Relationships between common forest metrics and realized impacts of Hurricane Katrina on forest resources in Mississippi

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Abstract

This paper compares and contrasts hurricane-related damage recorded across the Mississippi landscape in the 2 years following Katrina with initial damage assessments based on modeled parameters by the USDA Forest Service. Logistic and multiple regressions are used to evaluate the influence of stand characteristics on tree damage probability. Specifically, this paper addresses four primary questions related to post-hurricane damage: (1) do inventory data substantiate damage zone estimates made using remotely sensed and climate data following Hurricane Katrina; (2) were softwoods or hardwoods more susceptible to hurricane damage and does that susceptibility change as distance from landfall increases; (3) what are the primary stand-level factors influencing vulnerability to damage, based on observed damage and measured stand characteristics, and; (4) is tree-level damage related to tree species, and do damage types (bole, branch, lean, or windthrow) differ by species? We were able to accept the hypothesis that damage differed among the developed zones, and to confirm the acceptability of the figures initially generated. However, we were not able to accept the hypothesis that softwoods experienced more damage than hardwoods. Our data showed a marked increase in damage to hardwood species, except in the first zone of impact. Additionally, the likelihood of hardwood damage increased with increasing distance from the zone of impact. However, species group was confounded with the other predictor variables in many cases, making it difficult to separate the effects of each variable.
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1. Introduction

Hurricane Katrina made landfall in Plaquemines Parish, Louisiana on 29 August 2005. Katrina has been termed one of the most costly natural disasters in United States history, as well as one of the strongest hurricanes to make landfall on the U.S. coast in the last century (Graumann et al., 2005). In addition to hurricane-strength winds, Katrina brought massive amounts of rainfall over a very short timeframe, a storm surge of up to 8.5 m across southern Louisiana and Mississippi; extensive wind, rain, and related tornado damage throughout Mississippi, Western Tennessee and Western Kentucky; and extended hurricane-associated precipitation as far north as New York State (Graumann et al., 2005). Peak wind gusts associated with Katrina exceeded 80 km/h throughout the State of Mississippi (Graumann et al., 2005).

Damage assessment was an immediate priority for federal, State, and local governments. The U.S. Forest Service, Southern Research Station, Forest Inventory and Analysis program (USFS-SRS-FIA), among others, developed maps of damage zones using models developed by Jacobs (2007) to aid in damage assessment tasks (Fig. 1). Forest inventory data from 1994 were used in combination with the mapped damage zones to estimate damage potential and possible economic impacts across the State of Mississippi. Subsequently, zone maps and damage estimates were used by researchers and policy makers to aid in the development of recovery and salvage logging plans. Maps and estimates were used to further model hurricane effects on forest stands from the standpoint of individual-tree effects in order to suggest methods for reducing vulnerability to forests in hurricane impact zones (Stanturf et al., 2007). Therefore, estimates derived from models using available ground data, climate data, and remote sensing are important tools for forest management in a post-natural-disaster environment.

Initial estimates generated by USFS-SRS-FIA utilizing spatial models and 1994 inventory data indicated potential

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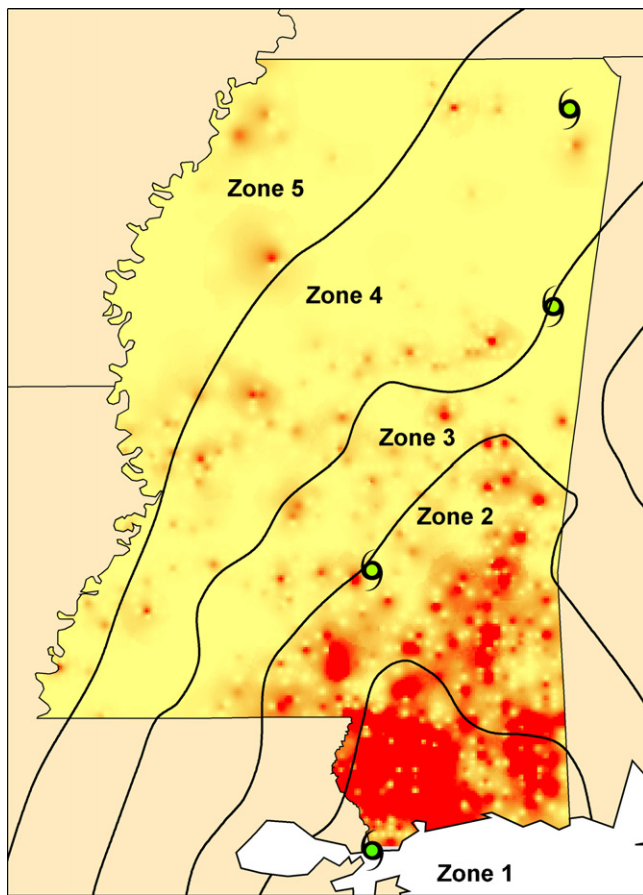 *E-mail address:* soswalt@fs.fed.us (S.N. Oswalt).

Fig. 1. Inverse distance weighting of percent trees ≥5 in. DBH damaged on FIA plots (dark shading) with an overlay of damage zones and Hurricane Katrina path. Hurricane path and damage zones were developed by Jacobs (2007).

timber losses of up to 84.9 million m³ (3 billion ft³) across 1.4 million ha of damaged forest land in Mississippi (USDA Forest Service, 2005). This equates to about 90% of standing timber in severe damage zones, and an average of 37% of standing timber across all damage zones (USDA Forest Service, 2005). Initial estimates (based on 1994 inventory data) suggested that more softwood volume was damaged than hardwood volume.

Using the USFS-derived damage zone information, combined with additional information from the Texas Forest Service, Stanturf et al. (2007) simulated equivalent hurricane forces to forecast stem breakage in a hypothetical set of nine softwood forest stands spanning an array of stand structure and density combinations. The resulting simulations suggested that stand spacing and tree height were more important in softwoods for determining stem-breakage potential than species, indicating that manipulating stand structure to reflect the least vulnerable conditions could aid landowners in decreasing the damage potential of forests in hurricane-impact zones (Stanturf et al., 2007).

Following Hurricane Katrina, the USFS-SRS-FIA began systematically sampling the forest resource across the entire State, following protocols outlined in the FIA sampling field guide (USDA Forest Service, 2005). One goal of the inventory was to determine the actual damage caused by Hurricane

Katrina at the forest landscape and individual tree level. Here, we compare and contrast hurricane-related damage recorded across the Mississippi landscape in the 2 years following Katrina with initial damage assessments based on modeled parameters by USFS. We also use logistic and multiple regression to evaluate the influence of stand characteristics on tree damage probability to see if our data reflect the findings of Stanturf et al. (2007). Specifically, we address four primary questions related to post-hurricane damage:

1. Do inventory data substantiate damage zone estimates made using remotely sensed and climate data following Hurricane Katrina?
2. Were softwoods or hardwoods more susceptible to hurricane damage and does that susceptibility change as distance from landfall increases?
3. What are the primary stand-level factors influencing vulnerability to damage, based on observed damage and measured stand characteristics?
4. Is tree-level damage related to tree species, and do damage types (bole, branch, lean, or windthrow) differ by species?

2. Methods

2.1. FIA field methods

The USDA Forest Service FIA program collects data on systematically arranged plots at the scale of roughly one plot for every 2428 ha of land base. Each field plot consists of four subplots about 0.016 ha in size (for a total of 0.06 ha for each complete plot). Each plot is designated as "sampled" or "not sampled" and each subplot within each plot is similarly designated. Subplots may be divided if they are partially forested, a procedure referred to as "condition mapping" (Bechtold and Patterson, 2005). For this study, partially forested plots and plots with multiple conditions were removed from the dataset to avoid unnecessary mathematical complications. FIA protocols have been extensively described and documented, and those protocols will not be repeated here. Detailed descriptions of the plot design and variable collection techniques utilized here may be found online at http://srsfia2.fs.fed.us/.

Hurricane damage was collected on each forested FIA plot within the State of Mississippi, beginning on 11 November 2005. The data reported here reflect the most currently available data, which are incomplete for damage zones 4 and 5. Each plot was assigned a weather event code of 0 = no impact, 1 = impacted by a wind event, or 2 = impacted by heavy snow or ice. The weather event code was reduced to a binary variable of 0/1 where 0 = no wind event and 1 = wind event. Wind events were assumed to be related to Hurricane Katrina, whether directly through hurricane force winds, or indirectly through off-shoot tornado events.

On each plot where wind event = 1, individual trees received a damage code of 0/1 for damage absence or presence. Where individual tree damage = 1, each tree received a 0/1 code for bole damage (broken, twisted, or splintered) and windthrow

Table 1
Damage zones (1 = closest to landfall, 5 = furthest from landfall), number of plots used in the analyses, and mean percent of plot-level damage (±1 S.E.) for Mississippi, 2005–2007 following Hurricane Katrina

Zone	N	Mean percent damage	S.E.
1	167	26.39	2.19
2	376	10.44	0.88
3	292	1.40	0.26
4	518	1.02	0.18
5	228	1.08	0.24

damage (uprooted). Each tree also received an ordinal code of 0–3 for branch damage (defoliation or other damage) and 0–2 for lean damage (angle of lean from vertical). Branch and lean damage were also reduced to binary 0/1 variables which indicated a simple presence or absence of that damage type for trees where individual tree damage = 1.

Plots were assigned to damage zones outlined by Jacobs (2007). Zones were numbered in ascending order from 1 through 5, with zone 1 encompassing landfall (and containing the greatest amount of forecasted damage) and zone 5 furthest from landfall (and containing the least amount of forecasted damage, Fig. 1).

2.2. Statistical analysis

Comparisons between remotely sensed damage zones and inventory data were made by mapping the locations of all completely forested plots collected and edited in the State of Mississippi at the time of the study. ArcGIS software was used to overlay damage zones with inventory plots. Damage percentages were computed for each plot as the number of trees with any damage divided by the total number of trees on the plot × 100. Plots were assigned the zone number into which they fell (Table 1). Inverse distance weighting was used to spatially portray the data for visual confirmation of patterns within the zone. We used analysis of variance (ANOVA) with generalized least square means (SAS, 1999) to test the hypothesis that damage percentages differed among zones.

We used contingency tables and Pearson chi-square test statistics to test the hypothesis that softwood species were more likely to be damaged than hardwood species, and to test the hypothesis that damage type differed between species groups. We repeated the tests by zone to see if patterns persisted as distance from landfall increased.

Multiple regression with stepwise variable retention ($a = 0.05$; SAS, 2006) was used to determine statistically significant variables influencing damage vulnerability at the plot level (calculated as percent of trees showing any sign of damage). Plot-level variables tested in the model included elevation, total tree basal area, mean tree height, mean tree diameter, and percent of species recorded that were hardwoods. Because distance from landfall is negatively correlated with the percent of damage (number of trees damaged/number of trees sampled) recorded on a plot ($r = -0.40$), regressions were run independently for each damage zone.

Multiple regression with stepwise variable selection was also used to determine statistically significant variables influencing the percentage of each damage type (bole, branch, lean, and windthrow damage) occurring at the plot level. Independent variables tested included total tree basal area, mean tree height, percent of species recorded that were hardwoods, and diameter. Regression models were run separately for each damage zone.

We used multiple logistic regression (SAS, 2006) in each damage zone to examine tree fate (damage vs. undamaged) as a response of species group (hardwood vs. softwood), diameter, height, and plot density (total number of trees on the plot in which a tree fell). Additional multiple logistic regressions, using only damaged trees in the model categorized by both species group and damage zone, tested the hypotheses that tree height, diameter, and total plot basal area could be used to predict the vulnerability of individual trees to particular types of bole breakage (0/1), branch damage (0/1), lean damage (0/1) and windthrow (0/1). The significance of logistic regression models was determined using the likelihood ratio, while the Wald test was used to examine the significance of individual variables (Peterson, 2007).

3. Results

3.1. Measured hurricane damage

A total of 1581 entirely forested single-condition plots had been collected in the state of Mississippi at the time of analysis. Of those plots, a total of 693 (44%) experienced some degree of wind-related damage. Eighty-seven percent of plots in zone 1 (the zone encompassing landfall) experienced hurricane damage, and the percent of plots experiencing damage decreased as distance from landfall increased, with the exception of zone 5 (Fig. 1). The amount of damage sustained on plots differed by zone ($p < 0.001$), decreasing as distance from landfall increased, as predicted. Damage amounts by plot appeared to align reasonably well to predicted zone boundaries (Fig. 1).

We measured 37,444 trees ≥ 12.7 cm diameter at breast height (DBH). Seven percent of measured trees experienced some degree of wind-related damage (Table 2). Fifty-three percent was damage to hardwoods and 47% was damage to softwoods (Table 2). Thirty percent of all damaged trees experienced bole damage, while 70% experienced branch damage, 40% experienced lean damage, and 25% were windthrown (Table 3). Almost 90% of damaged trees were recorded within the boundaries of the first two predicted damage zones. Hardwoods experienced more overall wind-related damage than softwoods ($p < 0.0001$). Two times as many hardwoods experienced bole damage; 1.4 times as many hardwoods experienced branch damage; 1.5 times as many hardwoods experienced lean damage, and 1.9 times as many hardwoods experienced windthrow (Table 3).

While hardwoods experienced more extensive damage, the degree of damage to hardwoods versus softwoods varied as distance from hurricane landfall increased. In

Table 2
Number of trees ≥5 in. DBH with wind-related damage/total number of trees ≥5 in. DBH recorded by damage zone and major species group; data also expressed as percent of total trees and percent of damaged trees

Zone	Hardwood	Softwood	All species total	Chi-square	*p*-Value
1					
Damaged trees/total	531/1591	738/2514	1269/4105	7.37	0.0066
Percent of total	33.38	29.36	30.91		
Percent of zone 1 damaged trees	41.84	58.16	100		
2					
Damaged trees/total	591/3280	384/6028	975/9308	307.30	<0.0001
Percent of total	18.02	6.37	10.47		
Percent of zone 2 damaged trees	60.62	39.38	100		
3					
Damaged trees/total	56/2785	43/4471	99/7256	14.03	0.0002
Percent of total	2.01	0.96	1.36		
Percent of zone 3 damaged trees	56.57	43.43	100		
4					
Damaged trees/total	104/6041	17/6472	121/12,513	69.44	<0.0001
Percent of total	1.72	0.26	0.97		
Percent of zone 4 damaged trees	85.95	14.05	100		
5					
Damaged trees/total	49/3766	1/496	50/4262	4.57	0.0325
Percent of total	1.30	0.20	1.17		
Percent of zone 5 damaged trees	98.00	2.00	100		
All zones					
Damaged trees/total	1331/17,463	1183/19,981	2514/37,444	43.06	<0.0001
Percent of total	7.62	5.92	6.71		
Percent of all zone damaged trees	52.94	47.06	100		

Chi-square and *p*-values are given for the test for differences between species groups.

zone 1, softwoods experienced more damage, while in zone 2 the reverse was true, even though softwoods were the more frequently measured species group in both zones (Table 2). As distance from landfall increased, hardwoods continued to experience more damage than softwoods. In zone 3, 1.3 times as many hardwoods were damaged, and in zone 4, 6 times as many hardwoods were damaged (Table 2).

We recorded 117 species on plots in Mississippi. State-wide, the individual species suffering the highest proportion of damage (31% of 545 recorded trees) was *Magnolia virginiana* L. (sweetbay), followed by *Quercus laurifolia* Michx. (laurel oak, 22% of 124 trees) and *Pinus elliottii* Engelm. (slash pine, 19% of 1306 trees, Table 4). *Juniperus virginiana* L. (eastern redcedar) suffered the lowest proportion of damage (0.4% of 244 trees). In zone 1, of species with more than 40 individuals measured, *Liriodendron tulipifera* L. (yellow-poplar) suffered the largest proportion of damage (53% of 73 recorded trees), followed by *Quercus nigra* L. (water oak, 48% of 171 trees) and *Liquidambar styraciflua* L. (sweetgum, 45% of 104 trees). For species with more than 40 individuals measured, *Nyssa biflora* Walt. (swamp tupelo) and *Taxodium ascendens* Brongn. (pondcypress) experienced the least amount of damage in zone 1, with 13% damaged out of 218 and 0 damaged out of 44 measured individuals, respectively (Table 4). Damage by species for zones 2–4 is given in Table 4.

3.2. Regression models

3.2.1. Plot-level damage

Multiple regression with stepwise variable selection identified total tree basal area as the sole variable to retain in the model of plot-level damage in zone 1. Although the model was significant there was little predictive capability ($R^2 = 0.04$). Three variables (percent of hardwood trees on the plot, elevation, and mean tree height) were retained in the zone 2 model. The whole model solution had little predictive ability ($R^2 = 0.18$). Variables selected for retention in zone 4 included percent of hardwood trees and total tree basal area, but again the whole model R^2 explained only 3% of the variation in percent Katrina damage on the plot. No variables were significant enough for retention in zones 3 or 5 (Table 5).

Stepwise, variable selection for percent of trees with bole damage (on damaged plots only) resulted in the selection of only one variable, percent of species recorded that were hardwoods, in zones 1 and 2. No variables were retained in any of the other zones, and no other models were significant. Percent hardwood species explained 12% of the variation in bole damage in zone 1, and 14% in zone 2 ($p < 0.001$ for both models).

Variable selection for the dependent variable "percent of trees with branch damage" on damaged plots resulted in the retention of only one variable in zone 1, total tree basal area, which explained <3% of the variation in branch damage among

Table 3
Number of trees ≥5 in. DBH with each damage type/total number of damaged trees ≥5 in. DBH recorded by damage zone and major species group

Zone and damage type	Hardwood	Softwood	All species total	Chi-square	p-Value
1					
Bole	178/531	145/738	323/1269	31.33	<0.0001
Branch	397/531	600/738	997/1269	7.83	0.0051
Lean	250/531	226/738	476/1269	35.68	<0.0001
Windthrow	183/531	114/738	297/1269	62.29	<0.0001
2					
Bole	215/591	97/384	312/975	13.22	0.0003
Branch	411/591	175/384	586/975	55.77	<0.0001
Lean	234/591	203/384	437/975	16.58	<0.0001
Windthrow	169/591	115/384	284/975	0.21	0.6498
3					
Bole	22/56	19/43	41/99	0.24	0.6237
Branch	43/56	29/43	72/99	1.07	0.3008
Lean	25/56	9/43	34/99	6.07	0.0138
Windthrow	12/56	2/43	14/99	5.64	0.0176
4					
Bole	41/104	7/17	48/121	0.02	0.8910
Branch	76/104	6/17	82/121	9.55	0.0020
Lean	51/104	6/17	57/121	1.11	0.2926
Windthrow	34/104	5/17	39/121	0.07	0.7885
5					
Bole	23/49	1/1	24/50	1.10	0.2931
Branch	34/49	0/1	35/50	2.17	0.1409
Lean	8/49	1/1	9/50	4.65	0.0311
Windthrow	2/49	0/1	2/50	8.40	0.8366
All zones					
Bole	479/1331	269/1183	748/2514	52.60	<0.0001
Branch	961/1331	810/1183	1771/2514	4.19	0.0407
Lean	568/1331	445/1183	1013/2514	6.66	0.0099
Windthrow	400/1331	236/1183	636/2514	33.83	<0.0001

Chi-square and p-values are given for the test for differences between species groups.

plots. In zones 2 and 4, the percent hardwood species variable was retained, and explained 13% ($p < 0.0001$) and 6% ($p = 0.007$) of the variation in branch damage, respectively.

Selection models for the dependent variable ''percent of trees with lean damage'' on damaged plots resulted in the retention of the percent hardwood species variable in zones 1–4 and the retention of the variable mean tree height in zone 3. No models explained more than 10% of the variation in lean damage among plots.

Stepwise regression models for the dependent variable ''percent of trees with windthrow damage'' on damaged plots resulted in the retention of only one variable, percent hardwood species, in zones 1–4. No other variables were retained in any of the models in any zones. Percent hardwood trees explained 10% of the variation in windthrow damage among plots in zone 1 ($p = 0.0001$), and <10% in all of the other zones.

3.2.2. Individual tree damage

Species group and DBH consistently affected the probability of trees suffering at least some wind-related damage in each zone. Height was a significant predictor in zones 1 and 3, as well, and interacted significantly with diameter and density in zone 2 to influence damage likelihood (Table 6). Density was significant only in interactions with the other main effect variables, and only in zones 1, 2, and 4 (Table 6). In zone 1, interactions indicated that the probability of hardwood damage increased as tree diameter increased, while for softwoods the probability of damage decreased as tree diameter increased. Additionally, the probability of damage to softwoods increased as stand density increased (Table 6). Patterns were similar for hardwoods in zone 2—the probability of damage increased with increasing diameter and height, while diameter had little influence on the probability of softwood damage.

Height, DBH, species group, and density all had some effect on the probability of bole damage (Table 6). The probability of hardwood bole damage decreased as height increased in zone 1, while height had no impact on softwood bole damage. The probability of softwood bole damage decreased as tree density increased in zone 1. In general, larger diameter trees, shorter trees, and trees in stands of lower densities had higher probabilities of experiencing bole damage (Table 6).

Tree height played a role in the probability of branch damage to both hardwoods and softwoods in zones 1 and 2. For both species groups in both zones, the probability of branch damage increased as tree height increased (Table 6). However, in zone 3, softwood branch damage probability decreased with increasing tree height. Density influenced hardwood branch damage probability in zone 1—trees in dense stands were more

Table 4
Percent of trees ≥5 in. DBH by species and damage zone

Damage zone	Species	N	Percent damaged	Species	N	Percent damaged
1	*Liriodendron tulipifera*	73	52.05	*Quercus laurifolia*	58	37.93
	Quercus nigra	171	47.95	*Pinus elliotii*	1013	23.69
	Liquidambar styraciflua	104	45.19	*Nyssa sylvatica*	198	18.18
	Ilex opaca	43	44.19	*Faxinus pennsylvanica*	54	14.81
	Acer rubrum	103	43.69	*Pinus palustris*	189	13.76
	Pinus taeda	1173	39.22	*Nyssa biflora*	218	13.30
	Magnolia virginiana	297	38.05	*Taxodium ascendens*	44	0.00
2	*Prunus serotina*	93	31.18	*Cornus florida*	64	10.94
	Quercus nigra	420	25.71	*Quercus falcata*	141	10.64
	Magnolia virginiana	232	25.00	*Quercus alba*	129	10.08
	Acer rubrum	200	24.00	*Quercus laurifolia*	59	8.47
	Liriodendron tulipifera	205	23.90	*Quercus stellata*	88	6.82
	Carya alba	48	18.75	*Fraxinus pennsylvanica*	44	6.82
	Oxydendrum arboreum	57	17.54	*Pinus taeda*	5018	6.72
	Nyssa sylvatica	233	17.17	*Pinus palustris*	240	5.83
	Liquidambar styraciflua	586	14.85	*Pinus elliotii*	451	4.43
	Nyssa biflora	104	14.42	*Pinus echinata*	238	3.36
	Carpinus caroliniana	66	12.12			
3	*Prunus serotina*	73	5.48	*Carya alba*	77	1.30
	Acer rubrum	134	4.48	*Quercus falcata*	79	1.27
	Quercus alba	161	4.35	*Pinus taeda*	4238	0.99
	Carya glabra	62	3.23	*Pinus echinata*	146	0.68
	Quercus nigra	275	2.91	*Juniperus virginiana*	54	0.00
	Nyssa sylvatica	87	2.30	*Fraxinus pennsylvanica*	65	0.00
	Quercus stellata	101	1.98	*Quercus pagoda*	54	0.00
	Liquidambar styraciflua	710	1.83	*Quercus phellos*	46	0.00
	Carpinus caroliniana	66	1.52	*Ulmus alata*	75	0.00
	Liriodendron tulipifera	132	1.52			
4	*Carya aquatica*	47	6.38	*Juniperus virginiana*	166	0.60
	Acer negundo	63	6.35	*Quercus alba*	401	0.50
	Salix nigra	59	5.08	*Pinus taeda*	5975	0.20
	Ulmus rubra	45	4.44	*Carya ovata*	51	0.00
	Acer rubrum	248	4.44	*Carya alba*	160	0.00
	Ostrya virginiana	111	3.60	*Celtis laevigata*	64	0.00
	Carpinus caroliniana	145	3.45	*Cornus florida*	76	0.00
	Prunus serotina	124	3.23	*Fraxinus americana*	43	0.00
	Quercus pagoda	219	2.74	*Fraxinus pennsylvanica*	115	0.00
	Quercus nigra	376	2.66	*Nyssa sylvatica*	115	0.00
	Fagus grandiflora	94	2.13	*Nyssa biflora*	49	0.00
	Quercus phellos	48	2.08	*Oxydendrum arboreum*	53	0.00
	Liriodendron tulipifera	310	1.94	*Platanus occidentalis*	48	0.00
	Diospyros virginiana	54	1.85	*Quercus falcata*	271	0.00
	Liquidambar styriciflua	1335	1.80	*Quercus lyrata*	78	0.00
	Pinus echinata	322	1.24	*Quercus stellata*	169	0.00
	Ulmus americana	125	0.80	*Quercus velutina*	68	0.00
	Carya glabra	142	0.70	*Ulmus alata*	195	0.00

Sample size (N) is also given.

likely to experience branch damage than trees in less dense stands.

Diameter impacted the probability of hardwood lean damage in zones 1 and 2, and in softwood lean damage in zones 2–4. In all instances the probability of lean damage decreased as diameter increased (Table 6). The same relationship existed for tree height and the probability of hardwood lean damage in zones 1 and 2, and softwood lean damage in zone 4 (Table 6). Windthrow probability was not influenced by most of the variables tested in this paper, though in zone 1 the probability of windthrow was higher for hardwoods (Table 6).

4. Discussion

4.1. Landscape level damage

Initial estimates of the damage caused by Hurricane Katrina were based on models produced by the USDA Forest Service and others (Jacobs, 2007). These models utilized data from the most recent FIA surveys in the effected States combined with maps of the hurricane storm track. The USFS-FIA initially estimated that 90% of timberland area within the approximately 8-county zone (zone 1) surrounding landfall had been damaged,

Table 5
Results of multiple regression with stepwise variable selection using plot-level percent of Hurricane Katrina damage as the dependent variable and elevation, total tree basal area, mean tree height, percent of hardwood trees, and mean tree diameter as predictor variables

Zone	Total model R^2	Predictor variable	Partial R^2	F	Pr > F
1	0.0352	Total tree basal area	0.0352	5.58	0.0194
2	0.1818	Percent hardwood trees	0.1016	22.18	<0.0001
		Elevation	0.0659	29.1	<0.0001
		Average tree height	0.0144	6.05	0.0144
3	–	–	–	–	–
4	0.0319	Percent hardwood trees	0.0237	11.44	0.0008
		Total tree basal area	0.0082	3.99	0.0464
5	–	–	–	–	–

and 37% of the entire State's timberland had been damaged. Our results indicate that this model was valid and performed well, but illustrates the need to appropriately interpret the data to the general public. For example, our data indicates that 87% of forested plots in zone 1 and 44% of forested plots statewide experienced some degree of wind-related damage—an estimate that compares quite closely with initial damage estimates produced by the USFS-FIA model (Jacobs, 2007). However, only 45% of measured trees in zone 1 and only 7% of trees measured on plots statewide experienced damage, suggesting that although damage to forests was widespread, and certainly

severe near landfall, it may not have been as catastrophic as the numbers initially suggested.

Unlike the initial USFS-FIA models (which suggested that 60% of damage occurred to softwoods) the field data indicates that a little less than one-half of the hurricane damage occurred to softwoods. Hardwoods experienced more overall damage, in addition to more severe damage in the form of bole damage, lean damage, and windthrow. One exception was in damage zone 1, where softwoods did experience more damage than hardwoods. The discrepancy between the modeled estimates of softwood versus hardwood damage and the measured values may be a function of using estimates of softwood and hardwood volume based on outdated (1994) plot values and/or remote sensing for the modeled damage estimates instead of using discrete counts based on individual tree species composition. Model parameters (Jacobs, 2007) may need to be revisited to better reflect wind-mediated softwood damage.

4.2. Individual tree damage and regression models

In zone 1, softwoods were more likely to be damaged than hardwoods, but a hardwood (*Liriodendron tulipifera*) suffered the highest proportion of damage. Species typical of upland sites (e.g. *Liriodendron tulipifera* and *Pinus taeda* L.) were among the most damaged, while typical bottomland species (e.g. *Taxodium ascendens*, *Nyssa biflora*, and *Nyssa sylvatica*) were among the least damaged. Almost 40% of the *Pinus taeda*

Table 6
Significant variables in multiple logistic regression models for (1) any tree damage, (2) bole damage, (3) branch damage, (4) lean damage, and (5) windthrow damage

Zone	Main effects	Interactions	Model significance
Any damage			
1	DBH (−), Ht (+), SpCd	DBH × SpCd, SpCd × density	$x^2 = 179.26$, 10 d.f., $p < 0.0001$
2	DBH (+), SpCd	DBH × Ht, Ht × density, SpCd × density	$x^2 = 381.50$, 10 d.f., $p < 0.0001$
3	DBH (+), Ht (+), SpCd	–	$x^2 = 33.48$, 10 d.f., $p = 0.0002$
4	DBH (+), SpCd	DBH × density	$x^2 = 100.16$, 10 d.f., $p < 0.0001$
Bole damage			
1	DBH (+), SpCd, Ht (−)	SpCd × Ht, DBH × density	$x^2 = 61.47$, 8 d.f., $p < 0.0001$
2	DBH (+), SpCd, Ht (−), density (−)	DBH × density, SpCd × density	$x^2 = 40.67$, 8 d.f., $p < 0.0001$
3	Density (+)	–	$x^2 = 11.68$, 8 d.f., $p = 0.1660$
4	Ht (−)	–	$x^2 = 11.50$, 8 d.f., $p = 0.1749$
Branch damage			
1	DBH (−), Ht (+), density (+)	DBH × SpCd, SpCd × density, Ht × SpCd	$x^2 = 65.56$, 10 d.f., $p < 0.0001$
2	Ht (+), SpCd	SpCd × density	$x^2 = 97.28$, 10 d.f., $p < 0.0001$
3	DBH (+), Ht (−)	DBH × Ht, Ht × density	$x^2 = 22.48$, 10 d.f., $p = 0.0128$
4	–	–	$x^2 = 13.87$, 10 d.f., $p = 0.1789$
Lean damage			
1	DBH (−), SpCd	–	$x^2 = 72.63$, 10 d.f., $p < 0.0001$
2	DBH (−), Ht (+), SpCd, density (+)	DBH × SpCd, DBH × density, SpCd × density, Ht × SpCd, Ht × density	$x^2 = 91.51$, 10 d.f., $p < 0.0001$
3	DBH (−), Ht (+), SpCd	DBH × SpCd, SpCd × density, Ht × SpCd	$x^2 = 34.37$, 10 d.f., $p = 0.0002$
4	–	DBH × Ht	$x^2 = 17.59$, 10 d.f., $p = 0.0623$
Windthrow damage			
1	SpCd	–	$x^2 = 77.88$, 10 d.f., $p < 0.0001$
2	DBH (+), Ht (−)	SpCd × density	$x^2 = 15.44$, 10 d.f., $p = 0.1169$
3	–	DBH × density	$x^2 = 17.38$, 10 d.f., $p = 0.0663$
4	–	–	$x^2 = 11.44$, 10 d.f., $p = 0.3241$

Predictor variables included diameter at breast height (DBH), height (Ht), species group (SpCd), and density. For the continuous variables DBH, Ht, and density, (+) indicates an increase in damage probability with increasing values and (−) indicates a decrease in damage probability with increasing values.

were damaged, but only 14% of *Pinus palustris* P. Mill. were damaged—a result that reflects the simulation study of Stanturf et al. (2007). Some studies of species influence on catastrophic wind damage have suggested that softwoods tend to be slightly more vulnerable than hardwoods (at least with regard to windthrow) when diameter is taken into account (Peterson, 2007). Additionally, models used to predict wind damage in stands also suggest that tree stability in catastrophic wind events is lower in tall, slender trees (Ancelin et al., 2004). Our data appear to confirm that for the zone of greatest impact (zone 1), where regression models suggest that tall, slender softwoods have a higher probability of experiencing damage. However, beyond zone 1, our data suggests that hardwoods were more vulnerable, and that vulnerability varied according to diameter and height—namely, as hardwood diameter and height increased, the probability of damage increased. Peterson (2007) also noted an increase in the probability of wind-related damage with increasing tree diameter in a study of tornado damage across eastern North America. A noteworthy difference between this study and the studies referenced above, however, is the scale of the population of interest—where those studies predict damage to a limited, somewhat homogenous population, our study attempts to extract variables influencing damage probabilities across an entire State, and does not take into account differences in soil type or other environmental factors, aside from elevation and distance from landfall (through the surrogate damage zone).

Putz and Sharitz (1991) studied the effects of Hurricane Hugo on bottomland trees in South Carolina, and reported that tree damage in bottomland forests appears to also be related to previous damage history. In other words, trees that had experienced previous damage were more susceptible to severe damage during the current event (Putz and Sharitz, 1991). In contrast, Peterson and Rebertus (1997) found that lowland stands in Missouri with prior wind-related damage were less likely to experience severe damage during a current wind event because, overall, trees tended to be smaller. We did not take previous damage into account in this study, but that may be an important variable for land managers to consider when evaluating the susceptibility of trees and stands to catastrophic wind events, and may be especially important in large-scale studies like ours, where the landscape is exceptionally heterogeneous.

Our study corroborates studies by Stanturf et al. (2007), Ancelin et al. (2004), and others who suggest that tree height plays an important role in determining an individual's vulnerability to damage, although our study also indicates that, while important, height alone cannot be used as a predictor of potential damage. In contrast to Stanturf et al. (2007), but in agreement with Foster (1988), the probability of individual tree damage increased as stand density decreased. Foster (1988) suggests that trees in dense stands may be taller and have less-developed root systems, rendering them susceptible to damage.

4.3. Damage type-plot and individual tree

At the stand level, the percentage of trees experiencing bole, branch, lean, and windthrow damage was related to the percent of hardwood trees present on the plot measured, suggesting that species group is an important determinant of damage type. We were surprised that the probability of bole damage decreased for individual hardwood trees as the tree height increased. Most studies suggest that as tree height increases exposure to rough air also increases (particularly in stands with variable structure), resulting in increased susceptibility to damage (Foster, 1988; Ancelin et al., 2004; Peterson, 2007). Perhaps one reason for the difference in our findings and others is the manner in which we grouped all hardwood species into one assembly, where other studies often look at individual species. Other authors (e.g. Peterson, 2007) have looked at individual species response and found it difficult to distinguish between species-specific effects and size-related effects. In our study, in zone 1, early-successional hardwood species like *Liriodendron tulipifera* and *Liquidambar styraciflua* experienced a higher proportion of damage than other species except *Quercus nigra*, which may be a function of size. Crown size may also be influencing susceptibility to bole damage as a result of high winds. Although we did quantify the size of each tree crown, crown size is often related to stand density. Smaller decurrent crowns in densely formed hardwood stands may be less susceptible to wind related bole damage due to reduced surface area available to catch bursts of wind. Future studies will attempt to separate species and size effects through ordination analyses similar to Foster (1988) to further investigate species effects on Hurricane Katrina damage.

While species group played an important role in the degree of overall damage and in the probability of bole damage, tree height and stand density influenced the probability of branch damage. Tall softwood and hardwood trees were more likely to experience branch damage, a phenomenon reported previously in the literature (Foster, 1988; Walker, 1991). Branch damage also increased with increasing stem density in zone 1 for hardwood trees, suggesting that canopy structure may result in trees hitting each other within a dense stand, causing damage in addition to wind-related breakage.

Unexpectedly, in our study the probability of lean damage decreased with tall trees and with larger diameter trees, regardless of the species, but the relationships were confounded by interactions with species group and density, making it difficult to interpret the results. It is possible that larger trees that may be susceptible to "lean" were completely uprooted, although our results for windthrown trees did not produce strong relationships between most of the predictor variables we used.

The lack of predictability among the numerous models presented here was surprising. However, it represents an important point in that predicting plot-level or individual tree-level damage in an extremely varied and heterogeneous environment is difficult. Care must be taken when using models to predict influences of large disturbance events on a landscape scale. Environmental variation can make it extremely difficult to develop a comprehensive predictive model that can be applied to the entire landscape. The results from this study are good example.

5. Conclusions

Our study illustrates the effectiveness of spatial models using remotely sensed data and USDA Forest Service FIA data to forecast damage following severe weather events. Models developed using 11-year-old data in the aftermath of Hurricane Katrina were still comparable to results derived from field data collected immediately following the storm. However, this study also illustrates the need to appropriately interpret the results to the general public. For example, stating that damage occurred on 90% of timberland acreage is not equivalent to stating that 90% of trees experienced damage. Minutia in reporting statistical figures can be confusing to individuals who are not accustomed to working with those types of numbers, and may be misleading.

While we were able to accept the hypothesis that damage differed among the developed zones, and to confirm the acceptability of the figures initially generated, we were not able to accept the hypothesis that softwoods experienced more damage than hardwoods. Our data showed a marked increase in damage to hardwood species, except in the first zone of impact. Additionally, the likelihood of hardwood damage increased with increasing distance from the zone of impact. However, species group was confounded with the other predictor variables in many cases, making it difficult to separate the effects of each variable.

Though our data suggest that tree structure, particularly height and diameter, play a consistent role in damage probabilities, none of our predictor variables fully explained the variation in damage on the landscape. The stochastic nature of severe wind events combined with landscape-level attributes affecting stand and tree condition (e.g. insect and disease infestation, drought, prior site history) results in an element of uncertainty that makes damage prediction highly variable and very difficult.

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