Assessment of Pre- and Post-Katrina Fuel Conditions as a Component of Fire Potential Modeling for Southern Mississippi

William H. Cooke III, Katarzyna Grala, David Evans, and Curtis Collins

ABSTRACT

Geographic information system models that assess fire hazard in southern Mississippi were developed in response to damage caused by Hurricane Katrina. Long time series of Landsat imagery, pre- and post-Katrina satellite imagery, and aerial imagery were integrated in a rapid-response sampling design to assess changes in fire hazard. The study assesses pre- and post-Katrina fuels as one component of fire potential models. Determining how these changes affect fire hazard is important for natural disaster response and recovery efforts. The analysis resulted in spatial depictions and summary statistics of fire hazard. Overall accuracy of the remotely sensed damage assessment was 72%. Because of the hurricane, areas of very low hazard decreased from 19 to 3%, whereas areas of very high hazard increased from 3 to 13%. These results were validated with actual fire occurrence data and indicate that increased numbers of fire suppression personnel may be needed for coming fire seasons in the region.

Keywords: fire hazard, GIS modeling, remote sensing, change analysis, Hurricane Katrina damage

Natural disasters such as Hurricane Katrina have multiple detrimental effects that can last for many years. Among these are erosion of barrier islands, impact to the fishing industry, and damage to forest resources (Ramsey et al. 2001, Wang et al. 2006). Damage to the structural components of ecosystems, forest stands in particular, has wide-ranging implications for flora and fauna, as well as local and state-level economies.

Rapid assessments of damage to the timber and forest resources have been undertaken in Katrina-impacted areas of southern Mississippi. Estimates by the Mississippi Forestry Commission (MFC) indicate that Hurricane Katrina generated about three times the amount of timber damage as that attributed to Hurricane Ivan. The initial estimate of damaged timber was 3.2 bbf with an approximate market value of $1.3 billion (MFC 2005).

It is unlikely that timber salvage operations will account for the removal of more than a small fraction of broken or downed timber. Although salvage operations likely will be targeted toward removal of merchantable timber, damage occurred across all age classes and forest types. Areas with damaged timber in southern Mississippi that have not been salvaged may be at increased future risk for wildfires. Adequate response and recovery efforts require timely assessment of changing conditions both spatially and temporally. Geographic information system (GIS) modeling supports mapping of these changing conditions.

National Aeronautics and Space Administration–funded collaborative studies by the Mississippi State University Departments of Forestry and Geosciences have

Received July 31, 2006; accepted August 7, 2007.

William H. Cooke III (whc5@geosci.msstate.edu) is assistant professor, and Katarzyna Grala (kgrala@geosci.msstate.edu) is research associate I, Department of Geosciences, Mississippi State University, 108 Hilbun Hall, East Lee Boulevard, Mississippi State, MS 39762. David Evans (dle@rs.msstate.edu) is professor, 353 Thompson Hall, Mississippi State, MS 39762, and Curtis Collins (ccollins@sitl.cfr.msstate.edu) is research associate II, Rm. 350C Thompson Hall, Mississippi State, MS 39762, Department of Forestry, Mississippi State University, Mississippi State, MS 39762. *The authors thank John Gilreath for his considerable contributions to this research project.*

concentrated on creating a linear additive GIS model designed to determine fire potential in southeastern United States. Although numerous fire potential models have been developed (Andrews and Queen 2001, Bonazountas et al. 2005, Hernandez-Leal et al. 2006), our model is specifically designed to address distinctive conditions of southern Mississippi. Most of the existing literature on fire modeling in the United States has been oriented toward the western United States. (Pew and Larsen 2001, Whitlock et al. 2003). Although fire potential generally is regarded as lower in the eastern United States, Mississippi has on average 3,760 wildfires each year that require personnel and resources to extinguish. The average number of wildfires was calculated based on 14 years (1991–2004) of historic fire data acquired from the MFC and in the analyzed period the minimum number of fires was 1,847, and the maximum number of fires reached 6,616/year.

Review of the literature on fire modeling indicates that fire potential is related to four factors: climate, topography, anthropogenic influences, and vegetation (Burgan et al. 1998, Mistry and Berardi 2005). Climate often is considered the most important factor in fire models. It is also the most dynamic fire influence, affecting fire potential through precipitation, evaporation, wind, and lightning. Topography is an important fire variable, especially in the western United States; however, Zhai et al. (2003) showed that topography was an insignificant fire variable for Mississippi. Anthropogenic factors also play an important role in fire incidence. Humans affect wildfire ignition by altering the vegetative fuel load characteristics and by providing an ignition source (Pye et al. 2003). Altered fuel characteristics such as forest harvests, construction, management practices, and nature of the urban/wildland interface all affect fire behavior and probability of occurrence (Zhai et al. 2003). Vegetation is a major component in fuel estimations, because fires tend to be more prevalent in some vegetation types than others. In Mississippi, fires occur more often in needle-leaf conifers, predominantly pine (*Pinus* sp.) and mixed coniferous and broadleaf deciduous stands than in broadleaf deciduous stands alone (Zhai et al. 2003). In addition, sudden changes in environmental conditions and substantial vegetation damage can contribute to rapid changes in fuel loads and increase in fire potential.

The term "fire potential" refers to the final model and for this study is defined as the likelihood or probability that a given part of the landscape is susceptible to fire should an ignition source be available. The final fire potential model will include variables describing climate, ignition, and fuels and will incorporate Light Detection and Ranging, Moderate Resolution Spectroradiometer, and other remotely sensed data as modeling components. However, the focus of this study is to evaluate the fuel component of the fire potential model by assessing changes in forest fuel conditions from pre- and post-Katrina aerial imagery. In fire terminology such assessment refers to a fire hazard and indicates the state of the fuel, independent of weather or the environs in which the fuel is found (Hardy 2005). Development of GIS layers that enable rapid characterization of changes in forest fuel conditions is important for determining how fire hazard can change due to hurricane impacts. These changes may be especially important in light of the low rainfall amounts before and after Katrina.

The drastic and rapid change in vegetation conditions after Hurricane Katrina constituted an immediate need to estimate the amount of timber damage as well as to assess implications of damage in determining fire potential. Pre- and post-Katrina fire hazard was compared for six counties in southern Mississippi using information on forest age classes, forest type, and damage categories. Our study incorporates a rapid-response sampling design with moderate resolution aerial imagery to estimate accurately the extent of timber damage. Characterization of the spatial distribution of timber damage enabled assessment of fuel conditions important for activities aimed at preventing additional damage to the state's forest resources because of the increased likelihood of wildfires.

Materials and Methods

Study Area. A combination of intense rainfall and extreme wind speeds contributed to extensive damage to southern Mississippi counties (Figure 1). High winds caused physical breakage of tree boles and limbs and caused extensive defoliation. Prolonged heavy rains saturated soils and contributed to windthrow (uprooted trees) in bottomlands and low-lying areas. Wind speed and rainfall data, acquired after the storm, supported selection of the study area. The study area comprised the six counties in southern Mississippi that were most severely impacted by Hurricane Katrina: Hancock, Pearl River, Harrison, Stone, George, and Jackson. The boundary of the study area was set to the combined inland sections of these six Mississippi counties. Please note that Hancock, Harrison, and Jackson counties have inland and coastal sections within their administrative boundaries (Figure 1). The coastal administrative sections and barrier islands were excluded from the analysis.

Data Preparation. *Classification of Forest Age and Forest Type from Landsat Imagery.* Characterization of pre-Katrina forest fuel conditions were based on age class and forest type maps derived from Landsat satellite data (Collins et al. 2005). Satellite imagery from the Landsat earth observation program was acquired at (approximately) 5-year intervals from 1974 to 2003 (Lillesand et al. 2004). These Multispectral Scanner, Thematic Mapper (TM), and Enhanced TM data were rectified to a common map base and were analyzed to derive forest age for relatively current (2003) forestland cover (Collins et al. 2005). Determination of forest age classes was performed using the basic "postclassification" change detection procedure described by Lillesand et al. (2004). In this approach, two dates of imagery are independently classified and compared to determine pixels that changed classes between dates. In addition to the forest age classification, three broad forest type classes (needleleaf conifers, broadleaf deciduous, and mixed [coniferous/broadleaf]) and three general land cover classes (water, forest, and nonforest) were determined using an unsupervised classification approach. This approach finds and aggregates statistically similar spectral clusters in the data and the analyst determines class names by comparing the classified image with ground reference data (Lillesand et al. 2004). Derived information on forest type and land cover classes was combined with information on forest age to create a single layer that contained nonforestlands, water, forest type, and forest age. For the purposes of this article we will refer to this product as the "Age–Type" grid.

Hurricane Damage Analysis from Advanced Wide Field Sensor (AWIFS) Imagery. Information generated from pre- and post-Katrina AWIFS imagery was used to produce a forest damage layer for southern Mississippi. A Normalized Difference Moisture Index (NDMI) was used for vegetation change analysis (Sader et al. 2003, Jin and Sader 2005). Vegetated areas yield high values for this index and by analyzing changes in index value over time, changes in vegetation can be quantified. The NDMI analysis was performed on pre- and post-Katrina AWIFS imagery to quantify damage to the forest resource that resulted from the hurricane. The result of this change analysis was an AWIFS change mask of damage due to Hurricane Katrina.

Sample Strata from Aerial Imagery. The Age–Type grid was combined with the AWIFS "change mask" to create six post-Katrina forest condition strata. These strata were created by partitioning the three forest type classes (needle-leaf conifers, broadleaf deciduous, and mixed) into either the "damaged" or "undamaged" condition derived from the AWIFS change mask. The six forested strata that resulted were damaged needle-leaf conifers, undamaged needle-leaf conifers, damaged broadleaf deciduous, undamaged broadleaf deciduous, damaged mixed, and undamaged mixed. Each county was allocated about 100 plots (⅕ ac each). These 100 plots were divided proportionally based on the area of each forest stratum.

Sample rates varied by stratum and by county; percent sampling rate per strata ranged from 4 to 19% and averaged 12% over the study area.

Assessment of Katrina Forest Damage. *Damage Assessment from Aerial Imagery.* Pre-Katrina aerial imagery was acquired from the National Agriculture Imagery Program (NAIP; USDA [2006]). The program acquires natural color and color infrared imagery during the agricultural growing seasons in the continental United States. NAIP imagery at 1-m ground sample distance was used to assess pre-Katrina forest conditions and was acquired during the 2004 growing season. ADS40 aerial imagery at a 0.3-m nominal horizontal resolution acquired from the USDA Service Center (Davenport and Odom 2005) was used to assess post-Katrina forest conditions. The ADS40 sensor is a push-broom sensor developed by Leica Geosystems that records red, green, blue, and near-infrared energy. Imagery was acquired at various dates within 2 months of Katrina landfall with no acquisitions after Oct. 13, 2005.

Teams of two interpreters each worked together to determine pre-Katrina forest stand conditions on the NAIP imagery for 100 randomly assigned plots by strata for each county. These plots were used to determine post-Katrina stand conditions on the ADS40 imagery. The choice to use two different imagery sources was made to enable rapid assessment of changed fuel conditions. To reduce personal bias and photo interpretation errors the teams worked in the same room and were provided with identical damage examples and training. Errors were assumed to be similar because teams did the interpretation process and all teams interacted during the first few days of the interpretation process.

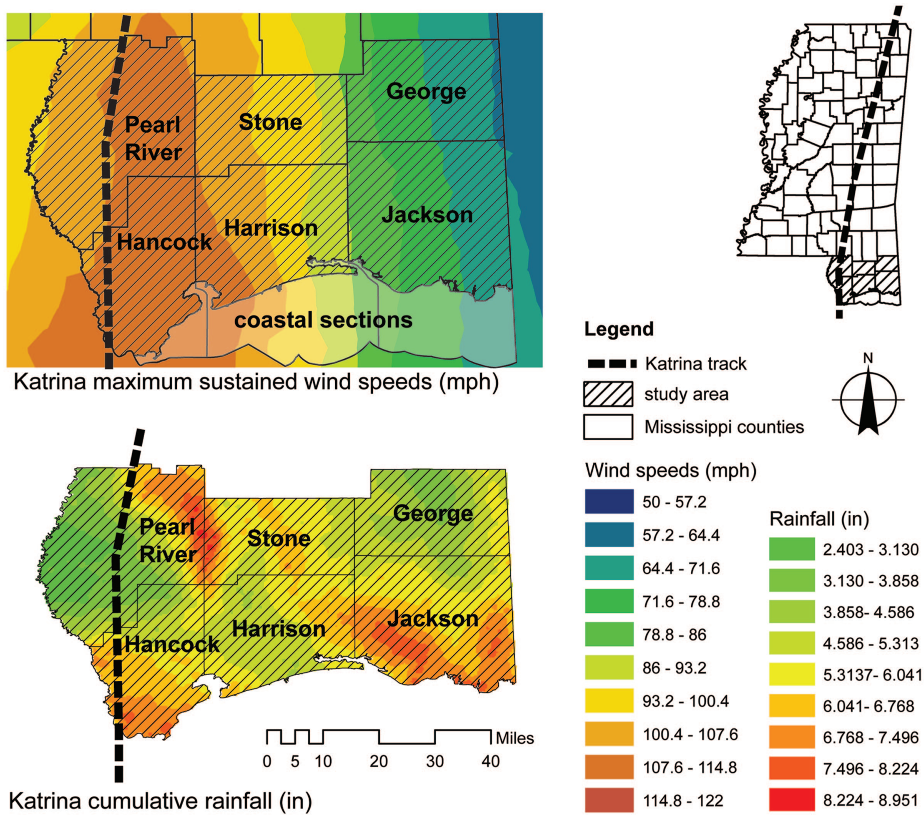

Figure 1. Map of the study area illustrating Katrina maximum sustained wind speeds (interpolation based on maximum wind speed data by census track) over Southern Mississippi with the storm track indicated by the dashed line. (Data source: http://gisdata.usgs.net/website/Katrina). Katrina cumulative rainfall (August 29–30, 2005) over the study area. Interpolation based on Multisensor Precipitation Estimates (MPE) point data (Data Source: National Weather Service).

The interpretation process for pre- and post-Katrina imagery consisted of differentiating between no damage (category 0) and three major forest damage categories including defoliation (category 1), top breakage (category 2), and downed timber (category 3). Two additional categories that were interpreted represented areas of change in land cover not caused by the hurricane. One category included aerial imagery plots in stands classified as forested in the Age–Type grid but interpreted as clearcut in the pre-Katrina NAIP aerial imagery (category 50). The other category included aerial imagery plots interpreted as forested in the pre-Katrina NAIP imagery that were clearcut in the intervening period between NAIP (pre-Katrina) image acquisition and ADS40 (post-Katrina) image acquisition (category 60). A final category (category 99) was added to account for plots that were obscured by clouds or were over water.

The aerial imagery interpretation served two purposes. First, the accuracy of the damage mask was assessed. Second, the amount of damage by category and forest type was summarized for each county. Contingency table (error matrix) calculations enabled assessment of the accuracy of the damage mask for each county as well as for the entire study area. The matrix contained information on the total number of plots, damage classification according to the damage mask and aerial imagery, and damage agreement (or disagreement) between the aerial imagery and the damage mask. From these data, errors of omission and commission were derived. Overall mask accuracy was computed by dividing the total number of plots identified correctly as damaged or undamaged by the mask, by the total number of plots interpreted from the aerial imagery. Percentage error of commission was calculated by dividing the number of plots identified as damaged by the mask and undamaged by the aerial imagery by the total number of plots interpreted from the aerial imagery. Percentage error of omission was calculated by dividing the number of plots identified as undamaged by the mask and damaged by the aerial imagery by the total number of plots interpreted from the aerial imagery.

Assessment of forest damage category by county was obtained from GIS-based "zonal" analyses. The GIS zonal function summarizes information from an input raster for each "zone" (i.e., plot polygon) and returns mean, sum, minimum, maximum, or range values from the input raster that fall within a specified zone. The plot polygons were used to extract information on damage and forest type.

In this study the aerial imagery was used only to assess the accuracy of the damage mask and to characterize damage trends across the study area. The Age–Type grid and damage mask were used for further GIS analysis to assess Katrina impacts on fire hazard.

GIS Modeling. Pre-Katrina fire hazard was derived from fire occurrence data that were obtained from MFC. The data set comprises historic (July 1990–June 2006) fire point locations for the state of Mississippi. Each record provides information on fire size, date, and cause. Pre- and post-Katrina wildfire occurrences were plotted on a line graph and revealed a rapid increase in number of fires after the hurricane (Figure 2). In a 20-month period preceding Katrina only 855 fires occurred, whereas 1,279 fires occurred during a 10-month period after Katrina. This increase in number of fires (average of 43 fires per month pre-Katrina and 128 fires per month post-Katrina) may indicate an increase in fire potential due to at least in part changes in fuel conditions.

Four age groups of similar within-class fire frequency were determined by summarizing the 20-month pre-Katrina fire occurrence data by the age grid. The "no-origin" class included forests of indeterminate age and generally was comprised of uneven-aged mixed forest species. Other age classes included 10–19 years (relatively young), 20–25 years (intermediate age), and 26–30 years and older (mature age). Age and forest type interactions were analyzed by combining the age classes with the forest type information (needle-leaf conifers, mixed, and broadleaf deciduous). Number of fires in each class, average fire size, number of fires normalized by area, and percentage of area burned in each class were evaluated and used as criteria for the assignment of fire hazard for each group. This resulted in the following unique age/type combinations: no origin conifers, 10- to 19-year conifers, 20- to 25-year conifers, 26- to 30-year and older conifers; no origin mixed, 10- to 19-year mixed, 20- to 25-year mixed, 26- to 30-year and older mixed; no origin hardwood, 10- to 19-year broadleaf, 20- to 25-year broadleaf, 26- to 30-year and older broadleaf. Once the class groupings were determined, fire hazard ranks were assigned on the basis of 20 months of actual pre-Katrina fire data, ranging from 0 (no fire hazard) to 5 (very high fire hazard). Other land cover classes that were not classified by age and type included open land and regeneration. Fire hazard was assigned heuristically for these classes because age and forest type information were not available. According to this a priori assignment of fire hazard classes, ranks were associated with the following area normalized fire frequencies: rank 0 (no fire hazard) = 0.018, rank 1 (very low fire hazard) = 0.052, rank 2 (low fire hazard) = 0.089, rank 3 (moderate fire hazard) = 0.109, rank 4 (high fire hazard) = 0.123, and rank 5 (very high fire hazard) = 0.143. Fire frequencies were calculated for each rank using the formula, number of fires/area (ha) in each rank ∗ 100.

The increase in fire frequency after Katrina and field evidence determined from visits by the authors to forested stands in Hancock County indicated the need to increase fire hazard rankings in damaged areas. Areas that were classified as damaged based on the AWIFS-derived change mask were assigned an increased fire hazard ranking. An example of the post-Katrina fire hazard class modifications included changing the pre-Katrina hazard value of 4 for pine age class 10–19 years to 5 after Katrina. Notice that pine 26–30 years and older age class was assigned the highest fire hazard rank both pre- and post-Katrina (Table 1).

GIS modeling was performed using raster data layers on a "cell-by-cell" basis. Each layer was represented as an integer grid on the landscape with a nominal cell resolution of 29 m. A reclassification function was used to depict the unique combinations of the forest type, age, and damage layers. There were 14 unique combinations in the fuel type pre-Katrina layer and 26 unique combinations in post-Katrina layer. As shown in Table 1, a unique number was assigned to each unique combination of layers to ensure that all combinations were assigned a fire hazard rank. This is an important consideration in GIS modeling that enables the analyst to assess the exact conditions at a given cell location that give rise to a risk value.

The post-Katrina fuel model was validated with MFC fire occurrence data. The validation data set included 1,279 records of wildfires that occurred in the study area between September 2005 and June 2006. The number of wildfires within each post-Katrina fire hazard class was determined, normalized by the land area in each class, and results were used to determine how well the model predicted actual fire frequency. Modeling results for pre- and post-Katrina fire hazard are presented at both the regional and the county level.

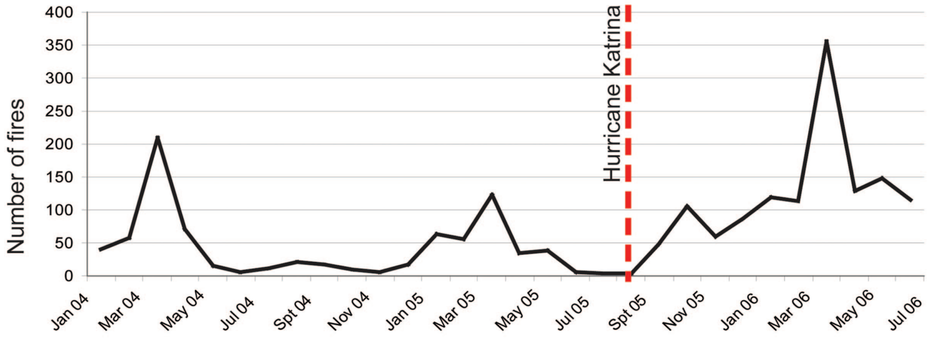

Figure 2. Analysis of pre- and post-Katrina fire occurrence data, showing a sharp increase in fire frequency after the hurricane.

Results and Discussion

In this section, we discuss how well the satellite-derived change mask agreed with the aerial imagery interpretation, trends in categories of damage, and how hurricane

Table 1. Forest type/damage and age classes and unique combinations of all forest type, damage, and age class assignment.

Pre-Katrina			Post-Katrina damaged		Post-Katrina undamaged		
Unique id	Fire hazard	Age/type classes (yr)	Unique id	Fire hazard	Unique id	Fire hazard	Unique age/type classes (yr)
31	4	Coniferous 10–19	131	5	31	4	Coniferous 10–19
32	4	Coniferous 20–25	132	5	32	4	Coniferous 20–25
33	5	Coniferous 26–30ab	133	5	33	5	Coniferous 26–30ab
34	2	Coniferous no origin	134	3	34	2	Coniferous no origin
41	1	Mixed 10–19	141	2	41	1	Mixed 10–19
42	2	Mixed 20–25	142	3	42	2	Mixed 20–25
43	1	Mixed 26–30ab	143	2	43	1	Mixed 26–30ab
44	1	Mixed no origin	144	2	44	1	Mixed no origin
51	3	Deciduous 10–19	151	4	51	3	Deciduous 10–19
52	2	Deciduous 20–25	152	3	52	2	Deciduous 20–25
53	1	Deciduous 26–30ab	153	2	53	1	Deciduous 26–30ab
54	1	Deciduous no origin	154	2	54	1	Deciduous no origin
20	2	Regeneration	—	—	20	2	Regeneration
10	3	Open	—	—	10	3	Open

Pre- and post-Katrina assigned fire hazard values for type/age/damage class combinations: 0 = no fire hazard, 1 = very low fire hazard, 2 = low fire hazard, 3 = moderate fire hazard, 4 = high fire hazard, and 5 = very high fire hazard, 30ab = 30 and above.

damage changed fire hazard for each county. The results of GIS modeling are assessed on the regional and county levels to indicate overall change in fire hazard within the study area as well as within individual counties.

Assessment of Katrina Forest Damage. *Assessment of the Damage Mask.* The accuracy of the satellite-derived change mask for the entire study area was 72%. Overall, the accuracy of the change mask was high. Mask accuracy was highest in Pearl River County (80%) and lowest for Stone and George counties (66%). These results indicate that the change mask was a good stratification tool for photo plot assignment and for the assessment of fuel conditions that are important predictors of post-Katrina fire hazard for southern Mississippi. The overall accuracy of the mask decreases from west to east and from south to north with the exception of Pearl River and Hancock counties. This could indicate that damage is better characterized using the NDMI method where actual damage to the landscape is greater. This result is consistent with the wind speed and rainfall patterns shown in Figure 1.

Accuracies for each county are detailed in Table 2. Errors of omission were larger than errors of commission for each county. This indicates that the NDMI threshold value could have been set higher, resulting in a greater percentage of the land area classified as damaged. Errors of omission and commission should have been approximately equal if the mask threshold was set

Table 2. Assessment of Katrina forest damage including accuracy assessment of the damage (change) mask accuracy and assessment of damage by category.

	County					
	George	Hancock	Harrison	Jackson	Pearl River	Stone
Accuracy assessment of the damage mask						
Overall accuracy (%)	66	76	75	69	80	66
Errors of commission (%)	6	0	8	7	0	9
Errors of omission (%)	28	24	17	24	20	25
Plots classified correctly by the mask	58	67	72	57	64	58
Plots classified incorrectly by the mask	30	21	24	26	16	30
Mask = damaged, photo = undamaged (commission)	5	0	8	6	0	8
Mask = undamaged, photo = damaged (omission)	25	21	16	20	16	22
Photo plots classified as (0, 1, 2, or 3)	88	88	96	83	80	88
Plots in other classes (50, 60, or 99)	12	14	7	18	19	12
Total plots	100	102	103	101	99	100
Damage by category and damage by forest type						
Damage category (%)						
No damage (0)	10.2	0.0	21.9	20.5	0.0	14.6
Defoliation (1)	22.7	18.2	30.2	21.7	7.5	38.2
Top breakage (2)	34.1	22.7	6.3	18.1	22.5	4.5
Downed timber (3)	32.9	59.1	41.7	39.8	70.0	42.7
Number of damage plots in coniferous forest	40	56	48	34	45	47
Number of damage plots in mixed forest type	8	18	13	8	16	16
Number of plots in deciduous forest type	28	13	13	23	18	12
Number of plots in regeneration class	1	0	0	0	1	0
Number of plots in nonforest (open) class	2	1	1	1	0	1
Total number of damage plots	79	88	75	66	80	76

Users' and producers' accuracies for analyzed counties. The number of coniferous and deciduous damage plots are shown by county; results of the plot percentage calculations for each of the six counties are by damage type.

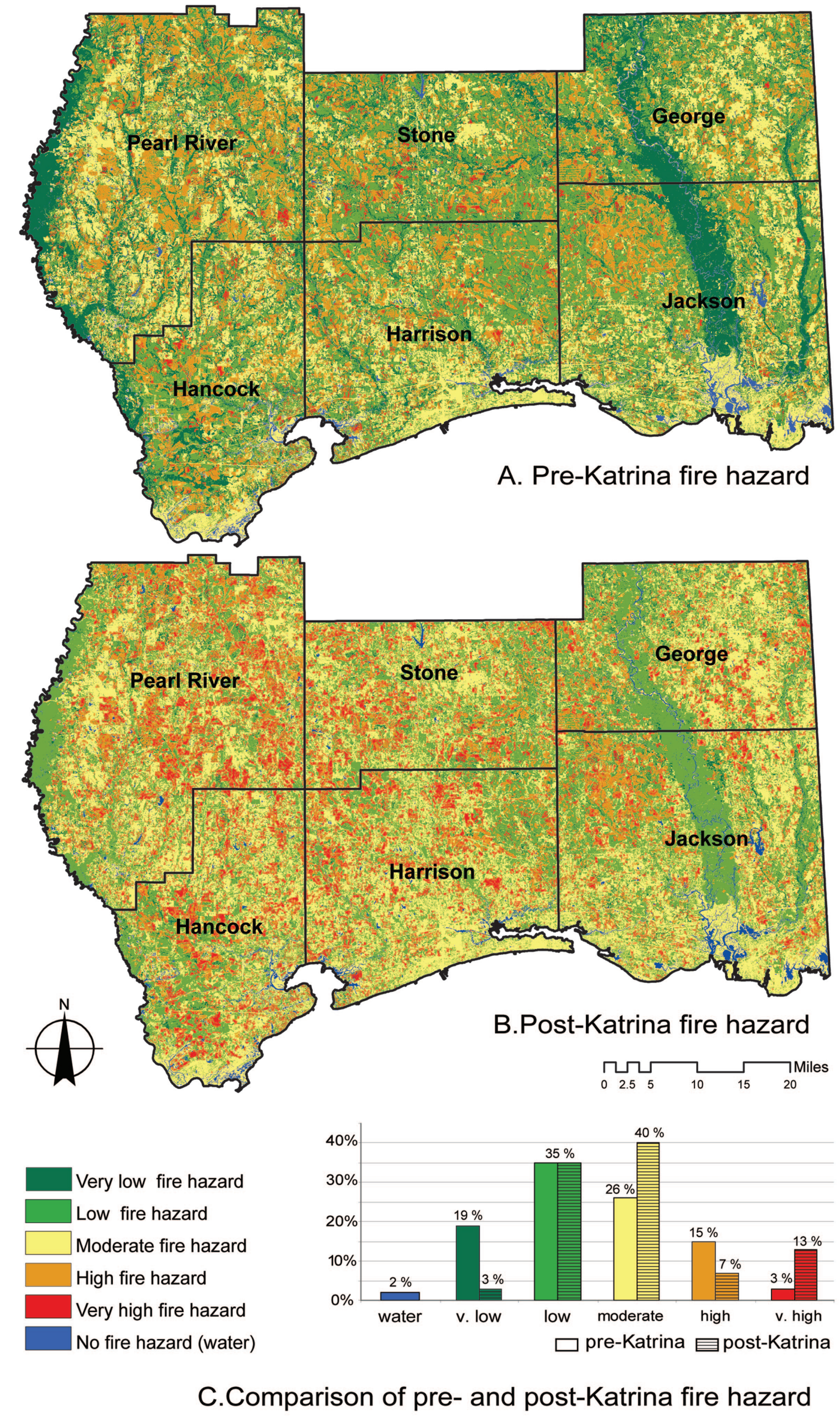

Figure 3. Pre- and post-Katrina fire hazard maps for southern Mississippi and a comparison of fire hazard classes of pre- and post-Katrina conditions.

correctly. The usefulness of the mask as a stratification tool is shown by the generally high overall accuracy but the high errors of omission indicate that the mask underestimated the extent of damage.

Assessment of Damage by Category and Forest Type. In addition to accuracy assessment of the change mask, additional information on damage by county is shown in Table 2. Notice that all the interpreted plots in Hancock and Pearl River counties showed damage; whereas only 75 of 96 plots for Harrison County and 66 of 83 plots for Jackson County showed damage (compare the total damage plots to plots classified as 0, 1, 2, or 3). This is consistent with damage expected due to higher wind speeds and greater rainfall in the western Mississippi counties.

Comparisons of forest damage by category also are shown in Table 2. In Hancock County defoliation (1), top breakage (2), and downed timber (3) comprised about 18, 23, and 59%, respectively, of the total damage plots. Pearl River County interpretations showed similar results (7.5% defoliation, 22% top breakage, and 70% downed timber). Assessment of damage by category indicated that Pearl River County had the largest amount of downed timber. The high percentage of downed timber in the two western Mississippi counties is consistent with the hurricane track and impact of the eastern eye-wall of the storm making landfall in these two counties. According to the literature, the eastern eye-wall, which is defined as right-front quadrant of the hurricane center, has the strongest winds and most intensive damage (Wakimoto and Black 1994). Damage estimates for Stone and Harrison counties are similar with both counties, showing a decrease in the percentage of downed timber and increase in defoliation, sharp decrease in broken tops, and the inclusion of no damage plot classification. These results are consistent with the decreasing wind intensities that are evident in these "middle" counties. George and Jackson counties had similar damage characteristics. These "eastern" counties had less downed timber and large amounts of defoliation but a significant increase in top breakage when compared with Stone and Harrison counties. Although the increase in top breakage appears to be an anomalous situation, the interpretation process may partially explain this phenomenon. Interpreter ability to separate broken tops from defoliation is more of a problem in deciduous forests. Numerous broken small limbs and partial top breakage often is difficult to distinguish because of small variation in texture between defoliation and broken top categories interpreted from the aerial imagery.

Finally, Table 2 shows the number of interpreted plots by forest type (coniferous, mixed, deciduous, regeneration, and open) and by county. The greatest number of damaged plots are within the coniferous forest

Table 3. Area (km^2) of pre- and post-Katrina fire hazard classes in analyzed counties.

County	Pre-Katrina fire hazard (km^2)					Post-Katrina fire hazard (km^2)					Water	Total area (km^2)
	Very high	High	Moderate	Low	Very low	Very high	High	Moderate	Low	Very low		
Hancock	55	184	346	429	199	192	57	535	406	23	38	1,251
Pearl River	74	413	558	559	492	333	175	820	705	64	23	2,119
Harrison	69	210	439	601	155	212	75	703	463	23	21	1,496
Stone	47	211	191	510	194	175	88	451	409	29	7	1,160
Jackson	49	218	533	657	387	150	133	761	738	62	62	1,906
George	21	174	291	472	282	121	81	474	512	50	13	1,252
Total	315	1,410	2,358	3,228	1,709	1,183	609	3,744	3,233	251	164	9,184

Using zonal statistics (county polygons used as zones) the number of pixels within each fire hazard category was derived and converted to area extent in squared kilometers.

type, which is the most prominent forest type in Mississippi and according to literature also the most fire prone (Zhai et al. 2003). Hancock, Harrison, Pearl River, and Stone counties (western and central counties) have a greater proportion of coniferous forest than Jackson and George counties (eastern counties) and are assumed to have higher fire hazard rankings.

The number of damaged plots in deciduous forests generally is lower than the number of damaged plots in coniferous forests, although a relatively high number of damaged plots occur in the deciduous forests of Jackson and George counties. Both of these counties have a large portion of timberland in the Pascagoula River Basin, which trends north–south through the middle of each county (Figure 2). The multistem nature of deciduous species increases the likelihood of top breakage, which further explains the increase in top breakage in these two counties. The lowest numbers of damaged plots occurred in the mixed forest type, except for Hancock and Stone counties. Finally, a few plots fell in regeneration and open classes. These plots may have been on edge pixels or incorrectly located on the imagery because all plots were supposed to be assigned to one of the six forested strata.

GIS Modeling Results. *Regional Pre- and Post-Katrina Fire Hazard.* GIS-based analysis of change in pre- and post-Katrina fuel conditions enables spatial depiction of fire hazard by class (Figure 3). Based on the modeling results, the fire hazard in the region increased after the hurricane. Large contiguous areas of very low fire hazard that generally are associated with stream floodplains dominated the pre-Katrina landscape (Figure 3A). Highly fragmented areas of very high fire hazard were scattered throughout the pre-Katrina landscape. The post-Katrina landscape is characterized by decrease in the amount of contiguity of areas classified as very low fire hazard, and increases in the amount and contiguity of areas classified very high fire hazard (Figure 3B). Although these results indicate overall increased hazard for fires after Katrina in the analyzed region of southern Mississippi (Figure 2), it is important to quantify the actual magnitude of change by each fire hazard class.

The greatest increase occurred in the amount of area classified as moderate fire hazard, which increased from 26% pre-Katrina to 40% post-Katrina conditions. Areas of very low hazard decreased from 19% to only 3%, while very high hazard areas increased from 3 to 13%. The low fire hazard area remained about the same, approximately 35% in pre-Katrina and post-Katrina conditions.

Table 3 shows the total area (in km^2) of fire hazard classes for pre- and post-Katrina conditions. Before the hurricane 315 km^2 was classified as areas of very high fire hazard, and post-Katrina classification indicated 1,184 km^2 areas at high or very high hazard. Areas of very low fire hazard decreased from approximately 1,709 to 249 km^2. These results indicated that increased numbers of fire suppression personnel and equipment might be needed for the coming fire seasons in the region.

Individual County Pre- and Post-Katrina Fire Hazard. The individual county analysis results are similar to the results of the regional analysis, indicating a shift in fire hazard after the hurricane. In general, in the six analyzed counties fire hazard increased with a notable shift toward the higher fire hazard classes overall (Figure 4). An increase of area classified in the very high fire hazard classes and a decrease of area in the very low fire hazard classes was observed in all counties (Table 3). The most notable difference was observed in the very high and moderate classes. The percentage of area in each of these classes increased in all six counties. Increases in the moderate class ranged from 11.97% in Jackson County to 22.42% in Stone County, and increases in the very high class ranged from 5.28% in Jackson County to 12.21% in Pearl River County.

Overall, the proportion of the landscape that was classified as very high fire hazard after Katrina is greatest in the western counties (Hancock, 15. 35%; Pearl River, 15.72%), somewhat lower in the central counties (Harrison, 14.15%; Stone, 15.12%), and lowest in the eastern counties (Jackson, 7.86%; George, 9.77%). This west– east fire hazard gradient corresponds closely with the wind-field strongest winds and highest amount of rainfall that occurred in Hancock, Harrison, Stone, and Pearl River counties.

Model Validation. Results of the validation based on 10 months (September 2005–June 2006) of actual post-Katrina fire events are shown in Figure 5 and indicate that the post-Katrina fuel model corresponds well with actual fire location and frequency. As expected, the ratio of number of fires to area was the lowest in the very low fire hazard class and highest in the very high hazard class. The only irregularity in validation results is apparent in the moderate fire hazard class, where a greater than expected number of fires occurred post-Katrina. It is possible, however, that fire potential could change with addition of the climate and ignition variables.

The increase of fire frequency in all fire hazard classes is a good indicator that the damage mask was effective as a stratification tool and that the class divisions based on within-class fire frequency were appropriate. The greatest increase in post-Katrina fire hazard observed in the very low hazard class (mixed and broadleaf stands) is important because an indicator that areas that are traditionally considered fire resistant have changed dramatically in terms of fire hazard after hurricanes.

Conclusions

Numerous concerns emerged after Hurricane Katrina, including potential for catastrophic wildfires in the affected region. State and federal agencies realized such risk. The need for immediate and accurate assessment of fire hazard became evident. This article presents results of such assessment based on estimation of change in fuel conditions. This project showed the usefulness of combining GIS raster modeling and remote sensing change analysis in assessing fire hazard. In this study, actual change in fire hazard was shown empirically by validating fire hazard predictions with actual fire occurrence data. This study establishes the capability of GIS-based analysis to provide rapid assessment of landscape conditions that favor fire ignition in coastal regions after destructive hurricane events. Such information is essential for emergency and wood recovery personnel to allocate their resources within areas of elevated fire hazard. The fire hazard maps were developed within a few months after the hurricane impact date. Such quick response is important for first responders, planning recovery efforts, and for personnel and equipment staging decisions in upcoming fire seasons.

The presented methodology used for the assessment of changes in fuel conditions provides an important tool for estimating fire hazard. There are some limitations to this methodology in terms of sampling design, accuracy assessment, and damage mask efficacy. The sampling design used in this study resulted in variations in sampling intensity among counties. This variation affects the confidence of accuracy assessment calculations. Sampling design could be improved by proportionally allocating plots to strata. Stratified random sampling at equal rates across all strata would assure that accuracy estimates are comparable across all strata. A two-phase sampling approach could be used to enhance the efficacy of the damage mask. In this approach randomly selected photo plots would be interpreted for damage to provide an estimate of omission and commission errors at an initial damage mask threshold value. This threshold value then could be modified to balance errors of omission and commission.

Hazard maps developed for fire management decisions can be developed quickly, but need to be validated continuously as fire occurrence data become available. Periodically, the a priori hazard rankings should be

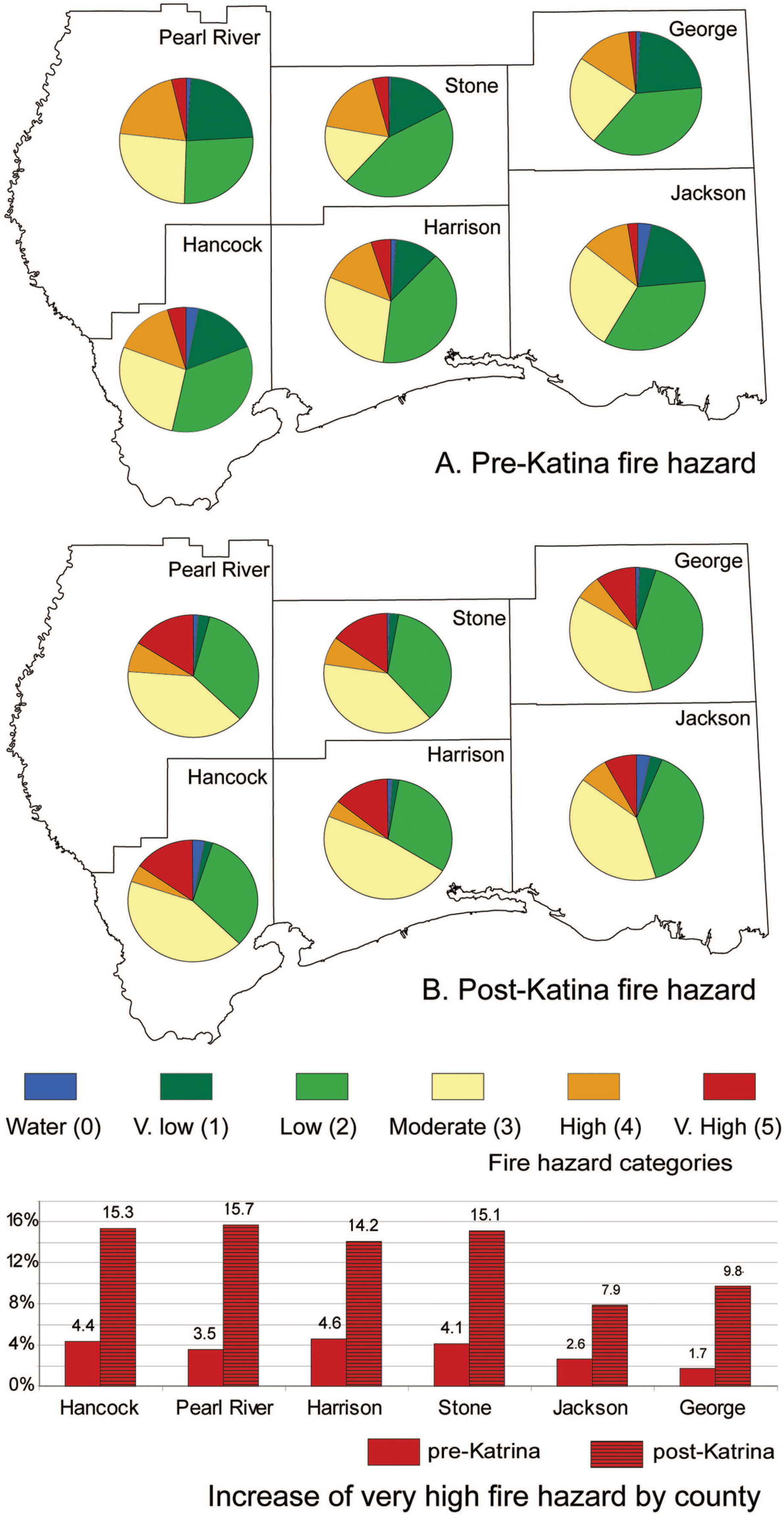

Figure 4. Pre- and post-Katrina fire hazard and an assessment of increase of fire hazard class by county.

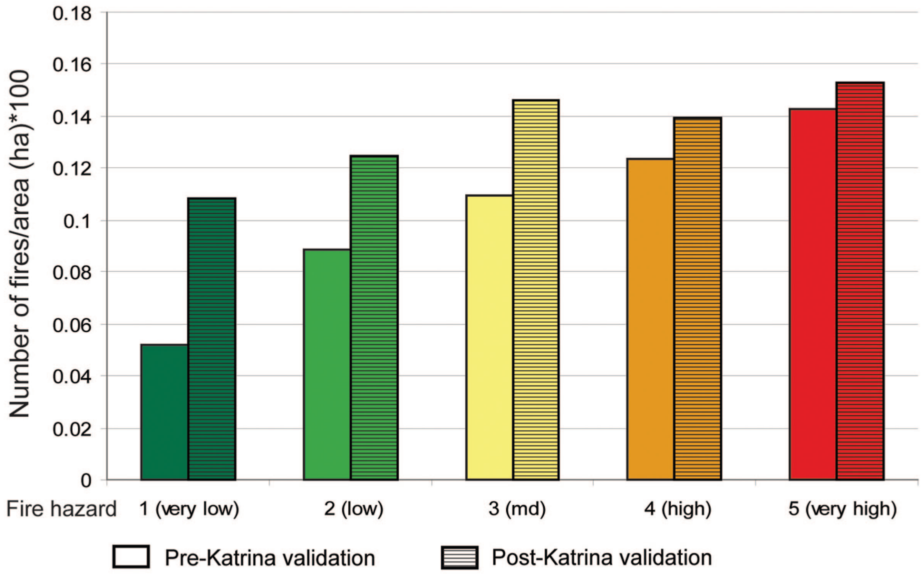

Figure 5. Validation results for pre- and post-Katrina models. Ratio of number of fires to area determined using actual fire occurrence data.

modified by the a posteriori probabilities (Malczewski 1999). These continued refinements make the model sensitive to changes due to catastrophic events, short-term climatic fluctuations, and long-term climate changes.

At the time of the study preparation, there was no official published information detailing the percentage of damaged timber that was salvaged and the amount of unusable timber left on the ground. However, according to MFC records (Patrick Glass, pers. comm., MFC, July 6, 2007), salvage operations in Mississippi coastal counties resulted in the recovery of almost 100% of the merchantable timber on private industry lands. On federal lands about 85% of the merchantable timber was recovered, and on private nonindustrial sites, which constitute the majority of the forested land within the study area, only 18% of the merchantable timber was salvaged. Hancock and Pearl River counties that have the highest fire hazard levels also have the greatest percentage of private forest ownership, 68 and 72%, respectively (Mississippi State University Extension Service 2005). Given that only a small fraction of the merchantable timber was salvaged on these lands, there is a high likelihood that fire hazard remains elevated in these areas.

Literature Cited

Andrews, P.L., and L.P. Queen. 2001. Fire modeling and information system technology. *Int. J. Wildland Fire* 10:343–352.

Bonazountas, M., D. Kallidromitou, P.A. Kassomenos, and N. Passas. 2005. Forest fire risk analysis. *Hum. Ecol. Risk Assess.* 11:617–626.

Burgan, R.E., R.W. Klaver, and J.M. Klaver. 1998. Fuel models and fire potential from satellite and surface observations. *Int. J. Wildland Fire* 8:159–170.

Collins, C.A., D.W. Wilkinson, and D.L. Evans. 2005. Multi-temporal analysis of Landsat data to determine forest age classes for the Mississippi Statewide Forest Inventory—Preliminary results. P. 10–14 in *Proc. of the 3rd International Workshop on the Analysis of multi-temporal remote sensing images,* Biloxi, MS, May 16–18, 2005. IEEE. [on CD-ROM.]

Davenport, L., and C. Odom. 2005. *Data management plan for ADS40 hurricane response imagery 7.5′ quadrangle mosaics*. USDA Service Center Agencies, Geospatial Data Management Team. 10 p.

Hardy, C.C. 2005. Wildland fire hazard and risk: Problems, definitions, and context. *For. Ecol Manag.* 211:73–82.

Hernandez-Leal, P.A., M. Arbelo, and A. Gonzalez-Calvo. 2006. Fire risk assessment using satellite data. *Adv. Space Res.* 37:741–746.

Jin, S.M., and S.A. Sader. 2005. Comparison of time series tasseled cap wetness and the normalized difference moisture index in detecting forest disturbances. *Remote Sens. Environ.* 94:364–372.

Lillesand, T.M., R.W. Kiefer, and J.W. Chipman. 2004. *Remote sensing and image interpretation.* John Wiley and Sons, New York. 763 p.

Malczewski, J. 1999. GIS and multicriteria analysis. John Wiley and Sons, New York. 392 p.

Mississippi Forestry Commission (MFC). 2005. *MFC 2005 Forestry commission reports $2.4 billion of tree damage, official news release.* MFC, Jackson, MS. 1 p.

Mississippi State University Extension Service. 2005. *Forestry statistics for Mississippi counties*. Available online at www.msucares.com/forestry/economics/counties/; last accessed July 11, 2007.

Mistry, J., and A. Berardi. 2005. Assessing fire potential in a Brazilian savanna nature reserve. *Biotropica* 37:439–451.

Pew, K.L., and C.P.S. Larsen. 2001. GIS analysis of spatial and temporal patterns of human-caused wildfires in the temperate rain forest of Vancouver Island, Canada. *For. Ecol. Manag.* 140:1–18.

Pye, J.M., J.P. Prestemon, D.T. Butry, and K.L. Abt. 2003. Prescribed burning and wildfire risk in the 1998 fire season in Florida. P. 15–26 in *Proc. RMRS-P-29 on Fire, fuel treatments, and ecological restoration*, Fort Collins, CO, Apr. 16–18, 2002. US For. Serv., Rocky Mountain Res. Stn., Fort Collins, CO.

Ramsey, E.W., M.E. Hodgson, S.K. Sapkota, and G.A. Nelson. 2001. Forest impact estimated with NOAA AVHRR and Landsat TM data related to an empirical hurricane wind-field distribution. *Remote Sens. Environ.* 77:279–292.

Sader, S.A., M. Bertrand, and E.H. Wilson. 2003. Satellite change detection of forest harvest patterns on an industrial forest landscape. *For. Sci.* 49:341–353.

USDA. 2005. *March 10, 2006 imagery programs, NAIP imagery*. USDA Farm Service Agency, Aerial Photography Field Office, Salt Lake City, UT. Available on-line at www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai-or; last accessed Sept. 10, 2005.

Wakimoto, R.M., and P.G. Black. 1994. Damage survey of Hurricane Andrew and its relationship to the eyewall. *Bull. Am. Meteorol. Soc.* 75:189–200.

Wang, P., J.H. Kirby, J.D. Haber, M.H. Horwitz, P.O. Knorr, and J.R. Krock. 2006. Morphological and sedimentological impacts of Hurricane Ivan and immediate poststorm beach recovery along the northwestern Florida barrier-island coasts. *J. Coastal Res.* 22:1382–1402.

Whitlock, C., S.L. Shafer, and J. Marlon. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *For. Ecol. Manag.* 178:5–21.

Zhai, Y.S., I.A. Munn, and D.L. Evans. 2003. Modeling forest fire probabilities in the South Central United States using FIA data. *South. J. Appl. For.* 27:11–17.