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Hurricane Katrina-induced forest damage in relation to ecological factors at landscape scale

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Abstract Forest stand stability to strong winds such as hurricanes has been found to be associated with a number of forest, soil and topography factors. In this study, through applying geographic information system (GIS) and logit regression, we assessed effects of forest characteristics and site conditions on pattern, severity and probability of Hurricane Katrina disturbance to forests in the Lower Pearl River Valley, USA. The factors included forest type, forest coverage, stand density, soil great group, elevation, slope, aspect, and stream buffer zone. Results showed that Hurricane Katrina damaged 60% of the total forested land in the region. The distribution and intensity of the hurricane disturbance varied across the landscape, with the bottomland hardwood forests on river floodplains most severely affected. All these factors had a variety of effects on vulnerability of the forests to the hurricane disturbance and thereby spatial patterns of the disturbance. Soil groups and stand factors including forest types, forest coverage and stand density contributed to 85% of accuracy in modeling the probability of the hurricane disturbance to forests in this region. Besides assessment of Katrina's damage, this study elucidates the great usefulness of remote sensing and GIS techniques combined with statistics modeling in assessment of large-scale risks of hurricane damage to coastal forests.

Keywords Forest disturbance · Stand stability · Windthrow · Landscape · Hurricane Katrina · Remote sensing · Geographic information system

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Introduction

Spatial patterns of disturbed forestlands by hurricanes and severities of the damage are controlled by a series of biotic and abiotic factors including species, stem size, canopy structure, stand density, intensity of the wind, topography, and soil characteristics (Everham and Brokaw 1996). Associations between these factors and hurricane disturbances have been investigated extensively at small scales (Bellingham 1991; Brokaw and Grear 1991; Gresham et al. 1991; Gardner et al. 1992: Everham and Brokaw 1996; Imbert et al. 1996; Ostertag et al. 2005; Van Bloem et al. 2005). However, applications of remote sensing and geographic information system (GIS) techniques to investigate relative roles of the different factors in controlling spatial patterns and severities of hurricane disturbance to forests at landscape scale is minimal and scant (Foster and Boose 1992; Boose et al. 1994; Ayala-Silva and Twumasi 2004; McMaster 2005). Based on an empirical function of wind damage with forest exposure, tree height and species composition, Foster and Boose (1992) constructed a GIS framework to analyze the forest responses to strong wind at landscape level. Boose et al. (1994) demonstrated that wind velocity gradients, variation in site exposure, local topography, and forest species composition and structure controlled hurricane damage to forests at landscape scale through assessment of actual forest damage with remotely sensed data. Furthermore, McMaster (2005) predicted forest areas damaged by a severe storm using slope, aspect, soil moisture, relative elevation and land cover as predictors and achieved an overall prediction accuracy of 60%.

Hurricane Katrina, the third deadliest hurricane in the US since 1900 (Knabb et al. 2006), swept through the coastal region of Louisiana and Mississippi states in August 2005. Forest landscape in the Lower Pearl River Valley, a portion of coastal Louisiana and Mississippi states, was disturbed at various intensities with some forest stands disturbed severely while others undisturbed. A series of factors including hurricane gusty winds, diverse forest types and properties, and changes in soil groups, elevation, slope and aspect may have contributed to the divergent vulnerability of forests in responses to Katrina's disturbance. Through applying remote sensing and GIS techniques, and logit regression analysis, this study was carried out to: (1) assess Hurricane Katrina damage to forests in the Lower Pearl River Valley and surrounding area; (2) analyze effects of forest characteristics and site conditions on the hurricane disturbance; and (3) model probabilities of forests disturbed by the hurricane. We hypothesize that the hurricane would create complex heterogeneous patterns across the landscape because of variations of the ecological factors within the affected area. A change detection technique, post classification comparison algorithm along with two composites of Landsat-5 TM bands 4, 5 and 3 imagery acquired pre- and post-Katrina was applied to identify the disturbed forests and severity of the damage. The assessed factors of forests and site conditions consisted of landform characteristics of elevation, slope, and aspect, soil great groups, buffer zones along river channels, forest types, and forest attributes derived from Landsat TM vegetation indices of normalized difference vegetation index (NDVI) and Tasseled cap wetness (TCW). The factors with continuous attributes were classified into discrete categories for analysis together with the categorical factors, such as soil groups (Table 1). The relative effects of the categories in each factor on the hurricane disturbance were assessed through comparing percentages of the total disturbed forest areas, percentages of the disturbed forest areas at three severity levels (high, moderate, and light), and odds ratios (exponents of the coefficients of independent variable in a full logit model). The relative effects of each factor on the disturbance were determined through comparing the full and reduced logit models.

Study area

In this study, we evaluated forest damage caused by Hurricane Katrina in the Lower Pearl River Valley and surrounding area in St. Tammany, Washington Parishes in Louisiana, and Hancock, Pearl River Counties in Mississippi, covering a geographical region between 90° 21′ W and 89° 19′ W, and 31° 00′ N and 30° 09′ N (Fig. 1). The eye of Hurricane Katrina passed through St. Tammany Parish, Hancock County, and Pearl River County. Pearl River travels southeasterly toward the Gulf of Mexico, forming an increasingly wide floodplain in the center portion of the area. Lake Pontchartrain, a 1,619 km^2 oligohaline estuary, is located in the southwest corner of the area and the city of New Orleans is on the lake's south shore.

Forests in this region occupy an area of about 370,000 ha, which is 53% of the total area investigated in this study. The main forest cover types are wetland forests, upland forests, and urban forests. In wetland forests, over 50% of the stands are comprised of water tupelo (*Nyssa aquatica*), swamp tupelo (*Nyssa biflora*), black gum (*Nyssa sylvatica*), sweet gum (*Liquidambar styraciflua*), oaks (*Quercus michauxii*, *Quercus pagoda*, *Quercus buckleyi*, *Quercus phellos*, and *Quercus lyrata*) and bald cypress (*Taxodium*

Table 1 Pre-Katrina forest distribution, types and environmental conditions in the Lower Pearl River Valley

Category 1[a]				2		3		4		5		6		7	8
	Soil groups	Drainage[b]	Forest (%)	Aspect	Forest (%)	Slope	Forest (%)	Forest types (ftypes)	Forest (%)	Elevation	Forest (%)	Buffers	Forest (%)	NDVI	TCW
1	Dystrudepts	5	7.4	0–45	10.2	0	55.5	Urban	4.3	0–24	48.2	< 100	22.5	< 0.660	< −0.0180
2	Hapludults	5	3.4	45–90	12.8	1	16.4	Deciduous	0	24–48	21.3	100–200	17.9	0.660–0.704	−0.018 to −0.011
3	Fluvaquents	2, 3	17.3	90–135	14	2	11	Evergreen	39.5	48–72	18.2	200–300	14.2	0.704–0.739	−0.011 to −0.003
4	Hydraquents	1	12.7	135–180	13.4	3	7.3	Mixed	1.7	72–96	10.6	300–400	11.1	0.739–1	−0.003 to 0.0516
5	Paleudults	2	33.8	180–225	13.4	4	4.5	Shrub/Scrub	13.2	96–122	1.8	400–500	8.4		
6	Fragiudults	4	4.4	225–270	13.8	5	2.6	Wetlands	41.3			> 500	25.9		
7	Glossaqualfs	2	2.9	270–315	11.4	6	1.4								
8	Haplosaprists	1	1.9	315–360	11.2	≥ 7	1.3								
9	Endoaquepts	3	5.8												
10	Sulfaquents	1	0.6												
11	Paleaquults	4, 3, 5	9.8												

[a]The numbers from 1 to 8 above the columns are numerical representations of the factors assessed in the study

[b]Drainage 1: very poorly drained; 2: poorly drained; 3: somewhat poorly drained; 4. moderately well drained; 5: well drained

distichum), and less than 25% are southern pines of loblolly pine (*Pinus taeda*), slash pine (*Pinus elliottii*), shortleaf pine (*Pinus echinata*), and longleaf pine (*Pinus palustris*) (Rosson 1995; USDA Forest Service 2007). Upland forests are predominantly mixed groups of loblolly-shortleaf-southern yellow pines, longleaf-slash pine forests mixed with oaks, hickories (*Carya spp.*), and gums, and oak–pine mix forests (Rosson 1995; USDA Forest Service 2007). Besides timber production, the forests in the region provide hunting, fishing and recreation opportunities, making an important contribution to the local economy and environmental well-being. The forests in the Bogue Chitto National Wildlife Refuge, the Pearl River and the Ben's Creek Wildlife Management Areas in the region are of national importance for wildlife migration in North America.

The region has a subtropical humid climate characterized by an annual average temperature of 19°C, varying from 12°C in January to 28°C in July, and by an annual average precipitation of 1,600 mm, ranging from 86 mm in October to 159 mm in July (Keim et al. 1995). Geologically, the region is dominated by Pleistocene river deposits that form terraces of decreasing elevation from approximately 122 m in the north to sea level in the south, with dominant soil great groups of paleudults, fluvaquents and hydraquents (USGS 2002).

Assessment approaches

Data collection and preparations

In addition to the disturbed forest cover map created in a previous study by Wang and Xu (2007), data collected for current study consisted of national land cover data (NLCD), state soil geographic (STATSGO) data, digital elevation model (DEM) data, and national hydrography dataset (NHD).

NLCD was created on the basis of Landsat 7 ETM+ imagery acquired circa 2000. However, land covers in the region have been changed since the year of 2000. In addition, our field inventory in 2006 showed that Hurricane Katrina severely

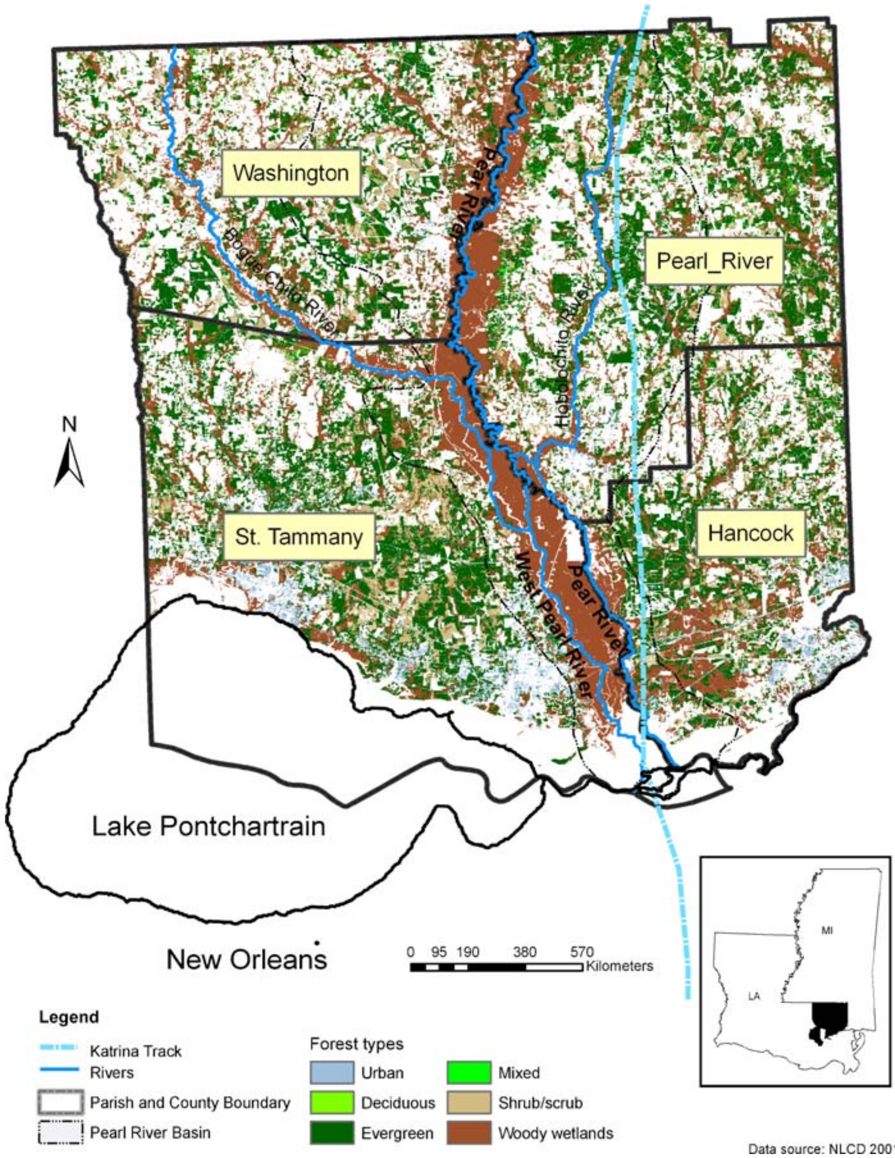

Fig. 1 Study area and spatial distribution of forest types pre-Katrina

damaged urban forests, which were classified as part of developed land cover in NLCD. If NLCD had been used directly, disturbance to urban forests would have not been assessed. Moreover, the forestlands which have been deforested before the hurricane, for instance, due to timber production, would have been detected incorrectly as disturbed land by the hurricane. Therefore NLCD map was masked with a 2005 forest cover layer generated in the study by Wang and Xu (2007). The land cover type, developed land cover, was then recoded as urban forest. In the end, five land cover types, urban forests, evergreen forests, mixed forests, shrub/scrub, and wetland forests, were studied.

The STATSGO data structure was designed at three levels of organizations: map unit, component and layer. A map unit (polygon on the map) is a collection of areas defined and named in terms of their soil components, miscellaneous areas or both. Each map unit contains up to 21 components. There are up to 60 soil properties in each component and 28 properties in each layer. This study used soil taxonomy given in the component layer to map the soil great groups at map unit scale.

The DEM data (in 30 × 30 m resolution) was extracted from the US Geological Survey National Elevation Database (http://ned.usgs.gov/), which is a seamless mosaic of best-available elevation data. Due to artifact removal processing, the elevation data greatly improves the quality of the slope, shaded-relief, and synthetic drainage information. Slope and aspect layers for this study were generated on the basis of the elevation layer with Topographic Tools of ERDAS Imagine 9.0 (Leica Geosystems Geospatial Imaging, LCC, CA, USA).

The NHD layer of flow lines (scale: 1:100,000) was generated from the content of USGS Digital Line Graph (DLG) hydrography data integrated with reach-related information from the EPA Reach File Version 3. A stream and river polyline GIS data layer for the study area was clipped from the NHD layer. Five buffer zones with intervals of 100 m were further created along the streamlines.

TCW and NDVI imagery pre-Katrina were derived from the Landsat 5 TM imagery taken on August 22, 2005. These two vegetation indices were used to relate to forest attributes, such as forest coverage and stand density.

After these data layers were generated, the categorical (e.g., soil groups) and the numerical attributes of the data were coded as thematic GIS data layers (column of category in Table 1) for numeric analysis.

Determination of disturbance severities

The damage to the forests identified by post-classification comparison method (Wang and Xu 2007) were further classified into three categories: high, moderate, and light disturbance according to the field inventories (Wang and Xu 2007) by applying the unsupervised classification method. The layer of undisturbed forests overlaid on the disturbed forest layer and generated a final map of the hurricane disturbance to forests in the region (Fig. 2).

Quantification of landscape metrics

Landscape metrics of the undisturbed and disturbed forests were quantified with FRAGSTATS 3.3, a spatial pattern analysis program developed by Mcgarigal and Marks (1995). Metrices of forests disturbed at the three severity levels were determined in the same fashion. The quantified metrics consisted of number of patches (NP), patch density (PD), patch area mean (AREA_MN), patch area standard deviation, largest patch index, total core area, total edge (TE), edge density (ED), and landscape shape index (LSI).

Multivariate regression analysis

A series of full and reduced logit models were developed to analyze the effects of forest characteristics and site conditions on the hurricane disturbance and to model probabilities that forests would be disturbed by hurricanes. First, a full model was constructed by entering forest disturbance (the disturbed forests coded as 1 and undisturbed coded as 0) as the dependent binomial variable, and the coded factors of forest type, soil, elevation, slope, aspect, buffer zone, NDVI, and TCW (Table 1) entered as independent variables. Then a series of reduced models were built by sequentially removing the independent variables. Subjects of the variables for fitting the models were from half of the total pixels (size: 28.5 by 28.5 m) in the region, and subjects from the remaining half of the pixels were used to validate the models. Criteria for evaluating the fit of models included percentages of correctly classified undisturbed and disturbed forests, percentage of the concordance of predicted probabilities and observed responses, and Akaike's information criterion (SAS 9.1, SAS Institute Inc. 2006). Odds ratios derived from the full model were used to compare relative effects of the categories in each factor on occurrence of hurricane disturbance. The comparison is made between the categories coded as lower numbers and the one coded as the highest number (column Category in Table 1). The odds ratio that is greater than 1 indicates that the effect of the lower coded category on

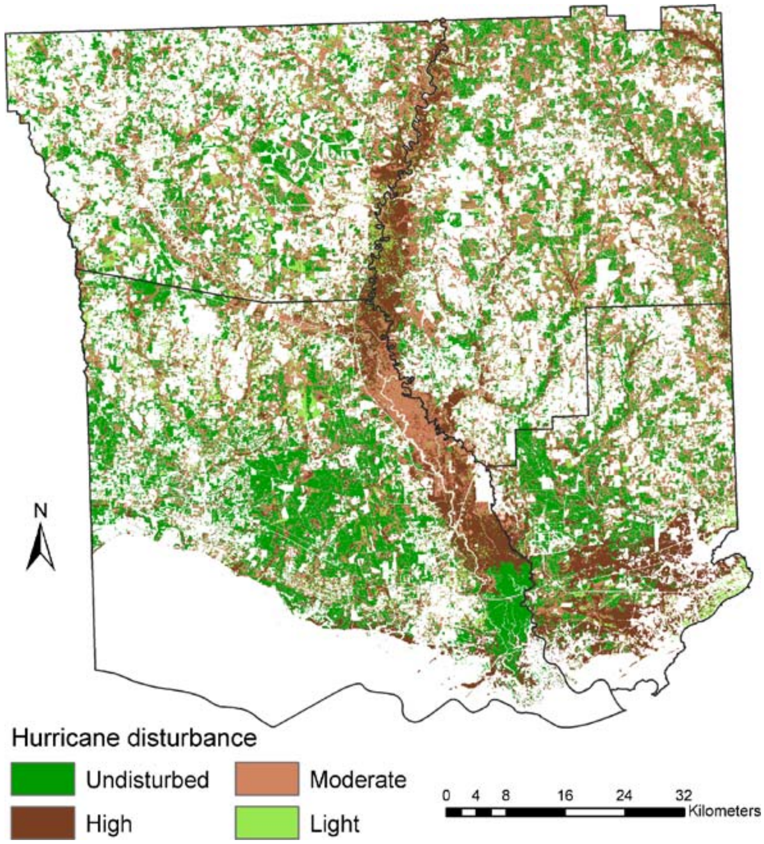

Fig. 2 Spatial distributions of the hurricane-induced forest disturbances by severity levels

hurricane disturbance is less than that of the category with the highest code, suggesting that forests associated to the lower category are less likely to be disturbed by the hurricane. On the other hand, the lower coded category would have stronger effects on the occurrence of hurricane disturbance if the odds ratio is less than 1. Moreover, if the odds ratio is not significantly different from 1, then the two categories have no significant effects on the disturbance probabilities.

Results

Pre-Katrina forest and site conditions

Prior to Hurricane Katrina, percentage of coverage and spatial distributions of forests in the region varied with forest types (Table 1). Wetland forests and upland evergreen forests were two major forest types. Upland forests distributed uniformly across the entire area (Fig. 1). In contrast, wetland forests noticeably clustered in the Pearl River and Bogue Chitto River valleys. Urban forests were mainly distributed in towns or cities along the north shore of Lake Pontchartrain and Bay St. Louis. Shrub/scrub cover appeared as large patches in St. Tammy Parish.

Percentage of forest coverage also varied with soil great groups, elevation, slope, and stream buffer zones too (Table 1). Among the 11 soil groups, percentage of forest coverage decreased from 34% on paleudults to 0.6% on sulfaquents. Forest coverage declined with increasing elevation and slope. About half of the forests were on 0–24 m elevation land or on the flat plain. Less than 2% of forests were on land with elevation above 100 m or on slope equal or greater than 7°. In addition, increases in distance to the river channels at interval of 100 m from 0 to 500 m were linked to gradually decreased percentage of forest coverage in each zone. Overall, approximately 75% of forests were within 500 m of the river channels. However, percentage of forested land

Table 2 Disturbed forestland areas and landscape metrics by the disturbance

Disturbances	Forestland Areas (ha)	Landscape metrics								
		NP	PD	AREA_MN	AREA_SD	LPI	TCA	TE	ED	LSI
Undisturbed	148,279.1	22,084.0	2.3	6.9	79.7	0.9	85,568.6	27,130,575.0	27.7	173.7
Disturbed	228,638.1	18,918.0	1.9	12.1	153.6	0.9	138,997.5	34,672,188.0	35.4	181.2
Highly disturbed	69,590.2	14,914.0	1.5	4.7	66.5	0.4	55,504.9	14,261,115.0	14.6	135.2
Moderately disturbed	133,444.6	27,270.0	2.8	5.0	28.6	0.3	35,668.2	33,236,073.0	33.9	225.3
Lightly disturbed	25,603.3	12,386.0	1.3	1.9	7.2	0.0	7,371.6	7,534,488.0	7.7	123.5

In this table and subsequent tables and figures, the highly, moderately, and lightly disturbed categories are subsets of the disturbed category
NP Number of patches, *PD* patch density (number of patches per 100 ha), *AREA_MN* patch area mean (ha), *AREA_SD* patch area standard deviation, *LPI* largest patch index, *TCA* total core area (ha), *TE* total edge, *ED* edge density (m), *LSI* landscape shape index

areas did not change greatly with various aspect categories (Table 1).

Disturbed forested landscape

In the Lower Pearl River Valley and its surrounding area, Hurricane Katrina damaged 60% of the forested land with 18% highly, 35% moderately, and 7% lightly disturbed (Table 2). The hurricane altered the forest landscape to a mosaic of undisturbed and disturbed forest patches across the region (Fig. 2). A large fraction of highly and a small portion of moderately disturbed forests apparently clustered in the Lower Pearl River Valley and south Hancock County (Fig. 2). Lightly disturbed forests were randomly scattered as small patches in the region, whereas undisturbed forests noticeably clustered in the Lower Pearl River Valley, the lower portion of St. Tammany Parish, and the northwestern portion of Hancock County (near the Lower Pearl River valley; Fig. 2).

Landscape metrics showed that spatial configurations of the landscapes were different between undisturbed and disturbed forests (Table 2). Compared to undisturbed forests, the lower NP, PD, and higher AREA_MN and TCA associated with disturbed forests indicated that disturbed forests were more aggregated. The higher LSI, ED, and TE of disturbed forests demonstrated that patch shape of disturbed forests was more complex and irregular. Higher TCA of disturbed forests at the three severity levels showed that patches of highly disturbed forests were more clustered than moderately and lightly disturbed forests (Table 2). Moreover, higher LSI and ED indicated that patch shape of the moderately disturbed forests was more irregular than that of lightly disturbed forests.

Spatially, there appeared to be a close association of disturbance intensity with drainage network in the watersheds (Fig. 2). Forests adjacent to streams and rivers in this area were found more severely disturbed by the hurricane (Fig. 3), indicating a high susceptibility of bottomland forests to the hurricane damage. With increasing distance away from the river channels, percentage of the highly disturbed forests declined, while percentages of the moderately and lightly disturbed forests escalated slightly.

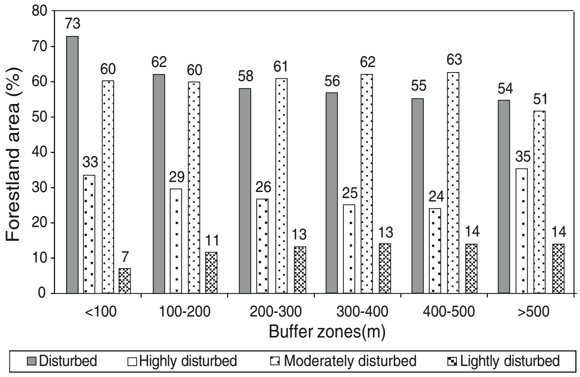

Fig. 3 Percentages of the disturbed forestland areas by the buffer zones

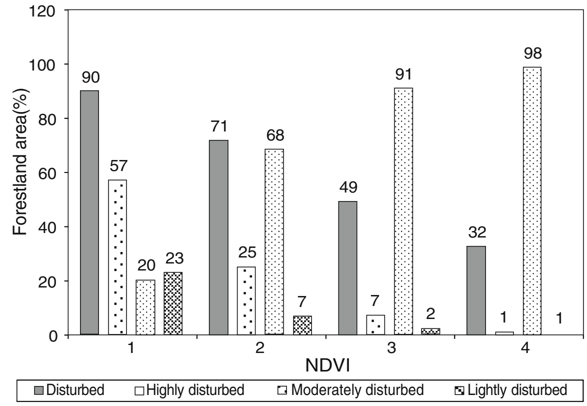

Fig. 5 Percentages of Katrina-induced forest disturbances by the four NDVI categories

Stand conditions versus disturbance intensities

Area of Katrina-disturbed forests and severity of the damage varied by forest types (Fig. 4). The largest portion of wetland forests was disturbed (78%), followed by urban (73%), mixed (69%), evergreen forests (47%), and shrub/scrub (43%). Among three severity levels of the disturbance, the greatest portion of wetland and urban forests were highly disturbed (39% and 30%, respectively). In contrast, percentages of the moderately disturbed areas for mixed forests and shrub/scrub were the highest (85% and 78%) even though percentages of the total disturbed areas were lowest.

As both NDVI and TCW categories (values) increased, percentage of disturbed forests declined gradually (Figs. 5 and 6), which indicated that hurricane disturbance was apparently severer as NDVI and TCW values were lower. Changes in percentage at three levels of the severity under NDVI categories were more noticeable than under TCW categories. The percentage of the highly disturbed forests in category 1 of NDVI was 57 times higher than that in the fourth category. In contrast, percentages of highly disturbed forests between the first and the fourth TCW categories differed only by 2%. Therefore, NDVI could be more valuable than TCW in detecting hurricane disturbance to forests.

Site conditions versus disturbance intensities

Effects of soils on disturbance magnitude depended largely on soil great groups. Forests growing

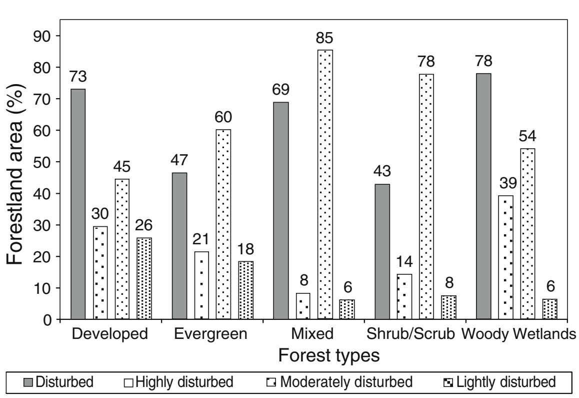

Fig. 4 Percentages of the disturbed forestland areas by the forest types

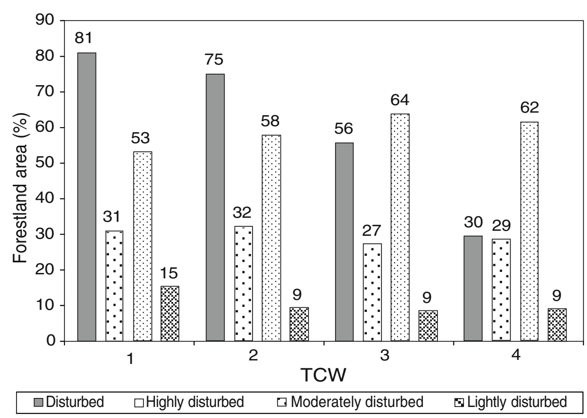

Fig. 6 Percentages of Katrina-induced forest disturbances by the four TCW categories

Table 3 Percentages of disturbed forested land areas by soil groups

Class	Undisturbed	Disturbed	Highly disturbed	Moderately disturbed	Lightly disturbed
Dystrudepts	31.53	68.47	24.28	64.54	11.18
Hapludults	47.89	52.11	4.16	78.48	17.37
Fluvaquents	39.26	60.74	19.62	72.57	7.81
Hydraquents	37.43	62.57	52.13	36.65	11.23
Paleudults	47.95	52.05	16.83	68.33	14.84
Fragiudults	32.99	67.01	23.24	63.33	13.43
Glossaqualfs	51.65	48.35	43.45	43.38	13.17
Haplosaprists	36.58	63.42	11.50	76.31	12.19
Endoaquepts	8.38	91.62	52.28	43.25	4.47
Sulfaquents	15.23	84.77	82.50	5.64	11.85
Paleaquults	34.62	65.38	52.79	38.67	8.54

on endoaquepts and sulfaquepts soils were found to be most susceptible to hurricane damage, with over 80% of the forests damaged (Table 3). In contrast, forests growing on glossaqualfs appeared to be most resistant to Katrina's winds, with less than half of the total forests disturbed. Forests on sulfaquents were susceptible to the hurricane winds, whereas forests on hapludults suffered only moderate and light disturbance.

Except for the coastal areas with elevation less than 24 m, percentage of disturbed forests declined gradually with increasing elevations (Fig. 7). The hurricane caused the highest percentage of disturbance at elevation 24–48 m, where areas of disturbed forests were twice of those of undisturbed forests. At elevation ranges 0–24 and 48–72 m, percentage of disturbed forests was about 20% higher than the undisturbed ones. At higher elevation (above 72 m), the percentage of disturbed forests was only about 5% higher than the undisturbed forests. Percentages of disturbed forests at three severity levels showed that percentage of the highly disturbed forests was higher at lower elevations while that of the moderately and lightly disturbed areas was higher at higher elevation (Fig. 7).

Percentage of the total disturbed areas gradually declined with rising aspects, except for at 0–45° and 315–360° (Fig. 8). The percentages at the three severity levels did not vary noticeably with aspects, except for 315–360°, where percentages of highly and moderately disturbed forests were much greater than those at the other aspect levels.

Percentage of disturbed forests slightly increased when the slopes were greater than 2° (Fig. 9). Forests on 1° slope appeared to be most susceptible to the hurricane disturbance. Among the three levels of severity, percentage of the

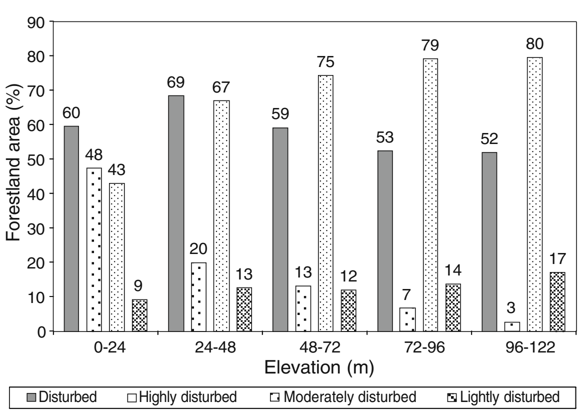

Fig. 7 Percentages of Katrina-induced forest disturbances by the elevation categories

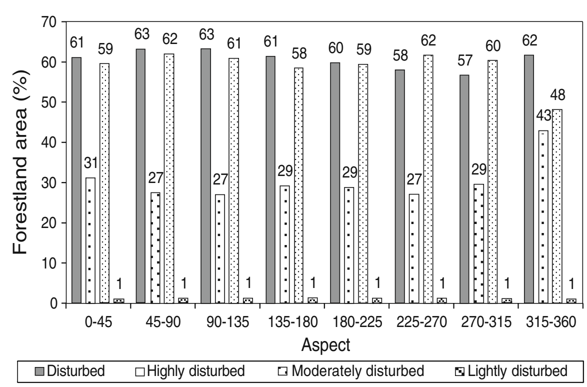

Fig. 8 Percentages of Katrina-induced forest disturbances by the aspect categories

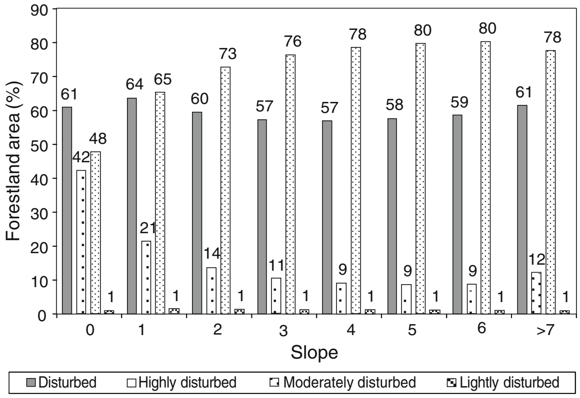

Fig. 9 Percentages of the disturbed forestland areas by the slope categories

highly disturbed forests varied noticeably with 42% on flat land and 8.7% on 6° slope. Percentage of the moderately disturbed forests rose gradually from 48% on flat land to 80% on 6° slope. On the flat land, almost the same amount of forestland areas was highly and moderately disturbed. However, for slopes greater than 0°, percentage of the highly disturbed forests was considerably lower than that of the moderately disturbed ones.

Integrated assessment

Results from a full logit regression model revealed that all factors were significant in explaining the variation in the probability of hurricane wind disturbance to forests in this region ($P < 0.0001$, respectively). Odds ratio of the forest types with codes less than 6 to wetland forests coded as 6 were less than 1, indicating that woody wetlands had the highest probability to be disturbed by the hurricane, compared to the other four types (Table 4). The lowest odds ratio of evergreen forests and shrub/scrub to wetland forests suggested that the former two forest types were more resistant to the hurricane disturbance than the latter.

Odds ratio of both NDVI and TCW categories showed similar decreasing trends when the category codes of these two factors increased from 1 to 3 (Table 4), which implied that forests with higher values of NDVI and TCW were less likely to be disturbed.

Odds ratio among the 11 soil groups denoted that forests on endoaquepts were most likely to be disturbed by the hurricane, compared to forests on the other soil groups (Table 4). The odds of forests disturbed by the hurricane was 3.2 times higher on endoaquepts than on paleaquults. By contrast, glossaqualfs had the least effects on hurricane disturbance to forests.

The highest odds ratio among elevation pairs (Table 4) demonstrated that forests on elevation of 24–48 m were most susceptible to the hurricane damage than those in other elevation ranges. Forests in coastal area with the lowest elevation of 0–24 m had the lowest probability to be disturbed (the lowest odds ratio = 0.4).

Forests on lands with an aspect of 0–225° showed a higher probability to be disturbed by the hurricane (odds ratio > 1) than those in the areas with an aspect of 225–315° (odds ratio < 1; Table 4), indicating greater exposure to the hurricane winds resulted in higher chances of forest damage.

Forests growing in areas with 0°, 2°, 3°, and 4° slopes had a lower disturbance probability compared to those on slopes greater than 7° (odds ratio < 1; Table 4). Forests in areas with 1°, 5°, and 6° slopes showed a higher probability to be damaged by the hurricane than those on slopes greater than 7° (odds ratio > 1). Forests on 1° slope appeared to be most susceptible to the hurricane disturbance (the greatest odds ratio).

Probabilities of the hurricane disturbance in stream buffer zones 1, 2 and 3 were significantly different from zone 6 (Table 4), whereas those in zones 4 and 5 were comparable to zone 6. This suggested that probabilities of the hurricane disturbance within 300 m of a river channel were significantly different from those at distances greater than 300 m. The highest odds ratio of buffer zone 1 versus zone 6 revealed that forests within 100 m of the river channel had a highest chance to be disturbed by the hurricane.

The reduced models showed that, when independent variables of buffer zone, aspect, slope and elevation were removed from the full model, the percentages of the correctly classified undisturbed and disturbed forests, the percentage of the concordance, and AIC value changed 0.27%, 1.14%, 1.1%, and 3.2%, respectively. Then, when

Table 4 Estimates of the odds ratios and the confidence limits

Pairs of the factors	Odds ratios	95% Wald Confidence limits	
ftype 1 vs 6	0.642[a]	0.630	0.654
ftype 3 vs 6	0.340[a]	0.337	0.343
ftype 4 vs 6	0.870[a]	0.847	0.892
ftype 5 vs 6	0.387[a]	0.383	0.391
NDVI 1 vs 4	24.975[a]	24.666	25.287
NDVI 2 vs 4	6.028[a]	5.970	6.087
NDVI 3 vs 4	2.010[a]	1.992	2.028
TCW 1 vs 4	8.501[a]	8.408	8.596
TCW 2 vs 4	6.452[a]	6.386	6.518
TCW 3 vs 4	2.921[a]	2.894	2.948
Soil 1 vs 11	0.779[a]	0.766	0.793
Soil 2 vs 11	0.618[a]	0.604	0.632
Soil 3 vs 11	1.039[a]	1.024	1.054
Soil 4 vs 11	0.489[a]	0.481	0.496
Soil 5 vs 11	0.641[a]	0.633	0.650
Soil 6 vs 11	0.806	0.790	0.823
Soil 7 vs 11	0.248[a]	0.242	0.254
Soil 8 vs 11	0.741[a]	0.721	0.761
Soil 9 vs 11	3.294[a]	3.212	3.378
Soil 10 vs 11	1.219[a]	1.157	1.285
Elevation 1 vs 5	0.411[a]	0.400	0.422
Elevation 2 vs 5	1.146[a]	1.117	1.176
Elevation 3 vs 5	0.987[a]	0.962	1.012
Elevation 4 vs 5	0.856[a]	0.834	0.878
Aspect 1 vs 8	1.052[a]	1.037	1.068
Aspect 2 vs 8	1.193[a]	1.177	1.210
Aspect 3 vs 8	1.232[a]	1.215	1.249
Aspect 4 vs 8	1.161[a]	1.145	1.177
Aspect 5 vs 8	1.089[a]	1.074	1.104
Aspect 6 vs 8	0.991[a]	0.977	1.004
Aspect 7 vs 8	0.890[a]	0.877	0.903
Slope 1 vs 8	0.783[a]	0.760	0.807
Slope 2 vs 8	1.010[a]	0.980	1.040
Slope 3 vs 8	0.976[a]	0.947	1.006
Slope 4 vs 8	0.959	0.929	0.989
Slope 5 vs 8	0.970	0.939	1.001
Slope 6 vs 8	1.005[a]	0.970	1.040
Slope 7 vs 8	1.031[a]	0.991	1.073
Buffer 1 vs 6	1.040[a]	1.027	1.054
Buffer 2 vs 6	0.951[a]	0.938	0.964
Buffer 3 vs 6	0.976[a]	0.962	0.990
Buffer 4 vs 6	0.996	0.982	1.011
Buffer 5 vs 6	0.999	0.984	1.014

[a]Odds ratio is significantly different from 1 ($P < 0.05$)

the soil variable was excluded along with buffer, aspect, slope and elevation, the percentages increased by 3.9%, 0.23%, 2.8%, and 7.2%, respectively. Additionally, when forest type, NDVI and TCW variables were sequentially removed from the model, the percentage of the concordance decreased 6.4%, 23.8% and 20.6%, and AIC value increased 11.9%, 25.6%, and 30.5%. Therefore, a model including only soil, forest types, TCW, and NDVI, which had only 3.2% increase of AIC value compared to the full model, was used to predict the probabilities of hurricane disturbance

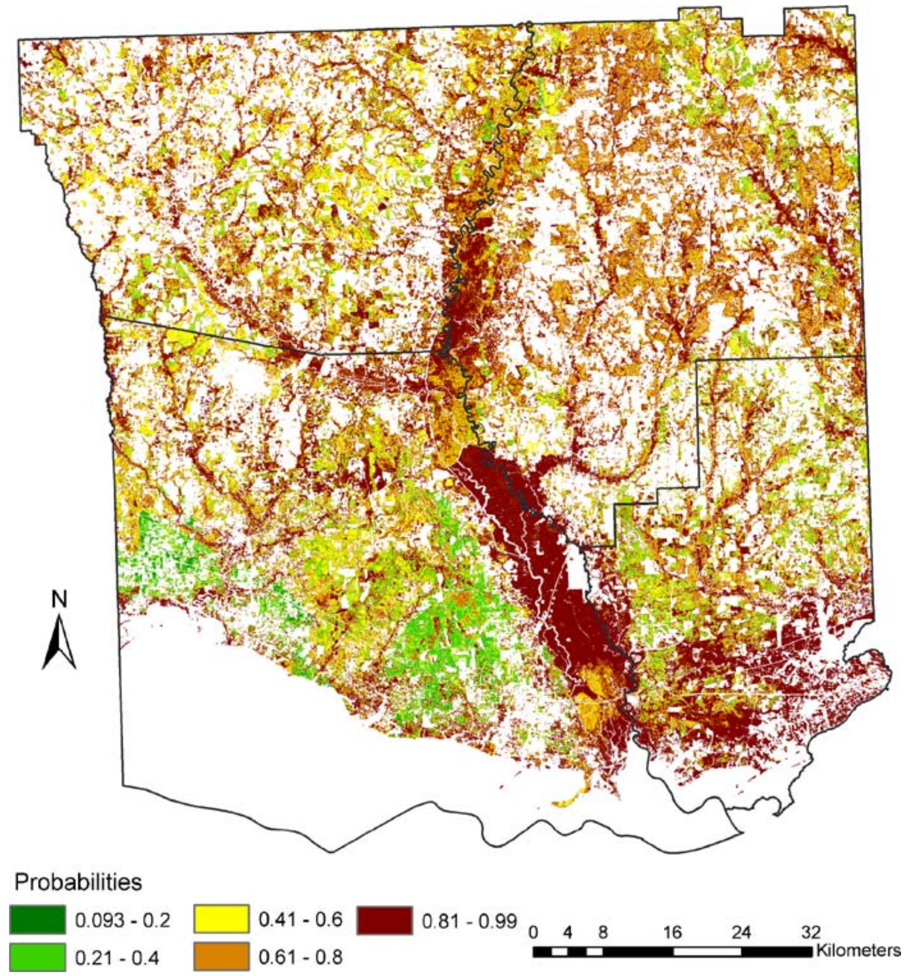

Fig. 10 Predicted probabilities of the forests disturbed by hurricanes

to the forests (Fig. 10). These four variables contributed to 85% concordance in prediction of the disturbance probabilities.

Discussion

Forest characteristics and stand stability

Our study showed that wetland forests in this region were more susceptible to the hurricane disturbance, followed by urban forests, mixed forests, evergreen forests, and shrub/scrub. In wetland forests, cypress (Touliatos and Roth 1971; Putz and Sharitz 1991) and tupelo (Gresham et al. 1991) were reported to be highly resistant to strong winds and their resistance may be related to presence of buttressed boles (Touliatos and Roth 1971; Putz et al. 1983; Mattheck and Bethge 1990; Peterson 2000) and deciduous habit of cypress, which greatly reduces the surface area exposed to high winds (Gresham et al. 1991). Southern red oak (*Quercus falcate*), water oak (*Quercus nigra*), and sweet gum were found to be more susceptible to strong tornado winds, compared to loblolly and longleaf pines (Glitzenstein and Harcombe 1988). This susceptibility may be attributed to their shallow rooting (Chambers 2006). In addition, Hurricane Katrina pushed Gulf waters up towards inner Lower Pearl River Valley, causing extensive flooding and saltwater intrusion in the area for several weeks, which may affected the wetland forests too.

In upland forests, we found that evergreen pines were more resistant to wind damage than the other types of forests. Gresham et al. (1991) also reported that in upland, oaks were more heavily damaged than pines. The resistance of longleaf pine to wind damage may be related to the firm anchorage of its large taproot and widespread lateral root system (Gresham et al. 1991).

Urban forests in the region were identified as the second most susceptible forest type to the hurricane disturbance. Urbanization, and changed environments, site quality, and management practices may result in changes in structure and resistance of forests to hurricane winds. Johnson and Johnson (1999) reported that roots cut during construction, root development hindered by restricted spaces, degraded old tissues, and incorrect irrigation could leave trees unstable and more prone to windthrow.

Shorter and smaller diameter trees are usually less severely damaged than taller and larger diameter trees (Lugo et al. 1983; Francis 2000; Reilly et al. 2002; Ostertag et al. 2005). We achieved similar results that shrub/scrub appeared to be the most resistant cover type to hurricane disturbance. The shrub/scrub in the valley was in general less than 5 m tall and consisted of true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions. The high resistance of shrub/scrub to Hurricane Katrina was apparently associated with its shorter height, smaller diameter, and smaller canopy.

This study demonstrated that NDVI and TCW values were closely related to percentage variations of the disturbed forests, and greatly contributed to the high accuracy in modeling probabilities of the hurricane disturbance to forests. NDVI is not an intrinsic physical measurement of vegetation characteristics, but is indeed correlated with certain vegetation properties such as percent vegetation cover, leaf area index (LAI), annual productivity, and stand density. NDVI values had a positive linear relationship with vegetation coverage (correlation values > 0.89; Ormsby et al. 1987; Purevdorj et al. 1998). NDVI values less than 0.3 signify vegetation cover of 5% or less, whereas a value of 0.7 or higher represents coverage greater than 80% (Ormsby et al. 1987). The relationship between NDVI and LAI is not linear across vegetation types. When LAI is greater than 5, NDVI tends to be asymptotic. In addition, in old conifer stands, NDVI values decline despite high LAIs (Turner et al. 1999). Forest growth is highly correlated to average NDVI values, with a correlation coefficient over 0.70 (Brown et al. 1989; Wang et al. 2004).

TCW is a linear combination of the Landsat TM six Bands (Crist and Cicone 1984). Cohen and Spies (1992) found that TCW was highly correlated to all 16 closed canopy forest stand structural attributes and appeared to respond to the degree of maturity in forest stands. Todd and Hoffer (1998) reported that TCW values increased as green vegetation cover increased for all soil backgrounds. Overall, these studies show that the TCW values are only positively correlated to the forest density and vegetation cover.

All of these previous studies on the relationships of attributes of forest structures and growths with values of NDVI and TCW indicate that NDVI or TCW values are correlated with numerous forest attributes, and percentage of coverage and stand density are the only ones that are positively correlated to both NDVI and TCW values. Therefore, we conclude that the relationships of NDVI/TCW values with the percentage and probability of hurricane disturbance to forests are negative. In other words, higher percentage of the forest cover and stand density are linked to lower forest susceptibilities to hurricane disturbance.

Soils and stand stability

Many studies have found a direct association between windthrow and tree rooting depth (Coutts 1986; Mattheck and Bethge 1990; Nicoll and Ray 1996). Soil chemical, physical and hydraulic properties have profound impacts on tree root development (Coutts 1986; Xu et al. 1997; Nicoll et al. 2006). In general, soil properties that contribute to shallow root development, such as poor drainage and seasonal water logging (Mayer 1989; Ray and Nicoll 1998), can lead to lower stand stability against wind damage. Gardner et al. (1992) documented that the most severe damage occurred in mixed bottomland hardwood sites on poorly drained Rutledge soils.

In our study, forests on endoaquept and sulfaquent soil groups were most susceptible to hurricane damage, whereas those on glossaqualfs were most resistant (Table 4). However, drainage properties of these three soil groups were similar (Table 1). Furthermore, forests on sulfaquents, a very poorly drained soil, were most susceptible to high disturbance. In contrast, forests on hapludults, a well drained soil, typically exhibited moderate and light disturbances. Our study was conducted at a landscape level with many tree species and various drainage conditions. Some forests such as cypress grow on poorly drained soils but are resistant to hurricane disturbance because the species has developed a unique root system resistant to wind damage. Therefore, we conclude that the soil drainage property alone cannot explain the relationships between soil groups and hurricane disturbance over a large area, which is supported by Lindemann and Baker (2002) and Lin et al. (2004). The frequencies of trees that die of uprooting do not differ significantly among soil drainage classes (Lin et al. 2004), and soil permeability and water-holding capacity are not correlated significantly with the blowdown pattern (Lindemann and Baker 2002).

Topographic features and stand stability

Topographic characteristics of forested land, such as aspect, slope, and elevation often help explain the spatial variations in wind damage and severity (Martin and Ogden 2006). Wind speeds usually peak above ridge crests and therefore the leeward side of hills experience increased turbulence (Finnigan and Brunet 1995). Forests growing on windward slopes are more vulnerable to windthrow than those on leeward slopes (Lugo et al. 1983; Bellingham 1991; Reilly 1991; Foster and Boose 1992), and forests in lower elevation receive more damage than those in higher elevation (Reilly et al. 2002). Lugo et al. (1983) and Putz and Sharitz (1991) found that hurricane winds caused greater damage to forests in coastal flat lowland areas. However, those topographic characteristics may not be able to solely explain the intensities of hurricane disturbance. For instance, Bellingham (1991) reported that mortality and uprooting did not seem to conform to a pattern that could be linked to topography. Walker (1991) found that most forest damage by Hurricane Hugo occurred on north-facing sites in Puerto Rico, whereas the hurricane struck the island from the southeast. Brokaw and Grear (1991) observed that a cloud forest plot sustained equal damage on windward and leeward slopes. Our results of descriptive statistics and logit regression analysis confirmed the sheltering effects of landform characteristics on hurricane disturbance, particularly in terms of disturbance severities (Figs. 7, 8, and 9, and Table 4). Windward slope (225–315° aspect) protected forests when Katrina made landfall in a south to north direction (Fig. 1). The hurricane tended to cause more severe damage (high disturbance) at lower slope and elevation areas (Figs. 8 and 9).

Disturbance versus landscape patterns

Spatial patterns of forested landscape disturbed by hurricanes are controlled by interactions of a series of biota and abiota factors, such as wind properties, topographic exposure, and differential stand susceptibility to strong hurricane wind (Foster et al. 1998). The patterns are highly variable at all scales with a patchy damage pattern characterized by a highly irregular border at a landscape scale (Foster and Boose 1992). Our study also showed Hurricane Katrina produced a heterogeneous disturbance pattern with the big patchy of damage within the study area as we hypothesized. The patchy damage pattern with more complex and irregular patch shapes clustered in the Lower Pearl River Valley and the southern portion of Hancock County (Fig. 2). The spatial continuity of the forest types, such as bottomland forests in the Lower Pearl River Valley and the same soil groups covering a large area, and high density of streams may have contributed to the aggregated and clustered patterns of the disturbed forests in the valley. The clustered patches of highly disturbed forests in the Lower Pearl River Valley may also contribute to lower patch density (1.5) and lower edge density (14.6) of highly disturbed forests compared to the undisturbed forests and moderately disturbed forests.

Conclusions

This study provides comprehensive assessment of the forest damage caused by Hurricane Katrina in the Lower Pearl River Valley and surrounding areas, USA. The hurricane disturbed 60% of forested lands across the region. The disturbance resulted in a highly fragmented landscape, with a large portion of the disturbed forests clustered on the Pear River floodplain and the southern portion of Hancock County. The factors of forest type, soil great group, elevation, slope, aspect, buffer zone along the river channels, forest coverage, stand density had various effects on overall percentage of the disturbed forests and percentages of the disturbed forests at three severity levels. These factors collectively played important roles in vulnerability of the coastal forests in response to Hurricane Katrina. Forest types, forest coverage and stand density, and soils groups contributed to 85% of accuracy in modeling the probability of hurricane disturbance to forests in this region.

Integration of a series of biotic and abiotic factors with GIS, remote sensing, and statistics modeling techniques showed a great advantage in revealing relationships between hurricane disturbance and the factors at landscape scale. With this approach, disturbance patterns at various severity levels were mapped with high accuracy over a large area based on changes in spectral properties of the forests before and after the hurricane event. Interpreting configurations of the disturbed landscape indicated how the hurricane disturbance spread across the wind swath and patterned the landscape. Without GIS algorithms and spatial data layers, effects of such factors as buffer zones along river channels could not be evaluated. Furthermore, forest attributes, including percentages of coverage and stand density, could not be derived for a large area if remotely sensed data are not available.

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