Assessment of pre- and post-Katrina fuel conditions as a component of fire potential modeling for southern Mississippi.

INTRODUCTION

Natural disasters like 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 billion board feet 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 will likely be targeted towards 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 Systems (GIS) modeling supports mapping of these changing conditions.

NASA-funded collaborative studies by the MSU Departments of Forestry and Geosciences have concentrated on creating linear additive GIS model designed to determine fire potential in southeastern U.S. While 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 U.S. has been oriented towards the western U.S. (Pew and Larsen, 2001; Whitlock et al., 2003). Although fire potential is generally regarded as lower in the eastern U.S., Mississippi has on average 3760 wildfires each year that require personnel and resources to extinguish. Average number of wildfires was calculated based on 14-years (1991-2004) of historic fire data acquired from MFC and in the analyzed period the minimum number of fires was 1847, while the maximum reached 6616 per 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 is often 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 U.S., however Zhai *et al.* (2003) demonstrated that topography was 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 like 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, as 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). Also, sudden changes in environmental conditions and substantial vegetation damage can contribute to rapid changes in fuel loads and increase in fire potential.

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 incorporate Light Detection and Ranging (LiDAR), Moderate Resolution Spectroradiometer (MODIS), 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 accurately estimate the extent of timber damage. Characterization of the spatial distribution of timber damage enabled assessment of fuel conditions important for activities aimed at preventing further damage to the state's forest resources due to 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 wind throw (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 (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper (ETM+) data were rectified to a common map base and analyzed to derive forest age for relatively current (2003) forest land cover (Collins *et al.*, 2005). Determination of forest age classes was performed using the basic 'post classification' 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 (needle-leaf conifers, broadleaf deciduous, and mixed (coniferous/broadleaf)) and three general land cover classes (water, forest and non-forest) 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 to 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 non-forest lands, water, forest type, and forest age. For the purposes of this paper we will refer to this product as the 'Age_Type' grid.

Hurricane Damage Analysis from AWIFS Imagery

Information generated from pre- and post-Katrina Advanced Wide Field Sensor (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 (Jin and Sader, 2005; Sader *et al.*, 2003). 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 (1/5 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 ranges 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, March 10, 2006). The program acquires natural color and color infrared imagery during the agricultural growing seasons in the continental U.S. NAIP imagery at 1 m ground sample distance (GSD) was used to assess pre-Katrina forest conditions and was acquired during the 2004 growing season. ADS40 aerial imagery at 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 two months of Katrina landfall with no acquisitions after October 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 since teams did the interpretation process and all teams interacted during the first few days of the interpretation process.

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 due to 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 (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 only used 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 Mississippi Forestry Commission. The dataset 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, while 1279 fires occurred during a 10-month period following Katrina. This increase in number of fires (average of 43 fires per month pre- and 128 fires per month post-Katrina) may indicate an increase in fire potential due at least in part to 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 was generally comprised of uneven-aged mixed forest species. Other age classes included: 10-19 (relatively young), 20-25 (intermediate age), 26-30 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, 10-19 conifers, 20-25 conifers, 26-30 and older conifers, no origin mixed, 10-19 mixed, 20-25 mixed, 26-30 and older mixed, no origin hardwood, 10-19 broadleaf, 20-25 broadleaf, 26-30 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 since 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 following Katrina and field evidence determined from visits by the authors to forested stands in Hancock County indicated the need to increase fire hazard 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 to 5 after Katrina. Notice that pine 26-30 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 illustrated in Table1, 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 dataset included 1279 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 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 county level.

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 damage changed fire hazard for each county. The results of GIS modeling are assessed on the regional and county levels to demonstrate 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 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 of the interpreted plots in Hancock and Pearl River counties showed damage; while only 75 out of 96 for Harrison and 66 out of 83 for Jackson showed damage (please 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 are also 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 hurricane center has the strongest winds and most intensive damage (Wakimoto and Black, 1994). Damage estimates for Stone and Harrison counties is 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, large amounts of defoliation, but a significant increase in top breakage when compared to Stone and Harrison counties. While 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 is often difficult to distinguish due to 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 damage plots are within the coniferous forest 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 (eastern counties), and are assumed to have higher fire hazard.

The number of damaged plots in deciduous forests is generally 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 multi-stem 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 since 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 are generally 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). While these results indicate overall increased hazard for fires following 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 sq. km) of fire hazard classes for pre- and post-Katrina conditions. Prior to the hurricane 315 sq. km were classified as areas of very high fire hazard, while post-Katrina classification indicated 1184 sq. km area at high or very high hazard. Areas of very low fire hazard decreased from approximately 1709 sq. km to 249 sq. km. 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, while increases in the very high class ranged from 5.28 % in Jackson County to 12.21 % in Pearl River.

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 % and Pearl River – 15.72 %), somewhat lower in the central counties (Harrison – 14.15 % and Stone – 15.12%), and lowest in the eastern counties (Jackson – 7.86 % and George – 9.77 %). This west-to-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 as an indicator that areas that are traditionally considered fire resistant have changed dramatically in terms of fire hazard following 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 paper presents results of such assessment based on estimation of change in fuel conditions. This project demonstrated the utility of combining GIS raster modeling and remote sensing change analysis in assessing fire hazard. In this study, actual change in fire hazard was demonstrated empirically by validating fire hazard predictions with actual fire occurrence data. This study demonstrates the capability of GIS-based analysis to provide rapid assessment of landscape conditions that favor fire ignition in coastal regions following 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 could then 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 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 manuscript preparation, there were no official published information detailing the percentage of damage 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, while on private non-industrial 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.

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CAPTIONS

Table titles

Table 1. Forest type/damage and age classes and unique combinations of all forest type, damage and age class assignment. 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, 5 – very high fire hazard).

Table 2. Assessment of Katrina forest damage including accuracy assessment of the damage (change) mask accuracy and assessment of damage by category. User‘s and producers accuracies for analyzed counties. Number of coniferous and deciduous damage plots by county; results of the plot percentage calculations for each of the six counties by damage type.

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

Figure captions

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 Multi-sensor Precipitation Estimates (MPE) point data (Data Source: National Weather Service).

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

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.

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.

TABLES

Table 1. Forest type/damage and age classes and unique combinations of all forest type, damage and age class assignment. 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, 5 – very high fire hazard).

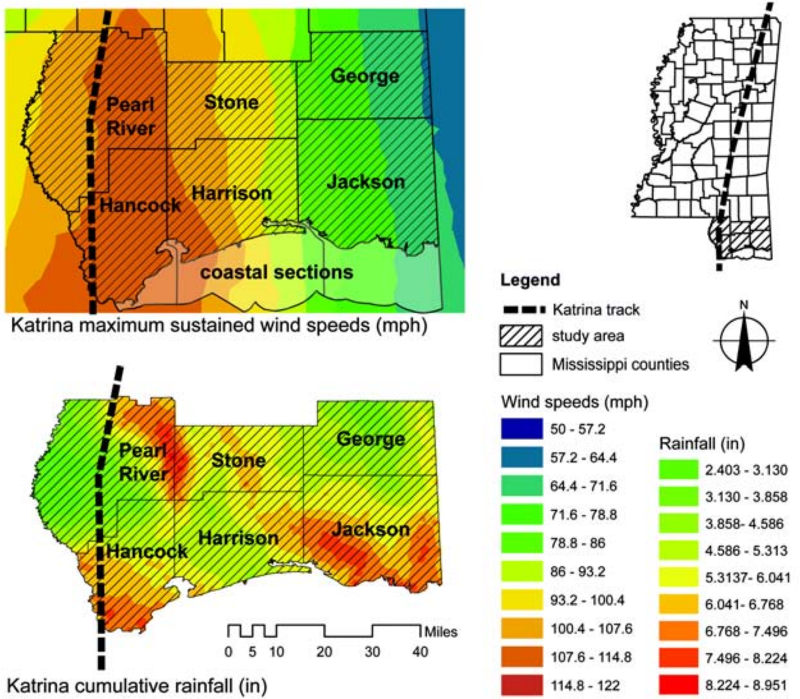
Pre Katrina		Age/type classes	Post Katrina damaged		Post Katrina undamaged		Unique age/type classes
Unique id	Fire hazard		Unique id	Fire hazard	Unique id	Fire hazard	
31	4	Coniferous 10-19	131	5	31	4	Coniferous 10-19
32	4	Coniferous 20-25	132	5	32	4	Coniferous 20-25
33	5	Coniferous 26-30ab	133	5	33	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

Table 2. Assessment of Katrina forest damage including accuracy assessment of the damage (change) mask accuracy and assessment of damage by category. User's and producers accuracies for analyzed counties. Number of coniferous and deciduous damage plots by county; results of the plot percentage calculations for each of the six counties by damage type.

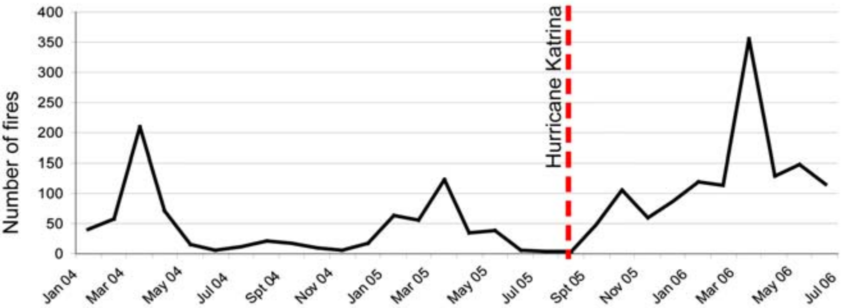
		County					
		George	Hancock	Harrison	Jackson	Pearl River	Stone
Accuracy assessment of the damage mask							
Overall Accuracy (%)		66	76	75	69	80	66
Errors of Commission (%)		6	0	8	7	0	9
Errors of Omission (%)		28	24	17	24	20	25
Plots classified correctly by the mask		58	67	72	57	64	58
Plots classified 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,or3)		88	88	96	83	80	88
Plots in other classes (50, 60, 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 non-forest (open) class		2	1	1	1	0	1
Total number of damage plots		79	88	75	66	80	76

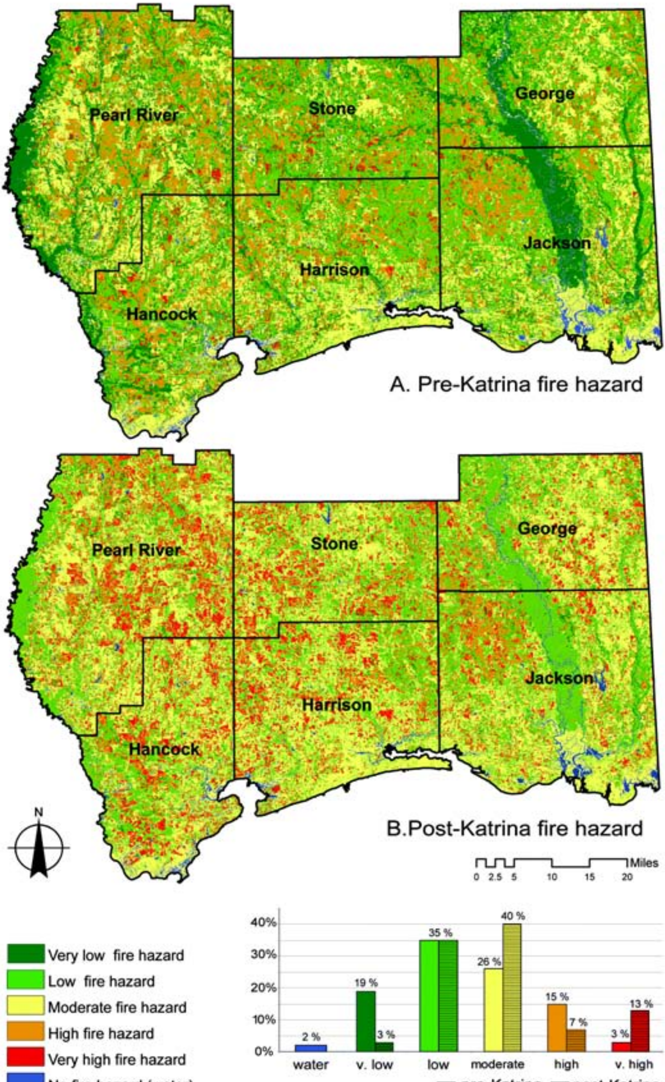
Table 3. Area (in sq. km) of pre- and post-Katrina fire hazard classes in analyzed counties. Using zonal statistics (county polygons used as zones) the number of pixels within each fire hazard category was derived and converted to area extent in sq. km.

County	Pre-Katrina fire hazard (sq.km)					Post-Katrina fire hazard (sq.km)					Water	Total area (sq.km)
	V.high	High	Mod.	Low	V.low	V.high	High	Mod.	Low	V.low		
Hancock	55	184	346	429	199	192	57	535	406	23	38	1251
Pearl River	74	413	558	559	492	333	175	820	705	64	23	2119
Harrison	69	210	439	601	155	212	75	703	463	23	21	1496
Stone	47	211	191	510	194	175	88	451	409	29	7	1160
Jackson	49	218	533	657	387	150	133	761	738	62	62	1906
George	21	174	291	472	282	121	81	474	512	50	13	1252
Total	315	1410	2358	3228	1709	1183	609	3744	3233	251	164	9184

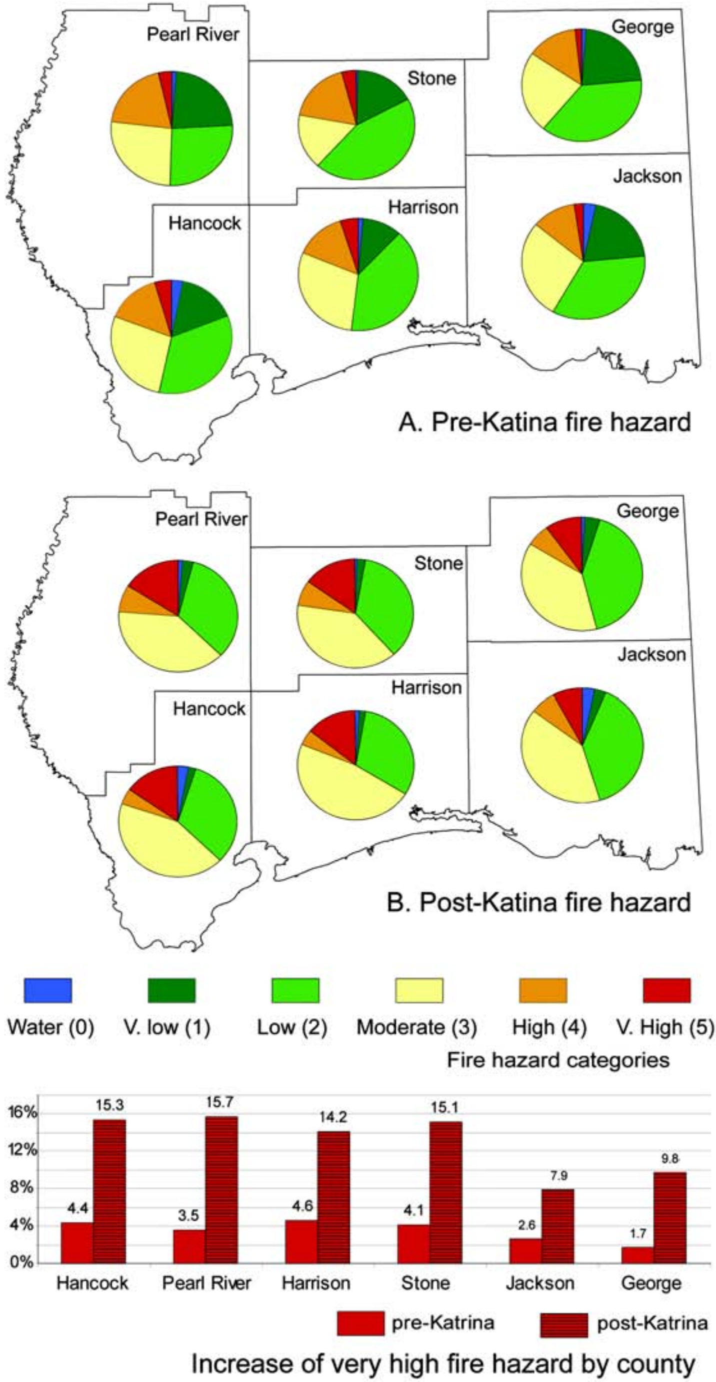


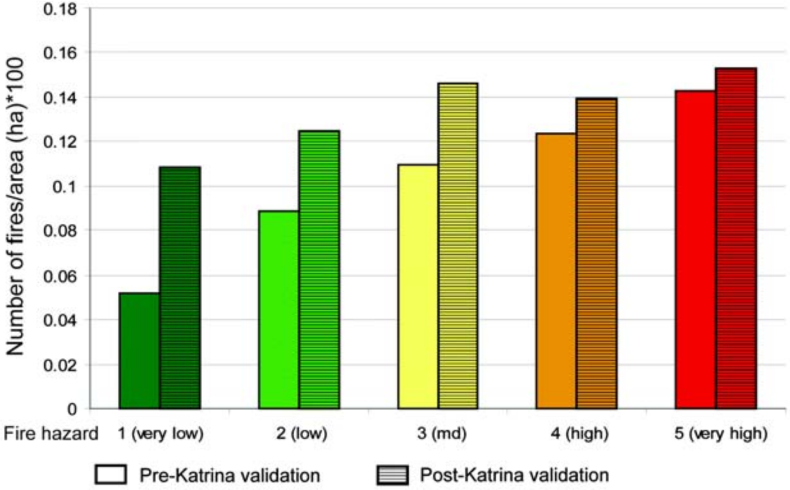
Pearl River
Stone
George
Hancock
Harrison
Jackson
coastal sections
Katrina maximum sustained wind speeds (mph)
Pearl River
Stone
George
Hancock
Harrison
Jackson
0 5 10 20 30 40 Miles
Katrina cumulative rainfall (in)
Legend
Katrina track
study area
Mississippi counties
N
Wind speeds (mph)
50 - 57.2
57.2 - 64.4
64.4 - 71.6
71.6 - 78.8
78.8 - 86
86 - 93.2
93.2 - 100.4
100.4 - 107.6
107.6 - 114.8
114.8 - 122
Rainfall (in)
2.403 - 3.130
3.130 - 3.858
3.858- 4.586
4.586 - 5.313
5.3137- 6.041
6.041- 6.768
6.768 - 7.496
7.496 - 8.224
8.224 - 8.951


Number of fires
400
350
300
250
200
150
100
50
0
Hurricane Katrina
Jan 04
Mar 04
May 04
Jul 04
Spt 04
Nov 04
Jan 05
Mar 05
May 05
Jul 05
Spt 05
Nov 05
Jan 06
Mar 06
May 06
Jul 06



C.Comparison of pre- and post-Katrina fire hazard


Pearl River
Stone
George
Hancock
Harrison
Jackson
A. Pre-Katina fire hazard
Pearl River
Stone
George
Hancock
Harrison
Jackson
B. Post-Katina fire hazard
Water (0)
V. low (1)
Low (2)
Moderate (3)
High (4)
V. High (5)
Fire hazard categories
16%
12%
8%
4%
0%
4.4
15.3
3.5
15.7
4.6
14.2
4.1
15.1
2.6
7.9
1.7
9.8
Hancock
Pearl River
Harrison
Stone
Jackson
George
pre-Katrina
post-Katrina
Increase of very high fire hazard by county


Number of fires/area (ha)*100
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Fire hazard
1 (very low)
2 (low)
3 (md)
4 (high)
5 (very high)
Pre-Katrina validation
Post-Katrina validation