Rapid Mapping of Hurricane Damage to Forests

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Abstract.—The prospects for producing rapid, accurate delineations of the spatial extent of forest wind damage were evaluated using Hurricane Katrina as a test case. A damage map covering the full spatial extent of Katrina's impact was produced from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery using higher resolution training data. Forest damage detected in MODIS imagery corresponded well with damaged areas mapped in aerial surveys and matched the patterns expected in relation to maximum sustained winds, topography, and forest type. The results were encouraging for the prospects of rapid assessment using MODIS and other environmental data.

Introduction

Hurricanes are a major natural disturbance process impacting forests in the southeastern and northeastern United States (Boose *et al.* 1994, Connor 1998). Although no standardized system for the quantification of wind damage to forests has been developed (Everham and Brokaw 1996), the 2005 hurricane season created awareness of forest managers' and policymakers' needs for extremely rapid assessments of resource damage caused by sudden, large-scale events. The U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) program and Remote Sensing Applications Center are therefore preparing methodologies for rapid estimations of land areas and forest resources affected by such events. Data from satellite sensors with high repeat frequency and large spatial footprint (e.g., the Moderate Resolution Imaging Spectroradiometer, or MODIS) appear to hold the most promise for allowing rapid delineation of impacted areas, but the impact of the coarse spatial resolution of these sensors on hurricane damage mapping accuracy has not been evaluated. This work is an initial investigation into the feasibility of producing rapid, accurate maps of hurricane damage using MODIS imagery.

Challenges to any hurricane damage assessment include the continuing accumulation of tree mortality for several years after an event, which has been found both in pines (Armentano *et al.* 1995, Platt *et al.* 2000) and hardwoods (Walker 1995). On the other hand, much immediately apparent damage to hardwoods consists of simple defoliation (Kelly 1993). Recovery of many hardwoods following defoliation or even substantial structural damage can be rapid, with releafing and sprouting often occurring within 3 to 4 weeks (Armentano *et al.* 1995, Loope *et al.* 1994). Understory forest vegetation, particularly vines, can also respond rapidly to increased light levels (Loope *et al.* 1994), confounding attempts to associate forest damage with drops in remotely sensed measures of leaf area. For example, Ramsey *et al.* (1998) observed an abnormal green-up in hardwood-dominated forests in autumn 1992 following the passage of Hurricane Andrew through coastal Louisiana. Defoliated sites experienced a flush of new leaf and sprout growth, while understory plants responded with rapid growth at more severely damaged sites. Walker (1995) stated that accurate mortality estimates require long-term monitoring; estimates made immediately after an event—before recovery from defoliation—may be too high, but subsequent estimates may be lower than the mortality realized after the passage of several years.

Remote Sensing of Hurricane Forest Damage

Hurricane damage to forests has been mapped via satellite-based remote sensing in a number of studies. Landsat Thematic Mapper (TM) data at 30-m resolution were used by Kovacs (2001) to map disturbance in mangrove forests and by Clark *et al.* (2006) to map Hurricane Katrina's impacts on pines and hardwoods in the DeSoto National Forest in southern Mississippi. Ramsey *et al.* (1998) used 1-km Advanced Very High

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Resolution Radiometer (AVHRR) imagery to map impacts to bottomland hardwood and bald-cypress/tupelo (*Taxodium distichum*/*Nyssa aquatica*) stands in coastal Louisiana. AVHRR imagery was also used by Ayala-Silva and Twumasi (2004) to investigate patterns of damage with relation to distance from the path of Hurricane Georges in Puerto Rico. All of these studies found change in the Normalized Difference Vegetation Index (NDVI) to be a useful indicator of forest damage, but none of the coarser resolution studies had the opportunity to systematically validate their estimates against reference data.

Environmental Patterns of Hurricane Forest Damage

Many studies have assessed hurricane damage in relation to meteorological and environmental variables (referred to henceforth as "auxiliary data"). To the extent that such relationships are consistent across forest types and study areas, they can be helpful in verifying damage estimates derived from remotely sensed data and for refining or applying spatial restrictions to such estimates.

Wind speed is the variable most directly related to forest damage. Doyle *et al.* (1995) found that the severity and spatial extent of hurricane damage declined at greater distances from the storm track, although damaging winds may extend farther from the center on the eastern side of the track (Kelly 1993). Ramsey *et al.* (2001) compared forest damage in Louisiana with modeled wind speeds and found evidence that damage severity depends on the duration for which forests are subjected to wind speeds exceeding a critical threshold. Jacobs (2006) used relationships found between maximum sustained wind speed and forest damage to create rapid assessment maps of forest damage resulting from Hurricanes Katrina and Rita.

The topographic slope and aspect associated with a forest stand determine its degree of exposure to peak winds (e.g., McNab *et al.* 2004). Topography also influences the soil conditions available for tree rooting. Damage has been found to be greater in valleys than on ridges and slopes, probably because of poor soil drainage, shallow rooting depths, and lack of root anchorage (Basnet *et al.* 1992). Boose *et al.* (1984) summed up the influence of both wind and topography by stating that regional scale damage corresponded with the distribution of peak wind speeds, while topographic exposure to predominant wind directions explained the distribution of damage at the landscape scale.

Leininger *et al.* (1997) found that certain highly susceptible tree species were generally associated with severely damaged bottomland hardwood sites in Louisiana. Gresham *et al.* (1991) quantified damage at a species level on the South Carolina coastal plain, finding that susceptible species generally grew in locations with high water tables and had physiognomic characteristics, such as shallow root systems and unbuttressed boles, that predisposed them to damage. Because such characteristics are shared by species among both pines and hardwoods, a map of forest type based on a fine-level of classification would be needed to exploit species-level susceptibility information for predicting storm damage. In general, forest type response patterns are difficult to elucidate in isolation from other auxiliary variables because of co-correlated geographic variation in wind speed (e.g., Kelly 1993) and the association of particular forest types with certain topographic environments that also affect their susceptibility.

The approach here is broken into two parts. First, an assessment is made of whether the MODIS sensor—given its spatial and spectral resolution—is able to accurately detect areas of hurricane damage, given no constraints on how rapidly after an event an assessment is required. Second, a test of the prospects for producing an accurate delineation within days of an event is made using MODIS and auxiliary data such as maximum sustained wind speed, topographic variables, and forest type. This question addresses the issues of image availability and the temporal evolution of forest response after an event.

It is important to note that we used higher resolution reference data here that had been collected specifically in response to Hurricane Katrina. Operational rapid delineation of damage over different regions or forest types in the absence of event-specific training data will depend on the consistency of spectral reflectance responses to forest damage or the repeatability of damage patterns in relation to auxiliary data such as wind speed, topography, and soil types. These are major concerns that require addressing in future work.

Methods

Predictor Data and Study Area Definition

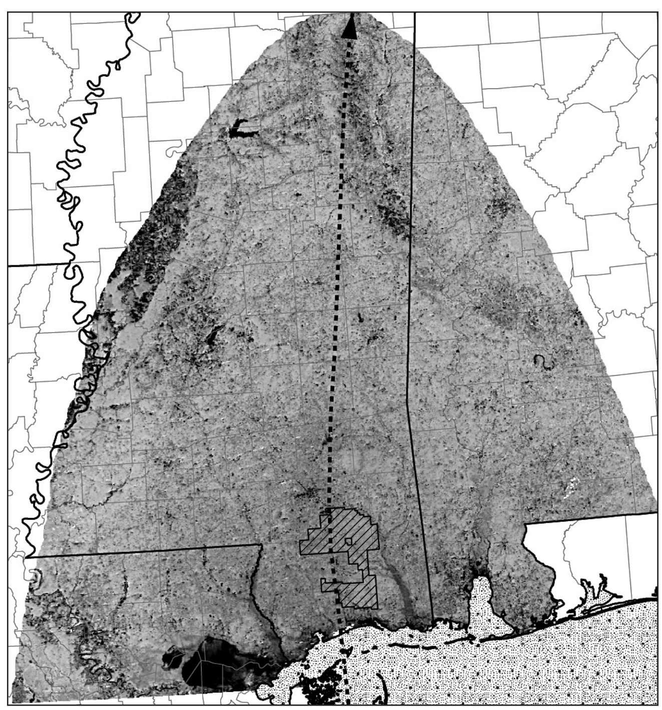
MODIS satellite data are available as tiles covering a fixed spatial area. Data from the tile overlapping the primary affected region in Louisiana, Mississippi, and Alabama were downloaded from the U.S. Geological Survey (USGS) Land Processes Distributed Active Archive Center (http://edcdaac.usgs.gov); the 250-m daily reflectance product (MOD09GQK) was chosen. All images with fairly low cloud proportions from the months of August through early November 2005 were obtained. A prestorm image was formed by mosaicking images collected on August 16 and 21, 2005, just before the hurricane's landfall on August 29, and the final image was collected on November 2, 2005. A forest analysis mask was created using the 30-m National Land Cover Dataset (NLCD) 2001 land cover classification. Forested classes (including wooded wetlands) were extracted from the NLCD and used to calculate forested proportion at the MODIS pixel resolution. Aggregated pixels containing less than 75 percent forest were eliminated from the analysis to diminish the negative impacts of nonforest land cover classes and misregistration error. The proportions of each MODIS pixel represented by each NLCD forest type—deciduous upland, evergreen upland, and wooded wetland—were calculated. A water mask was similarly created to restrict analysis near large bodies of water, where minor spatial registration errors could have major impacts on calculated spectral differences.

Maximum sustained surface wind speed data, available at 3-hour intervals, were downloaded from the Atlantic Oceanographic and Meteorological Laboratory (AOML Hurricane Research Division 2006). For each analysis pixel, the maximum value was extracted from the stack of 3-hour wind speed images. The values were classed into equal wind speed interval categories, and the envelope for each wind speed category was digitized on-screen. The study area (fig. 1) was then defined to incorporate all predominantly forested areas within the region estimated to have experienced tropical storm force winds. Finally, digital elevation model data at 30-m resolution were downloaded from the USGS National Elevation Dataset website (http://ned.usgs.gov/) and slope and aspect were computed using standard algorithms.

MODIS Data Preprocessing

An automated masking procedure was applied to the MODIS images to remove cloud and shadow areas. The procedure used variation from the time-series median reflectance values for each pixel to detect clouds and shadows, so it was necessary to first standardize the data by applying a relative radiometric normalization to correct for view angle variability and residual atmospheric effects. The normalization was performed by applying Reduced Major Axis (RMA) regression (see Cohen *et al.* 2003) to the predominantly forested pixels in each pair of images, using a preliminary threshold-based cloud and shadow mask. Clouds and shadows were then removed from the nor-

Figure 1.—*The study area was defined by the intersection of the region exposed to tropical storm-force winds or greater (the northward-trending oval) with Moderate Resolution Imaging Spectroradiometer (MODIS) tile h10v05 (which sets the southern boundary of the study area). The backdrop is a MODIS Normalized Difference Vegetation Index image acquired on the 10th day after Hurricane Katrina's landfall, with flooding and forest damage evident along the major floodplains. The study area overlaps the states of Louisiana, Mississippi, and Alabama, with Lake Ponchartrain and the flooded New Orleans visible at the southern boundary. The bold dashed line illustrates the path of Katrina's eye. The crosshatched polygon represents the DeSoto District of the DeSoto National Forest, the area from which the damage estimates used as training data were derived.*



malized imagery and replaced with data interpolated from the best previous and subsequent images. The procedure resulted in a complete normalized time-series of MODIS imagery with no missing values.

Reference Data

Clark *et al.* (2006) produced a categorical damage probability map of the DeSoto District in the DeSoto National Forest (see fig. 1), based on change in Landsat TM NDVI between October 15, 2004 and November 3, 2005, and calibrated to damage photointerpreted from aerial photography collected soon after the hurricane's passage by the Forest Service Forest Health Technology Enterprise Team. We determined the mean damage probability represented by each of the mapped damage classes using the statistics provided and then spatially aggregated the probabilities to the MODIS pixel resolution. The aggregated damage probabilities were treated as estimates of the MODIS pixel fraction that had sustained damage and used as reference data here.

Another source of reference data was a Forest Service Forest Health Protection (FHP) aerial sketchmap product that illustrated hurricane damage over several parishes in southeastern Louisiana (Steiner *et al.* 2006). A graphical representation of this map was converted to digital form and georeferenced. This product was the only other spatially explicit reference data discovered that was feasible for use. Although other aerial photography may be available from various sources, its interpretation at the coarse MODIS pixel scale would be extremely time-consuming.

Modeling Approach

Damage Class Discriminant Analysis. Because of the ubiquity of NDVI differencing as a change detection technique, an initial assessment of the capability of the MODIS sensor to detect hurricane damage was made by modeling the TM damage estimates using the MODIS time-series NDVI values. For this purpose, the aggregated forest damage estimates derived from Clark *et al.* (2006) were converted into three discrete classes via an agglomerative clustering technique using Ward's distance criterion. The MODIS NDVI values were converted to a series of difference values by subtracting each of the poststorm time step NDVI values from the initial, prestorm NDVI value for that pixel. Use of difference data only reduced the likelihood of modeling potentially erroneous information in the training data that could have been caused by other land cover change in the year between the prestorm and poststorm TM images. Discriminant analyses were then performed to separate the three TM damage classes on the basis of the MODIS NDVI difference values. The accuracy of the functions was assessed via cross-validation, holding out one sample at a time, and compared with the accuracy expected due to chance alone using a kappa statistic.

Continuous Damage Estimation. A predictor of continuous forest damage based on MODIS data was trained using the aggregated TM damage data. The predictor was constructed using forward stepwise multiple regression on the NDVI difference time series as well as time-series differences based on the raw red and near-infrared MODIS reflectance data. The multiple regression fits were then adjusted to match the mean and variance of the damage training data using RMA regression. Because the application of this predictor to the entire area impacted by the hurricane involved an extrapolation from the small training area, some care was taken to immunize it against potential spatial heterogeneity in the relationship between spectral reflectance and forest damage. In particular, an analysis of the MODIS time-series data indicated that deciduous leaf senescence was well under way in the northern portion of the study area by the date on which the last MODIS image was collected. Therefore, the continuous damage predictor was trained using only the images collected before the date at which senescence was estimated to have begun at any location in the study area. The predictor was then applied to all pixels estimated to have experienced sustained tropical storm force winds, producing a spatially complete estimate of forest damage due to the hurricane.

Damage Estimation Assessment. The resulting damage map was evaluated by comparison with the independent Steiner *et al.* (2006) sketchmap product. Because of spatial uncertainties in the sketchmap, this comparison was done on a simple visual basis. The reasonableness of the regionwide forest damage map was also assessed through statistical assessment of the degree to which expected relationships between the auxiliary data (in particular, maximum sustained winds, dominant forest type, and slope) and the damage estimate were realized. Because the damage estimate was based solely on MODIS spectral data, assessment of its relationship to the independent auxiliary data constitutes an indirect test of its accuracy. This evaluation was performed by examining the correlation coefficients between the damage estimate and each of the auxiliary variables and by breaking the continuous auxiliary variables into logical discrete classes and determining the significance of differences between class sample means via analysis of variance. Maximum sustained wind speeds experienced by forests across the study area were broken into four classes, corresponding to weak tropical storm force (< 60 mph), strong tropical storm force (60 to 73 mph), Category 1 hurricane force (74 to 95 mph), and Category 2 hurricane force (96 to110 mph), while the aggregated NLCD forest cover percentages were recoded into discrete classes by coding any pixel with greater than 50-percent cover in either deciduous upland, evergreen upland, or wooded wetland forest into the corresponding class.

Rapid MODIS Mapping Feasibility. The prospects for creating rapid, accurate maps of forest damage within days of an event were tested by repeating the previous regression estimation approach using only the spectral differences between the prestorm and immediate poststorm (3 days after landfall) MODIS images rather than the time series used previously. The estimates produced were evaluated using the same approaches described previously.

Rapid Mapping Feasibility Using Auxiliary Data. Finally, the feasibility of producing a rapid forest damage map based solely on auxiliary data (a fairly likely contingency, given the typically cloudy summertime conditions in the southeastern United States) was assessed by using the time-series damage estimate described previously to train a similar multiple regression estimator based on wind speed, NLCD forest type, and slope. The indirect approach of training the auxiliary damage estimation using the MODIS-modeled data was necessary because the small spatial extent of the TM-derived damage map did not incorporate a significant range of variability in the auxiliary data, particularly for wind speed. The auxiliary damage estimate was assessed visually.

Results

Damage Class Discriminant Analysis. The clustering technique produced three forest damage classes, referred to here as little to no damage (0 to 11.35 percent of MODIS pixel damaged), moderate damage (11.35 to 25.8 percent), and severe damage (>= 25.8 percent). The best discrimination between these classes was achieved with a quadratic discriminant function based on both the immediate poststorm and the early November changes in NDVI relative to the prestorm value. The discriminant function produced a cross-validation accuracy of 77.8 percent (Kappa = 0.552) and achieved a fairly even balance between omission and commission errors (table 1). Class discrimination based on immediate poststorm data only was only slightly poorer, with an accuracy of 76.3 percent (Kappa = 0.507). The best linear discriminant function using all time-series data had an accuracy of 73.0 percent (Kappa = 0.488). On the basis of these results, it appears that MODIS data have the inherent spatial and spectral properties needed to produce reasonably accurate maps of forest hurricane damage.

Continuous Damage Estimation. The forward stepwise regression based on all time-series MODIS reflectance and NDVI data indicated a total of 13 predictor variables with significance $p < 0.05$ and a resulting adjusted R^2 of 0.666. No relationships were found between the residuals and the model fits, and residuals were essentially normally distributed. The application of the derived regression equation across the study area yielded

Table 1.—*Cross-validation accuracies of the quadratic discriminant function produced to separate Thematic Mapper-derived forest damage classes on the basis of Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index change data.*

	True damage class		
Classed as	**Little to none**	**Moderate**	**Severe**
	0–11.35%	11.35%–25.8%	>=25.8%
Little to none	1,205	112	14
Moderate	241	178	44
Severe	11	41	237
Proportion correct	0.827	0.538	0.803

Total proportion correct = 0.778 (95% confidence interval = 0.759 - 0.795); Kappa = 0.552.

the forest damage estimate map shown in figure 2. The damage represented is concentrated in the southern portion of the study area, where wind speeds were highest, and in floodplain areas, in keeping with the general findings of Gresham *et al.* (1991) and Basnet *et al.* (1992).

Damage Estimation Assessment. The visual comparison of the continuous damage map with the Louisiana aerial sketchmap data (Steiner *et al.* 2006) showed a good degree of correspondence (fig. 3). Although the spatial alignment of the data is not perfect, probably due to uncertainties in the sketchmapping process, the general patterns are similar, with extensive damage in the floodplains and scattered damage elsewhere. The expected relationships between the predicted forest damage and the auxiliary variables were found, with a positive correlation (r = 0.545) between maximum sustained wind speed and predicted damage, a negative correlation (r = -0.379) between slope and predicted damage (i.e., greater damage predicted in floodplains), and a positive correlation (r = 0.486) between the percentage of wooded wetland and predicted damage (again, more damage in floodplains). Normal curves fitted to the predicted damage histograms for each of the four wind speed

Figure 2.—*The percentage of forest damage predicted across the southern portion of the study area that was more dramatically impacted. The lightest grays visible indicate an estimated damage fraction of 10 to 15 percent while the darkest colors indicate an estimated damage fraction of 50 percent or more. Damage is concentrated near the coast, where wind speeds were highest, and in floodplains, in agreement with the assessment by Windham (2005).*

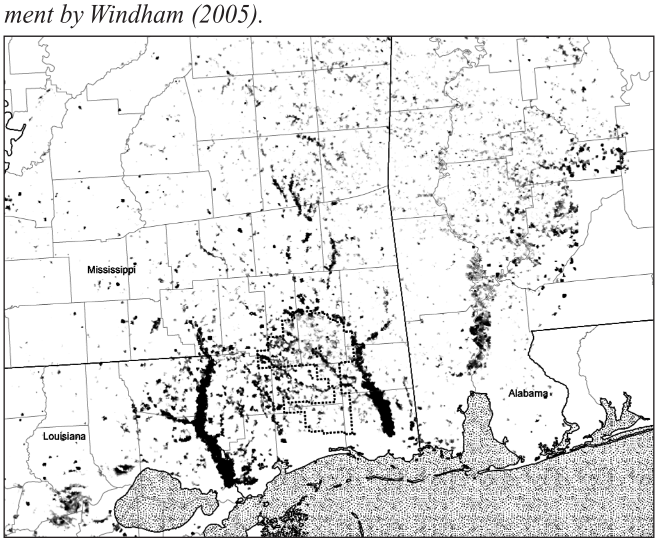
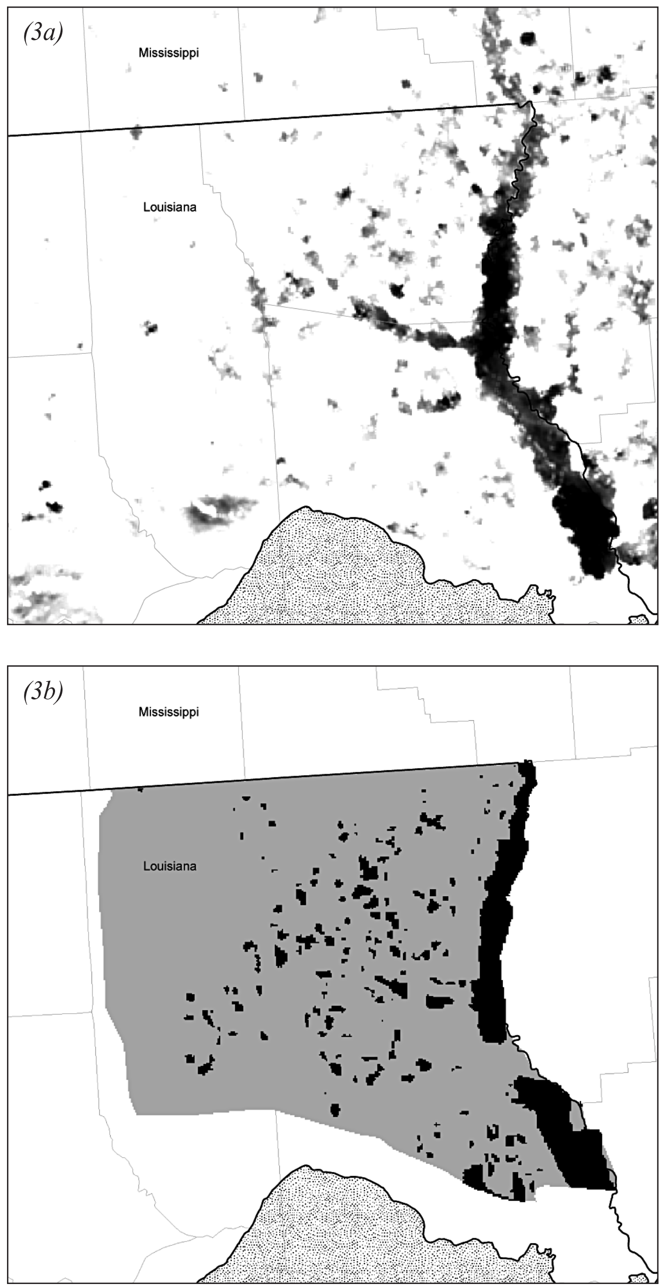


Figure 3.—*The correspondence of forest damage as mapped using Moderate Resolution Imaging Spectroradiometer (MODIS) data (fig. 3a) with Forest Service Forest Health Protection aerial sketchmap data (fig. 3b, Steiner et al. 2006). In the MODIS map, darker grays represent more intense damage. In the sketchmap data, areas in black were mapped as damaged forest, while gray indicates the area flown. Misregistration is present, but the general patterns are similar, with extensive damage in the floodplains of the Pearl River (including a more lightly damaged section in the southern part of the mapped area) and its tributary from the west, the Bogue Chitto, and scattered damage elsewhere.*



classes are shown in figure 4, while similar curves in figure 5 illustrate the damage histograms corresponding to the three forest types. In all cases, the expected associations between the auxiliary data and predicted damage were found, and the 99-percent confidence intervals for all class means were distinct and nonoverlapping.

Rapid Mapping Feasibility. Forward stepwise regression based on only the reflectance and NDVI differences between the first poststorm MODIS image collected—3 days after Katrina's landfall—and the prestorm image indicated that the model was best constructed with only the red and near-infrared reflectance differences and had an adjusted R^2 of 0.522. Application of the equation across the study area yielded a predicted map (not shown) that looked remarkably similar to that based on the complete time-series data. The primary differences between the two maps occurred in less-strongly affected areas in the central portion of the study area. Determination of the relative accuracies of the maps was impossible using the available reference data. The immediate poststorm model, however, matched the Steiner *et al.* (2006) sketchmap data slightly better than the full time-series model. Again, all the expected relationships against auxiliary data were found at statistically significant levels.

Rapid Mapping Feasibility Using Auxiliary Data. Forward stepwise regression found that the best predictive model for forest damage based on auxiliary data was constructed using the maximum sustained wind speed and the fractions of the pixel occupied by deciduous upland forest and wooded wetland forest. The equation generated, which had an adjusted R^2 of 0.434, led to the damage prediction shown in figure 6. Although the overall spatial patterns found in the other predictions are seen here also, the map has a blurriness that could likely be improved only by having more detailed forest type and stand history information. As it is, the auxiliary data prediction provides at least a useful spatial envelope within which most forest damage can be expected to occur.

Figure 4.—*Normal curves fitted to the predicted damage histograms for four maximum sustained wind speed classes, corresponding to weak tropical storm force winds (< 60 mph), strong tropical storm force winds (60 to 74 mph), Category 1 hurricane force winds (75 to 96 mph), and Category 2 hurricane force winds (96 to 111 mph). Higher wind speeds correspond to greater predicted damage, and the 99-percent confidence intervals for the class means are all nonoverlapping.*

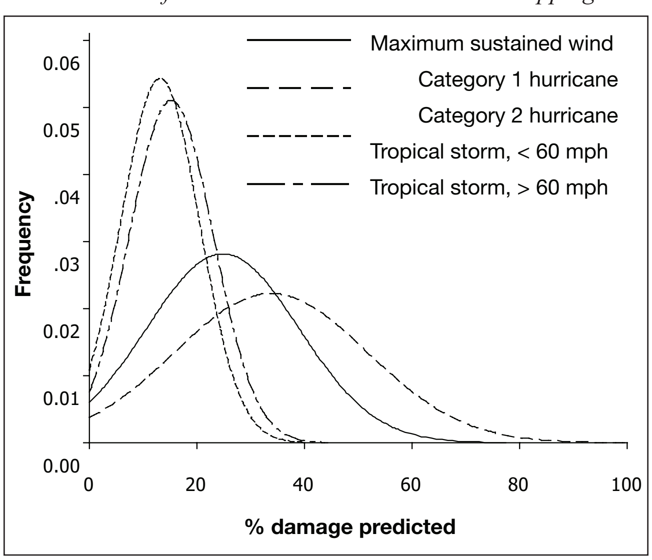


Figure 5.—*Normal curves fitted to the predicted damage histograms for three forest type classes, dominated by deciduous upland forests, evergreen upland forests, and wooded wetlands (predominantly bottomland hardwood forests). Damage is predicted to concentrate in the wooded wetland class, with evergreen upland forests experiencing somewhat more damage than deciduous upland forests. These results are in keeping with the generalizations of Gresham et al. (1991) and Basnet et al. (1992) and with the specific observations of Windham (2005).*

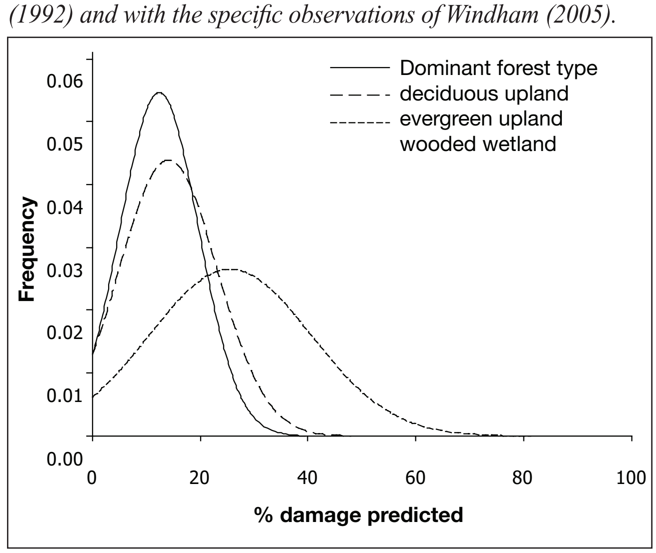
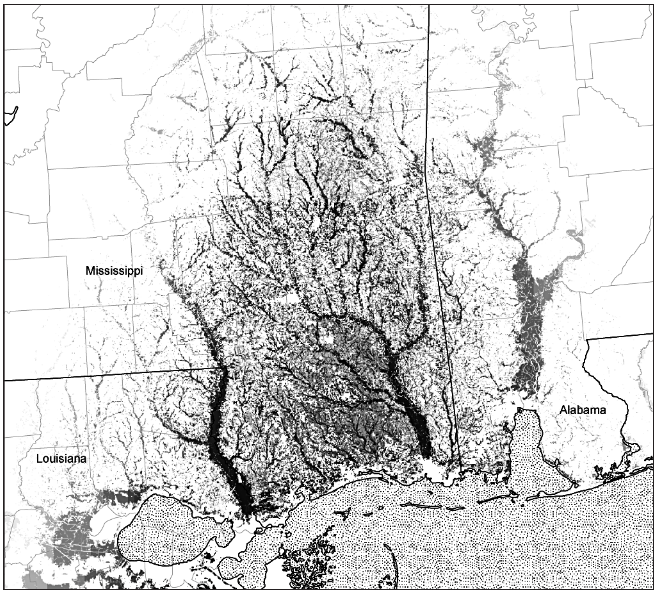


Figure 6.—*Damage estimate predicted on the basis of auxiliary data alone. The model is based on maximum sustained wind speed and pixel percentage occupation by deciduous upland forest and wooded wetland forest. This more general map can serve as a first approximation in the absence of satellite data or as a spatial constraint on predictions based on satellite data.*



Discussion

The results here are encouraging for the prospects of rapid mapping of hurricane damage using MODIS imagery, auxiliary data, or some combination thereof. In fact, immediate postevent mapping has some advantages over use of time-series data: by reducing the analysis window to the shortest possible duration, unrelated land cover change is less likely to become confounded with disturbance due to the event. Considering the variety of possible temporal biological responses to an event, it may be hard to take full advantage of time-series data anyway, and the advantages of rapid mapping may outweigh its disadvantages. In addition, it is possible that the higher R^2 found here for the prediction based on the full time-series data resulted from an overfit to noise or other local phenomena in the training data and did not result in a more accurate map over the full study area.

It is quite likely that rapid postdisturbance mapping will have to occur in the absence of good, clear-sky satellite data. Although the results generated here for predicting damage using auxiliary data provide a starting point, three degrees of separation existed between the primary training data and the auxiliary damage modeling: photo interpretation, derivation of the damage map across the DeSoto District using TM imagery, and extrapolation to the full affected area using MODIS imagery. It would be helpful and probably more reliable to derive relationships based on other results that are more closely tied to field research or detailed air photo work. It is possible that such relationships could be exploited using more detailed forest type maps, which may be forthcoming through the LANDFIRE project or Regional Gap Analysis program.

More accurate rapid mapping could be accomplished by combining satellite imagery with auxiliary data, either through the use of the auxiliary variables as an envelope with which to constrain the spectral estimates or through some more complex multivariate procedure. An approach based on canonical correspondence analysis, in which a spectral damage index is derived through constraint of spectral change scores to linear combinations of auxiliary variables known to influence damage susceptibility, might be helpful.

The fact that floodplain forests appear to be more susceptible to hurricane damage creates one difficulty. These are the same areas that experience heavy flooding in the days and possibly weeks after an event. Change metrics based on simple NDVI differences may be particularly susceptible to the confusion of understory flooding with forest damage, especially in fairly open forests. The strong similarity between the map produced here and the FHP sketchmap is some assurance that the problem is not very severe. Despite this assurance, mid-infrared spectral bands, which are available from the MODIS sensor at 500-m resolution, would likely be helpful in discriminating flooding from forest damage. They could also assist in separating defoliation from more severe structural damage, as indices based on mid-infrared reflectance have been found to have high sensitivity to changes in forest structure (e.g., Jin and Sader 2005). Investigation of the utility of the mid-infrared bands is another matter for further work.

It is important to note that this work makes the assumption that the Landsat TM-based damage maps used as reference data accurately reflect genuine forest damage. However, it is uncertain whether temporary effects such as defoliation could be fully separated from structural damage based on interpretation of aerial photography collected soon after the storm, and any shortcomings in that process would have propagated through the subsequent TM and MODIS analyses. Conditions during the following year's growing season likely provide a more reliable indication of persistent damage. That is the approach taken by one recently published study of Hurricane Katrina's impacts (Chambers *et al.* 2007). Greater confidence could be placed in these results if comparison with data derived from subsequent years were made.

Conclusions

The results here are encouraging, but only a beginning. To make accurate rapid assessment an operational procedure, it will be necessary to investigate whether such appraisals can be achieved in the absence of event-specific training data. The answer to that question will begin with determining the constancy of forest spectral response to particular damage types and the repeatability of patterns of damage with respect to auxiliary variables. If generalizable relationships cannot be relied upon, the investigation of multivariate techniques by which satellite and auxiliary data can be combined to isolate and reveal unique damage signatures may be profitable.

Acknowledgments

Jess Clark at the Remote Sensing Applications Center (RSAC) produced the damage map that served as the essential training dataset for this work. His work in turn relied on aerial photography collected by the Forest Service Forest Health Technology Enterprise Team. Chris Steiner's work at the Forest Health Protection program enabled the visual validation of the damage map shown here. RSAC's rapid assessment work is funded by the Forest Inventory and Analysis program (FIA), and I thank Dennis Jacobs and other members of the FIA Remote Sensing Band for interesting and amusing discussions.

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