A PROTOTYPE MODEL FOR ESTIMATING THE LOCATION OF FOREST DAMAGE FROM TROPICAL CYCLONES

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ABSTRACT:
The potential impact of tropical cyclones on forests varies due to forest and land conditions, along with recent management and weather activity, thus it is difficult to predict. To understand the potential damage to forests of the southern United States from a severe tropical cyclone several factors should be considered, including the forest's proximity to damaging winds and exposure along stand edges. A prototype landscape model was developed to relate tropical storms in the Northern Hemisphere, with counter-clockwise wind rotations, to the potential deposition of tree debris onto roads or utility rights-of-way. The model is based on wind speed, wind direction, storm direction, tree heights, and the juxtaposition of forests to stand boundaries, open areas, roads, and utility rights-of-way. The purpose of the model is to provide opportunities for land managers to visualize the potential location of forest damage and inform the development of debris removal and recovery plans. In addition, the model can facilitate the development of forest damage scenarios based on varying characteristics of tropical cyclones. We demonstrate the application of the model on Fort Stewart, Georgia.

Keywords: *Prototype model, forest damage, wind speed, tropical cyclones.*

1. INTRODUCTION

In the Northern Hemisphere, tropical cyclones develop over warm oceans in the tropical regions, are fueled by wind and heat energy, and can significantly disturb forested areas once landfall has occurred. Tropical cyclone activity along the coastal areas of the southern and eastern United States, while variable, is active, and the vulnerability of some coastal land areas to severe weather events is greater than others. *Bettinger et al.* (*2009b*) describes the inherent variation in intensity for storms affecting the Atlantic Ocean and Gulf of Mexico coasts. Land managers are not only interested in the potential of landfalling tropical cyclones directly striking their property, but they are also interested in understanding where trees may fall with respect to roads and utility rights-of-way that they must maintain or that provide access to other resources. A discussion of the biological and physical responses of forests to tropical cyclones has been presented in a few recent works (*Stanturf et al., 2007; Merry et al., 2009*); here we present a few salient issues. In general, the potential for tree fall is associated with some factors that we can model, such as the geographic position of forests in relation to the eye of the storm (*Armentano et al., 1995; Ayala-Silva and Twumasi, 2004; Hook et al., 1996; Brokaw and Walker, 1991*), tree characteristics (average height, diameter, etc.) (*Tanner et al., 1991*), soil conditions (*Grisez, 1954; Croker, 1958; Fraser, 1962; Trousdell et al., 1965; Mayer, 1987; Schaetzl et al., 1989*), tree species type (*Brokaw and Walker, 1991*), and topographic exposure (*Boose et al., 1994; Bellingham 1991*). Other important factors, such as the influence of recent

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weather or management activity (*Merry et al., 2010*), may be too variable and too unpredictable across broad areas to model.

In general, taller and larger trees are more susceptible to wind damage than shorter, smaller trees (*Boucher et al., 2005; Stanturf et al., 2007; Gresham et al., 1991; Gardner et al., 1992; Slater et al., 1995; Greenberg and McNab, 1998; DeGayner et al., 2005*), and taller trees are more likely broken than windthrown (*Touliatos and Roth, 1971*). Also, tree species type affects vulnerability to damage (*Barry et al., 1998*). For instance, in the southern United States baldcypress (*Taxodium distichum*) and live oak (*Quercus virginiana*) are relatively resistant to wind damage (*Duryea, 1997*) as compared to loblolly pine (*Pinus taeda*). It has been suggested that pine (coniferous) forests are more often damaged than hardwoods (deciduous forests) (*Stanturf et al., 2007*), yet researchers have also found that hardwoods are more often windthrown while pines are more often broken (*Hedlund, 1969; Van Hooser and Hedlund, 1969*). Further, tree taper, a ratio of total height to diameter, has been identified as an important factor in determining whether a tree might be damaged (*Petty and Swain, 1985*). Trees of a specific species characterized as having higher taper (fatter in the lower bole, and shorter in height) are more stable at certain high wind speeds than trees of the same species characterized as having lower taper (tall and thin) (*Petty and Swain, 1985; Mayer, 1987; Blackburn et al., 1988*). These relationships are not absolute, but provide a general guide as to the relative vulnerability of forests of the southern United States to severe wind events.

While we may be able to develop a risk assessment for forests based on these general relationships, the actual direction in which trees may fall is related to the direction of sustained, damaging winds. A tropical cyclone has a large, low pressure center that may be free of clouds and characterized as having sinking air flow which can become an eye. Along the edge of the low pressure center are the bands of strongest winds, and the distance from the geographic center of the storm to this point is commonly called the radius of maximum winds. When passing over land, trees within this radius could be subjected to forces from all directions, and thus may fall in any direction. Between the radius of maximum winds and the outer edge of the radius of damaging winds is an area of land where trees may be subjected to directional winds, and will likely fall in a predictable line or course. We define the outer edge of the radius of damaging winds (with respect to trees) as the point where wind speeds have decreased to about 58 knots (kt) (67 MPH). Trees that are exposed to 58 kt winds for more than 10 minutes are unlikely to survive (*Mayer, 1987*). Therefore, if the course and intensity of a storm (its track) is estimable, it is possible to model where trees may fall with respect to stand boundaries, open areas, nearby roads and utility rights-of-way. This issue is the central focus of this work.

Previous work related to the modeling of tree windthrow or breakage

The United Kingdom Forestry Commission has invested a significant amount of time and effort into the development of models for understanding the risk of forests to severe winds events. Although the type of wind storms typically encountered in the United Kingdom are different than those encountered in tropical regions, their mechanistic model, ForestGALES, can be used to estimate the critical wind speed required to overturn or break a tree, and to estimate the probability of windthrow or breakage of the average tree in a stand or small forest unit (*Gardiner et al., 2006; Gardiner et al., 2008, Elie and Ruel, 2005*). ForestGales is a stand-alone computer program that uses estimated drag coefficients based on aerodynamic roughness to estimate the critical wind speed necessary to break or windthrow a tree. The roughness of the canopy is a function of the average size of a tree crown and the average area occupied by a tree. A combination of critical wind speed and species-specific resistance thresholds results in a prediction of forest or individual tree damage. Initially, ForestGALES was developed for unthinned or lightly thinned coniferous forests of the United Kingdom (*Gardiner et al., 2000*), and has since been modified and applied to pine forests of southwest France (*Cucchi et al., 2005*), radiata pine (*Pinus radiata*) forests of New Zealand (*Moore and Quine, 2000*), and black spruce (*Picea mariana*), jack pine (*Pinus banksiana*) (*Elie and Ruel, 2005*), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca*) (*Achim et al., 2005*) forests of eastern Canada. Theoretically, this model can be applied to any region of the world where tree-pull data, which describes the force necessary to pull over a tree, is available for the dominant tree species in a stand (*Gardiner et al., 2008*). A combination of stand and species characteristics allows ForestGALES to derive morphological characteristics of the average tree in a stand, such as the weight of the crown and stem, and the dimensions of the tree canopy (*Gardiner et al. 2000*). However, the model assumes that the average tree is representative of the stand as a whole, which limits simulations to single tree species conditions (*Lanquaye-Opoku and Mitchell 2005*).

HWIND is a mechanistic model developed in Finland that can be used to predict the critical wind speed for tree damage given the tree species under consideration and local landscape conditions (*Peltola et al., 1999*). Thresholds of potential tree damage are estimated through both wind loading and gravitational force computations. Gravitational forces are based on the weight of the stem and crown of a tree, and snow accumulation can also be acknowledged. Previous research using the model has been performed on Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), and birch (*Betula pendula*, *Betula pubescens*) in Finland (*Peltola et al., 1999; Talkkari et al., 2000; Blennow and Sallnäs, 2004*). HWIND differs from ForestGALES in that HWIND focuses on damage to trees at the edges of stands, whereas ForestGALES focuses on damage to trees in the interior of a stand (*Gardiner et al., 2000*). *Talkkari et al*. (*2000*) found that local topography and wind conditions, particularly assumptions about gusts, were critical in determining the likelihood of the occurrence of the critical wind speed on a stand of trees. HWIND software has been developed as an ArcGIS extension (*Zeng et al., 2009*), and further modified as the WINDA model which includes a version of the HWIND model and the WASP airflow model (*Blennow and Sallnäs, 2004*).

Unlike the ForestGALES and HWIND models, which are generally applied to homogenous forest conditions, the FOREOLE model was developed for uneven-aged stands containing different tree species (*Ancelin et al., 2004*). FOREOLE is applied to individual trees within a stand, and does not rely on critical wind speed projections to determine damage. FOREOLE was designed to determine whether increasing wind speed can lead to incremental damage across a stand or whether the critical wind speed affects the entire stand at once. Forces are estimated at varying heights along a tree stem, and the force on a stand of trees is reduced the further one moves away from the edge and into the interior of the stand. The predicted wind profiles are a function of the total weight of the crown and the vertical distribution of stems. Thresholds for breakage and windthrow are determined by simulating stress on a tree stem at various height intervals, and comparing this stress to predetermined stress limits for specific species. With this information, forest damage is estimated for an entire stand of trees (*Ancelin et al., 2004*). A previous study compared model predictions found that in a comparison of models, predictions of windthrow using FOREOLE were comparable to those provided by ForestGALES, while predictions of breakage using FOREOLE were comparable to those provided by HWIND (*Ancelin et al., 2004*).

Schelhaas et al. (*2007*) describe the FORGEM wind model, which is linked to a tree growth and yield model. Here, a forest's resistance to wind damage is closely tied to the diameter of trees at breast height (1.37 m above ground). Wind loads on trees are represented by direction and average speed at a reference height in the forest canopy, and determined as if trees were located at edges. These mechanistic procedures are based on the HWIND model, and estimated windthrow and breakage are a function of thresholds for each tree species. In addition, FORGEM uses a wind gust factor that is based on a tree's distance from an edge, average tree density per unit area, and average tree height. FORGEM determines a gust factor based on trees that are between the individual tree being assessed and those upwind of it, and focuses on those trees that are taller than the tree being assessed. This process acknowledges the sheltering effects of upwind trees, and since wind loading is assessed on individual trees, indirect damage to adjacent trees can be incorporated into damage estimates. In contrast, HWIND utilizes mean tree height and average density for a forest as a whole in assessing a gust factor (Peltola et al., 1999). The FORGEM model has been used to estimate damage to Douglas-fir (*Pseudotsuga menziesii*) forests of different densities grown in The Netherlands (*Schelhaas et al., 2007*). In test scenarios, the height-to-diameter ratio (taper) was the most important variable, although stand density was also important in determining the likelihood of damage. Forests of higher density provided more shelter to trees inside the edges, reducing the probability that these would be damaged (*Schelhaas et al., 2007*).

The models discussed above focus on winds arising from a certain direction and placing forces on trees of given characteristics. The HURRECON model is larger in scope, and can be used to predict wind speeds based on tropical cyclone direction of travel, speed, eye diameter, maximum wind speed, and the surface type over which the storm is traveling (i.e., water or land). HURRECON was originally tested retrospectively on the 1938 New England (USA) hurricane and Hurricane Hugo (1989) where it affected Puerto Rico. The model predicts peak gust speeds, sustained wind direction and speed, and uses a simple topographic exposure model to take into account variations in topography (*Boose et al., 1994*). HURRECON has been used in forest damage risk analyses (*Boose et al., 2001*) to estimate gradients of forest damage at regional and landscape levels due to topographic exposure to predicted wind gusts.

Logistic regression and Classification and Regression Tree (CART) analysis have both been used to estimate damage arising from winds with a predominant direction (*Lindemann and Baker*, *2002*). In these efforts, topography (elevation, aspect) and land cover were important determinants in explaining variations in windthrow for high elevation forests in the southern Rocky Mountains of Colorado. Other factors that were incorporated into the models developed by *Lindemann and Baker* (*2002*) included soil conditions, distance to edges, and vegetation types. *Dobbertin* (*2002*) also used CART methods to determine the variables associated with the likelihood of wind damage to forested areas in Sweden. Artificial neural networks have also been used to assess the susceptibility of a forest to wind damage (*Hanewinkel, 2005; Hanewinkel et al., 2004*). An artificial neural network is a modeling approach that emulates how the human brain derives patterns, through a learning process that allows a network to determine relationships or correlations in information (*Pijanowski et al., 2002*). In order to effectively use artificial neural networks, multiple sets (perhaps years) of data are necessary to teach or inform the network. In modeling wind damage to forests, the required information might include the diameters and heights of the dominant tree species, tree species type, and topographic measures such as elevation, aspect, and slope. In each of these cases, extensive wind storm, forest, and topographic information is needed to assess the correlation between damage observed and potentially explanatory factors.

Motivation for this work

Given the 300-year management history of the southern United States, forest conditions are generally discontinuous and contain a variety of forest ages and tree structures. In other words, the forests are not characterized as a carpet of tall, old trees. If this were the case, it would simplify greatly the problem we are addressing. Therefore, given the patchwork of forest conditions distributed across a landscape, land managers in the southern United States are concerned about the potential debris-related issues associated with wind damage from severe storms. For many, the estimated return interval for damaging storms and the actual time that has passed since the last damaging storm have led to considerable concern on their part (*Bettinger et al., 2009c*). Therefore, the main goal of this research was to develop a prototype model for estimating the location of windthrown and broken trees that may be deposited on roads, open areas, and utility rights-of-way as a result of strong winds that accompany tropical cyclones. This represents a more specific analysis of windthrow and breakage than previous studies, and takes into account tree heights and relative differences in tree heights with respect to the direction of prevailing winds and potential effects on transportation and energy transmission infrastructure. Our approach to tropical cyclone wind analysis on a landscape scale evolved from a review of peer-reviewed and other scientific publications that analyzed the impacts of landfalling storms on forests of the southern United States. Our raster-based model is different from other models that analyze or provide real-time analysis of wind fields (e.g., *Powell et al., 2010*) in that wind relationships are simplified and the emphasis is placed on the damage to transportation and energy resources that would require immediate attention after the passage of a damaging storm. As *Peltola et al.* (*1999*) suggested, models such as these can serve as a means of identifying forested areas that are subject to particular levels of vulnerability, and we see our model as an advance along these lines.

2. MODEL DEVELOPMENT

The likelihood of damage to a forest from the winds of a tropical cyclone is related to a number of factors, including the proximity to the radius of maximum winds, ground conditions, and forest conditions. Translating this likelihood into a probability is nearly impossible, given the broad variability expressed in site-specific forest damage studies (*Merry et al., 2009*), and given the fact that some variables not recognized in site-specific research could also be important (*Merry et al., 2010*). While attempts have been made to relate potential damage to tree species present (*Barry et al., 1998; Williams et al., 1999*), we take a conservative approach and assume that when a severe storm passes over an area, some (or all) of the trees near roads or utility rights-of-way will fall or break. Therefore, it is these areas of concern that need to be identified. Our prototype model determines the Euclidean distance from the eye of the storm in relation to the radius of maximum winds, and the direction that the storm is traveling in relation to the forest resources situated on the landscape. Given a certain distance from the eye, the direction that they will likely fall, and the location and height of trees with respect to roads and rights-of-way, we can estimate the areas that may require tree-related debris to be removed.

Determining distance from radius of maximum winds

The estimated wind speed along a radial line outward from the center of a tropical cyclone is a function of the radius of maximum winds, the wind speed at the radius of maximum winds, and the rate at which these winds decline as one moves further away from the storm center. *Boose et al.* (*2001*) developed methods for estimating wind velocity and direction at any one point on a landscape that are based on the maximum sustained winds, the clockwise angle of the landscape point with respect to the storm center and forward motion, the forward velocity, and a few parameters related to the effects of friction and the shape of the wind profile curve. Assumptions regarding the distance outward from the eyewall (or radius of maximum winds) to which forest damage is likely are important in modeling the effects across the landscape. Winds damaging to forests in ways that result in windthrow or breakage have been estimated to be, at a minimum, 26 m s^{-1} (*Boose et al., 2001*) or 30 m s^{-1} (*Mayer, 1987*), although resistance varies by tree species (*Barry et al., 1998*). Therefore, as we noted earlier, we define the radius of damaging winds (with respect to trees) as the point where wind speeds have decreased to about 58 knots (kt) (67 MPH). Early work by *Jordan et al.* (*1960*) suggested that the strongest wind speeds were found at about the same distance from the eye in all directions, however more recent work by *Blake et al.* (*2007*) suggests otherwise. In the Northern Hemisphere, the right front quadrant of a tropical cyclone has been determined to be an area where the heaviest tree damage will likely occur (*Armentano et al., 1995; Doyle et al., 1995; Mayfield et al., 1994; Pearson and Sadowski, 1965*). For our modeling purposes we use a circular representation of the direct hit zone (the area of forest likely to be damaged), rather than an elliptical representation suggested by *Blake et al.* (*2007*), recognizing that this assumption may lead to conservative estimates of forest damage.

Determining direction of windthrow or breakage

Although the relationship between tree windthrow and breakage orientation and sustained wind direction may be complex, in general, trees (or pieces of trees) tend to fall in the direction of the sustained, applied force. Therefore, if sustained winds are strong enough to cause windthrow or breakage, one should expect that damage over larger areas will reflect that sustained wind direction (*Boose et al., 1994*). However, the direction of the damaging winds can change during the passage of a tropical cyclone, particularly in areas of close proximity to the radius of maximum winds. The topographic model described by *Boose et al.* (*1994*) classifies each point on a landscape as either protected or exposed, depending on a calculated wind shadow, which involves assessing the inflection of air streams as they pass over land. In contrast to the topographic model presented in *Boose et al.* (*1994*), our model examines tree height differences of adjacent landscape features to determine where tree damage is likely to occur if trees fall outside of their stand's boundary. We focus primarily on debris falling on to roads, powerline rights-of-way, and open areas as these areas will be of primary importance to emergency management personnel and forest managers for clearing debris immediately following the passage of a severe storm.

3. METHODS

In our prototype model, analyses are performed in a raster database environment. Because many of the input databases were originally stored as vector data, we converted each to a raster database using a 5 m spatial resolution. The procedures were developed using the Python programming language, and the program was designed to operate in ArcGIS 9.3.

Wind direction is determined in a manner similar to *Boose et al.* (*1994*) focusing on eight cardinal directions in relation to the storm track direction. The counter-clockwise rotational direction of the storm is accounted for using a Euclidean direction function and the azimuth of the storm track. Unlike *Boose et al.* (*1994*), this prototype model does not weight damage in the right front quadrant of the storm. We use an irregular kernel moving window to weight raster cells by the windthrow direction derived from the azimuth of the storm track line and its relationship to the counter-clockwise rotational direction of the tropical cyclone. Our model assumes that tree damage within a radius of maximum winds will be uniform. However, beyond this radius, we model treefall as a function of the location of a stand of trees in relationship to the storm category, the radius of maximum winds, and the user-defined storm track. The radius of maximum damaging winds is determined through linear regression analysis using historical storm data including windspeed, radius of maximum winds, and storm category (*Pennington et al., 2000*). A relationship is derived between the average distance from the eye of the storm to the radius of 50 knot (kt) (67 mph) winds. This approach was chosen for the prototype model rather than one that required users to assume the shape of a wind profile. Through the linear regression analysis, a relationship develops where the wider the radius of maximum winds, the wider the radius of damaging winds, which is incorporated into the model using the outer edge of the radius of damaging winds to determine the distance from the radius of maximum winds where damage will occur.

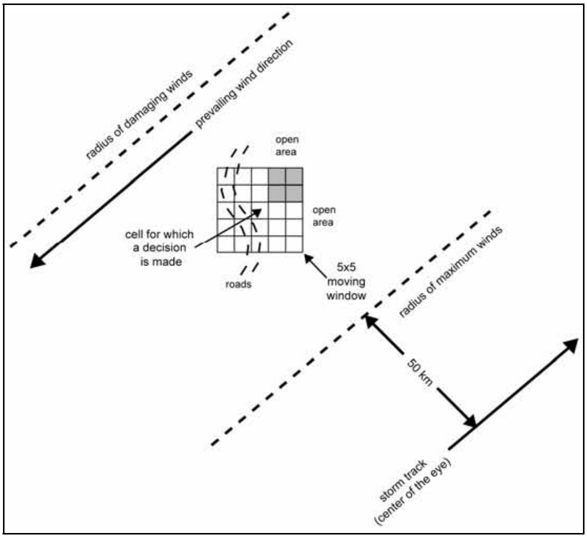

Fig. 1 Conceptual description of the model.

Our model uses a set of seven moving window kernels with a 5 m spatial resolution to identify trees (raster cells) that are within the appropriate windthrow and breakage direction (**Fig. 1**). We use seven moving window sizes because our case study maximum tree height database is 35 m, these window sizes easily can be modified to fit local site conditions. The smallest kernel file is 15 x 15 m (3 x 3 cells) and is used to determine whether any 5 m (16 foot) tall trees are within 5 m of the centroid of the window. If the center cell of this kernel file is an open area, road, or powerline right-of-way, and if any forest in the appropriate wind direction has trees 5 m or greater, the center cell is noted as one that will potentially be a location of downed trees. The largest kernel file is 45 x 45 m (15 x 15 cells) and is used to determine whether any 35 m (115 foot) tall trees are within 40 m of the centroid of the moving window. The differential kernels allow the model to query the spatial databases to estimate whether trees of the maximum height observed on our test site may be within their height-distance from the open area, road, or right-of-way. We chose a 5 m tree height increment as a compromise between processing efficiency and data accuracy. The results of these moving window assessments are used to identify potential areas of downed trees following a tropical cyclone. These areas are then spatially overlaid on roads and powerlines to identify specific locations of debris. Below we provide an example application of our model to the Fort Stewart military installation (Georgia).

4. CASE STUDY

The Fort Stewart military installation (**Fig. 2**) is located in southeastern Georgia, just west of Savannah, and its eastern edge is only about 32 km (about 20 miles) from the Atlantic Ocean coastline. The installation contains 113,099 ha (279,463 acres) of forest, range, military maneuver areas, and impact areas in addition to the main cantonment adjacent to Hinesville, GA.

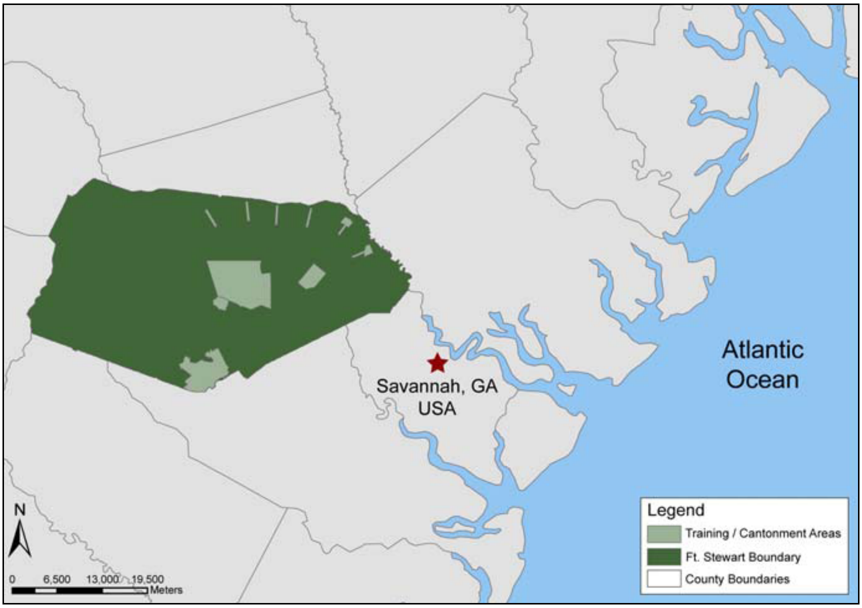

Fig. 2 Location of Fort Stewart military installation.

The installation plays an important role both in the mission of the United States Army (for training and maintaining readiness and rapid deployment of forces throughout the world), and in providing one of the largest areas of longleaf pine (*Pinus palustris*) forestland in the southeastern United States. In addition, Fort Stewart supports a large population of federally listed red-cockaded woodpecker (*Picoides borealis*).

Because the red-cockaded woodpecker is a cavity nester, it is vulnerable to the loss of nest trees resulting from wind damage and breakage (*Stanturf et al., 2007*). Between 1851 and 2006, three major tropical cyclones (Category 3 to 5 hurricanes) have directly struck the coast of Georgia, along with twenty Category 1 and 2 tropical cyclones. The estimated return period for a major storm directly striking the Savannah area is roughly 34 years, yet the last one to do so was over 150 years ago. Further, the estimated return period for any type of a tropical cyclone directly striking the Savannah area is 8 years, yet the last one to do so was almost 30 years ago (*Bettinger et al., 2009a*). Therefore, it is important to understand the potential extent of forest damage to the forest and wildlife resources, and to understand the extent of tree debris deposited on roads and utility rights-of-way in order to facilitate timely access to the ranges, military maneuver areas, and impact areas.

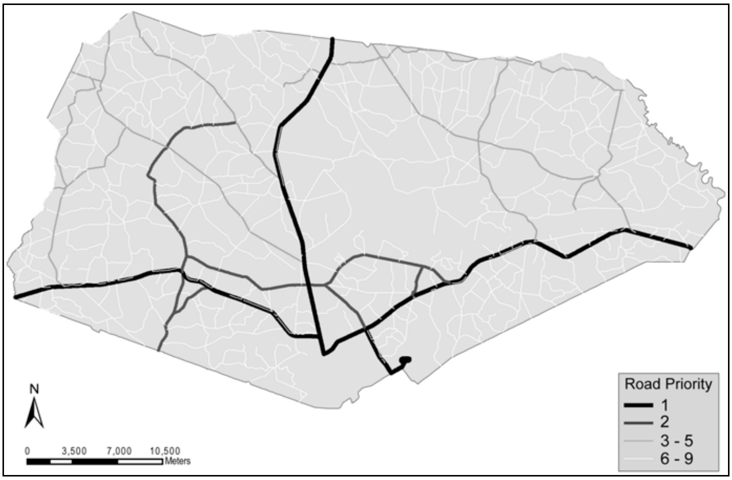

Fig. 3 Prioritized roads of Fort Stewart military installation.

On the military installation, there are nearly 1,400 km of state and federally-administered roads. Of these, a priority has been established (**Fig. 3**) that is based on needs regarding the training and readiness of military personnel. In addition, outside of the cantonment area, there are nearly 154 km (95.5 miles) of utility rights-of-way (powerlines) that would be of high concern should tree debris fall in their direction during a severe wind storm (**Fig. 4**). Should a severe tropical storm, one with wind speeds greater than about 58 knots (kt) (67 MPH) pass over or near this area, one would expect that tree debris from windthrow or breakage processes would be deposited on these resources. While the risk of tree damage may be related to tree characteristics, soil conditions, recent weather activity, and recent management activity, the probability of damage based on these variables is unknown at this time. Therefore, our prototype model was designed to illustrate areas of potential tree deposition based on one tree characteristic (height), the proximity of roads and utility rights-of-way to trees, and the storm direction and intensity.

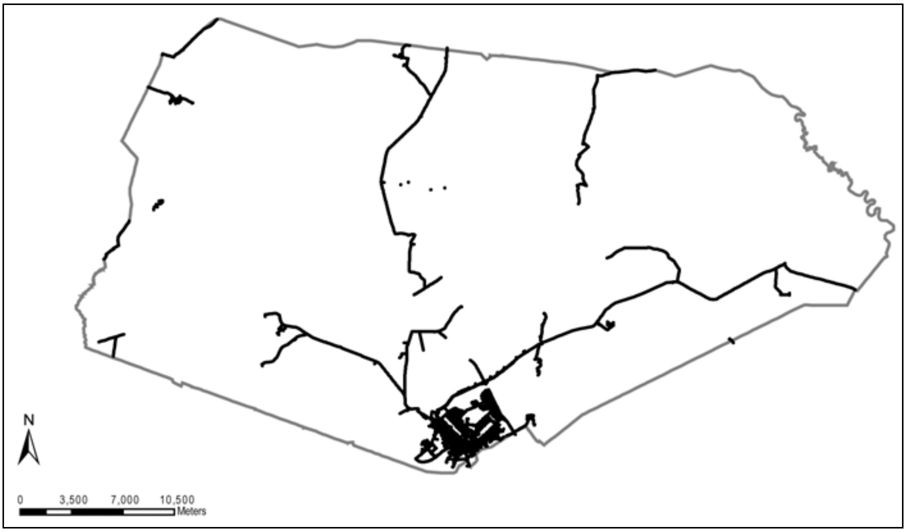

Fig. 4 Above ground powerlines of Fort Stewart military installation.

As an example, if one were to imagine a severe storm travelling directly west (270° azimuth) and passing 50 km or so north of the installation (**Fig. 5**), trees within the radius of maximum winds will likely be windthrown in all directions since a relatively equal force will be applied on them in all directions (from the north as the storm approaches, from the south as the storm passes, etc.).

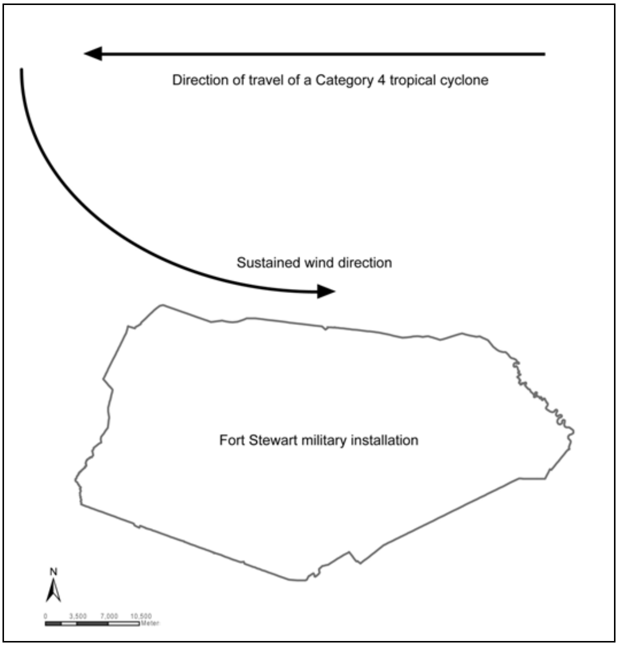

Fig. 5 Example of sustained wind direction in relation to the storm track

However, for forests outside the radius of maximum winds, yet within the radius of damaging winds, the greatest wind forces applied will generally be from the west, given that cyclones rotate counter-clockwise in the Northern Hemisphere. In these cases, we would need to know the direction of the sustained damaging winds in relation to the direction the storm is moving. This is computed using standard trigonometry relationships. In this simple example, the maximum sustained winds are moving on a 90° azimuth (situation A in **Fig. 6**).

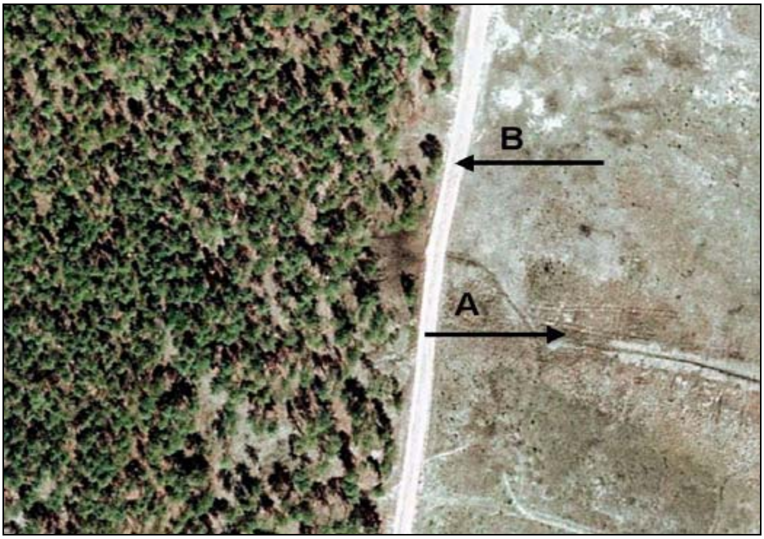

Fig. 6 Example of the direction of debris fall.

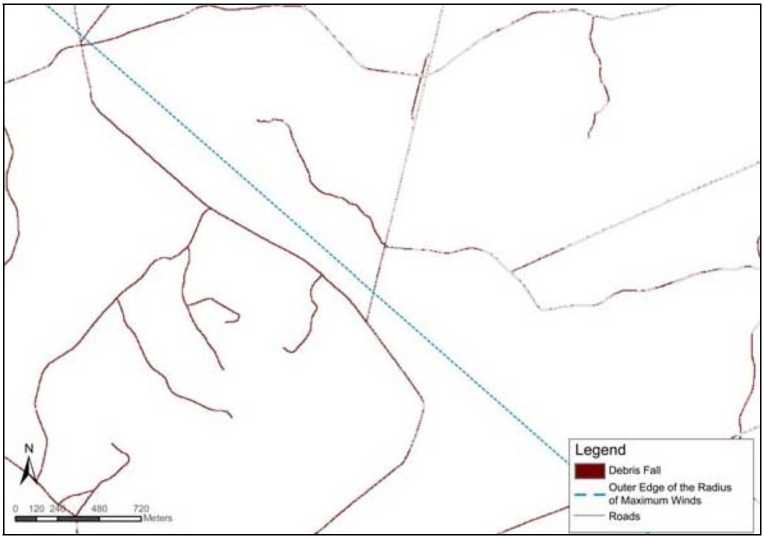

Fig. 7 Example of areas affected by potential tree debris following a tropical cyclone.

Given the height of the trees in the forest near the road, and the distance to the road, we then determine, in 5 m intervals, whether a chance exists that trees of the given height will fall on the road. If so, those areas are noted and communicated through a raster GIS database (**Fig. 7**) as areas of potential concern with respect to tree debris (boles, limbs, tops) from windthrow or breakage processes. Situation B in **Fig. 6** illustrates the case where a storm is traveling on a 270° azimuth south of the installation, yet the installation is outside the radius of maximum winds and inside the radius of damaging winds. Therefore, we would expect that the sustained damaging winds would be moving along a 270° azimuth. In this case, the trees would likely fall inside the forest and not on the adjacent forest road.

5. DISCUSSION

After addressing immediate health and safety concerns, a main resource management concern following the passage of a severe tropical cyclone over forested areas will be to clear prioritized roads and utility rights-of-way. For example, in our case study, roads were prioritized for military training activities and would need to be cleared quickly following a tropical cyclone. A subsequent step in the disaster recovery process, after determining *where* the debris-prone areas of roads and powerlines lie, would be to determine *when* to clear these resources of debris and restore the areas to their normal function. The development of an optimal recovery plan would ideally use shortest path algorithms to provide guidance for efficiently addressing the prioritized debris clearing. *Dror et al.* (*1987*) and *Chernak et al.* (*1990*) have described approaches for similar problems, yet what makes using a shortest path algorithm in determining an optimal recovery plan is the variable rate of speed (clearing vs. simply driving along cleared roads), the open-ended nature of the road system, and the priority system used to identify the roads and right-of-ways following a tropical cyclone.

Our model is a prototype method for determining roads, open areas, and utility rights-of-way that may need attention after the passage of a tropical cyclone. Some assumptions we have made may need refinement or may require further consideration prior to becoming an effective decision support tool. One of these involves topography.Modeling the movement of wind around a geometric solid is difficult as *Boose et al.* (*1994*) noted, and becomes even more complex when topographic conditions are acknowledged.

However, in the development of our model, we concentrated in an area of the southeastern United States (the Coastal Plain) where topographic changes are insignificant, since we showed earlier (*Bettinger et al., 2009a*) that tropical cyclone strength decreases by about one Saffir-Simpson category for each 50 km band inland. Elevation changes, in fact, are on the order of about 10 m per every 10 km inland. Further, when the location of a tropical cyclone moves inland, storm conditions and characteristics change. However, in our landscape simulations, storm conditions were assumed to be constant because we are interested in the effects on specific forested areas, which collectively may be no wider than about 40-50 km. Finally, maximum wind speeds at low-level elevations are usually situated near the storm eye wall, in the right-front quadrant relative to the movement of the storm, and one would expect higher levels of forest damage in these areas. These situational differences were not acknowledged in the prototype model described here, but are planned for future model enhancement efforts.

6. CONCLUSIONS

Although predicting the location and extent of forest damage as a result of tropical cyclones is difficult, simplified models such as the prototype we described here can be of value to foresters and natural resource managers in their effort to estimate the likelihood of damage across a broad landscape. The direction of sustained damaging winds will vary according to the path of a storm and the distance from the storm center. While producing a conservative estimate of the location of tree debris, our approach can be used to prioritize road and right-of-way clearing efforts as well as timber salvage efforts following a tropical storm. The prototype model has the potential and flexibility to be used in any area of the Northern Hemisphere with a few minor adjustments (coordinate and projection systems assumed, etc.). In general, the prototype model presented here provides reasonable spatial estimates of the potential debris deposition risk for varying forest and storm conditions. The model can therefore be employed in the development of risk analyses or response plans.

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