens of hectares. However, since computational speed is constantly increasing, this problem will resolve itself in time.

The veracity of the major models and decision support systems has been examined using sensitivity analysis and by comparing results with observational data sets of stand- or landscape-scale windthrow outcomes (Gardiner et al. 2008; Byrne and Mitchell 2013). The tendency in these validation exercises, however, is to find real-world situations where the simplicity of stand, landform, and management matches the level of sophistication of the model. Plenty of opportunity remains to improve representation of the windthrow process and the heterogeneity of tree, stand, landscape, and climatological conditions.

2.5 Discussion of Modeling Gaps and Potential Approaches

2.5.1 Representation of Spatial Variability in Factors Contributing to Windthrow

Hybrid-mechanistic windthrow models can be broadly viewed as stand-scale models such as ForestGALES (UK model, roughness-approach), and tree-scale models such as FOREOLE, ForestGALES_BC, and ForGEM-W. For stand-scale models, the outcome is total damage or no damage for a given above-canopy wind speed. Tree-scale models can be used to identify which trees in the stand are vulnerable at a given above-canopy wind speed. Outcomes for individual trees can be aggregated to outcomes for cells or polygons, giving stand-scale outcomes as the number or percentage of tree loss. In ForestGALES_BC/WindFIRM, the individual tree outcomes are aggregated into 25 m × 25 m cells and the tree loss in one cell affects wind exposure of downwind cells. Where tree- and stand-scale models are incorporated in a decision support system that is integrated with a GIS, outcomes can be examined and represented across the landscape (e.g., Zeng et al. 2007a; Blennow et al. 2010).

The cellular approach used in ForestGALES_BC/WindFIRM suggests how the resolution of stand-level prediction models could be improved by better representing the variability in above-canopy wind speed, stand, or soil attributes across landscapes. Improving the resolution of wind loading and resistance components of tree-scale models depends on the resolution of the input spatial layers. With spatial tree lists, it is easy to represent loss of upwind trees via clear-cut, partial harvesting, or wind damage, by removing trees from the tree-list. Where upwind stand density is variable due to irregular thinning or variable retention harvesting, empirically derived fetch indices such as VRFetch (Scott and Mitchell 2005) can be used, but these only crudely represent the effects of canopy heterogeneity on wind flow. Schelhaas et al. (2007) used the height and crown dimensions of upwind trees to calculate their sheltering effect on the subject tree and used this to modify the gust factor. Hale et al. (2012) have found a relationship between the applied turning moment experienced by individual trees and competition indices that represent their immediate growing environments, suggesting an alternative way to represent wind loading in heterogeneous stands. Computational techniques such as large eddy simulation (LES) allow for the three-dimensional simulation of airflow over and through canopies with varying porosity and gaps (e.g., Clark and Mitchell 2007; Dupont and Brunet 2008). Although LES is computationally intensive, as processors improve it may be possible to couple LES simulation directly with windthrow prediction models to evaluate partial harvesting and thinning scenarios. Landscape-scale variability in wind speed can be represented via gridded data sets derived from numerical weather prediction or climatological modeling (e.g., Goodrick and Stanturf 2010; Guthrie et al. 2010).

Soil conditions affect windfirmness, and vary in space and time. Peltola et al. (2000) have examined the effects of soil freezing on tree resistance to uprooting, and trees have been pulled on sites across a gradient of soil drainage (Nicoll et al. 2006). Kamimura et al. (2012) have explored the effect of intense precipitation and soil saturation on critical turning moments, but these ephemeral effects have not been incorporated into windthrow models. Some sites are more prone to soil moisture accumulation during storms. Information on soil drainage is usually coarsely mapped, and representation of spatial and temporal patterns of soil moisture could be improved using higher resolution ground surface maps derived from field mapping or LIDAR, integrated with water flow models (e.g., Murphy et al. 2009).

Rudnicki et al. (2001) have documented tree collisions, and their effect on tree motion at sub-lethal wind speeds. Schelhaas et al. (2007) have taken the first steps to integrate tree collisions into ForGEM-W. They use the overlap in crown area between the subject tree and downwind neighbors to reduce the applied turning moment. They partially account for tree collisions once critical wind speeds are exceeded by adding a moment derived from the mass and contact height of failed trees to the self-loading moments of downwind neighbors that they contact as they fall. However, ForGEM-W does not simulate damage propagation via iterative calculations, momentum transfer during multiple tree cascades, nor directional effects. Alternative approaches to modeling wind damage propagation within and between stands include cellular automata models used in slope failure or wildfire modeling (e.g., Malamud and Turcotte 2000).

2.5.2 Representation of Temporal Variability in Factors Contributing to Windthrow

Each of the major windthrow models has been coupled with stand growth models, including ForestGALES with the UK Forestry Commission Yield Models (Gardiner et al. 2006), ForestGALES and FOREOLE within CAPSIS (Ancelin et al. 2004; Cucchi et al. 2005), and HWIND with SIMA (Zeng et al. 2007b). With this coupling, information on stand growth over time is used in windthrow models to estimate the age and height at which the stand will reach the point where annually recurring peak winds exceed critical wind speeds (critical height) for a site with a particular wind exposure and soil type. Tree-scale windthrow models can be linked with spatially explicit stand growth models. For example, ForestGALES_BC uses tree lists from, and can be directly coupled with, the Tree and Stand Simulator (TASS) growth model (Byrne 2011). At a given time step, TASS provides a tree list to ForestGALES_BC for calculation of whether the tree would fail for a given above-canopy wind speed. Once a high wind event has been simulated, the resulting list of surviving trees can be re-entered into TASS for further growth simulation. In this way, the short- and long-term growth and yield implications of a given harvesting or thinning prescription can be represented, with windthrow losses accounted for.

Stand growth models account for the effect of growing space on tree size, height, and diameter for the average tree, or for spatially explicit tree lists, depending on the sophistication of the model. Growing space depends on the number of stems per ha at the time of regeneration (initial stand density), and changes through the life of a stand as the number of stems decreases due to competition-induced mortality or planned thinning treatments. Reduced growing space typically leads to greater stem slenderness for a given height and shorter live-crown length. When coupled with stand growth models, windthrow models can be used to explore the implications of initial spacing for stand stability—in particular, the trade-off between reduced stem slenderness (and therefore stem and root resistance) and increased wind loading due to increased wind penetration into the canopy and larger crown sizes. In general, model simulations reveal that stands planted at wider initial spacings are more stable for a given tree or stand height, and this is consistent with field observations (e.g., Schelhaas et al. 2007). Thinning leads to more growing space for individual trees, but also increases canopy porosity and wind loading. Healthy, vigorous trees gradually respond to increased growing space by a general increase in crown volume and diameter increment, but also acclimate via preferential thickening of the lower stem and temporary reduction in height increment, leading to rapid reductions in stem slenderness (Mitchell 2000; Ruel et al. 2003). The representation of stand and tree growth following thinning varies among growth models. Stand-scale models can represent immediate changes in average tree diameter due to the removal of smaller trees during thinning. They can also represent the increase in radial growth due to increased growing space in the years following thinning. Post-thinning acclimative growth patterns are not represented, even in spatially explicit tree-scale models such as TASS. Such growth pattern changes could be represented in growth and yield and windthrow prediction models by linking with functional-structural plant growth models (e.g., Fourcaud et al. 2008).

In addition to projected changes due to stand growth, natural and human-caused disturbances will occur. These can be tracked via change-detection techniques using high or moderate resolution satellite imagery (e.g., Rossi et al. 2013). Climate change is expected to affect the frequency, intensity, and timing of severe weather events, as well as forest growth (Dale et al. 2001). Hybrid-mechanistic windthrow risk models have been used to explore the implications of climate change scenarios in storm-prone landscapes (e.g., Blennow et al. 2010; Peltola et al. 2010).

2.5.3 *Improving Windthrow Modeling at the Landscape-Scale*

Empirical windthrow models have been fit for landscape-scale data sets, and can be used to predict damage from routine winds to stand edges recently exposed by harvesting (“endemic damage”, e.g., Mitchell and Lanquaye-Opoku 2005) and to examine risk factors for stand-replacing damage from infrequently occurring extreme winds ("catastrophic damage"; Ruel and Benoit 1999). However, empirical models have been fit for only a few forest types or regions. Representation of gap or stand-replacing windthrow across landscapes via hybrid-mechanistic models remains simplistic, particularly for the effects of upwind canopy properties and propagation of damage. Many of the required elements are in place for rapid expansion of coverage by empirical windthrow models to more forest types and regions, and refinement of hybrid-mechanistic models to support landscape-scale prediction of windthrow.

Using successive moderate to high-resolution satellite images (e.g., MODUS, IKONOS) enables detection and mapping of gap or stand-replacing damage across landscapes shortly after damage occurs. The same data sets could be used to detect thinning or harvesting activities that expose trees or stand edges to higher within-canopy wind loads (e.g., Coops et al. 2009). Change-detection results could be linked with gridded wind and precipitation climatologies derived from weather data or from numerical weather predictions (e.g., Goodrick and Stanturf 2010; Guthrie et al. 2010), and with spatial data sets of terrain, soil, and stand attributes. Regional LiDAR data sets are becoming available, and LiDAR has improved the resolution of terrain mapping, the evaluation of soil drainage, and the characterization of stand structure (e.g., White et al. 2012; Wulder et al. 2012). Significant computational capacity would be needed to iteratively run tree-scale damage propagation calculations for large landscapes, but computational efficiency of hybrid-mechanistic models could be improved by aggregating trees into cells and examining cell-to-cell interactions.

2.5.3.1 Integrating Model Predictions with Consequences and Responses

An ideal decision support tool for windthrow management would provide forest managers with the capacity to predict the probability of wind damage in a particular site and stand, and explore how alternate growing, tending, and harvesting regimes, and climate change scenarios, would affect this probability. Ideally, the results could be represented spatially within a GIS so that both stand- and landscape-scale outcomes could be examined relative to other resource values and management objectives. Hanewinkel et al. (2011) identify the following sequential steps for integrating risk of natural hazards into forest management decision-making, in the context of changing climates: (i) create analysis framework, which includes choosing climate scenarios, downscaling a global climate model to a regional climate model, and determining storm recurrence intervals; (ii) evaluate probabilities of hazards; (iii) estimate costs of acting versus not acting to reduce hazards; and (iv) choose action. Steps (iii) and (iv) of Hanewinkel et al.'s framework link the likelihood of a damaging event to its consequences and choice of action. The consequences of windthrow extend from benign ecological impacts, such as soil turnover and acceleration of stand development in natural stands (e.g., Schaetzl et al. 1989), to human injury or death (Schmidlin 2009). In locations with recurrent wind storms, it makes sense to consider the potential consequences, determine the acceptable level of loss and impact, and act when predicted losses and impacts exceed acceptable levels. Actions can include acceptance of loss, insurance to minimize severe financial losses, and modification of management regimes to reduce loss (Gardiner and Quine 2000; Fig. 2.9). Mickovski et al. (2005) demonstrate how windthrow susceptibility can be incorporated into a

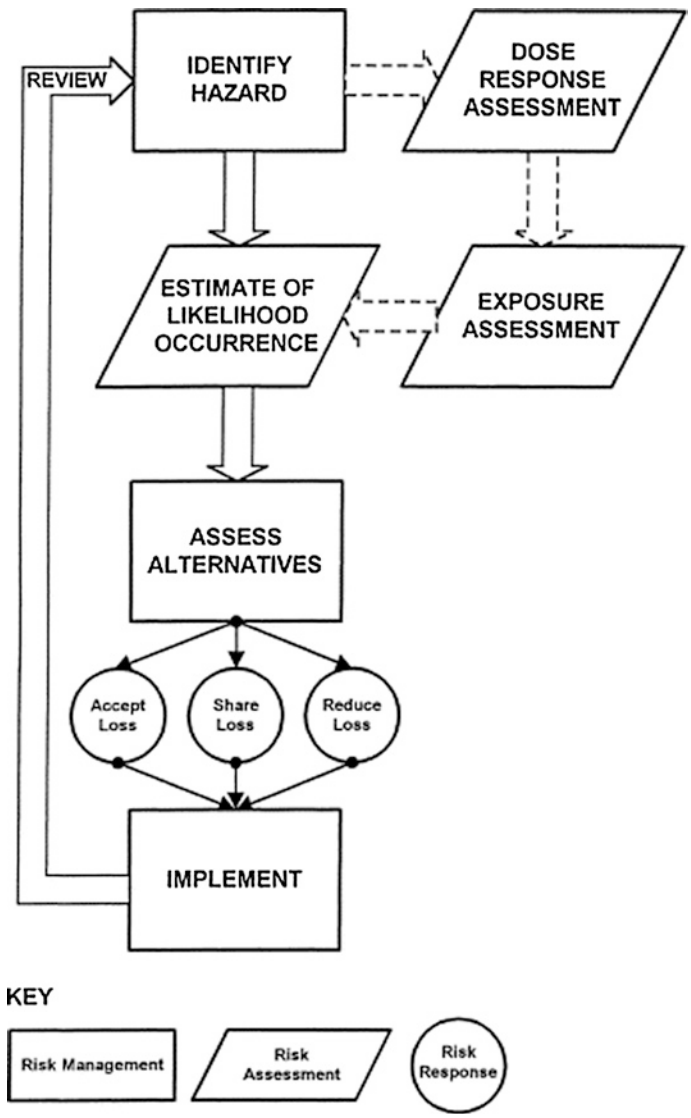

Fig. 2.9 Elements of a risk management framework (from Gardiner and Quine 2000)

generic tree- and stand-scale decision support system. von Gadow (2000) suggests an approach to integrating risk from windthrow and other hazards into forest-level planning, via examination of alternate management scenarios using age dependent cumulative survival rates at the stand scale, and optimizing harvest scheduling at the forest scale. At this point no windthrow risk decision support systems integrate all of these components. Only ForestGALES version 2.1 (Gardiner et al. 2006), which enables users to examine stand-scale outcomes, nonspatially, using the roughness method, is available in a format and with supporting documentation that allow practitioners to easily input data and examine their own scenarios using a stand-alone computer or the internet.

2.6 Conclusions

Empirical windthrow models capture the range of variability in natural and managed stands. The relative portability of empirical models points to consistency in underlying processes over large geographic areas, but provides only limited insights into the biomechanics of windthrow. Hybrid-mechanistic windthrow models have allowed for the integration of expert knowledge and research results from forestry, atmospheric sciences, engineering, biology, and ecology, but many functions remain empirical surrogates for, or simplified versions of, component processes and some key processes (soil saturation during storms, for example) are not represented in any current models. New techniques and information sources are available to improve representation of many of these processes. Both empirical and hybrid-mechanistic models are useful in decision support, and have been used by researchers to explore stand- and landscape-scale implications of climate change. GISs-based decision support systems that integrate tree-based windthrow modeling with stand- and landscape-scale scenario analysis and optimization have been developed by researchers, but are not yet available in formats and with supporting documentation that enable easy use by practitioners.

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