Tree damage risk factors associated with large, infrequent wind disturbances of Carolina forests

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Summary

Past studies of large, infrequent wind disturbances have shown that meteorological, topographic and biological factors interact to generate complex damage patterns, but have left open the extent to which these limited past findings are representative and can be used to predict future damage. We present a multi-scale, comparative analysis to examine how risk factors change over spatial scales and to evaluate the consistency in risk factors associated with three major wind events: a North Carolina Piedmont tornado of 1988, Hurricane Hugo of 1989 and Hurricane Fran of 1996. Our results reveal that the risk factors that best explain variation in damage vary with scale of observation. Tree size and species explain damage variation at the stand scale; topographic, site and stand factors explain damage variation at the landscape scale and wind speed and precipitation explain damage variation at the regional scale. However, it is possible to integrate these factors by incorporating factors from the finer scales into coarser-scale studies. We also found distinct differences in the damage caused by the hurricanes relative to the tornado, and to some extent consistency between hurricanes.

Introduction

Large hurricanes and other catastrophic wind events such as tornados and severe downbursts are major natural disturbance agents impacting forests of the eastern United States as well as those of many other areas of the world. They often cause severe though highly variable tree damage across the affected landscape (e.g. Frelich and Lorimer, 1991; Peterson and Pickett, 1991; Walker *et al.*, 1992; Foster and Boose, 1994; Webb, 1999; Kramer *et al.*, 2001; Harcombe *et al.*, 2002; Woods, 2004; McNab *et al.*, 2004). It has been well documented that various meteorological, topographic and biological factors interact to influence the patterns of damage (e.g. Bellingham, 1991; Boose *et al.*, 1994, 2004; Coutts and Grace, 1995; Everham and Brokaw, 1996; Bellingham and Tanner, 2000; Peterson, 2000, 2004; Ruel, 2000; Ulanova, 2000; Canham *et al.*, 2001; Papaik and Canham, 2006; Rich *et al.*, 2007), yet it is unclear the extent to which these previous

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findings are broadly representative and can be used to predict future forest damage.

Wind-induced tree damage is difficult to predict for several reasons. First, wind intensity varies greatly among different types of windstorms, as well as spatially and temporally during an event. Complex air flows and tremendous variation in wind gusts during storms often make it difficult to accurately determine wind intensity. Second, the predictive power of a given factor may change with wind speed during an event or among different wind events (e.g. hurricanes *vs* tornados). Although several researchers have specifically examined major damage factors in various forests, the spatial and temporal variation of these risk factors has not been well studied. Third, catastrophic wind events are never precisely replicated.

To predict damage risk, we must have a sound understanding of (1) the magnitude of damage risk factors and their consistency among wind disturbance events, (2) the interaction of factors in controlling patterns of damage severity and (3) the relative roles of the different factors at different spatial scales. Although the importance of a comprehensive study of factors determining tree damage and the dynamics of recovery has long been recognized, to date few studies have examined the interactions of various factors across spatial scales, and even fewer studies have compared the consistency of risk factors among different windstorms (but see Glitzenstein and Harcombe, 1988; Foster and Boose, 1992; Boose *et al.*, 1994; Peterson and Rebertus, 1997; Peterson, 2000).

Carolina forests experience occasional intense wind events. Historically, hurricanes and tornados have been the major natural disturbance factors causing serious forest damage. Hurricane Hugo in 1989 caused substantial tree damage and mortality in parts of South Carolina and adjacent North Carolina. Since 1900, nine hurricanes have passed through central North Carolina (Barnes, 2001). Hurricane Fran in 1996 was the most destructive hurricane of the past century to visit the North Carolina Piedmont region. The total timberland damaged by Hurricane Fran for North Carolina was estimated as 3 332 960 ha (Doggett, 1996).

We present a multi-scale, comparative analysis to evaluate the consistency in damage risk factors associated with Hurricane Fran and two other major wind events that occurred in Carolina forests in the late 1980s: a tornado that caused significant damage to Umstead State Park in central North Carolina (1988) and Hurricane Hugo (1989). The goal of the present study is to better understand the roles of various meteorological, topographic and biological factors in determining damage risks at three spatial scales: the stand scale (<1 km), the landscape scale (<10 km) and the regional scale (~100 km). At the stand scale, we focus on the relationship between tree damage and tree characteristics: size, species and growth rate. At the landscape scale, we examine the influence of stand age, height, basal area, density, site exposure, relative topographic position, elevation, slope and aspect on damage severity. At the regional scale, we examine the influence of wind speed, precipitation, pre-disturbance species composition and proximity to the hurricane path.

In this study, we investigate the consistency of damage risk factors among storms as well as their interactions to address the following two questions: (1) What are the relative contributions of wind speed, precipitation, topography, site factors, pre-hurricane community attributes and tree characteristics (species, size and growth rate) in determining tree damage risk at scales ranging from a forest stand to a region? (2) Are the damage risk factors consistent among windstorms? We compare the risk factors that predict tree damage resulting from Hurricane Fran with the factors we found to be important for predicting tree damage resulting from Hurricane Hugo and the Umstead tornado.

Methods and background

We used five datasets in this multi-windstorm, multi-scale comparative study of tree damage risk. Two of the five datasets are stand-scale studies, one is landscape-scale analysis and another two are regional studies. The first stand-scale dataset includes a set of long-term tree-census plots located in or near the Duke Forest. Many of these plots were significantly damaged by the intense winds of the 1996 Hurricane Fran. The second stand-scale dataset contains stand and tree damage information from a field survey in 1989 after a severe (F4) tornado damaged forests of Umstead State Park in Wake County, North Carolina. We also conducted risk factor analysis among the tree-census plots across the Duke Forest (referred to as landscape scale). The first regional-scale dataset contains results of a statewide forest damage survey conducted following Hurricane Fran by Coleman Doggett of the North Carolina Department of Environment and Natural Resources. The second regional-scale dataset includes a total 2351 forest inventory plots with data from before and after the 1989 Hurricane Hugo distributed across South Carolina and maintained by the US Forest Service Forest Inventory and Analysis (FIA) programme.

Duke Forest and Hurricane Fran

The Duke Forest is located near the south-eastern edge of the Piedmont Plateau in Orange and Durham Counties, NC, USA (~ 35° 52′ N, 79° 59′ W; Figure 1). Much of the forest exhibits rolling terrain with elevation ranging from 85 to 250 m. The forest is floristically diverse with over 80 native tree species identified (Xi *et al.*, 2008). Prominent stand types include even-aged successional loblolly pine (*Pinus taeda*, biological nomenclature follows Kartesz 1999) forest (~80 to 100 years old), mature, uneven-aged upland deciduous forest and mature lowland alluvial hardwood forest (Peet and Christensen, 1980; Palmer *et al.*, 2007). The Duke Forest database contains both stand-scale and landscape-scale tree damage and mortality information.

On 6 September 1996, Hurricane Fran struck Durham and Orange counties of the North Carolina Piedmont causing significant damage to the Duke Forest. Hurricane Fran's eye passed ~24 km east of the Duke Forest, and maximum sustained surface wind (as measured at Raleigh–Durham International Airport, the nearest official weather station to the Duke Forest) was ~26.8 m s^{-1} with maximum wind gusts of 31.6 m s^{-1} (Figure 2a).

Hurricane Fran brought heavy rainfall along its path. Total rainfall at Raleigh–Durham International Airport was 224 mm during the storm period. In addition, the Duke Forest received nearly

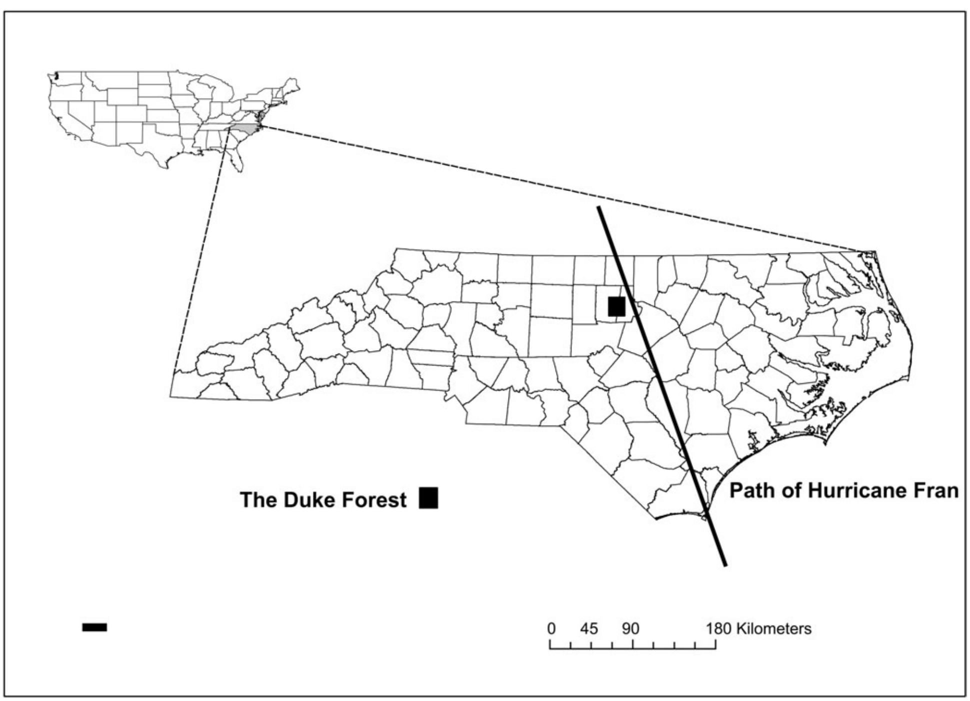

Figure 1. The location of the Duke Forest and the path of the 1996 Hurricane Fran in North Carolina, USA.

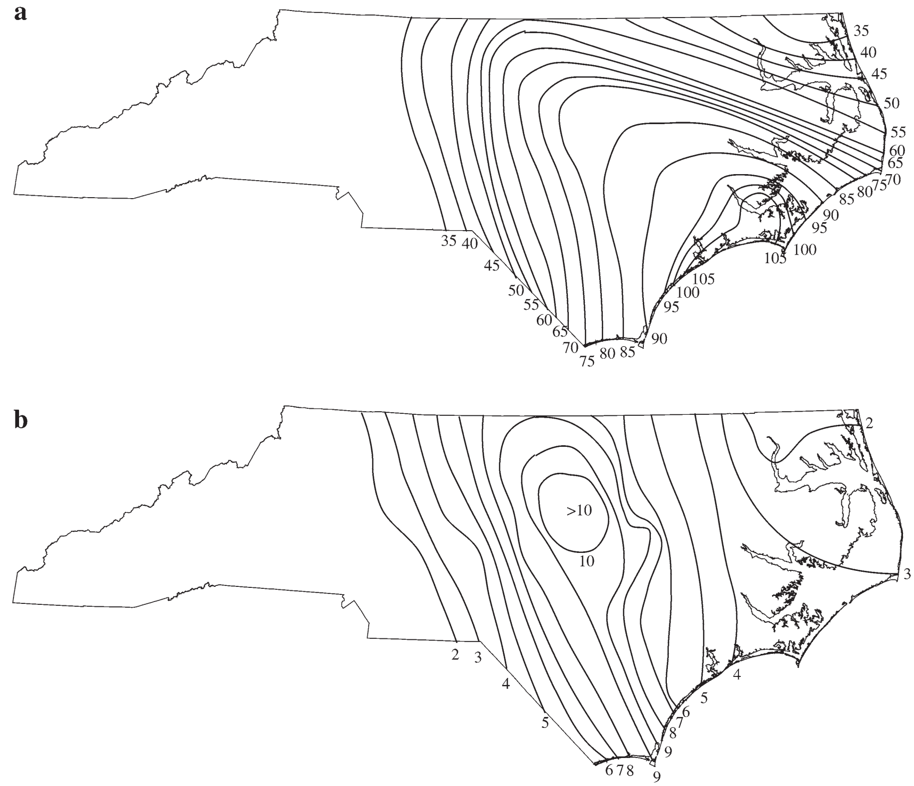

Figure 2. (a) Estimated maximum sustained wind speeds across North Carolina during Hurricane Fran. Wind speed data are from Joel Cline, US National Weather Service. Isobars indicate wind speeds intervals of 5 mile h^{-1} (=2.24 m s^{-1}). (b) Map of precipitation across North Carolina during Hurricane Fran. Precipitation data are from Joel Cline, US National Weather Service. Isobars indicate precipitation intervals of inches.

76 mm of rainfall 2 days prior to Hurricane Fran and another 51 mm immediately afterward. Overall, this forest region experienced ~423 mm rainfall total for September 1996, the highest ever in a single month since 1908 (Figure 2b).

The Duke Forest contains series of long-term tree monitoring plots distributed across a range of forest types, including 34 permanent sample plots (PSPs, 0.04–0.1 ha) and 8 mapped forest permanent plots. Information was recorded for all woody stems ≥2.5 cm diameter at breast height (d.b.h.) (≥1 cm after 1978), including d.b.h., height and condition. In addition, three hardwood plots (4047 m^2 in size) located in the Hill Experimental Forest (Durham County, NC, USA) were included in the study. The size of the eight mapped forest permanent plots ranged from 5250 to 65 530 m^2. These mapped permanent plots represent three major forest types: successional pine forest 80–100 years old and approaching transition to hardwood dominance (Graveyard, Land's End), uneven-aged upland hardwoods (Bormann, Bryan Center, Oosting, Rocky, Wooden Bridge) and uneven-aged lowland alluvial hardwoods in the North Carolina Botanical Gardens (Big Oak Woods).

From May to October, 1997, the first growing season following Hurricane Fran, all 37 extant PSPs were resampled, as were five mapped tree plots. The other three mapped tree plots were resurveyed in the summer of 1998 as were the Hill Forest plots. Beside the conventional survey attributes (d.b.h., height, tree condition), hurricane-induced damage was assessed for each individual using four damage categories: uprooted, breakage, leaning and leaned on. All of the tree data were compiled and merged with the dataset from before Hurricane Fran. Site conditions including elevation, slope and aspect were measured for each PSP and the eight mapped plots.

The 1988 Umstead tornado

We used forest damage data from the 1988 William B. Umstead State Park tornado to compare stand-scale damage risk factors with those found in our hurricane damage analysis. Umstead Park is located in the North Carolina Piedmont between the cities of Raleigh and Durham, ~24 km east of the major study sites in the Duke Forest. Elevations range from 75 to 125 m.

On 28 November 1988, a series of thunderstorms traversed central and eastern North Carolina spawning several tornados. The strongest of these first touched down in Umstead State Park and carved a discontinuous corridor for 130 km through northern North Carolina. The tornado was rated F4 on the Fujita scale, indicating a high-intensity storm with winds ranging between 92 and 116 m s^{-1}. Throughout the majority of its track, however, including its passage through Umstead State Park, the tornado only rated F2 on the Fujita scale, indicating wind speeds of 50–70 m s^{-1} (National Climatic Data Center, 1988).

In the summer following the tornado, five sites were selected for study and 11 transects were established perpendicular to the tornado track, with two or three transects located in each site. Those transects were 10 m wide, and their ends were determined by the last tree that had sustained severe damage (i.e. snapped, partially snapped or uprooted). Within each transect, all trees with pre-tornado d.b.h. >4 cm were sampled. For each tree, species, d.b.h. and type of damage sustained (snapped, partially snapped, uprooted, pinned and leaning) were recorded.

Regional study of Hurricane Fran

To evaluate damage risk factors at a regional scale, we used a statewide survey of forest damage caused by Hurricane Fran obtained from the North Carolina Division of Forest Resources (Doggett, 1996). The impacted portion of North Carolina was first gridded into 16.09 km (10-mile) blocks over the 53-county area. Each grid intersection was located on the ground and a plot was established to document forest type and amount of tree damage. A total of 299 plots were collected in the survey. The plots consisted of the 20 trees nearest to the plot centre. Each was classified as uprooted, top completely removed, top broken or undamaged. Each plot was assigned to a damage-class code based on the percentage of trees in the plot that were uprooted or with the top completely removed. Information from the ground plot surveys was loaded into ArcGIS (the Geographic Information Systems by Environmental Systems Research Institute, Inc.), and a damage-class map was projected over the area.

The statewide wind speed and precipitation data associated with the hurricane were obtained from the North Carolina State Climate Office and the US National Hurricane Center. All available wind speed and precipitation data from weather stations were used to create maps of maximum sustained wind velocities and precipitation (Figure 2). The wind speed data and precipitation records were temporally and spatially interpolated, and then merged with the locations of the 299 tree plots to provide wind speed and precipitation estimates for each plot.

South Carolina forest damage from Hurricane Hugo

The second regional-scale database we used was the US Forest Service's FIA database consisting of permanent plots representing a random sample of forests across South Carolina. Hurricane Hugo made landfall on 22 September 1989, impacting forests in 17 South Carolina counties on the Coastal Plain and Piedmont (Gresham *et al.*, 1991). After Hurricane Hugo, the Forest Service conducted an additional sampling of all plots in the 17 counties most severely impacted by the storm in order to assess the impact on forest resources. Numerous variables are typically recorded for permanent FIA plots, including both tree and site variables. Each plot contains up to five sampling points, each of which is the centre for a subplot. The sampling design uses the Bitterlich method to sample all trees greater than 12.7 cm d.b.h. Trees between 7.62 and 12.7 cm d.b.h. are measured in circular plots with a fixed area of 13.5 m^2 (1/300 acre). For each tree in the 'plot', species, d.b.h., height, crown ratio, canopy position, presence of rot and other variables are recorded. Site data are collected and include soil texture, hydrology, if the site was planted and if it is a forest edge. In the sampling period following Hurricane Hugo, data specifically related to tree damage were collected, including presence of root damage, bole missing and per cent of crowing missing. In total, the dataset contains information on 29 397 trees from 2352 plots.

Wind speed data for Hurricane Hugo were obtained from the US National Hurricane Center. All available wind data from weather stations and reconnaissance aircraft were used as input for a hurricane model, creating maps of maximum sustained wind velocities for 3-h intervals (Powell *et al.*, 1991). We interpolated these datasets by overlaying the maps on one another and manually connecting the maximum wind in wind-speed isobars. This provides a map of maximum sustained wind speeds in 1-min averages. The wind speeds were digitized and merged with the locations of the FIA forest inventory plots to provide plot-specific wind speed and precipitation estimates.

Data analysis

Logistic regression, a multivariate technique that uses a logit function to predict the outcome of a dichotomous or polytomous response, was used for all five databases to identify the factors indicating significant risk of damage (e.g. Jalkanen and Mattila, 2000).

At the stand scale for the Duke Forest and the Umstead Park plots, a dichotomous logistic regression was used to identify possible risk factors for individual trees as a function of pre-hurricane tree size (d.b.h.) and species. Relative tree growth rate was also included in the Duke Forest analysis. For both damage models, the response variables were classified into severe damage *vs* light or no damage. For the Duke Forest plots, severe damage was defined as completely uprooted or loss of more than 90 per cent of the crown. We ran separate models for each species in each of the five mapped forest plots to examine their damage risk factors. Three mapped plots (Oosting, Wooden Bridge and Bryan Center) were excluded from this analysis out of concerns for unbalanced plot sizes (i.e. we excluded plots that were either too large or too small). For the Umstead Park plots, severe damage was defined as trees uprooted, snapped or partially snapped. Species were included in the models as dummy variables.

For the landscape-scale portion of the Duke Forest study, 22 pine PSPs with stand age and tree height were used for analysis, and plot-level damage severity was analysed as a function of stand age, density, height, basal area, elevation, aspect, slope and site exposure. The hardwood PSPs were not included in this analysis due to the limited number of survey plots. For the landscape-scale damage models, the response variable was plot-level damage severity, which was classified as light or no damage, moderate damage or severe damage. A polytomous logistic regression was performed at this scale. We assigned an 'integrated stem damage code' to each tree stem: 0 = no hurricane damage; 1 = crown loss 10–35 per cent, leaning over 10 per cent or bent and crown displace >10 per cent; 2 = partially uprooted, crown loss was 35–90 per cent, the tree was leaning but supported by other trees or pinned against another tree; 3 = completely uprooted, lost >90 per cent of the crown or was pinned to the ground. We weighted the code by multiplying by the stem relative basal area (i.e. the basal area of the stem divided by the stand basal area). We used the average value of the weighted 'integrated stem damage code' of all stems in a plot as an index of plot-level damage. The range of the stand damage index (SDI) was thus 0–3. We then assigned plot-level SDI values: light or no damage if $SDI \leq 1$, moderate damage if $1 < SDI \leq 2$ and severe damage if $2 < SDI \leq 3$.

At the regional scale, Hurricane Fran damage was modelled as the probability of plot-level tree damage as a function of stand age, mean d.b.h., ratio of pine to hardwoods, wind speed, rainfall and distance to the path of the hurricane. The response variable was classified into four damage levels based on the percentage of trees uprooted or with the crown completely gone: no damage or light damage = 0–25 per cent, moderate damage = 25.1–50 per cent, heavy damage = 50.1–75 per cent and severe damage = 75.1–100 per cent. Again, a polytomous logistic regression was performed for those multilevel damage responses.

Hurricane Hugo damage was analysed as the probability of severe tree damage as a function wind speed, species, tree architectural characteristics (height, crown ratio, canopy position, rotten bole, height–diameter ratio), site factors (soil texture, hydrology, forest edge, plantation) and community attributes (density, basal area). The response variables were classified into severe damage *vs* light or no damage. The severe damage was defined as trees that had exposed roots, a broken or twisted bole, a portion of bole missing or the trees had died. Multiple linear regression was used to assess the amount of variation in the data explained by the model and the relative importance of the independent variables. In this analysis, per cent crown missing was used as the dependent variable.

All logistic regression analyses were performed using the SAS PROC LOGISTIC function (SAS Institute Inc., 2003: http://www.sas.com). A robust, locally weighted scatter plot smoothing was performed using the LOWESS macro (with PROC LOESS) and a smoothed curve was plotted. The empirical log odds were also plotted for the logistic regressions using the LOGODDS macro (Friendly, 2000). For all the logistic regression analyses, non-significant interactions were removed using backwards selection with an $\alpha = 0.05$ significant level. Reduced models without interaction terms were created to facilitate interpretation of the variable responses. The multiple linear regression was performed using SAS PROC GLM (SAS Institute Inc., 2003).

Results

Risk factors for tree damage at the stand level

Due to the small extent of the areas sampled, tree characteristics and species are the only factors that can be analysed in stand-scale studies. In both the Duke Forest (Table 1, Figures 3–5) and the Umstead Park studies (Figure 6), tree d.b.h. was found to be a significant predictor of damage, with larger trees being more susceptible to damage. The pre-hurricane relative growth rate was not a significant predictor of tree damage in the Duke Forest study (Table 1).

Table 1: Logistic regression models of hurricane damage during Hurricane Fran in two pine stands and three hardwood stands in the Duke Forest

Variables	Parameter estimate	Standard error	Wald χ^2	$P > \chi^2$	
Even-aged successional pines					
Graveyard					
Pre-hurricane d.b.h.	0.0397	0.00584	46.2109	<0.0001	***
10-year relative growth	n/a	n/a	1.3465	0.2459	ns
Land end					
Pre-hurricane d.b.h.	0.0250	0.00709	12.4430	0.0004	***
10-year relative growth	n/a	n/a	0.1177	0.7315	ns
Uneven-aged upland hardwoods					
Bormann					
Pre-hurricane d.b.h.	0.0423	0.0043	98.4993	<0.0001	***
10-year relative growth	n/a	n/a	0.7446	0.3882	ns
Rocky					
Pre-hurricane d.b.h.	0.0831	0.0096	75.1505	<0.0001	***
10-year relative growth	n/a	n/a	1.4185	0.2337	ns
Uneven-aged lowland alluvial hardwoods					
Big oak woods					
Pre-hurricane d.b.h.	0.0250	0.0100	6.2473	0.0124	*
10-year relative growth	n/a	n/a	0.4425	0.5059	ns

Tree damage was examined as a function of pre-hurricane d.b.h. and relative tree growth rates. ***$P \leq 0.001$, *$P \leq 0.05$, n/a = not applicable, ns = not significant. The 10-year relative growth is defined as the diameter increase of ~10-year period divided by the previous tree diameter.

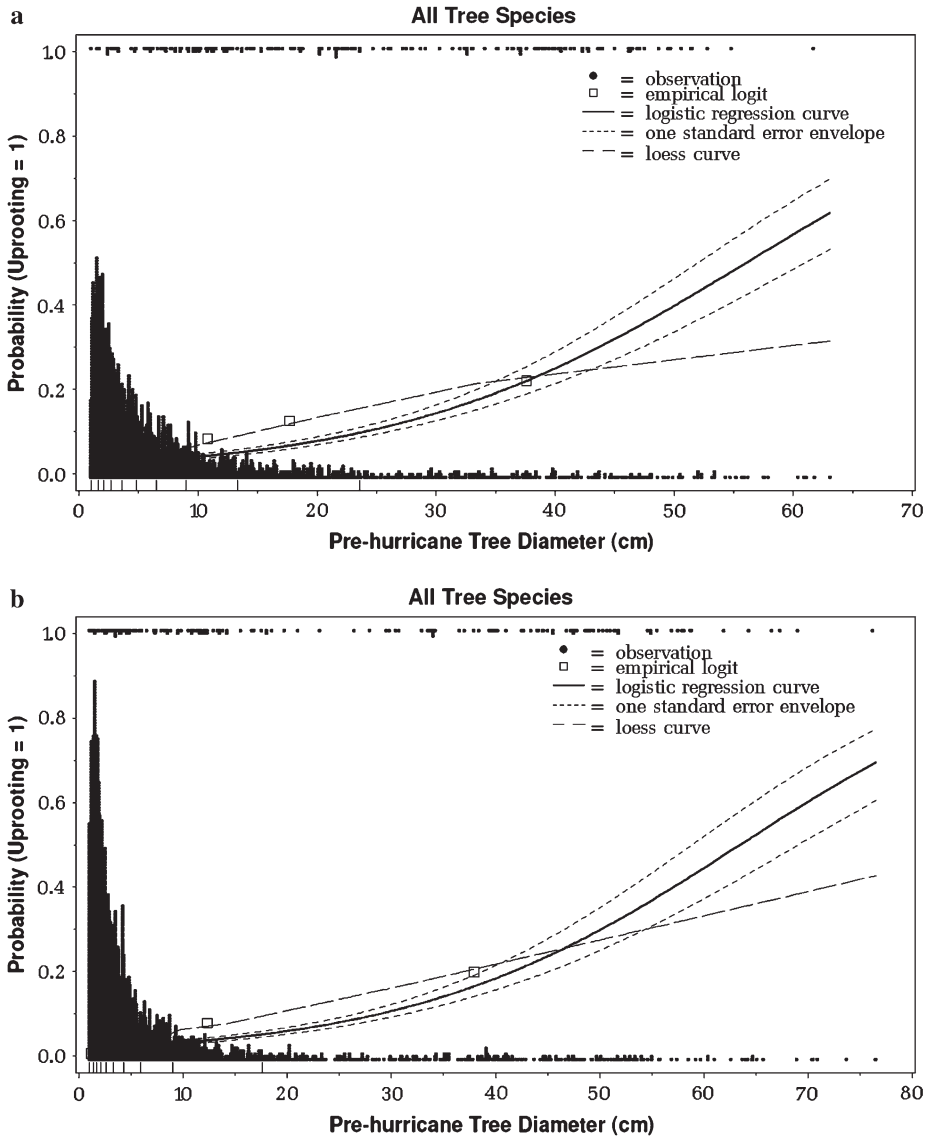

Figure 3. The probability of a tree uprooting increased with increases in tree size in (a) the graveyard plot and (b) the Bormann plot. Empirical log odds and the probability for uprooting increased as a function of pre-hurricane tree size. The observed responses are plotted as stacked points at the top (i.e. uprooting) and bottom of the figure (i.e. no such type damage). The squares show the empirical sample logits and the analogous adjusted sample probability. The curves on these plots show predicted probabilities and 95 per cent confidence bands.

In addition to tree size, species differed in their damage probabilities in both the Duke Forest and Umstead studies. In the Umstead study, species showed a hierarchy in damage probability with *P. taeda* at the high end, through *Liquidambar styraciflua*, *Quercus* spp. and *Fagus grandifolia*, to *Liriodendron tuliperfera* at the low end. Interactions between species and d.b.h. demonstrated

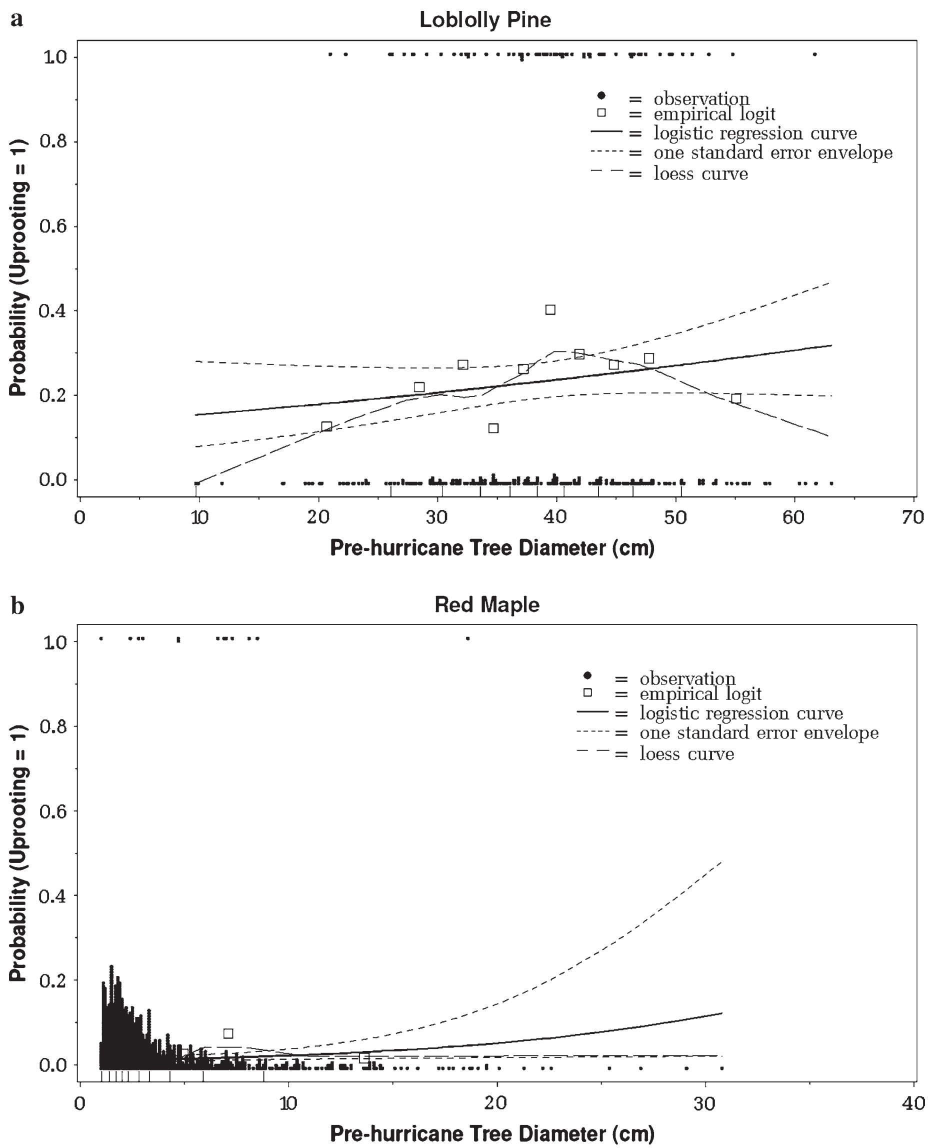

Figure 4. The probability of (a) loblolly pine and (b) red maple uprooting during Hurricane Fran in the graveyard plot of Duke Forest increased with increasing tree size (d.b.h.). Interactions between diameter and species showed that rate of increase with diameter varies among species. Results for other species are available from the senior author upon request.

that the rate of increase in damage probability varied among species (Figures 6).

The Duke Forest study showed similar patterns, although the overall damage probabilities were lower. In the Graveyard plot during Hurricane Fran, the dominant *P. taeda* experienced a high level of uprooting, whereas the younger, sub-canopy *Acer rubrum* sustained much less damage. *Oxydendrum arboretum* particularly experienced a high level of uprooting, presumably due to its

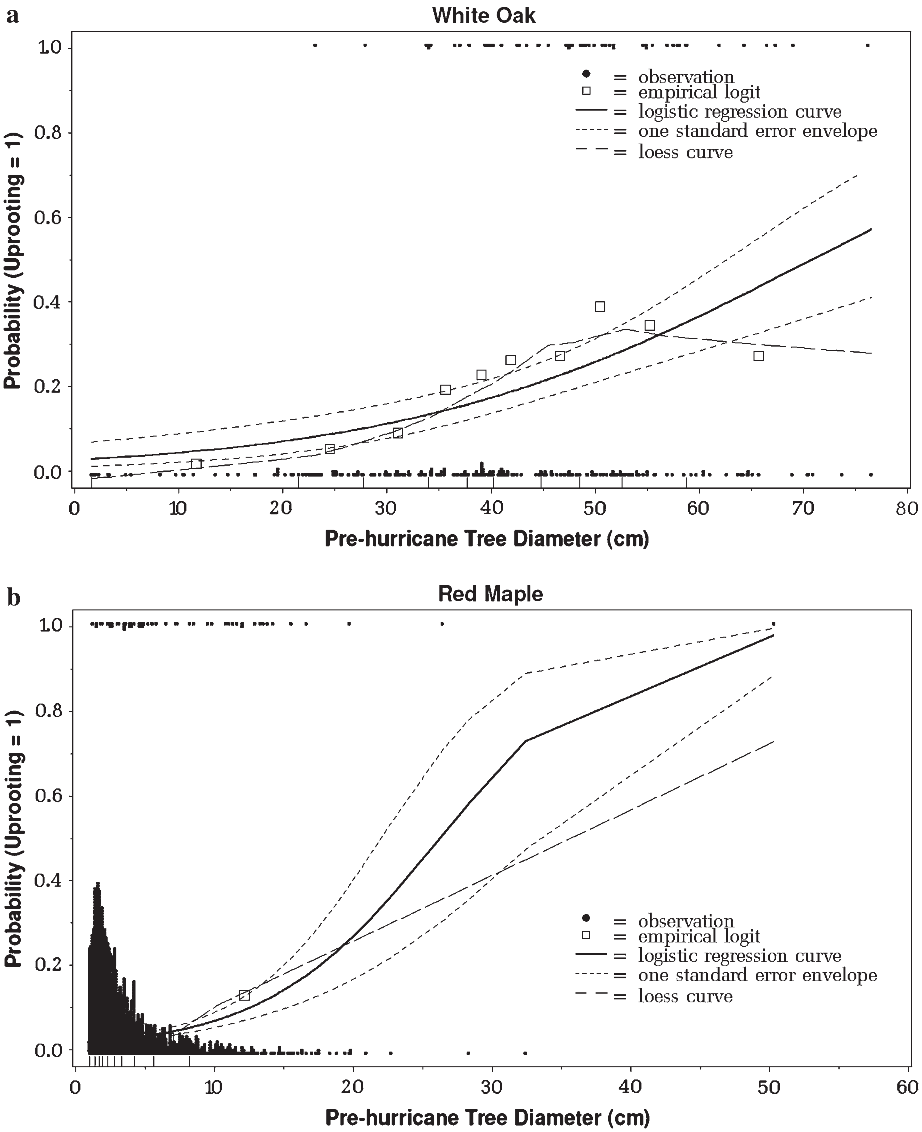

Figure 5. The probability of (a) white oak and (b) red maple uprooting during Hurricane Fran increased with increasing tree size (d.b.h.) in the Bormann plot in Duke Forest. Results for other species are available from the senior author upon request.

characteristically leaning growth form (Figure 4). In the Bormann plot, both the dominant *Quercus alba* and the increasingly dominant *A. rubrum* sustained high levels of uprooting, whereas other tree species such as *O. arboretum* and *Carya* spp. sustained modest damage (Figure 5).

Risk factors for tree damage at the landscape scale

In the Duke Forest landscape study, stand height of the forest stand was a significant predictor of hurricane damage, with damage risk increasing with stand height (Table 2). Slope and site

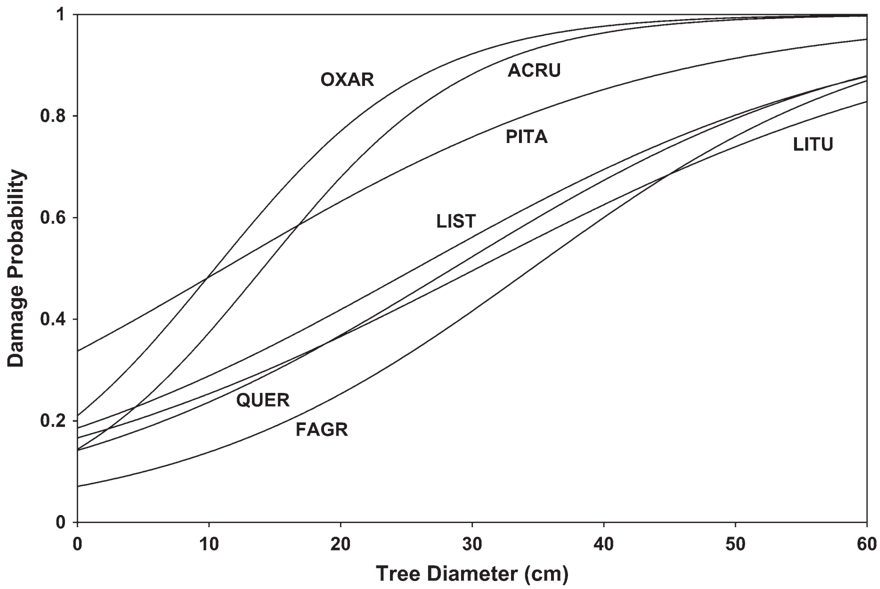

Figure 6. Damage risks for species in the Umstead tornado study. Damage probability is shown to increase with diameter for seven species: *Acer rubrum* (ACRU), *Fagus grandifolia* (FAGR), *Liquidambar styraciflua* (LIST), *Liriodendron tulipifera* (LITU), *Oxydendrum arboretum* (OXAR), *Pinus taeda* (PITA) and *Quercus* spp. (QUER).

Table 2: Logistic regression models of hurricane damage during Hurricane Fran for 22 pine stands in the Duke Forest

Variables	Parameter estimate	Standard error	Wald chi square	$P > \chi^2$	
Height	0.4660	0.2198	4.4943	0.0340	*
Exposure	2.4924	0.9132	7.4494	0.0063	**
Slope	0.6519	0.3056	4.5502	0.0329	*
Stand age	n/a	n/a	0.6817	0.4090	ns
Stand density	n/a	n/a	0.0179	0.8936	ns
Elevation	n/a	n/a	1.3566	0.2441	ns
Aspect	n/a	n/a	1.6275	0.2020	ns
Stand basal area	n/a	n/a	0.3088	0.5784	ns

Plot-level damage severity was examined as a function of stand age, density, basal area, height, aspect, slope and site exposure. $**P \leq 0.01$, $*P \leq 0.05$, n/a = not applicable, ns = not significant.

exposure were also found to be significant predictors of damage, with the most severe damage on ridge tops with the greatest exposure. This is consistent with the observation that much of the hurricane damage was concentrated at topographic extremes in the Duke Forest (Carpino, 1998; Xi, 2005; Xi *et al*., 2008).

Risk factors for tree damage at the regional scale

For both regional Hurricane Fran and Hurricane Hugo, wind speed served as a strong positive predictor of damage risk (Tables 3 and 4). Of the 21 per cent of the variation in tree damage explained in the Hurricane Hugo model, 58 per cent of this

Table 3: Logistic regression models of hurricane damage during Hurricane Fran at a regional scale

Variables	Parameter estimate	Standard error	Wald χ^2	$P > \chi^2$	
d.b.h.	0.0576	0.0150	14.6852	0.0001	***
Pine ratio	−0.8893	0.3106	8.1975	0.0042	**
Wind speed	0.0772	0.0160	23.1965	<0.0001	***
Rainfall	0.1330	0.0500	7.0661	0.0079	**
Distance to path	−0.0257	0.0063	16.5021	<0.0001	***

Heavily damaged trees are examined as a function of wind speed, the amount of rainfall, tree size (d.b.h.), tree species composition ratio and the distance to the hurricane path. ***$P \leq 0.001$, **$P \leq 0.01$. Tree species composition ratio (pine ratio) is the ratio of the number of pine trees to deciduous trees in each plot.

Table 4: Relative importance of variables during 1989 Hurricane Hugo

Variables	Relative importance of variables during 1998 Hurricane Hugo % Variation explained
Wind speed	58.39
Tree size/height	6.37
Other tree characters	12.13
Species	9.30
Site variables	0.56
Community attributes	0.98
Interactions	11.81

The full model was compared with reduced models, and the differences in the R^2's were calculated. The R^2 of the full model was 0.2151. Of the 21.51% of the variation explained in this model, the groups of variables explained the relative amount of this explained variation. The full model is not presented out of concerns for space.

variation is explained by wind speed (Table 4). For Hurricane Fran, stand damage severity similarly exhibited a strong positive relationship with wind speed. Tree size was also found to be a significant predictor of regional-scale forest damage in both the Hugo and Fran studies (mean d.b.h. was used in the Fran study, whereas height was used in the Hugo study). In the Fran study, the pine ratio was significant in influencing damage risks, suggesting that pine forests were less susceptible to damage (Table 3). This is consistent with the findings in the Hugo study where *P. taeda* had a lower probability of damage.

In the Hurricane Fran study, precipitation and distance to hurricane path were significant predictors of wind damage (Table 3), with damage increasing with precipitation and decreasing with distance to the hurricane path. The Hurricane Hugo study found significant damage risk factors associated with species, tree characteristics (low height–diameter ratios, rotten boles, low crown ratios), site characteristics (forest edges) and community characteristics (low density) (Tables 4 and 5).

Discussion

Previous studies of wind damage of forests have suggested that the relative importance of different predictors varies with scale of observation (e.g. Bormann and Likens, 1979; Foster and Boose, 1992, 1994; Boose *et al.*, 2001), and our multiscale analysis (i.e. stand, landscape, regional) supports this observation (Table 5). Our results show that to understand forest damage patterns, it is important to examine risk factors at ecologically relevant scales. In addition, our study provides insight into the consistency of possible risk factors at these three spatial scales. Our previous studies have shown that predictors of wind damage also vary in their relative importance with disturbance intensity and damage severity (DeCoster, 1996).

Risk factors for tree damage at the stand scale

The small spatial extent of the individual study areas at the stand scale inherently limits the number

Table 5: Factors that were significantly related to wind damage at three relevant scales (i.e. regional, landscape and stand

	Hurricanes				Tornado
Damage risk factors	Regional Fran	Regional Hugo	Landscape Fran	Stand-scale Fran	Stand-scale Umstead Park
Abiotic					
Wind speed	***	***	n/a	n/a	n/a
Rainfall	**	n/a	n/a	n/a	n/a
Exposure	*	n/a	**	n/a	n/a
Slope	n/a	n/a	*	n/a	n/a
Aspect	n/a	n/a	ns	n/a	n/a
Soil texture	n/a	ns	n/a	n/a	n/a
Hydrology	n/a	ns	n/a	n/a	n/a
Biotic					
Tree size	***	***	*	***	***
Species/stand composition	*	***	n/a	**	***
Growth rates	n/a	n/a	n/a	ns	n/a
Stand density	n/a	**	ns	n/a	n/a
Stand basal area	n/a	***	ns	n/a	n/a
Height–diameter ratio	n/a	***	n/a	n/a	n/a
Rotten bole	n/a	***	n/a	n/a	n/a
Canopy position	n/a	***	n/a	n/a	n/a
Crown ratio	n/a	***	n/a	n/a	n/a
Plantation	n/a	ns	n/a	n/a	n/a
Others					
Distance to path	***	n/a	n/a	n/a	n/a
Forest edge	n/a	***	n/a	n/a	n/a

***$P \leq 0.001$, **$P \leq 0.01$, *$P \leq 0.05$, n/a = not applicable, ns = not significant.

of factors that can be examined. Although wind speed is presumed to account for much of the variability in damage among trees, it is not feasible to measure the variability in wind regimes at such small spatiotemporal scales (i.e. measure the speed of individual wind gusts; Boose *et al.*, 1994; Peterson, 2004). Larger scale wind regimes can be measured (e.g. 1-min wind speeds), but these are not measurable at the scale of the stand. Similarly, information on within-stand variation in topographic and edaphic conditions is generally not available, and where it is available high spatial autocorrelation precludes meaningful analysis of these factors. At the stand scale, analysis of risk factors is generally limited to characteristics of the individual.

The Umstead tornado study and Duke Forest stand study demonstrate that tree size and species are important risk factors for damage. Tree size has been cited in many studies as being associated with high damage levels (e.g. Glitzensten and Harcombe, 1988; Gresham *et al.*, 1991; Peterson and Pickett, 1991; Arévalo *et al.*, 2000; Canham *et al.*, 2001; Peterson, 2004). Tree size is important in that the largest trees are the ones subjected to the greatest forces of winds (Weidman, 1920). In addition, differential damage among species has been documented (e.g. Zimmerman *et al.*, 1994; DeCoster, 1996; Peterson, 2004; Xi, 2005; Xi *et al.*, 2008). This species effect is likely the result of a combination of wood strength, shape and size of the crown, extent and depth of the root system and stem biomechanical properties (Asner and Goldstein, 1997). Although we did not examine crown and root properties in our comparative study, we explicitly examined stem biomechanical properties using tree size as a surrogate and wood strength using relative growth rate as a surrogate.

Risk factors determining tree damage at landscape scale

Studies at the landscape scale may allow for the examination of topography and other site factors and community variables as damage risk factors, provided they cover a sufficiently large spatial extent and have a sufficient sample size. In a landscape-scale study of site variables influencing damage by Hurricane Fran in the Duke Forest, Carpino (1998) found that the patches of most severe damage were ~0.2 ha in size, presumably conforming to the scale of downbursts of wind associated with turbulence cells.

Generally, studies at the landscape scale use a relative level of stand damage as the dependent variable. As in the Duke Forest stand-level study, tree size can be incorporated directly into such models as stand height or diameter or indirectly as tree age. The literature confirms the pattern of stand height being associated with higher levels of damage (Foster, 1988; Foster and Boose, 1992, Boose *et al.*, 1994).

Although it is well documented that topography influences tree damage at the landscape scale, it is difficult to predict the influence of topography on tree damage due to the complex nature of topographic exposure and because topographic features can alter both wind speed and direction. Generally, areas with high exposure to winds, such as exposed slopes and ridges, sustain the greatest levels damage, whereas lee slopes and valley bottoms sustain the lowest levels of damage (Foster and Boose, 1992). In our Duke Forest landscape, study slope and site exposure best explained variation in damage with the most severe damage recorded on ridge tops with the greatest exposure and with relatively little damage observed on the lower. However, valley bottoms, which were prone to soil saturation, also experienced high damage levels. Site exposure (e.g. natural or human-caused openings) in the forest increased damage risk (Foster and Boose, 1992), although trees that grow along a forest edge may through time develop resistance to wind (Foster, 1988).

Although not found to be important risk factors in the Duke Forest landscape study, stand characteristics such as tree density may be important at this scale and were found to be significant in the Hurricane Hugo study. Low stand density is associated with high levels of damage, perhaps as a result of increased exposure of the individual trees (Foster, 1988). A less dense understorey would also reduce the risk of understorey trees being damaged by canopy tree fall (Webb, 1988, 1989).

Risk factors determining tree damage at regional scale

Whereas precipitation generally does not significantly vary at the stand and landscape scales and wind speeds generally cannot be measured at these sales, these variables can be incorporated into regional-scale studies. In the regional models for Hurricane Hugo and Hurricane Fran, the 1-min average wind speeds explained much of the variation in damage severity. Wind speeds inevitably vary greatly at fine spatiotemporal scales in the forms of wind gusts, microbursts and tornados spawned by the hurricanes, creating much of the unexplained variation in the models.

Precipitation is important in that it causes instability of the root structure, causing trees to be more susceptible to uprooting. Precipitation associated with the storm tends to loosen the soil and causes greater risk of tree uprooting. In the absence of precipitation, tree roots typically withstand such force, and with increased wind speed trees will snap along the bole rather than uprooting (Day, 1950; Fraser, 1962; Foster, 1988; Putz and Sharitz, 1991; but see Peterson, 2007). In our previous studies, 70.2 per cent of the severely damaged trees Duke Forest study were uprooted (Xi, 2005; Xi *et al.*, 2008), whereas in the Umstead tornado study 70.7 per cent of the heavily damaged trees were snapped (DeCoster, 1996).

Integrating damage risk across spatial scales

Although specific risk factors tend to be most predictive at a specific scale (e.g. tree characteristics at the stand scale, topography, edaphic and stand features at the landscape scale and wind speed and precipitation at the regional scale), it is possible to incorporate risk factors from finer spatial scales into regional- or landscape-scale studies. This can be conducted in two ways.

The first method of incorporating risk factors from multiple scales is to transform tree variables to stand variables and examine risk factors for stand damage. As was done in the Duke Forest landscape study, the average tree height can be converted to the independent aggregate variable stand height. Similarly, tree species can be transformed into stand species composition. In the regional Hurricane Fran study, the independent variable pine ratio was created based on the trees species. More detailed stand composition variables can be created and analysed as categorical variables.

A second means to incorporate risk factors from multiple scales is to examine the damage to individual trees and examine damage risk as a function of regional- and landscape-scale variables, in addition to the individual tree variables. For example, in the Hurricane Hugo study, individual tree damage was examined as a function of wind speed, community variables (density, basal area), edaphic variables (soil moisture, soil texture, forest edge and plantation), tree species, tree height and tree architecture (canopy position, crown ratio, height–diameter ratio and rotten bole).

One advantage of integrating risk factors across spatial scales is that it can create models that explain more of the variability in the data. For example, of the 21.51 per cent of the variation in tree damage explained in the Hurricane Hugo model, the regional-scale wind variable explained 58.4 per cent of this variation, tree variables explained an addition 27.8 per cent of the variation and site and community variables explained 1.54 per cent of the variation (Table 4). Moreover, regional datasets allow for the possibility of large sample sizes and hence the ability to examine more explanatory variables than is often possible in stand-level studies. For example, the FIA dataset used in the Hugo analysis allowed examination of tree architectural variables such as crown position, crown ratio and height–diameter ratio as damage risk factors.

Comparison of windstorms

A comparison of these five studies shows that some risk factors are consistent across the storms, whereas others are not (Table 5). Not surprising, wind speed was found to be consistent between the two regional hurricane studies, with damage risk increasing with wind speed. Moreover, tree height was found to be consistent across all four studies, with greater risk of damage occurring in larger trees or in stands of greater height.

The most obvious differences between a hurricane and a tornado are size and intensity. Tornado impacts are more localized, but tend to result in severe damage to a majority of the trees in the impacted area.

Although species were found to differ in their relative susceptibilities to damage, they were not consistent among studies. Particularly striking is that *P. taeda* demonstrated high damage risk in tornado study, whereas it sustained relatively low levels of damage in the three hurricane studies (DeCoster, 1996; Xi, 2005). This may be the consequence of the differences in wind regimes. Hurricane wind regimes are characterized by longer duration (hours *vs* seconds) and have much less wind shear than wind regimes of tornados. The flexibility of *P. taeda* boles may allow them to bend with the gusts of the hurricane, but break in the sudden wind shear of tornados. In contrast, the extended winds of hurricanes may cause deciduous hardwood trees with flexible broad leaves to catch the drag force of the extended wind more readily than the stiff, narrow needles of pine trees (Vogel, 1996).

A final difference among the studies was the relative importance of site factors and topography in determining stand damage at the landscape and regional scales. The Duke Forest landscape study showed that topographic position (slope and site exposure) was important in explaining the variation in damage patterns, whereas the Hurricane Hugo study showed that site factors explained only a small portion in the damage patterns, and topography was not important. This may have been due to fact that much of the study area fell on the South Carolina coastal plain, which has little topographic relief.

Management implications

Comparative studies of damage risk factors provide a better understanding of variation in damage patterns within and among forests and has implications for risk assessment and management practices. Ability to predict severity of large, infrequent disturbance events is an important step towards explaining forest composition (Turner *et al.*, 1998; Peterson, 2004). The information presented in this study should help ecologists in other forested regions better understand the likely impacts of large, infrequent wind disturbances on long-term forest dynamics. Forest managers may use this information both to assess the vulnerability of forest lands to hurricane damage and to design efficient campaigns for mapping forest damage after heavy storms.

Conclusions

Although wind speed is undoubtedly the most important factor for predicting tree damage, to date it has only been quantified at the spatial scale of a region and a temporal scale of 1-min averages. Fine-scale spatiotemporal variability in wind speeds is undoubtedly important in accounting for patterns in tree damage and is presumably responsible for the large amount of unexplained variation in wind disturbance models. Second to wind speed, tree size is consistently found to be a major predictor of damage severity with large trees being associated with a high risk of uprooting or breakage. Landscape-scale analyses show relatively predicable patterns controlled by a combination of topographic position, and stand height, in contrast to stand-level patterns, which can be understood only in the context of tree size, species and possibly other individual tree characteristics.

Certain variables are appropriate for predicting damage only at certain spatial scales: meteorological variables at the regional scale, site and community variables at the landscape scale and tree variables at the stand scale. However, variables observed at finer scales can be integrated into broader-scale studies, providing greater ability to predict tree or stand damage. Thus, our ability to predict tree damage increases with spatial scale, suggesting the importance of examining broad geographical patterns when assessing risk factors for broad-scale disturbances such as windstorms.

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Conflict of Interest Statement

None declared.

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