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LANDSCAPE ANALYSIS AND PATTERN OF HURRICANE IMPACT AND CIRCULATION ON MANGROVE FORESTS OF THE EVERGLADES

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Abstract: The Everglades ecosystem contains the largest contiguous tract of mangrove forest outside the tropics that were also coincidentally intersected by a major Category 5 hurricane. Airborne videography was flown to capture the landscape pattern and process of forest damage in relation to storm trajectory and circulation. Two aerial video transects, representing different topographic positions, were used to quantify forest damage from video frame analysis in relation to prevailing wind force, treefall direction, and forest height. A hurricane simulation model was applied to reconstruct wind fields corresponding to the ground location of each video frame and to correlate observed treefall and destruction patterns with wind speed and direction. Mangrove forests within the storm's eyepath and in the right-side (forewind) quadrants suffered whole or partial blowdowns, while left-side (backwind) sites south of the eyewall zone incurred moderate canopy reduction and defoliation. Sites along the coastal transect sustained substantially more storm damage than sites along the inland transect which may be attributed to differences in stand exposure and/or stature. Observed treefall directions were shown to be non-random and associated with hurricane trajectory and simulated forewind azimuths. Wide-area sampling using airborne videography provided an efficient adjunct to limited ground observations and improved our spatial understanding of how hurricanes imprint landscape-scale patterns of disturbance.

Key Words: aerial videography, damage assessment, Everglades National Park, Hurricane Andrew, remote sensing, southwest Florida, spatial analysis, Ten Thousand Islands National Wildlife Refuge

INTRODUCTION

The effects of hurricanes on forested ecosystems can range from very minor defoliation of only a few trees to catastrophic blowdown of whole forests. Landscape analysis of hurricane events assumes that the degree of damage and direction of observed wind damage of trees relate to circulation and intensity of hurricane vortices (Fujita 1980, Wakimoto and Black 1994, Doyle et al. 1995, Foster and Boose 1995). Capturing the imprint and range of ecosystem impact is more often masked by landscape fragmentation and urban development given the wide-area effect of hurricanes. The concentration of severe damage near the eyepath can be related to a radius of maximum winds known to decrease incrementally with perpendicular distance from the storm's eye; this wind attenuation function has been described as the negative exponent of the storm's radius (Frank 1977). Yet, it is also fairly evident that wind speed attenuates to a lesser degree on the storm's right side in the Northern Hemisphere with the additive effect of forward speed from storm movement (Simpson and Riehl 1981). Hence, damage and subsequent recovery of mangrove or other coastal forest after hurricane passage will necessarily vary with hurricane size, strength, and path across an impacted landscape.

Research has yielded limited insight on how hurricanes alter mangrove forest structure and function, shifts in tree species composition, or effects of wind stress and recovery patterns on mangrove-associated fauna. One of the causes for this limited information base is that post-hurricane ground surveys are very difficult to conduct. Not only are mangrove field sites challenging to access, but also storm effects on human infrastructure (e.g., roads, commerce, power, etc.) compound already difficult field logistics. Several investigations have, however, quantified the impact that hurricanes wreak on mangrove vegetation based on field observations (Craighead and Gilbert 1962, Stoddard 1963, Lugo et al. 1983, Roth 1992, Smith et al. 1994, Doyle et al. 1995, Cahoon et al. 2003, Krauss et al. 2005). As a vegetation type, mangrove systems are both vulnerable and susceptible to wind and surge damage mostly due to their coastal proximity and exposure to unsheltered winds and waves as hurricanes make landfall. Most post-hurricane field studies are fairly parochial due to site access difficulties and logistical restraints.

Aerial videography offers an effective supplement to field studies for wide-area assessment of ecological storm damage as well as for monitoring short and long-term recovery of forested habitats. Aerial videography is one of the simplest and least expensive remote sensing techniques, yet videography can offer the investigator a fairly high spatial resolution (see McGraw et al. 1998). The use of aerial videography is not new to natural resource investigations and has been employed for a variety of applications including mapping and determining characteristics of wetland and rangeland habitat (Everitt et al. 1991, 1992, Seibert et al. 1996), delineating habitat change in remote environments (Marsh et al. 1994, Wood et al. 1995), conducting forest inventories (Bobbe et al. 1993, Evans and Beltz 1992, Jacobs et al. 1993), assessing the area of insect defoliation within a forested landscape (Alfaro and Shore 1984, Everitt et al. 1997), describing ice storm damage (Jacobs 2000), mapping and monitoring hazardous waste sites (Marsh et al. 1991), and conducting rapid and timely evaluations of hurricane impact (Jacobs and Eggen-McIntosh 1993, Kelly 1993).

In this investigation, we analyzed aerial video images from the mangrove zone of southwest Florida flown in August 1993, approximately one year after the passage of Hurricane Andrew. The specific objectives were 1) to quantify landscape patterns of mangrove forest damage along parallel transects roughly perpendicular to the storm path, 2) to correlate observed treefall patterns with reconstructed wind profiles of Hurricane Andrew, and 3) to demonstrate the benefits of remote sensing techniques for assessing hurricane damage at an ecosystem scale and across isolated and inaccessible landscapes.

STUDY AREA

Most of this survey was conducted in Everglades National Park (NP) and Ten Thousand Islands National Wildlife Refuge (NWR) in southwest Florida (Figure 1). Everglades NP contains approximately 600,000 ha, comprising mostly open water, marsh, mangroves, hardwood hammocks, and cypress domes. Ten Thousand Islands NWR consists of a total refuge area of about 14,000 ha along the northern extent of the Everglades region; mangrove forests comprise approximately 30% of this area. Mangrove forests encompass approximately 150,000 ha in the Everglades region (c.f., Olmsted and Loope 1984) and contain three principal tree species - *Rhizophora mangle* L., *Avicennia germinans* L., and *Laguncularia racemosa* Gaertn. f. An additional species, *Conocarpus erectus* L., occurs as a mangrove associate at slightly higher microtopographic locations. Rainfall for the region varies from 101 to 165 cm y^{-1} by location (McPherson et al. 2000) and seasonally depending on periodic droughts and tropical storms.

South Florida is subject to frequent tropical storms and hurricanes, with an estimated 60 or more storms intersecting some part of the Everglades region since 1851 (Doyle and Girod 1997, Platt et al. 2000). In August of 1992, Hurricane Andrew traversed across the lower peninsula of Florida and caused massive destruction to personal property (Wakimoto and Black 1994) and natural ecosystems (Ogden 1992). Maximum sustained winds of approximately 232 km h^{-1} (Armentano et al. 1995), and tornado-associated gusts between 253 and 333 km h^{-1} (Wakimoto and Black 1994), caused tremendous destruction of mangrove forest vegetation in the study area (Smith et al. 1994, Baldwin et al. 1995, Doyle et al. 1995).

METHODS

Aerial Transects

Two semiparallel aerial transects were flown using a helicopter along a predetermined flight path that crossed roughly perpendicular to the path of Hurricane Andrew (Figure 1). Flight lines for an approximately 108 km "coastal transect" originated in the northern portion of Everglades NP near the Fakahatchee River, traversed southward over Ten Thousand Islands NWR, Jewel Key, Snake Key, Lostmans Key, Broad River, Harney River, Shark River, Northwest Cape, and terminated at East Cape. Flight lines for an approximately 82 km "inland transect" originated just outside of Flamingo and proceeded northward across several mangrove/marsh ecotones as well as intact mangrove forests associated with the middle reaches of the Shark, Harney, Broad, Chatham, and Huston Rivers. The inland transect continued over Deer Key and terminated at Everglades City. In all, a total flightline of nearly 200 km in length encompassing a sampling area of 1520 ha of mangrove and open water habitat, including minor coverage of freshwater marsh, were overflown above the Everglades landscape.

Images of forest damage were recorded using a Panasonic AG-160 Proline Camcorder with a wide angle lens. The camera was manually suspended vertically beneath the helicopter while maintaining a fixed point relative to the aircraft. This ensured a straight and consistent point of reference (nadir)

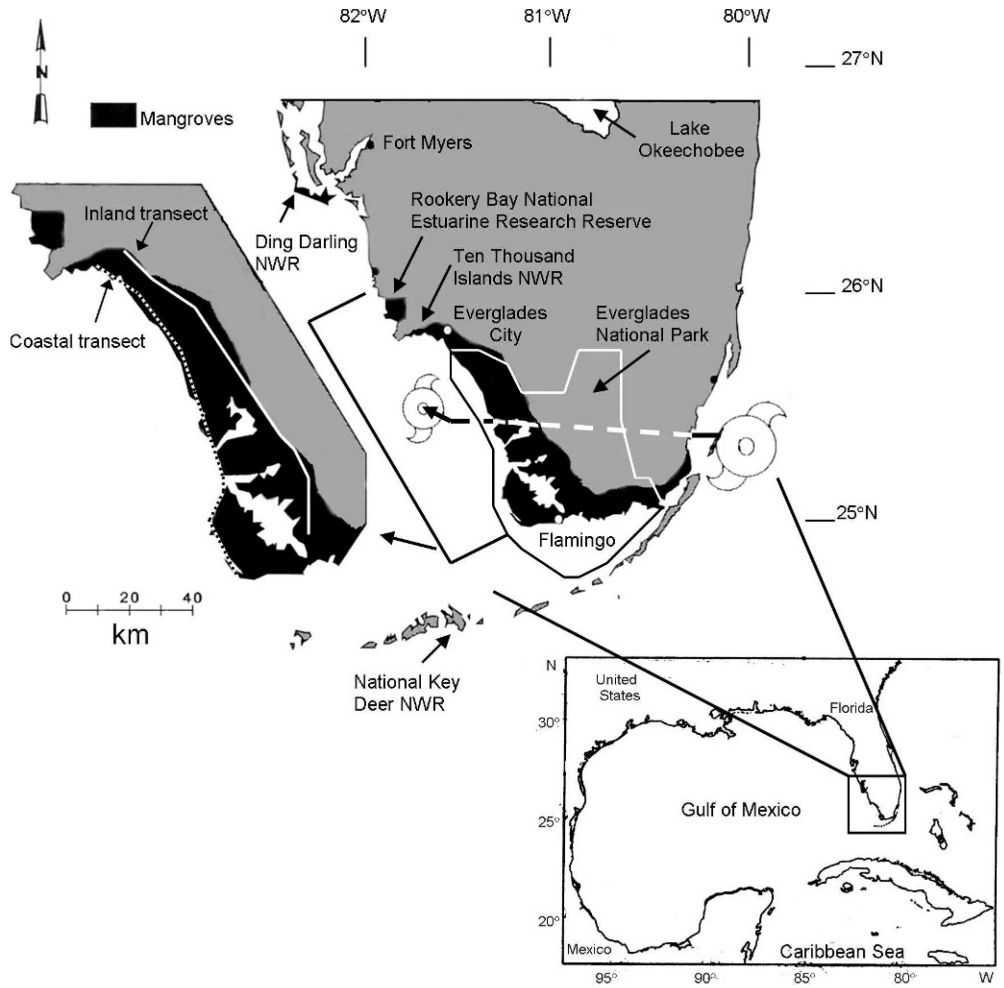

Figure 1. Location of coastal and inland transects along the southwest coast of Florida in relation to the path of Hurricane Andrew.

with helicopter trajectory, wind tack, and ground speed. In-flight audio transmissions by pilot and observer of flight status (i.e., altitude, bearing, speed, geographic position, etc.) and degree of forest damage were recorded directly onto the video audiotrack on a continual basis. A nominal altitude of 120 m above mean sea level and a nominal ground speed of 93 km h^{-1} were maintained throughout the overflight. The slow and relatively stable aerial platform of the helicopter, combined with a video scan rate of 30 frames s^{-1}, provided high quality images. Flight conditions were calm throughout and tack alignment with video frame orientation was sustained without gusts or flight deviations. Likewise, the flight altitude was predetermined to obtain video clarity equivalent to a ground resolution of at least 20 cm per image pixel sufficient to calculate fairly accurate tree height and compass direction of fallen trees. Video frame size captured a continuous ground swath of 80 m by 60 m wide along the entire transect, equal to an area of approximately 0.48 ha per frame.

Image Analysis

Post-flight assessment of video coverage was conducted on-site to ensure proper quality and resolution of image and audio. Actual playback of video tape medium (VHS) was achieved with a 4-head video cassette recorder (VCR) and analog television set. Individual video frames, starting with the first image with complete mangrove coverage along each transect, were analyzed at 30 second systematic frame-capture intervals. This interval translated into a ground distance of between 720 and 830 m between each video frame. Image intervals were adjusted slightly to include mangroves if none appeared at a particular location but were nearby. A total of 149 and 100 frames, dictated by individual transect length, were analyzed as interval

Table 1. Classification of Hurricane Andrew damage to southwest Florida mangrove vegetation.

Damage category	Canopy disturbance
0	No apparent damage; 0–10% damaged
1	10–30% damaged
2	30–50% damaged
3	50–70% damaged
4	70–90% damaged
5	> 90% damaged

samples of the coastal and inland transects, respectively, for a total image-analyzed area of approximately 120 ha. This frame-capture approach and analysis represented a stratified random sampling scheme replicated by transect.

Each frame was subjected to visual analysis of percent disturbed or defoliated canopy, percent water cover, felled tree height, and felled tree azimuth. Tree heights were calculated from on-screen ruler measurements in relation to an interpolated curvilinear function based on altitude and an equivalent ground distance scaled from known airstrip and helicopter pad markings and dimensions. Polar protractors and straight rulers were placed directly on the screen to obtain quantitative measurements of tree height and treefall direction. Tree height was determined from tree base at the root collar to the top end of the former canopy. Trees without evidence of intact canopies noted by substantial branch structure were not measured for tree height. Height data were analyzed for differences between transects and among impact quadrants with ANOVA procedures after a square-root transformation (SAS Institute, Inc. 1999). Where individual downed trees were distinguishable, azimuths were determined based on a known magnetic flight bearing ($+3^\circ$ to true bearing). A damage classification system, ranging from 0 to 5, was used to assess the degree of forest damage based on canopy displacement for each frame (Table 1). A grid overlay on plastic mylar was used to aid determination of displaced or disturbed canopy area based on the percentage of standing and fallen canopy clearly distinguished by green leaves of erect trees and gray-brown woody debris of downed trees.

Correlation with Storm Path and Circulation

Doyle et al. (1995) described the application of a hurricane tracking and circulation model, HURASIM, which was used to correlate predicted wind velocities and vectors of Hurricane Andrew with data from posthurricane ground surveys. HURASIM hindcasts hurricane behavior across a spatially explicit landscape by incorporating historical tracking and meteorological data of North Atlantic tropical storms from 1851 to present. Wind profiles are generated by storm and location within the HURASIM model based on a set of tangential wind functions, inflow angle offset, forward speed of the storm, and maximum wind radius for a given geographic position and maximum sustained wind speed (Doyle et al. 1995, Doyle and Gorham 1996, Doyle and Girod 1997). Mathematical functions of hurricane form and funneling used in HURASIM were adopted from Harris (1963), Bretschneider and Tamaye (1976), Neumann (1987), Kjerfve et al. (1986), and Boose et al. (1994).

We used the HURASIM model to reconstruct peak wind speeds and azimuths for each sampled video frame along the coastal and inland transects interpolated for every 10 minute interval of storm track. We used linear regression to relate model-simulated wind fields to observed treefalls obtained from aerial image analysis, and to determine if observed (tree fall azimuths) and model predicted wind directions were correlated.

RESULTS

Aerial Transects and Image Analysis

Percent Canopy Displacement. Both the coastal and inland transects revealed a distinct landscape pattern of forest damage from Hurricane Andrew (Figure 2). Forest damage in the storm's left quadrants (i.e., southern portion of each video transect) demonstrated a stair-step pattern from minimal damage to 50% canopy displacement or more near the southern eyewall zone. Full and partial blowdowns of 70 to 100% canopy displacement were observed in both transects for forest sectors within the eyepath of Hurricane Andrew. Comparatively, the expanse and extent of complete destruction was less overall in the eyepath zone along the inland transect than on the coastal transect. For both transects, damage intensity was greatest and most consistent in areas subject to Hurricane Andrew's forewinds (i.e., right quadrants or northern storm boundary), than backwinds (i.e., left quadrants or southern storm boundary). The coastal transect sustained more than 50% canopy disturbance for nearly all transect intervals within the storm's right-side quadrants, while the inland transect exhibited mostly less than 50% canopy removal from forewinds. The propensity for nearly complete tree canopy blowdown was more clearly evident in the eyewall zone and along the northern storm boundary than on the storm's backside

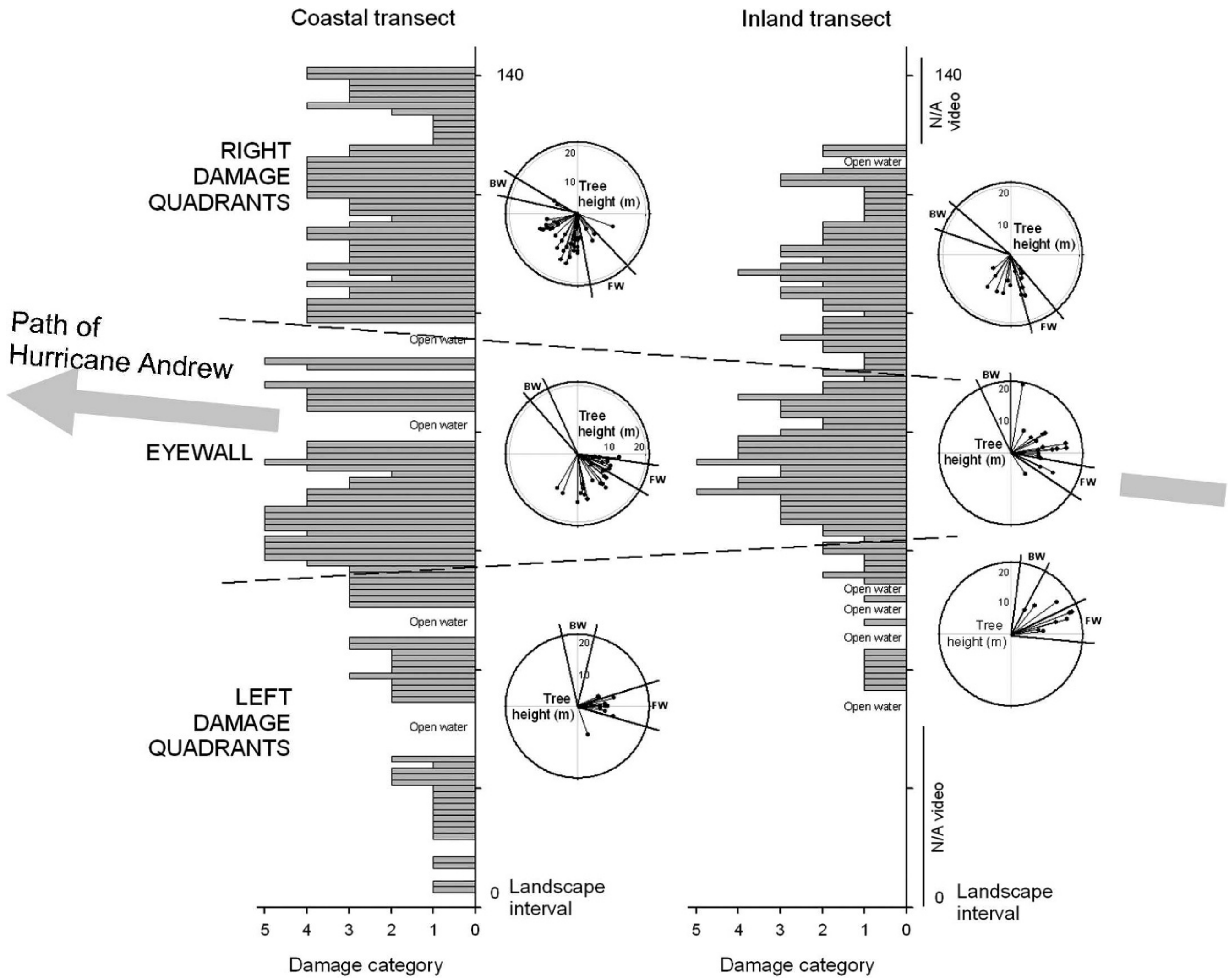

Figure 2. Categorization of damage, tree height, and treefall azimuth along the coastal and inland transects on the southwest coast of Florida, USA. Each video sample (landscape interval) is between 720 and 830 m apart. Hurricane Andrew tracked from East to West over the two transects, as indicated by the gray arrow. FW = Forewinds; BW = Backwinds.

encompassing the southern portion of Everglades NP (Figure 2).

Reconstructed Tree Heights. The propensity for mangrove blowdowns along the coastal transect relative to the inland zone was apparent during image analysis. Tree heights of fallen trees were determined from calibrated image measurements related to altitude, and then contrasted between transects and quadrants to test for differences. Observed tree heights were significantly lower along the coastal transect than along the inland transect ($F_{1,129}$ = 10.09; P = 0.002). These differences in height were slight, however, with trees along the coastal transect averaging 9.1 ($\pm$ 0.3 SE) m in height and trees along the inland transect averaging 10.4 ($\pm$ 0.5 SE.) m in height. These slight differences in height profile may be skewed by sample size and stand density variation between transects given that many areas containing scrub mangroves along the inland transect did not have measurable downed trees. There were no tree height differences among impacted quadrants ($F_{2,129}$ = 2.38; P = 0.097); tree heights from our transects in the right quadrants, eyewall, and left quadrants of Hurricane Andrew were 9.1 m, 10.2 m, and 9.5 m, respectively.

Treefall Patterns. Landscape analysis of treefall azimuths by transect interval and quadrant indicated a fairly consistent pattern of southerly to easterly treefalls from north to south and west to east across the study area (Figure 2). All quadrant summaries demonstrated non-random windthrow patterns restricted to fairly narrow wind rows despite the latitudinal expanse by quadrant grouping. The number of quantifiable treefalls was proportionally fewer for southern quadrants given the precipitous decrease in canopy damage. Measurable downed trees were, on the other hand, plentiful in plots with extreme damage ($> 70\%$) common in the eyepath zone and northern quadrants. Treefall azimuths ranged from 95 to 210° for coastal transect eyewall images and from 10 to 145° for inland transect eyewall images, reflecting the differences in proximity to storm approach and wind exposure. The greatest variation in treefall pattern of 190° was found in the right quadrant of the coastal transect where more trees were downed on both storm approach and passing. Model predictions of peak forewind azimuths with observed windthrow by quadrant demonstrated a consistent 20 to 30° offset that may reflect the fact that trees are falling at critical windspeeds prior to peak winds during eye passage.

Correlation with Storm Path and Circulation

Predicted forewind azimuths generated from HURASIM at maximum predicted wind speed for Hurricane Andrew and each transect interval showed striking agreement with observed treefalls for all quadrants (Figure 3). Predicted backwind azimuths from the HURASIM model correlated with the wide spread of treefall azimuths for the northern right quadrant of the coastal transect and a possible outlier site for the eyewall zone of the inland transect. These results indicate that the primary cause of blowdowns and wind damage was applied during the initial approach of Hurricane Andrew. Predicted wind speeds for all quadrants exceeded 209 km h^{-1} or Category 4 winds that are more than sufficient to break and fell mangrove trees and forests (Doyle et al. 1995).

Predicted forewind azimuths for peak wind speeds derived from the HURASIM model were plotted against measured azimuths from both transects by quadrant groupings and tested for linearity (Figure 3). Except for the more variable spread of treefall azimuths across the right quadrant of the coastal transect ($r^2 = 0.053$; $P = 0.232$), all other correlations of observed and modeled windfall by quadrant corresponded well to HURASIM forewind predictions ($0.261 \leq r^2 \leq 0.753$; $P \leq 0.001$).

DISCUSSION

Hurricanes are large-scale climatic phenomena that cause landscape scale disturbance and are problematic for subsequent field investigations in remote natural areas. In this report, we investigate the landscape impact of Hurricane Andrew, an upgraded Category 5 storm (Landsea et al. 2004), which created massive wind damage across the larger expanse of the Everglades ecosytem in August of 1992. This study and others have documented the type and extent of forest disturbance to mangrove swamps that may leave a residual impact and imprint on the landscape for many years (Ogden 1992, Smith et al. 1994, Doyle et al. 1995). Ground studies following hurricane impact are usually hampered by lack of funding and logistics to collect data useful for landscape analysis. Aerial reconnaissance surveys following hurricanes are common, but are usually qualitative and not structured to relate hurricane wind speeds and trajectory to ecosystem response and recovery on a landscape basis. The lack of actual meteorological instruments in remote natural areas precludes the ability to relate hurricane conditions with damage observations without employing modeling capabilities. Aerial videography and a simulation model of hurricane meteorology have been blended to capture an understanding of the expression and extent to which hurricanes disturb natural landscapes.

Lugo et al. (1983) argued that, at a minimum, duration of hurricane winds and maximum sustained wind speeds should accompany forest damage assessments. Others have included additional hurricane descriptors, such as mortality of vegetation, structural impacts, and estimated peak wind gusts (Everham 1995, Myers and van Lear 1998). In the case of Hurricane Andrew, the maximum reported sustained winds were 232 km h^{-1} (Armentano et al. 1995), and the eyewall was over the Everglades landscape for at least 4 h (Platt et al. 2000) with peak wind gusts, probably associated with tornado activity, ranging from 253 to 333 km h^{-1} (Wakimoto and Black 1994). However, generalized descriptions of hurricane force are usually only well defined in populated areas and airports where instrumentation and post-hurricane damage assessments of homes and properties can be readily assessed. Models of hurricane wind fields are useful for field and modeling studies of natural systems by predicting the probable wind speeds and vectors of remote locations based on site position relative to hurricane trajectory and intensity (Gorham 1992, Boose et al. 1994, Doyle et al. 1995, Doyle and Gorham 1996, Doyle and Girod 1997).

Distance from storm center and the extent of the radius of maximum winds for a given storm determines to a large degree the wind force that is applied to a given location notwithstanding erratic downbursts and tornadoes. Landscape terrain and

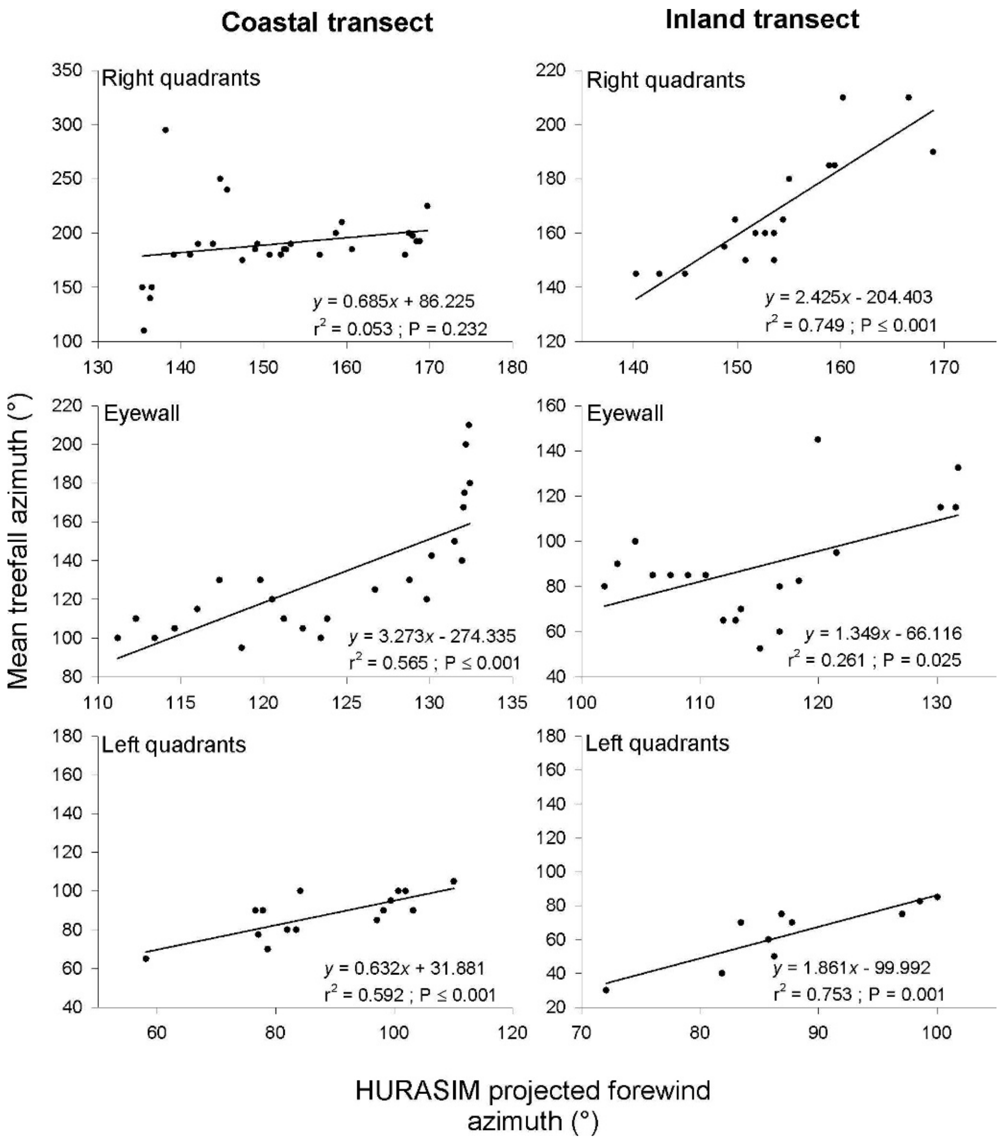

Figure 3. Projected forewind treefall azimuth (°) from HURASIM model simulations in relation to actual treefall azimuths (°) from aerial video images by transect and quadrant for Hurricane Andrew damage overflights.

vegetation features can also locally deflect wind force and direction whether from sustained or peak gusts, which can under or overestimate hurricane force, based solely on a report of maximum sustained wind speed. The strongest sustained wind speeds generally occur about the hurricane's eyewall (Jordon et al. 1960) and in the right-front quadrant of hurricane circulation where damage is also usually most severe (Shea and Gray 1973, Wakimoto and Black 1994). Landscape analysis of 250 forest sites (video frames), both coastal and inland, confirmed that the greater impact of more than 70% canopy displacement was concentrated along the eyepath and on the right side of the storm track encompassing the northern mangrove reaches of Everglades NP (see Figure 2). While this region is associated with maximum tornado activity and can spur the formation of unpredictable turbulent eddies from unpredictable directions (Novlan and Gray 1974), treefall directions corresponded tightly with predicted hurricane circulation. The strength of Hurricane Andrew likely caused treefalls prior to a given site reaching its maximum wind speed due to the susceptibility of mangroves to windfall of Category 3 wind force (177 km h^{-1}) (Doyle et al. 1995). The many islands and channels of the northern Everglades coastal margin created wind funnels that account for downed tree azimuths associated with unsheltered sites beside or at the terminus of open water bodies that were exposed and vulnerable at specific times during the forewind or backwind circulation (Doyle et al. 1995).

In addition, large wind gusts with greater destructive force typically last only a few seconds (Simpson and Riehl 1981, Savill 1983); at 10 m above the ground, these gusts can be larger than sustained wind estimates by 30% to 50% depending upon ground topography (Foster and Boose 1995). Craighead and Gilbert (1962), likewise, determined that hurricane wind velocities greater than 225 km h^{-1} must have occurred locally during the passage of Hurricane Donna over the Everglades in 1960; many 5-cm diameter trees were simply sheared off. The lack of orographic features and the low-relief of the Everglades are thought to account for the distinct landscape imprint of forest damage and treefall orientation observed in this study with the effects of initial forewinds mostly overriding the effects of other wind vortices. Although there was evidence of some backwind effects in video images, the range in this signature indicated that initial winds probably felled most trees directly and skewed the azimuth orientation of many of those trees remaining after forewind passage and resumption of backwinds.

Low-altitude photography and videography can provide a robust sampling approach to rapid and wide-area forest damage assessment in contrast to ground surveys. In this study, we arbitrarily chose to sample the video stream on an interval basis that provided a continuous record of rectangular video observations of forest cover on intervals at 0.8 km spacing. This approach provided nearly 250 still video frames to approximate damage extent, maximum tree height, and compass direction of felled trees along two belt transects. Data from ground studies serve as a complimentary adjunct to aerial observations due to the level of certainty and detail that can be used to groundtruth the forest's original condition prior to impact and to detail related species and size information. In contrast to the 120 ha of quadrat sampling in this study by video analysis, Doyle et al. (1995) established paired forest plots of 0.05 ha in size at 16 locations with replicate sites within the eyepath, right, and left quadrants of Andrew's path totaling less that 2 ha of sampled mangrove forest, or less than 2% of land area censused by videography.

The overall assessment of damage extent and pattern was similar between the video analysis of this study and published field studies with damage in the eye zone > right-side (northern) > left-side (southern) locations (Smith et al. 1994, Doyle et al. 1995). Field plots established in the eyepath zone of Hurricane Andrew exhibited woody basal area reductions of 50–100% (Doyle et al. 1995, McCoy et al. 1996); estimates of 70–100% damage from video image analysis fall within this range. However, damage assessments based solely on tree survival from ground observations were comparatively less overall and much more variable than assessed by video. A wider range of damage was observed from video assessments of left-side (southern) sites (0–70%) based upon greater coverage and broad damage categories than was reported for changes in basal area found in ground plots south of the eye zone (2–34% reduction in basal area). Likewise, the low estimates and high variability of damage assessment in ground plots within the right-side (northern) zone (1–51% reduction in basal area) were also evident but can be explained given the more northerly locations far outside Everglades NP (Doyle et al. 1995, Krauss et al. 2005). In contrast, the video assessment provides a survey of sites within the right-side quadrants more proximal to the eye zone within Everglades NP where damage was expectantly much greater (50–100% reduction in canopy structure) and more uniform across the region (see Figure 2). This result reiterates the value of stratified sampling by aerial videography that can fill the major spatial gaps in ground observations largely dictated by logistical difficulties of site access following hurricane impact.

Canopy displacement along the coastal transect was greater overall than observed on the inland transect (Figure 2). Plot-level field data revealed a similar pattern, with coastal islands and shoreline populations sustaining more damage because of increased wind exposure (Doyle et al. 1995). Although wave erosion uprooted some trees along the coastline and on some bay islands, in general, surge was not very important along the southwest coast of Florida except for depositing marine sediment into mangrove interiors, which may prove beneficial for forest recovery (Risi et al. 1995, Tedesco et al. 1995). Hence, most damage was wind-related (Smith et al. 1994, Doyle et al. 1995). In contrast, canopy displacement was moderate and more variable along the inland transect than on the coast, probably related to tree size and density of mangrove bordering on freshwater marsh/swamp habitat. One explanation for this pattern may be the lower stature of some of the mangrove forest communities encountered along the landward edge ecotone boundary. A statistical comparison of tree heights between the two transects is slightly misleading, since data only represent readily observable trees and do not always include the shorter trees along the ecotone (or taller trees along the coast) (Simard et al. 2006).

The vast coverage of aerial videography includes mangrove communities of all types, fringe and basin, dwarf and tall, different species, etc. that may limit data analysis and interpretation without further site characterization criteria (but see Jacobs et al. 1993). Much of the area covered by the inland transect did, in fact, include short mangrove forests. These sites and trees may be adapted to withstand high winds with less leaf area and retention strength, broad root zones for stability, or root penetration into shallow karst formations that may anchor them from direct windthrow by hurricane winds. Under normal intact forests, mangrove saplings with diameters of less than 5 cm demonstrated stem elasticity and wind sheltering from larger neighbors to withstand less than 10% mortality as a stem class (Smith et al. 1994). This result ties directly into other hurricane assessments that demonstrate a greater susceptibility of larger trees to wind throw (Putz and Sharitz 1991, Roth 1992, Doyle et al. 1995, McCoy et al. 1996) or to uproot rather than snap (Lugo et al. 1983, Walker 1991). Hence, damage is expected to be lower in scrub forests with a lower site quality based on reduced exposure, stature, and leaf cover.

Wide-area sampling using airborne videography improved our spatial understanding of how hurricanes imprint landscape-scale patterns of disturbance. Model simulations of the circulation and movement of Hurricane Andrew conformed to the general direction and non-random pattern of observed windthrow azimuths of trees. Windfall patterns indicated that most blowdowns were caused by forewind effects on the hurricane's approach, although some sites exhibited backwind effects. Treefall angles also indicated that felling occurred at critical wind speeds above 177 km h^{-1} prior to reaching site maximum wind speeds estimated up to 225 km h^{-1} for the western coastal margin of the Everglades. The spatial imprint and understanding of how hurricane winds and circulation influence forest damage can also be applied to conduct a retrospective analysis of disturbance history and how the sum condition of overlapping hurricane trajectories have influenced the type and structure of contemporary mangrove forests of the Everglades.

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