CONCEPTUAL FRAMEWORK FOR IMPROVED WIND-RELATED FOREST THREAT ASSESSMENT IN THE SOUTHEASTERN UNITED STATES

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Abstract—In the Southeastern United States, forests are subject to a variety of damage-causing wind phenomena that range in scale from very localized (downbursts and tornadoes) to broad spatial scales (hurricanes). Incorporating the threat of wind damage into forest management plans requires tools capable of assessing risk across this range of scales. Our conceptual approach involves breaking down the risk into components of event risk and resource vulnerability. Event risk can be simply stated as the probability of an event of a certain magnitude occurring in a given area and can be evaluated based on climatology. For wind related threats, resource vulnerability is determined by a complex function of stand and site characteristics. Although there is little that can be done to mitigate event risk, resource vulnerability can be manipulated through management activities. We have proposed a framework that includes a hierarchy of models for evaluating forest vulnerability to wind damage across a range of scales (from an individual tree, to a forest stand, up to the landscape scale); which, when combined with climatological models of event risk will provide a consistent wind-related threat-assessment tool.

INTRODUCTION

Forests are subject to a variety of damage-causing wind phenomena that range in scale from very localized (downbursts and tornadoes) to broad spatial scales (hurricanes). In the Southeastern United States all of these phenomena impact some portion of the region's forest on almost an annual basis. The magnitude of a wind-related disturbance is a complex function of the magnitude of the wind event along with topography, climate, and soil properties, as well as stand age, composition, and structure. To mitigate the threat of wind damage to southern forests requires an improved understanding of the disturbance process, which includes both the nature of the disturbance event (e.g., a hurricane) and the forest's response.

A hurricane represents the largest and perhaps most spatially complex of the wind-related disturbance events that affect southern forests. As a hurricane makes landfall, hurricane force winds, embedded squall lines, and associated tornadoes create a complex pattern of damage across a range of spatial scales—from a single tree up to an entire landscape (Boose and others 1994, Brokaw and Walker 1991, Walker 1995). The winds act to dissipate the energy of the storm by transferring it to the trees, which respond by swaying, twisting, and rocking; transferring energy down to the ground as well as to other trees (Drouineau and others 2000, Ennos 1997, Peterson, 2000). The first part of the tree to sustain damage is the crown, as leaves and small branches are stripped by wind, entrained soil particles, blowing debris, and friction with other crowns (Brokaw and Walker 1991). As the crown becomes streamlined, larger branches may break off and cause damage to understory trees (Frangi and Lugo 1991). Ultimately, with sufficient energy input, individual stems may bend, break, tip (full or partial uprooting), or remain standing with root system unstable (possibly broken loose from soil contact).

Stanturf and others (2007) present a conceptual approach to incorporating disturbance into forest management, using Hurricanes Katrina and Rita as example disturbance events. This paper builds on that work by providing a first step towards developing a system for assessing wind-related threats to southern forests. While the methodology is described for hurricanes it can be applied similarly to other wind threats such as downbursts and tornadoes. Ultimately this wind threat assessment will be combined with similar risk assessments of other threats such as ice storms, drought, insect or disease outbreaks, and invasive species to provide a comprehensive view of threats to southern forests.

APPROACH

Our approach to assessing wind-related threats involved separating the significance of an event (outcome risk) into the risk of a hurricane of some magnitude occurring (event risk) and the vulnerability of forest resources to that event (resource vulnerability) (Pielke and others 2005, Sarewitz and others 2003). For wind-related weather events, the event risk component cannot be affected directly by managers, but it is important to understand the frequency and variability of these events, especially when associated with severe weather such as hurricanes and other wind-related disturbances. For natural ecosystems such as coastal forests, resource vulnerability to wind-related disturbances, such as hurricanes, is a complex function of stand and site characteristics, which are largely independent of event risk (Pielke and others 2005). While event risk represents that portion of the overall risk that is beyond human control, resource vulnerability can be manipulated by management activities that may reduce the outcome risk.

Event Risk

In the case of hurricanes (or any other wind-related disturbance) event risk is a measure of the frequency of an event of some magnitude in an area, and it necessitates the development of a climatology. A first-cut hurricane climatology for examining forest wind damage is represented by the tracks of major (Category 3 through 5) hurricanes making landfall in the United States (fig. 1). These storm tracks were obtained from NOAA's HURDAT data set for

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1851-2005 (Javeinen and others 1984). For each tropical cyclone (hurricane), this data set contains information on location and intensity (maximum winds and minimum central pressure) every six hours as determined in a post-storm analysis. While storm tracks do provide a history of tropical storm activity in the Atlantic basin, they lack the spatially explicit wind information required to estimate the event risk for hurricane-strength winds in forests.

One means of obtaining a spatial wind field from the HURDAT information is to use a parametric hurricane model that describes the radial distribution of winds about a storm's center. Holland (1980) introduced a simple axisymmetric model that describes a hurricane based upon cyclostrophic balance between the wind and pressure fields as

$$P(r) = Pc + (Pa - Pc)\exp^{-(R\max/r)^B}$$

$$V(r) = \left[\frac{B}{\tilde{n}}\left(\frac{R\max}{r}\right)^B (Pa - Pc)\exp^{-(R\max/r)^B} + \left(\frac{rf}{2}\right)^2\right]^{\frac{1}{2}} - \frac{rf}{2} \qquad (1)$$

where P(r) is the pressure as a function of radius (r) from the storm center, Pc is the central pressure, Pa is the ambient pressure, Rmax is the radius of maximum wind, B is a storm profile parameter, V is the wind speed at r, ρ is the density of air, and f is the Coriolis parameter. Although this model is axisymmetric—that is, it predicts an equal wind speed distribution in all quadrants of the storm—actual hurricanes are not symmetric about their axis, particularly at landfall (Houston and others 1999). Georgiou (1985) added a modified form of the velocity equation that includes storm motion to introduce asymmetry into the Holland model. This simple model has been found to produce reasonable descriptions of hurricane wind distributions once appropriate values for Rmax and B have been determined. Vickery and others (2000) present equations to represent these values as functions of central pressure and latitude.

The Holland model is only appropriate for tropical cyclones over the ocean; it does not include the influence of changes in land surface or topography. During landfall, changes in surface roughness increase surface friction which reduces wind speeds and alters wind direction. In a similar parametric hurricane model, Boose and others (1994) simulated land fall by introducing a friction parameter that reduced wind speeds by 20 percent over land and increased the cross-isobar flow angle from 20 to 40 degrees. Realistic topographic effects are difficult to simulate in these simple parametric models. Boose and others (1994) employed a simple topographic sheltering effect that provided a basic means of determining areas that may be protected from damaging winds from a certain direction.

In the present study, the model of Georgiou (1985) with the parameter estimates of Vickery and others (2000) and landfall formulation of Boose and others (1994) is used to describe the hurricane wind fields. This approach is preferred over that of Boose and others (1994), because the hurricane model is completely described by parameters contained in the HURDAT data set (location, central pressure, and

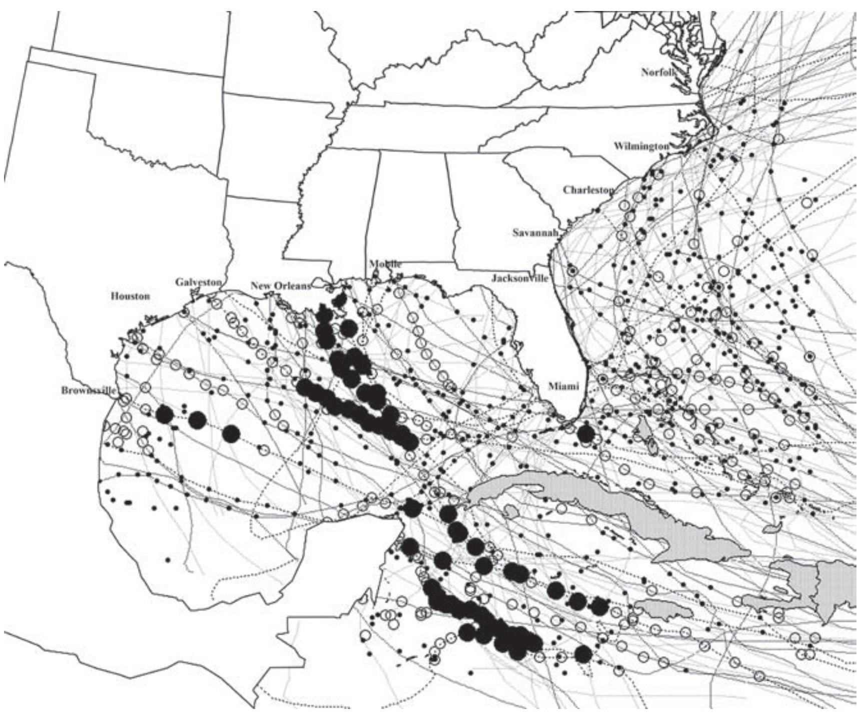

Figure 1—Major (Category 3-5) hurricanes making landfall in the eastern United States (1851-2005). The circles represent storm intensity during storm lifetime (small filled circles are Category 3, large open circles are Category 4, and large filled circles are Category 5). The tracks are for those storms that were Category 3 to 5 at some point in their lifecycle. The hurricane track map is from NOAA's HURDAT data set for 1851-2005 (Source: Jarvinen and others 1984; figure adapted from Stanturf and others 2007).

maximum sustained winds). The model of Boose and others requires specification of the storm's eye wall radius which is not available for historical storms and would otherwise need to be estimated from satellite imagery. While this approach is possible for modern-day hurricanes, it cannot be determined for the historical hurricanes that are needed to construct a climatology. Figure 2 shows a sample wind field for hurricane Katrina on August 28, 2005 when the central pressure dropped to 902 mb and maximum sustained winds peaked at 175 mph. The composite of maximum winds for Katrina determined by the model are shown in figure 3.

A coarse-scale hurricane wind climatology will be developed by creating daily 10 km spatial resolution grids of tropical storm winds for all tropical storm days in the HURDAT data set for which sufficient storm information is present to run the model. The spatial domain of the climatology must be sufficient to cover the Atlantic and Gulf of Mexico coasts of the United States. The temporal resolution of the climatology will match the six-hourly reports of the HURDAT data set. The grids for each time period will be composited to provide information on mean tropical storm force winds and frequency of occurrence for various threshold wind values. This re-creation of historical tropical storm winds will provide a broad view of hurricane winds, but does not provide the detailed wind fields required for examining disturbance at the stand or individual tree scales. In the future these scales will use a multilayer boundary layer model forced by initial and boundary conditions from the climatology to examine more closely the influence of land cover changes and topography.

Resource Vulnerability

In the case of wind-related disturbances, resource vulnerability can be simply stated as the likelihood that winds of a given magnitude will cause damage to the forest. If only determining this vulnerability were as easy as defining it. Vulnerability to wind damage is a complex function of more than just wind speed, because factors such as stand age, structure, and composition must be considered along with soils, topography, climate, and management history. In this first pass at assessing resource vulnerability, we recognized the need to consider potential stem breakage as a function of sustained wind speed, tree height, and tree spacing.

The simulation applied to loblolly pine (Pinus taeda L.) and longleaf pine (P. palustris Mill.) followed the methodology of the GALES windthrow model, with most parameters set for Pinus sylvestris L., Scots pine (Gardiner and others 2004). Species-dependent streamlining of the canopy is neglected here as wind tunnel data for the southern pine species used were unavailable; the canopy of each species of pine was treated as Scots pine. Nine hypothetical stands were created from combinations of three tree heights (20, 25, and 30 m) and three spacings (2.5, 5.0, and 7.5 m). For each of the nine stands the maximum bending moment at a height of 1.3 m above the ground was determined for both the interior of the stand and its edge; results were compared to the

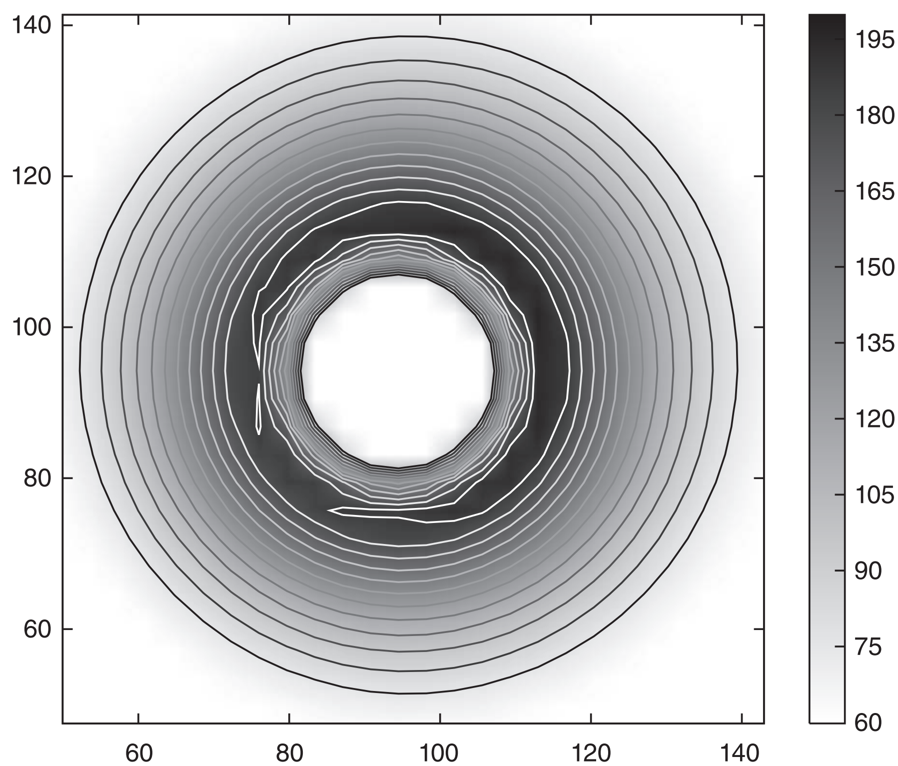

Figure 2—Simulated wind speed distribution for hurricane Katrina on August 28, 2005. At 12 GMT peak winds were 175 mph. Contours range from 60 to 170 mph with an interval of 10 mph. The x and y axes represent distance in kilometers. Note that this image is zoomed in on the hurricane and therefore shows only a fraction of the model domain.

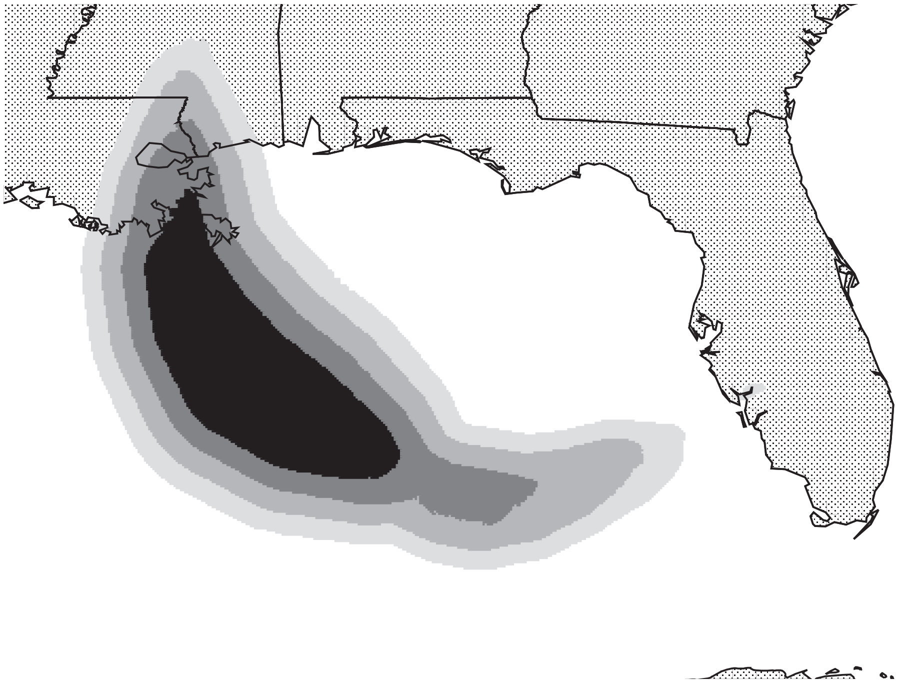

Figure 3—Simulated wind field for hurricane Katrina showing distribution of winds for Saffir-Simpson scale categories 2-5 (darker shades are higher intensity categories).

bending moment that signifies stem failure for both longleaf and loblolly pine species. For the interior portion of the stand (fig. 4), tree height was a primary factor in determining stem failure. At stand edges (fig. 5), the threshold for stem breakage was much lower, and tree spacing appeared to be a more important factor in avoiding wind damage than tree height, suggesting that managers may be able to reduce losses due to wind damage by altering planting densities along stand edges.

Note that we looked only at stem breakage for individual trees and not damage due to uprooting of trees; therefore, these modeling results are intended only as an illustrative tool rather than a detailed, species-specific study of tree failure. For a full assessment of wind-related disturbance vulnerability, the GALES model will need to be combined with a model for determining the resistive turning moment of the root-soil system (Lundstrom and others 2007) in order to fully describe the vulnerability of individual stems. Further

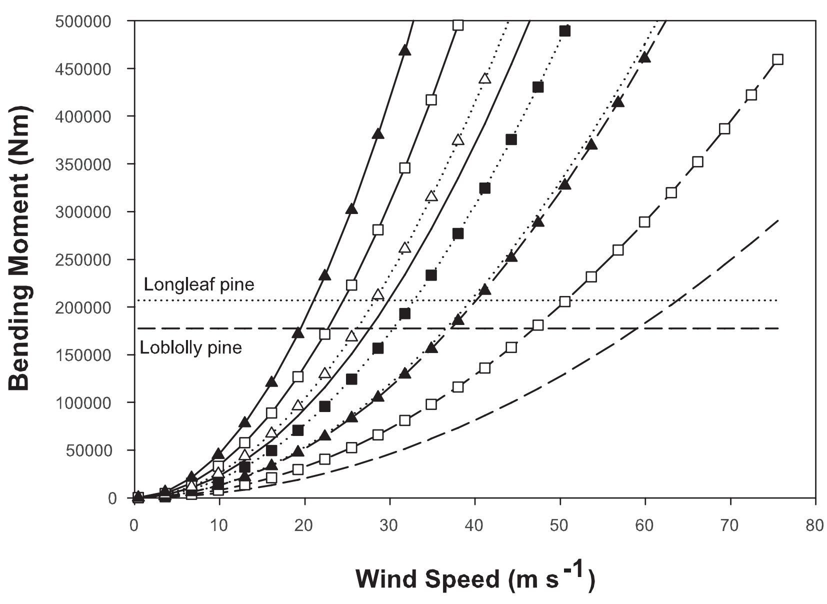

Figure 4—Bending moments of trees at the stand interior as a function of wind speed. Dashed, dotted, and solid curves represent 20-, 25-, and 30-m-tall trees; curves with no symbol are closed stands (tree spacing of 2.5 m); squares symbols represent semi-closed stands (spacing of 5 m); and triangles are open stands (spacing of 7.5 m). (Adapted from Stanturf and others 2007).

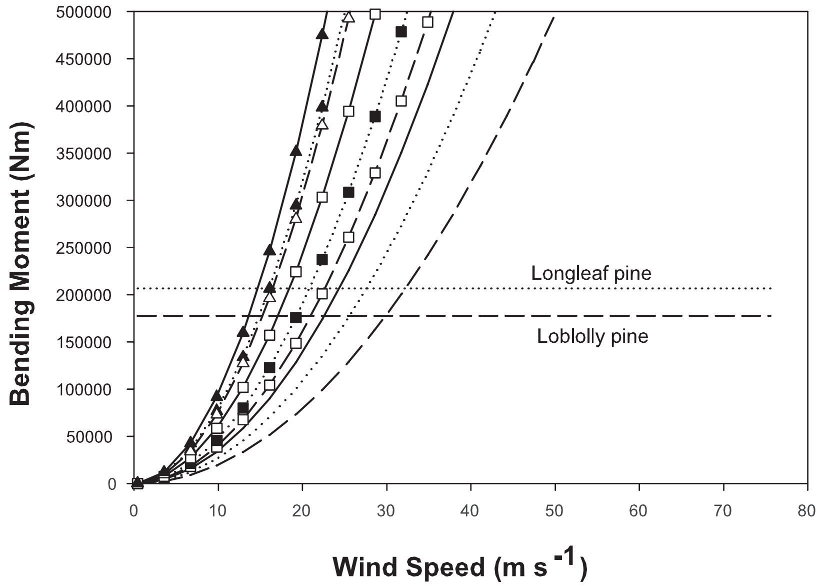

Figure 5—Bending moments of trees at the stand edge as a function of wind speed. Dashed, dotted, and solid curves represent 20-, 25-, and 30-m-tall trees; curves with no symbol are closed stands (tree spacing of 2.5 m); squares symbols represent semi-closed stands (spacing of 5 m); and triangles are open stands (spacing of 7.5 m). (Adapted from Stanturf and others 2007).

refinements will be needed to examine interactions among trees within a stand. Additionally, parametric uncertainty requires that distributions of the various input parameters for both the wind field model and the windthrow model will need to be developed in order to cast the wind-damage problem in terms of failure probabilities.

SUMMARY

This paper presents first steps in developing a framework for building wind-related threat assessment for southern forests. The first level, coarse-scale assessment tools (a hurricane wind climatology and GALES windthrow model) have been described. Next steps will involve improving the wind fields by adding of a three-dimensional boundary layer model to better capture the flow transitions that occur with landfall and topographic interactions. Extending the resource vulnerability component to include overturning as well as stem breakage will provide a broader view of forest vulnerability. Ultimately, the tools for evaluating event risk and resource vulnerability will be linked through a GIS to allow managers to plan and experiment with various management strategies.

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