Identification of Structural and Spatial Features that Influence Storm-Related Dune Erosion along a Barrier-Island Ecosystem in the Gulf of Mexico

Alexander J. Pries*,†, Deborah L. Miller‡, and Lyn C. Branch†

*Department of Wildlife Ecology and Conservation
University of Florida
Gainesville, FL 32611-0430, U.S.A.
alex.pries@myfwc.com

†Department of Wildlife Ecology and Conservation
University of Florida
West Florida Research and Education Center
Milton, FL 32583-1713, U.S.A.

ABSTRACT


Observations of hurricane impacts on coastal communities and predicted increases in tropical storm activity have spurred an interest in protection and restoration of coastal dunes. Dunes are valued for their role in the protection of infrastructure and aesthetic beauty. Past research on dune erosion has focused primarily on laboratory research or mathematical models. We directly assessed impacts of Hurricanes Ivan (2004) and Dennis (2005) on coastal dunes along Santa Rosa Island, a barrier island in the Gulf of Mexico. We recorded dune area for foredunes and secondary dunes, examined the spatial context of each dune, and recorded structural features of each dune before and after each hurricane. Both hurricanes severely impacted foredunes, and removal of foredune protection by Ivan led to severe impacts on secondary dunes from Dennis. Structural features of the dune, such as height and width, influenced resistance against storm-related erosion, but spatial context, such as location with respect to shoreline, also was important. Coastal dunes on this barrier island may be shifting to a state where their formation, recovery, and restoration are influenced heavily by tropical storm activity. The future success of coastal restoration efforts for maintenance of infrastructure or habitat protection should be cognizant of the importance of spatial context in addition to the structural and vegetation characteristics of dunes.

ADDITIONAL INDEX WORDS: Storm impacts, hurricane, coastal restoration, dune recovery, coastal planning.

INTRODUCTION

Coastal dunes are valued for their aesthetic beauty and their ability to protect human-made structures during storms (NORDSTROM, LAMPE, and VANDEMARK, 2000; NORDSTROM and MITTEAGER, 2001). Because dunes absorb wave energy, block storm surge, and act as a sand reservoir, they reduce damage to infrastructure. Coastal dunes also are important as wildlife habitat (MARTINEZ, PSUTY, and LUBKE, 2005). In the last decade, tropical cyclones have dramatically altered coastal dune structure on barrier islands along the northern portion of the Gulf of Mexico (STONE et al., 2004). For example, 28 tropical cyclones of hurricane intensity passed within 125 miles of Santa Rosa Island, Florida, from 1886 to 1993 (NOAA, 2006), but sufficient storm surge to breach dunes did not occur for 48 years (1927 to 1975). Recently, storm surge from direct or near direct hits by category 3 (Saffir Simpson scale) hurricanes (1995 Hurricane Opal, 2004 Hurricane Ivan, and 2005 Hurricane Dennis) has repeatedly washed over the island, eliminating established dunes at multiple locations along the island's entire length. As a consequence, prioritizing protection and restoration of dunes has become an important issue in coastal management strategies (NORDSTROM, LAMPE, and VANDEMARK, 2000). Strategies for dune protection and restoration will benefit from information on physical and spatial factors that influence storm impacts on dunes.

The quantity of storm-generated dune erosion is a function of storm characteristics and dune structure. Dune erosion occurs when storm surge and waves repeatedly narrow a dune face, causing irregular slumping of sediment and an eventual breach, or when overtopping by storm surge completely overwashes a dune and pushes sediment landward (HESP, 2002; JUDGE, OVERTON, and FISHER, 2003). Although severity of surge and length of a storm influence dune erosion (KRIEBEL et al., 1997; SALLENGER, 2000), key structural features of dunes (e.g., height, width) also alter severity of dune erosion (JUDGE, OVERTON, and FISHER, 2003; MORTON and SALLENGER, 2003). Laboratory research and numerical models of dune evolution are extensive (Basco and Shin, 1999; BAUER and DAVIDSON-ARNETT, 2003; KRIEBEL and DEAN, 1985; LARSON, ERIKSON, and HANSON, 2004; VELLINGA, 1982), but few studies have quantified the importance of dune structure to storm-related erosion in the field (but see JUDGE,
OVERTON, and FISHER, 2003). Additionally, past evaluations of dune erosion often have been limited to foredune structures (i.e., dunes nearest to the high-tide line).

Coastal foredunes are formed from aeolian processes; dune development occurs where sediment is trapped by vegetation (HESP, 2004; PSUTY, 2005). Secondary dunes generally are found landward of foredunes and develop from sediment originating on foredunes or may be relict foredunes that are no longer controlled by aeolian processes (HESP, 2004). Foredunes are differentiated as either incipient or established. Incipient foredunes are low-lying developing dunes associated with pioneer plant communities. Established foredunes evolve from incipient dunes and are distinguished by presence of an intermediate plant community, including woody species. These dunes have greater height and width than incipient dunes (HESP, 2002). Although the location and development of incipient dunes may change annually, development of large established foredunes takes decades, and these dunes remain in a relatively fixed position unless removed by storms or anthropogenic disturbance. Evolution and maintenance of established foredunes are not determined solely by sediment flows but rather by a suite of additional factors like vegetation density and the frequency of wave and wind forces (HESP, 2004). Specialized coastal vegetation aids in poststorm recovery of dunes by quickly colonizing bare patches of sand or by growing into eroded dune faces. The establishment of these pioneer plants initiates a process of sediment trapping, which effectively returns dune morphology and shapes the plant community (HESP, 2002). In the absence of storm events, vegetation on foredunes shifts from a community dominated by sediment-trapping grasses and low-lying vines to one where shrubby species and other woody vegetation may exist (EIHENFELD, 1990).

Established foredunes and secondary dunes, by way of their size, should provide greater resistance to increased tide levels and storm events than incipient dunes. However, storm surge and waves associated with hurricanes of category 3 or above on the Saffir-Sampson scale can cause even large (>3 m tall) established foredunes to return to a more erosional form or to be destroyed (HESP, 2002). Effects of strong hurricanes on secondary dunes are less well documented. The impact of storm surge on secondary dunes may be less severe because these structures are no longer governed by sand exchange, storm tides, or wave activity associated with foredune development (HESP, 2004). Additionally, as a result of their spatial location behind wave-absorbing foredunes, dune erosion from storm events may be lower for secondary dunes.

We assessed dune erosion along a barrier island ecosystem in the Gulf of Mexico after Hurricane Ivan and again after Hurricane Dennis. The objectives were to examine impacts of these hurricanes on established foredunes and secondary dunes and to evaluate structural features of dunes as predictors of dune vulnerability for these two dune types. We also examined dune erosion as a function of landscape context, including island width at the location of the dune, distance to neighboring dunes, and distance of the dune from the position where the hurricanes passed over the island. Identification of structural features that allow dunes to resist storm-related erosion and evaluation of landscape attributes that influence erosion are important for developing priorities for dune protection and future manipulation of coastal dunes in a restoration context.

METHODS

Study Area

The study was conducted on Santa Rosa Island, Florida, a barrier island that is ~60 km long and 0.5 km wide, in the Gulf of Mexico. The study site is located on property owned and managed by Eglin Air Force Base (30°24’N, 81°37’W). This portion of the island is ~20 km long and includes the island’s entire width (Figure 1). This area contains several military structures and a paved road for military traffic but otherwise is undeveloped.

A thorough description of Santa Rosa Island’s geomorphology can be found in STONE et al. (2004). Foredunes are located near the high-tide line, and, in the absence of hurricane activity, they can run the continuous length of the island. Prior to Hurricane Opal (1995), mean dune height was 3.8 m (STONE et al., 2004). Foredunes are dominated by sea oats (Uniola paniculata), cakile (Cakile spp.), and seashore elder (Iva imbricata), but various woody species can be present on established foredunes in the absence of frequent disturbance. Secondary dunes are located behind foredunes on the bay side of the island. Woody species dominate these dunes, including false rosemary (Ceratiola eriodes), woody goldenrod (Chryso mic paccfolosulosa), scrubby oaks (Quercus geminata), and sand pine (Pinus clausa). Between these two types of dunes, grassland is dominated by maritime bluestem (Schizachrium maritimum) and bitter panic grass (Panicum amarum) interspersed with densely vegetated ephemeral wetlands.

Characteristics of the Hurricanes

Hurricane Ivan made landfall as a category 3 hurricane on 16 September 2004, west of Gulf Shores, Alabama, and ~100 km west of our study site. A highly organized storm with an eyewall diameter of 92 km, Ivan’s storm surge was estimated at 3–4.5 m from Mobile, Alabama, to Destin, Florida, which encompassed all of Santa Rosa Island (STEWART, 2005). Estimated storm tide at the study area from Ivan was ~3.1 m (WANG and MANAUSA, 2005). Historical tide information from a National Oceanic and Atmospheric Administration (NOAA) buoy located near Navarre Beach indicates that Ivan’s early morning landfall coincided with an incoming high tide. Tide levels near the study area during the landfall were estimated to be 0.17–0.47 m above the mean low water mark. Peak wind gusts near the study area were 144.8 km/h. Ivan was one of the most destructive hurricanes to make landfall along the Gulf coast in 100 years, and a majority of damage resulted from wave action associated with an unusually high storm surge (STEWART, 2005).

Hurricane Dennis made landfall as a strong category 2 hurricane on 10 July 2005, near Navarre Beach, Florida, ~10 km west of our study site. Though weakly organized compared to Ivan, Dennis produced a storm surge that was markedly higher than expected from surge model estimates (BEVEN, 2005). At
the study area, overwash deposits from Dennis moved sediment further landward than from Ivan. Storm surge was estimated at 1.8–2.2 m across Santa Rosa Island, and it washed over the island near Navarre Beach (Beven, 2005). Estimated storm tide throughout the study area was ≥3.7 m (Clark, 2006). Peak wind gusts near the study area were 194.3 km/h. Tide levels during Dennis’ landfall were estimated to be 0.06–0.35 m above the mean low water mark and falling.

Dune Mapping

Established dunes (foredunes, \( n = 93 \); secondary dunes, \( n = 484 \)) were delineated in the field after Hurricane Opal (1995). Because established dunes change very slowly over time, except when they are impacted by storms, these data could be used as a baseline for dune structure prior to Hurricane Ivan. Geographic locations of dune perimeters were recorded with a TRIMBLE global positioning system (GPS) unit in UTMs (Universal Transverse Mercator) and differentially corrected for <1 m accuracy. Dunes were included if they were greater than 1.0 m in height with woody vegetation or greater than 1.5 m in height with grasses or other herbaceous vegetation. Dunes were considered distinct if they were separated by more than 3.0 m of sand. Dune height (m) was measured every 15 m along the long axis of each dune using a telescoping pole. Dune perimeters were incorporated into ArcView 3.3 (ESRI, 1996), and the following variables were calculated: dune area (ha), dune width (perpendicular to the shoreline), length (parallel to the shoreline), and distance of each dune from the position where Hurricanes Ivan and Dennis made landfall. Coordinates for the position where Hurricanes Ivan and Dennis made landfall were obtained from the National Oceanic and Atmospheric Association (Beven, 2005; Stewart, 2005). Aerial photographs taken in 1995 were overlaid on dune location in ArcView to calculate island width at each dune location. We also recorded presence or absence of foredunes located seaward of secondary dunes before each hurricane. Gap distance for each dune was calculated as the average of the distance between the closest dunes located immediately to the west and east of the target dune.

After Hurricane Ivan, all remaining foredunes (\( n = 26 \)) were remapped or recorded as completely destroyed (100% loss) if not found during remapping (\( n = 67 \)). Because of the large number of secondary dunes, we randomly selected 61 large (≥0.25 ha) dunes and 34 small (<0.25 ha) secondary dunes to be remapped. After Hurricane Dennis, all remaining foredunes (\( n = 22 \)) and the same subset of secondary dunes sampled post-Ivan were remapped. The percentage of each
foredune or secondary dune lost from Hurricane Ivan was calculated by subtracting the dune’s area after Hurricane Ivan from the post-Opal dune area and dividing this value by the post-Opal dune area. The percentage of dune lost as a result of Hurricane Dennis was calculated by subtracting the dune’s area after Hurricane Dennis from the post-Ivan dune area and dividing this value by the post–Ivan dune area. Total percent loss in area for foredunes from each hurricane was calculated by subtracting total area of foredunes posthurricane from the prehurricane total area. Total percent loss in area for secondary dunes from each hurricane was determined by separately calculating the total percent loss of large and small secondary dunes and then calculating total percent loss in area using the proportional makeup of large and small secondary dunes on the landscape prior the hurricanes.

Statistical Analyses

Variables were examined for normality using a Shapiro-Wilks test prior to univariate tests. For all univariate tests, percentage of area lost was transformed using arcsine transformation, and dune area and dune height prior to the hurricanes and dune area after the hurricanes were transformed using log-transformation (Zar, 1998). Univariate tests were conducted in SPSS version 13.0 (SPSS INC., 2004).

Differences between foredunes (n = 93) and secondary dunes (n = 484) in dune area and dune height before the hurricanes were examined with t tests. The statistical significance of percent loss in mean dune area for foredunes with the impact of each hurricane was examined with paired t tests. The number of foredunes present before and after Ivan was too disparate to test for statistical differences in structural variables using values from all 93 foredunes present before Ivan. Thus, for the t-test comparisons of area, height, width, length, and gap distance between foredunes pre- and post-Hurricane Ivan, we randomly selected 26 foredunes from the 93 foredunes found before Ivan to compare with the 26 foredunes remaining after Ivan. Because only four foredunes were lost during Hurricane Dennis, a paired t test was used to compare structural variables of foredunes present before and after Dennis.

We used the proportion of the landscape occupied by large and small secondary dunes prior to Hurricane Ivan to determine the samples size for large and small dunes to be used in subsequent analyses. The total area of secondary dunes prior to Hurricane Ivan was 131.55 ha, where large dunes made up 109.99 ha (83.6%) of this total. To maintain this proportional area, we randomly selected 34 small secondary dunes and 18 large secondary dunes for inclusion in the analysis to describe dune loss and difference in structure of dunes remaining after each hurricane. Mean percent loss in area of secondary dunes with the impact of each hurricane was examined with paired t tests. Differences in the structural characteristics of secondary dunes after each hurricane also were compared with paired t tests. The difference in mean percent loss of dune area between secondary and foredunes was determined with t tests.

We used classification trees to simultaneously evaluate the influence of physical features and the spatial location of dunes on dune erosion. Classification trees explain variation in a single response variable by repeatedly splitting one or more predictor variable into homogeneous groups, which are then described by the mean value of the response variable, group size (n), and range of the explanatory variables defining it (De’ath and Fabricius, 2000). We used classification trees, as opposed to multivariate or cluster analysis, because our data contained a mixture of parametric and nonparametric variables. Trees do not require variables to fit a normal distribution and also can handle categorical or nominal data (Breiman et al., 1984). In contrast, traditional multiple regression techniques do not work well if variables do not meet parametric assumptions, predictor variables are not numerical, or when relationships between variables are complex or nonlinear (Bourg, McShea, and Gill, 2005). Classification trees also are simple to create, provide intuitive descriptions of complex relationships, and explain variance in a data set in a manner similar to multiple regression or analysis of variance procedures (De’ath and Fabricius, 2000).

We used the RPART package in R (Ihaka and Gentleman, 1996) to build and evaluate classification trees. Trees for foredunes were constructed with the percentage of dune area lost as the response variable and the following predictor variables: dune area (ha), dune width (m), dune height (m), island width (km), gap distance (m), and distance from where the eye of Hurricane Ivan or Dennis made landfall (km). For both Ivan and Dennis, all predictor variables used to explain storm-related dune erosion reflect conditions prior to the specific hurricane except distance from the eye of the hurricane (i.e., post-Ivan, pre-Dennis conditions predict storm-related erosion from Dennis). Classification trees for secondary dunes used the same response and predictor variables as the trees for foredunes but also included presence or absence of a foredune before Ivan or Dennis. We used a cross-validation procedure to evaluate the rate of misclassification as a function of tree size (e.g., number of groupings) to select trees that were not over-fit (Breiman et al., 1984).

RESULTS

Dune Structure and Configuration before Hurricane Ivan

Before Hurricane Ivan, small dunes (<0.25 ha) comprised 80 of the 93 (86.1%) foredunes and 403 of the 484 (83.3%) secondary dunes. On average, individual secondary dunes were larger in area but not taller than foredunes (dune area, t = −2.265, DF = 575, p < 0.05; dune height, t = 1.020, DF = 575, p > 0.10; Table 1).

Hurricane Impacts on Foredunes and Secondary Dunes

Mean area of foredunes and secondary dunes was reduced significantly by Hurricane Ivan (foredunes, t = 5.160, DF = 92, p < 0.01; secondary dunes, t = 3.67, DF = 51, p < 0.01; Table 1). Hurricane Ivan’s storm surge physically removed 71.9% of the total foredune area (Table 1). Of the original 93 foredunes measured, 67 were destroyed. Based on proportion of area occupied by small and large dunes on the pre-Ivan landscape, total
Table 1. Means and standard errors for structural variables measured to explain dune erosion in foredunes and secondary dunes on Santa Rosa Island from Hurricanes Ivan and Dennis. Differences between means before and after hurricanes were compared using two-sample t tests for foredunes and paired t tests for secondary dunes adjusted with Bonferroni’s correction for multiple tests; ** indicates p < 0.05 after Ivan; *** indicates p < 0.05 after Dennis.

<table>
<thead>
<tr>
<th>Variable†</th>
<th>Foredunes Before Ivan (n = 93)</th>
<th>Foredunes After Ivan (n = 26)</th>
<th>Secondary Dunes§ Before Ivan (n = 52)</th>
<th>Secondary Dunes§ After Ivan (n = 48)</th>
<th>After Dennis (n = 48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area (ha)</td>
<td>12.34 (7.3)</td>
<td>3.46 (2.6)</td>
<td>19.32 (5.5)</td>
<td>13.66 (5.1)</td>
<td>12.51 (5.1)</td>
</tr>
<tr>
<td>Dune area (ha)</td>
<td>0.14 (0.03)</td>
<td>0.15 (0.06)</td>
<td>0.13 (0.03)</td>
<td>0.12 (0.03)</td>
<td>0.37 (0.09)</td>
</tr>
<tr>
<td>Dune height (m)</td>
<td>2.84 (0.15)</td>
<td>2.67 (0.29)</td>
<td>3.17 (0.20)</td>
<td>1.62 (0.16)</td>
<td>3.28 (0.18)</td>
</tr>
<tr>
<td>Dune length (m)</td>
<td>42.2 (5.8)</td>
<td>44.8 (14.6)</td>
<td>42.9 (7.5)</td>
<td>39.4 (7.0)</td>
<td>39.4 (7.0)</td>
</tr>
<tr>
<td>Dune width (m)</td>
<td>29.9 (2.6)</td>
<td>28.4 (4.5)</td>
<td>38.0 (4.6)</td>
<td>38.1 (6.2)</td>
<td>56.6 (6.2)</td>
</tr>
<tr>
<td>Gap distance (m)</td>
<td>95.6 (25.9)</td>
<td>30.7 (5.9)</td>
<td>188.8 (25.1)</td>
<td>321.8 (70.9)</td>
<td>50.8 (6.8)</td>
</tr>
</tbody>
</table>

† All values presented here, except for total area, represent the mean value for that particular variable.
‡ Dunes were subsampled to represent proportional area of large (83.6%) and small (16.4%) dunes on the landscape (n = 52, with 34 small dunes and 18 large dunes).
§ Twenty-six dunes were selected randomly from the original 93 dunes mapped in order to equalize the sample size for pre- and posthurricane measurements.

estimated loss of secondary dune area with Hurricane Ivan was 19.3%. The 34 small secondary dunes sampled lost 42.1% of their total area. The 61 large dunes lost 14.8% of total area. Mean loss of area for foredunes was significantly greater than mean loss of area for secondary dunes (t = −9.953, DF = 143, p < 0.01). Because narrow, short foredunes were removed by Ivan, the remaining foredunes were wider (t = −1.96, DF = 50, p = 0.05) and taller (t = 2.03, DF = 50, p < 0.05) than pre-Ivan foredunes but similar in area (t = 1.68, DF = 50, p > 0.10) and length (t = 1.27, DF = 50, p > 0.05) to pre-Ivan foredunes (Table 1). Secondary dunes remaining after Ivan were smaller in area (t = 2.63, DF = 51, p < 0.05), height (t = 6.04, DF = 51, p < 0.01), and width (t = 3.82, DF = 51, p < 0.01) compared to pre-Ivan secondary dunes (Table 1). Gap distance between dunes was much larger after Hurricane Ivan for both foredunes and secondary dunes (t = 5.33, DF = 51, p < 0.01) (Table 1).

Hurricane Dennis further significantly reduced mean area of foredunes and secondary dunes (foredunes, t = 3.57, DF = 21, p < 0.01; secondary dunes, t = 8.77, DF = 51, p < 0.01). Storm surge removed 24.9% of the total foredune area and completely destroyed four dunes. Based on proportional area occupied by small and large dunes on the landscape before Ivan, total loss of secondary dunes was 11.49%. Small secondary dunes lost 20.1% of their total area, and four dunes were no longer present. Large secondary dunes lost 9.8% of their total area. In contrast to the pattern observed with Hurricane Ivan, storm-related mean loss of area for secondary dunes from Hurricane Dennis was not significantly different than that of foredunes (t = 1.05, DF = 76, p > 0.10). Mean percent loss in dune area for secondary dunes from Dennis was similar to Ivan (x_{dune} = 49.1%, SE = 6.2; x_{iv} = 64.0%, SE = 4.9; t = 1.89, DF = 102, p > 0.05). Foredunes remaining after Dennis were significantly smaller in height (t = 5.22, DF = 47, p < 0.01) and length (t = 2.09, DF = 47, p < 0.05) but not width (t = 2.00, DF = 47, p > 0.05) compared to pre-Dennis (post-Ivan) foredunes (Table 1). Gap distance between foredunes also increased significantly with Hurricane Dennis (t = 2.66, DF = 47, p < 0.05). Secondary dunes remaining after Dennis were smaller in area (t = 3.16, DF = 47, p < 0.01), length (t = 4.93, DF = 47, p < 0.01), and width (t = 2.16, DF = 47, p < 0.05) compared to pre-Dennis (post-Ivan) secondary dunes (Table 1). Height of secondary dunes was not measured.

Classification Trees

Cross validation indicated that the smallest classification trees to fit data from foredunes and secondary dunes after Ivan without an increase in misclassification error rate had five branches (Figures 2a–b). The classification error plot for foredunes after Hurricane Dennis (Figure 2c) revealed that any split of the data into branches would not aid in describing storm-related erosion; hence, creation of a classification tree would not be informative, and we did not create one to explain foredune erosion from Hurricane Dennis. Cross validation for secondary dunes after Hurricane Dennis indicated that the smallest classification tree to fit the data had four branches (Figure 2d).

The classification trees indicated that both structural features and spatial context were important in determining dune erosion during Hurricane Ivan for dunes on the oceanfront and bay side of the island (Figure 3). Percent of dune loss for foredunes after Ivan was related to the distance from landfall of the eye of Ivan and to the height and width of the dunes prior to Hurricane Ivan (Figure 3a). These three variables explained 78.9% of the variance (R²) in dune erosion. At distances greater than 114 km from where the eye of the hurricane made landfall, dune height was the most important structural feature determining dune loss. At closer distances, dune width was most important. Narrower and shorter dunes experienced the greatest erosion.

The classification tree for secondary dunes sampled to represent proportional area of small and large dunes on the landscape indicated that dune erosion of secondary dunes from Ivan was related to structural features of the dune, their position on the landscape, and the presence of foredunes (Figure 3b). This
Figure 2. Cross validation relative error for classification trees for (a) foredunes after Ivan, (b) secondary dunes after Ivan, (c) foredunes after Dennis, and (d) secondary dunes after Dennis to explain dune loss from hurricanes in relation to measured predictor variables. We used the one standard error rule (Breiman et al., 1984) to identify regression trees that had the smallest number of branches but were closest to the overall minimum misclassification error (dotted line). The figure indicates that no tree should be created with foredune data after Hurricane Dennis. Arrows point to the best-sized regression tree for each dune type. The complexity parameter, cp, is a balance between the complexity of a tree (i.e., more branches) and the costs of utilizing a simpler tree.

Figure 3. Classification trees relating percentage of dune lost from Hurricane Ivan for (a) foredunes (n = 93) and (b) secondary dunes (n = 52) to physical features of dunes, spatial location of dunes with respect to where Hurricane Ivan made landfall, and width of island. Data for secondary dunes are based on sampling of small (≤0.25 ha) and large dunes (>0.25 ha) according to their proportional area on the landscape. Numbers at the ends of terminal nodes are the average percentage of dune lost for all observations in that group; n is the number of observations within that group.

Figure 4. Classification tree relating percentage of dune lost from Hurricane Dennis for secondary dunes (n = 52) to physical features of dunes, spatial location of dunes with respect to where Hurricane Dennis made landfall, and width of island. Data for secondary dunes are based on sampling of small (<0.25 ha) and large dunes (≥0.25 ha) according to their proportional area on the landscape. Numbers at the ends of terminal nodes are the average percentage of dune lost for all observations in that group; n is the number of observations within that group.

tree explained 76.3% of the variance in dune erosion for secondary dunes. For wider dunes, the presence or absence of a foredune was important in determining dune erosion. Dune erosion was lowest where foredunes were present. Where foredunes were absent, dune erosion increased with distance from where Hurricane Ivan made landfall. For narrow secondary dunes, island width was the only important factor influencing dune erosion. Erosion of secondary dunes was greater where the island was wide. Island width and distance from where Hurricane Ivan made landfall are correlated (r = 0.46) and, thus, may provide some of the same information.

Dune width (post-Ivan) influenced storm-related erosion of secondary dunes from Hurricane Dennis (Figure 4). Wider dunes larger than 0.07 ha experienced the least amount of erosion, and narrow and long dunes ≤0.006 ha experienced the highest erosion. This classification tree explained 65.2% of the variance in dune erosion for selected secondary dunes.

**DISCUSSION**

This field study and mechanistic research in the laboratory indicate that dune structure plays an important role in resistance of dunes to storm damage. In addition, this study clearly demonstrates the influence of landscape context of dunes on their vulnerability to erosion, including spatial lo-
cation relative to a hurricane’s eye and presence of other dune structures. The current trend of increased severity and frequency of tropical cyclones is predicted to continue, which will further modify dune configuration, reduce infrastructure protection, and disturb wildlife habitat (EMANUEL, 2005). Hence, identification of features that promote resistance to storm-related erosion can aid agencies in the classification of coastal areas that are especially vulnerable to future storm events. This information also can assist in defining targets for coastal restoration.

Wider dunes on Santa Rosa Island experienced less erosion than narrower dunes from Hurricane Ivan and Dennis. However, the importance of location on the landscape and the structural features of dunes that were important when describing the variation in erosion were different for foredunes and secondary dunes. This suggests that the processes that act upon dunes during storms differ with distance landward from the shoreline. Much of the erosion of foredunes probably was a result of storm surge from incoming wave action. Foredunes that remained after both hurricanes showed signs of sediment slumping, dead or uprooted vegetation, and blowouts, all of which are common effects of storm surge, wave action, and overwash. Under these conditions, height of a dune is likely to play a key role in resistance of dunes to erosion, as demonstrated by the importance of this variable in our classification trees for foredunes and from previous research on storm impacts on barrier islands. Foredunes are eroded by collision or overwash regimes, depending on the relationship between storm surge and dune height. Overwash regimes (and further sediment movement) occur when storm surge is greater than the foredune ridge’s maximal height (SALLENGER, 2000). Along exposed oceanfront beaches, the magnitude of storm surge and wave action decreases with distance from the edge of the hurricane’s eyewall; damage to foredunes on Santa Rosa Island followed a similar spatial pattern.

Secondary dunes on the island lost sediment along dune edges from passing storm surge. Because of their position further inland, these dunes may not have been subjected to continual wave action (BROWN and MCLACHLIN, 1990). Dune erosion of secondary dunes is likely influenced by storm surge from the Gulf of Mexico merging with rising water levels in the Santa Rosa Sound, located between the island and the mainland. Foredunes substantially reduced erosion of secondary dunes, in particular that of large dunes during the higher storm surge of Ivan. This observation reinforces the importance of foredunes as buffers of storm surge for coastal features located further landward and for protection of human-made structures.

One nonintuitive result of this research is that secondary dunes located farther from the eye of the hurricane and on the widest part of the island were eroded more than secondary dunes located closer to the eye of Hurricane Ivan and on the narrower part of the island. Storm damage on secondary dunes increased from west to east. The island widens from west to east, and the Santa Rosa Sound narrows as the island widens. We hypothesize that the magnitude of storm surge on the bay side of the island increased as the sound became more narrow and secondary dunes were impacted more strongly, resulting in an inverse relationship between storm damage and distance from the hurricane and an inverse relationship between storm damage and island width. When the flow of storm surge is confined and water is shallow, as in the case of Santa Rosa Sound, high penetration distances have been observed for overwash during other storm events (MORTON and SALLENGER, 2003).

Previous research on coastal dunes has suggested that dune systems exist in two opposing states: one where dune structure and vegetation communities are arranged by environmental gradients generated from normal wind and wave activity and one dominated by periodic but high levels of disturbance (e.g., hurricanes and tropical storms; SNYDER and BOSS, 2002; STALLINS and PARKER, 2003). We believe that coastal dunes on Santa Rosa Island are beginning to shift toward a state where dune structure and vegetation are controlled by frequent overwash, though assessment of dune erosion and plant recovery after additional storms is needed to evaluate this statement. Prior to Hurricane Opal in 1995, the island’s shoreline contained continuous foredunes with woody vegetation on many dune crests (STONE et al., 2004). Repeated hurricane activity and exposure to multiple storm impact regimes (SALLENGER, 2000) have influenced the presence and structure of the remaining foredunes. Furthermore, our analysis indicates that foredunes are important in protecting...
secondary dunes, and further storms may impact secondary dunes more severely (Figure 5). As evidenced of this effect, foredunes were eroded more than secondary dunes with Hurricane Ivan. This reduction in foredunes reduced resistance of secondary dunes to future storm surge. The reduced foredunes experienced more overwash during Dennis and allowed water (and sediments) to flow further landward. Erosion to secondary dunes from Dennis was similar to the erosion experienced from Ivan, largely because of the loss of protective foredunes. Ten years after Hurricane Opal, overwash sites contained embryonic dune fields of ~2 m (Miller, unpublished data). These embryonic dunes were reestablished through the sand trapping of perennial grasses. However, colonization by woody vegetation was lacking, and these dunes were again reduced in height and vegetative cover by overwash from Hurricanes Ivan and Dennis. The consequences of this changing coastal landscape are large for maintenance of human-developed infrastructure, success of restoration projects, and conservation of wildlife species that depend on coastal dune habitat.

ACKNOWLEDGMENTS

We thank T. Alvarez, C. Hardin, M. Schneider, and L. Young for assistance with field work. Logistic support was provided by Eglin Air Force Base, and funding was provided by Gulf Islands National Seashore and the University of Florida. We especially thank B. Hagedorn and R. Hoggard for their support.

LITERATURE CITED


Journal of Coastal Research, Vol. 24, No. 4C (Supplement), 2008