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The Effects of Coastal Dune Volume and Vegetation on Storm-Induced Property Damage: Analysis from Hurricane Ike

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ABSTRACT

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In response to numerous recent high-profile cases of tropical storm and hurricane damage to coastal communities, there has been increasing attention on the storm protection services provided by coastal ecosystems. However, substantial knowledge gaps exist regarding the quantitative economic benefits of such services, particularly for coastal vegetated dune ecosystems. A novel geographic information system (GIS)-based technique for delineating, quantifying, and relating coastal dune volume, vegetation area, and geographic and built-environment covariates to sustained property damage was used for the upper Texas coast following Hurricane Ike in 2008. The multivariate regression analysis contained more than 1000 homes spanning both sides of the storm's path. Dune volume and vegetation were both significantly related to reduced sustained property damage for the west side of the storm. For this area, model results showed that dune sediment was worth roughly \$50 per cubic meter and dune vegetation was worth roughly \$140 per square meter. However, because these variables were collinear and modeled separately, these amounts should not be viewed additively. The total property damage offset value of dunes across the study area was estimated to be more than \$8 million, or approximately \$8200 per homeowner. Based on the frequency of storms for this area over the last 115 years, coastal vegetated dunes were valued at roughly \$86,000 per hectare per year. The results indicate that dunes could play an integral role in coastal hazard mitigation strategies and offer a unique opportunity where bioengineered, green infrastructure can be used as an alternative to hard coastal structures.

ADDITIONAL INDEX WORDS: *Erosion, economic, ecosystem, hazard, mitigation, Texas, Galveston, Bolivar, GIS, geographic information system.*

INTRODUCTION

Hurricanes and tropical storms inflict a massive economic and social strain on coastal communities worldwide. In the United States alone, hurricane damage has totaled to roughly \$10 billion per year (normalized) over the last century (Pielke *et al*., 2008). As largely a consequence of coastal development and population growth, the last two decades have brought about the costliest storms in U.S. history (Blake, Landsea, and Gibney, 2011; Hurricane Research Division Staff, 2014). Coastal barriers and other structural flood mitigation strategies (*e.g*., sea walls, levees, and floodgates) can reduce this storm-induced economic strain, though often with large financial and environmental costs (Long *et al*., 2011; Pilkey and Wright, 1988). Because of these large costs, nonstructural hazard mitigation strategies have gained traction. Typical nonstructural mitigation strategies include property buyouts, land use controls, flood insurance, and building codes (Brody, Highfield, and Kang, 2011; Burby, 1985, 1998; Highfield, Norman, and Brody, 2013; Larson and Plasencia, 2001; White, 1945), but these strategies can be countered by the market forces that drive coastal development (Highfield, Peacock, and Van Zandt, 2014). As a complement to these nonstructural mitigation plans aimed at modifying the built environment, conservation and restoration of coastal ecosystems and the storm damage mitigation services they provide should be a major focus of coastal planning (Costanza, Mitsch, and Day, 2006). The purpose of this study was to determine the storm damage mitigation benefits of one such ecosystem: vegetated coastal sand dunes.

Coastal ecosystems, such as marshes (Yang *et al*., 2012; Ysebaert *et al*., 2011), mangroves (Thampanya *et al*., 2006), kelp beds (Løvås and Tørum, 2001), and reefs (La Peyre *et al*., 2014; Piazza, Banks, and La Peyre, 2005), can attenuate wave energy, affecting shoreline erosion in the process (Coops *et al*., 1996; Feagin *et al*., 2009). Most research on this topic shows the capabilities of coastal ecosystems in dissipating wave energy under normal circumstances, likely affecting long-term accre-

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tion and erosion. However, the ecosystem's ability to actively reduce wave and surge impact on coastal human communities during extreme conditions is debatable (Cochard *et al*., 2008; Feagin *et al*., 2008, 2015; Gedan *et al*., 2011; Wamsley *et al*., 2010). Furthermore, it can be difficult to test such extreme conditions in either field or lab experiments because of the complexity of natural systems and the magnitudes of the storm conditions (*e.g*., surge and wave heights and wind speeds). Therefore, indirect analyses based on pre- and poststorm data are a practical way to determine the impact of these ecosystems during extreme storm events. Costanza *et al*. (2008) used multivariate regression to relate prestorm marsh area in the wake of a hurricane (and other covariates such as wind speed and local gross domestic product) with economic damage using multiple storms as data points. Such multivariate analyses provide insight for coastal conservation and management because they give a tangible economic perspective for coastal ecosystem services. In the wake of Hurricane (Superstorm) Sandy in 2012, the storm protection capacity of coastal sand dune ecosystems has been increasingly discussed in scientific literature and mainstream media (Barone, McKenna, and Farrell, 2014; Elko *et al*., 2016; Navarro, 2012). However, no research uses flood damage data to empirically assess dune worth in terms of storm damage mitigation.

Dunes form a concentrated buffer zone along a coastline that likely protects homes close to the dune system against extreme surge and wave conditions. Two main spatial features of a dune could affect its storm protection capabilities. The first feature is the geometry (volume, crest elevation, slope, *etc*.) of the dune, for example, as outlined in the U.S. Federal Emergency Management Agency (FEMA) 540 Rule (FEMA, 1988; MacArthur *et al*., 2005). Dunes erode as they are exposed to storm surges and waves, protecting landward homes against hazardous conditions in the progress. The larger volume of sediment that the dune buffer possesses, the longer it takes to erode and likely the greater protection it provides. The second feature is texture, with regards to both the surface and the substrate of the dune (*e.g*., vegetation and substrate properties). Vegetation likely plays a prominent role in this context, in which above-ground structures (*e.g*., stems, trunks, leaves, and branches) could attenuate wave energy in a similar manner as other coastal vegetation (*e.g*., Yang *et al*., 2012; Ysebaert *et al*., 2011) and belowground aspects (*e.g*., roots and microbial-driven processes) could play a role in dune sediment stability and erosion resistance (Feagin *et al*., 2015; Figlus *et al*., 2014; Sigren, Figlus, and Armitage, 2014; Silva *et al*., 2016). Therefore, a dune system with more vegetation could offer more protection than a dune system with less vegetation.

The overall goal was to use the prestorm parameters of dune systems (both vegetation and sediment volume) and poststorm flood insurance claims to quantify the economic effects of coastal dunes on storm-induced property damage. Other built and geographic covariates were also analyzed in this multivariate regression. Dunes are garnering attention in the wake of recent hurricanes, but rigorous economic evaluation will be a crucial part of providing justification to use dunes in storm damage mitigation strategies.

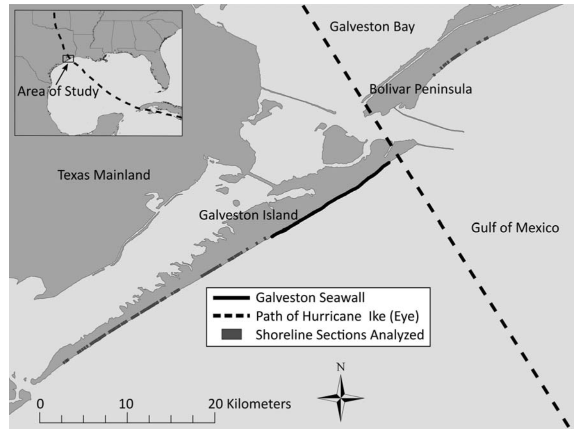

Figure 1. Location map of the study area. The path of Hurricane Ike split the regions of Bolivar Peninsula and Galveston Island. Homes that were protected by the Galveston Seawall were not included in this analysis.

METHODS

The overarching approach to evaluate the storm protection value of vegetated sand dunes was to apply multivariate regression to relate prestorm ecological, built, and geographic variables to the sustained flood damage of homes.

Storm and Area of Study

Hurricane Ike made landfall on September 10, 2008, between Galveston Island (hereafter called Galveston) and Bolivar Peninsula (hereafter called Bolivar) on the Texas coast (Figure 1). It was an uncharacteristically broad category 2 storm with at least some surge encountered along most of the Gulf of Mexico shorelines. It directly caused 12 fatalities in the United States and roughly $27.5 billion in damage to the Texas and Louisiana coastlines (Berg, 2009; DeBlasio, 2008). Offshore significant wave heights ($H_{1/3}$) up to 6 m were recorded by National Oceanic and Atmospheric Administration (NOAA) buoys moored off the Texas coast (Doran *et al*., 2009). The east side of the hurricane affected Bolivar and had higher wind speeds and more severe surge and wave conditions. This increased severity is partly because of counterclockwise rotation of the hurricane wind field, with predominantly onshore-directed winds east of the eye and offshore-directed winds west of the eye at landfall. Sustained wind speeds on Bolivar were between 130 and 148 km/h, while sustained wind speeds on the west end of Galveston were between 120 and 130 km/h (Overpeck, 2009). The surge affecting Bolivar was roughly one-third higher than the surge for Galveston (3.5 m at the west end of Galveston and nearly 5 m on Bolivar; Houston and Galveston, TX, Weather Forecast Office Staff, 2008; Sebastian *et al*., 2014). The surge and waves from Hurricane Ike affected coastal dunes and the many landward structurally elevated communities located on west Galveston and Bolivar. The surge also affected areas of the city of Galveston that were protected by the Galveston Seawall, but these areas are not bordered by dune structures and therefore were not included in this analysis.

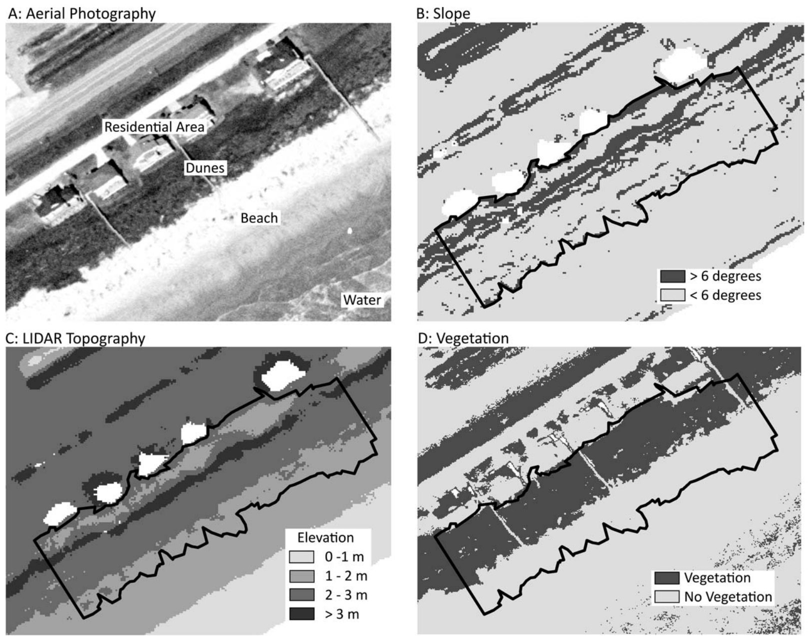

Figure 2. Illustration of the dune delineation mechanism and quantification of vegetation and topographic parameters. (A) Aerial photography for a typical upper Texas coast shoreline. (B) The 6° threshold delineation (black line) based on the LIDAR-generated topography data in (C). (D) Location of vegetation based on a simple spectral analysis of aerial photography.

Data Sources and Assembly

ArcMap 10.1 was used for all spatial data development and manipulation. Shoreline blocks were defined as 300 m cross-shore by 200 m alongshore sections; 78 blocks (65 on Galveston and 13 on Bolivar) containing 1030 homes (878 on Galveston and 152 on Bolivar) were created in total (Figure 1). Blocks were separated by a buffer of more than 40 m to promote the independence of samples in different blocks. Because homes along the study area were distributed in clusters of small communities, randomizing block locations along the entire stretch of coastline was not practical. Rather, blocks were defined specifically in representative residential areas with the intention of including as many homes as possible in the analysis. Of all potential homes within 300 m of the water's edge along this stretch of coastline, more than 70% were included in this analysis (those excluded fell between gaps in the shoreline blocks). Dune regions within blocks were defined by shoreline slope, which was calculated from LIDAR data using ArcMap's slope function. The beach and nearshore along Galveston and Bolivar have shallow slopes, ranging between 1/50 to 1/30, typically creating an upward angle between 1.14° and 1.91° (Morton and Paine, 1985). Therefore, a spatially continuous line of topography that exceeded a threshold of 6° was used to distinguish coastal dunes from the beach and shore (Figure 2). The 6° threshold ensured that all shoreline blocks possessed some dune volume and vegetation quantity, even if they only contained shallow-sloped embryonic dunes.

Several ecological, built-environment, and geographic variables for each block or home were evaluated for relation to the predicted variable: dollar value of residential structural damage sustained during Hurricane Ike (log transformed). Data on property damage were obtained from National Flood Insurance Program claims from FEMA after Hurricane Ike. The ecological predictor variables were dune sediment volume and vegetated area and were determined using 2006 LIDAR data and spectral analysis of 2006 aerial photography (Aerials Express Staff, 2006; Office of Coastal Management Staff, 2007); this process is shown in Figure 2. Though these data sources were collected 2 years before Hurricane Ike, they were the temporally closest LIDAR and aerial photography datasets available for the region. Furthermore, there were no major storm events in this 2-year period before Hurricane Ike, meaning that dune parameters were unlikely to change drastically. A simple spectral threshold was used for the aerial photography dataset to distinguish vegetated areas from whitish sand. Minor interference can be seen on some darker rooftops and out in the surf zone (Figure 2D), but such areas were manually excluded from the dune boundaries. The built predictor variables of home structure value and age were obtained from the Galveston County Appraisal District. The geographic predictor variables were home distance from the shoreline and from the eye of Hurricane Ike at landfall and were calculated in ArcMap 10.1.

Statistical Analysis

A backward, stepwise, multivariate regression analysis was used to identify significant ecological, built-environment, and geographic predictors of the dollar value of residential structural storm damage. A Chow test was applied to determine that Galveston and Bolivar should be modeled separately because surge, wave, and wind conditions were different for each area. It is likely that dunes reduce surge and wave damage to homes close to the shoreline, but it is not known how far from a shoreline this protection extends. Therefore, multiple Chow tests were used to assess whether different quartile zones of Galveston, organized by distance from the shoreline, could be modeled separately. This provided insight into which homes were most affected by dunes and the limit of a dune's landward influence across a coastline. Bolivar was not divided into quartile shoreline zones because it had fewer homes (152) and blocks (13) compared to Galveston (878 homes and 65 blocks). Lastly, hierarchal partitioning, a statistical technique that evaluates each predictor variable's average independent contribution to r^2 based on every possible model (Chevan and Sutherland, 1991; Walsh and Mac Nally, 2013), was used to identify the variables that explained the most variability in the predicted variable for all models.

The modeling technique used for this analysis contains two distinct sample sizes for different variables. Because dune ecological variables (dune vegetation and volume) could only be quantified by shoreline block, their sample size is the same as the total number of shoreline blocks (65 for Galveston, 13 for Bolivar). To maintain variation among the built and geographic variables (*i.e.* retain values for each home for these variables to maximize the power of the analysis), observations were not aggregated by shoreline block but were analyzed at the level of homes (878 for Galveston and 152 for Bolivar). In other words, each home had a specific value for built (home age and property value) and geographic (shoreline setback distance and distance from the eye of the storm) variables but shared values with other homes within their block for ecological (dune volume and vegetation area) variables. To compensate for the intrablock correlations and redundancies in the dataset, robust standard errors were clustered by shoreline block (Huber, 1967; Zeileis, 2004).

The value of the dune ecosystems in terms of storm damage mitigation was estimated using the principle of log-linear model semielasticity. This technique approximates the average per unit value of dune ecosystem variables based on the derivative of the model's equation with respect to a dune variable (Wooldridge, 2000). However, because the model's semielasticity operates at the level of homes, per unit values obtained by this technique were reaggregated by shoreline block and averaged:

$$DV = \frac{\sum_{x=1}^{n_s}\left(\sum_{i=1}^{n_{hx}}(\beta_d * y_{ix})\right)}{n_s} \tag{1}$$

where,

DV = per unit value of a dune variable
β_d = coefficient of a dune variable
y_{ix} = property damage sustained by home i in shoreline block x
n_{hx} = number of homes within shoreline block x
n_s = total number of shoreline blocks

This valuation methodology equates to the average amount of damage reduction brought about by a unit change of a dune variable (*i.e.* adding a cubic meter of sediment or a square meter of vegetation before the storm), roughly being the equivalent of the value of investment in dunes.

For the total value of all dunes within the study area, two model states were compared. In the first state, existing prestorm dune values were used to compute the total expected damage:

$$TEPD = \sum_{i=1}^{n} e^{(\beta_1 V_{1i} + \beta_2 V_{2i} + \ldots + \beta_D V_{Di})} \tag{2}$$

where,

$TEPD$ = total expected property damage
V_{1i} = value corresponding to a home for the model's first significant predictor variable
β_1 = slope of the first significant predictor variable of the model
V_{Di} = value of a dune-related variable (*e.g.*, dune vegetation area or sediment volume) for a given home
β_D = slope of dune variable V_D
n = total number of homes analyzed

The property damage dataset was log transformed, hence the exponential formulation. In the second state, a model was again evaluated but with a minimal dune size value rather than the actual value:

$$TEPDwD = \sum_{i=1}^{n} e^{(\beta_1 V_{1i} + \beta_2 V_{2i} + \ldots + \beta_D V_{Dm})} \tag{3}$$

where,

$TEPDwD$ = total expected property damage without dunes
V_{Dm} = minimal dune value for the study area

The difference between these two states is the predicted total damage mitigated by the presence of dunes for the study area:

$$\text{Total Storm Mitigation Value of Dunes} = TMV = TEPD - TEPDwD \tag{4}$$

In other words, if all dunes had been removed (or reduced to a minimal state) before the storm, how much more damage would have been sustained? This value could then be divided by the total number of homes for an estimate of dune worth to the average homeowner. All dollar values mentioned throughout this paper were converted to 2015 U.S. dollars (using the Bureau of Labor Statistics Consumer Price Index Inflation Calculator). Additional details on methodological techniques can be found in Sigren *et al*. (2015).

RESULTS

Dune vegetation area and dune sediment volume were highly collinear (Figure 3). Therefore, for the purpose of value calculations, these dune variables were modeled separately. A structural break in the dataset occurred along the lines of E-W orientation to the eye of Hurricane Ike (Chow test, $p < 0.001$). Therefore, homes on Galveston and Bolivar were modeled separately, creating four distinct models, which are summarized in Table 1. Table 1 shows the slope coefficient of significant predictor variables as related to the predicted variable: log-transformed dollar value of residential structural

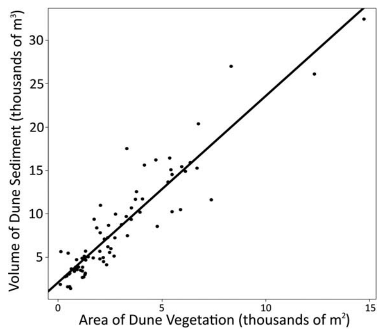

Figure 3. Regression plot showing the highly collinear nature of the dune predictor variables: volume of sediment contained in a dune and area of vegetation growing on the dune.

damage (hereafter, when reference is made to home damage, it is in this sense). Significance of a given slope coefficient is noted by an asterisk, and standard error is noted in parentheses. Negative slopes indicate that sustained flood damage is reduced by an increase of a given variable, the opposite for a positive slope. In addition, r^2, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC) are reported as goodness-of-fit measures. Lastly, pie charts indicate each variable's individual percentage contribution to r^2, calculated by hierarchal partitioning (Figure 4).

All four multivariate models had a significant negative shoreline distance coefficient, a positive building-age coefficient, and a positive home value coefficient. In other words, older, more valuable homes that were closer to the shoreline sustained significantly more damage across the entire study area. On Galveston, both dune vegetation area (Model 1) and sediment volume (Model 2) were significantly ($p \leq 0.01$) and negatively related to sustained property damage; larger and more vegetated dunes reduced damage. On Bolivar, dune vegetation area (Model 3) and sediment volume (Model 4) were also negatively related to sustained damage but had higher p

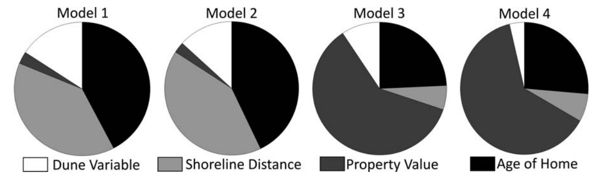

Figure 4. Hierarchal partitioning of variance (individual variable contribution to r^2) for Models 1–4.

values than the Galveston models ($5.01E^{-2}$ and 0.387, respectively). On average, homes on Bolivar sustained 472.8% more damage during Hurricane Ike than those on Galveston ($146,700 and $25,600, respectively). This occurred despite Bolivar having 12.8% larger dune ridge heights (2.91 m above sea level North American Vertical Datum of 1988 [NADV88] compared to Galveston's 2.58 m above sea level NADV88) and homes set back 27.1% farther from the shoreline on Bolivar (192.5 m from the shoreline for Bolivar and 151.4 m from shoreline for Galveston). However, the storm surge on Bolivar was more than 1 m higher than on Galveston (5 m on Bolivar compared to roughly 3.5 m on Galveston; Houston and Galveston, TX, Weather Forecast Office Staff, 2008; Sebastian *et al.*, 2014). Median home values for Galveston and Bolivar were comparable ($156,700 and $157,600, respectively; both datasets were right skewed) while homes on Bolivar were 38.2% older than on Galveston.

In Table 2, the property damage offset values of dune variables are summarized for Models 1 to 4. The per unit value of dune sediment was 76.6% lower on Bolivar. Likewise, the per unit value of dune vegetation was 68.5% lower on Bolivar than on Galveston. The worth per cubic meter of dune sediment for Galveston and Bolivar was mapped by shoreline block in Figure 5. Galveston was highly variable in this regard, with some areas displaying high dune sediment worth (>$50 per cubic meter) while others displayed fairly low worth (<$10 per cubic meter). Bolivar had less spatial variability, with worth in

Table 1. *Galveston and Bolivar regression models.*

Models†	Model 1: Galveston (Vegetation)	Model 2: Galveston (Sediment)	Model 3: Bolivar (Vegetation)	Model 4: Bolivar (Sediment)
Ecological Variables				
Dune vegetation area (10^4 m^2)	−4.024** (1.395)	NA	−0.2557† (0.1295)	NA
Dune sediment volume (10^4 m^3)	NA	−1.498** (0.5804)	NA	−0.07678‡ (0.08142)
Geographic Variables				
Home distance from shore (10^2 m)	−1.918*** (0.2014)	−2.005*** (0.1979)	−0.1255† (0.06512)	−0.1485* (0.05714)
Home distance from eye of storm (km)	ns	ns	ns	ns
Built Variables				
Age of home (y)	0.1134*** (0.01365)	0.1324*** (0.01372)	0.01479*** (0.003985)	0.01535*** (0.004123)
Value of home (log transformed)	0.7734** (0.2527)	0.6827** (0.2328)	0.4826*** (0.1166)	0.4854*** (0.1240)
Intercept	−0.3037(3.036)	1.003(2.998)	5.725*** (1.387)	5.700*** (1.466)
r^2	0.3269	0.3246	0.3286	0.3168
AIC	4424.61	4427.63	259.459	262.091
BIC	4453.28	4456.29	277.602	280.234
n (total homes)	878	878	152	152
Shoreline blocks	65	65	13	13

†*Values outside parentheses indicate the slope coefficient (values inside parentheses indicate standard error). The hierarchal partitioning of variance for these models is summarized in Figure 4.*
***$p \leq 0.001$, **$p \leq 0.01$, *$p \leq 0.05$, †$p \leq 0.1$, ‡$p = 0.3868$, *reported for consistency.*
ns = p *was not significant, variable removed stepwise.*

Table 2. *Per unit value in terms of storm protection of dune parameters.*

Area	Worth per Cubic Meter of Dune Sediment	Worth per Cubic Meter of Dune Vegetation
Galveston	\$51.83	\$139.25
Bolivar	\$12.13	\$43.87

Table 3. *Chow test* p *values for Galveston shore quartiles.*

	Shoreline Quartile 2	Shoreline Quartile 3	Shoreline Quartile 4
Shoreline Quartile 1	0.509	<0.001	<0.001
Shoreline Quartile 2		0.0118	<0.001
Shoreline Quartile 3			0.0294

different blocks ranging from \$4.20 per cubic meter to \$21.47 per cubic meter. The minimum dune comparison technique described in Equations (2) to (4) estimated that the total mitigation value of dunes within the study area was \$8.43 million. Because of collinearity of dune variables, this total was the average obtained from using vegetation models (Models 1 and 3) and sediment models (Models 2 and 4). For the average homeowner living in these areas, dunes were worth roughly \$8200.

Because the cross-shore extent of dune protection was not understood before analysis, different Galveston shoreline quartile zones were tested for structural breaks with Chow tests and summarized in Table 3. Chow test results indicate that all shoreline zones, apart from the two nearest the shoreline, can be modeled separately. Table 4 shows a summary of these shoreline zone models, and Figure 6 summarizes the hierarchal partitioning for these models. All three zones had a significant positive building-age term, in which older buildings sustained more damage. The zone farthest from the shoreline (Model 7) lacked a significant dune-related term but was the only model in which the distance from the eye of Hurricane Ike was a significant term, with homes farther from the eye sustaining less damage. Homes in the closest shoreline zone (Model 5) sustained 65.1% more damage (\$42,300 of damage per household) than Galveston as a whole (\$25,600), while the middle zone (Model 6) sustained 60.6% less damage (\$10,100) and the farthest zone (Model 7) sustained 70.3% less damage (\$7600).

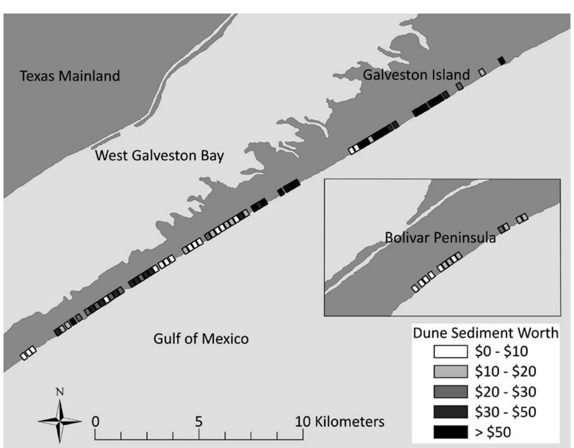

Figure 5. The value of dune sediment within each shoreline block is visualized using the Galveston and Bolivar sediment models (Models 2 and 4) and Equation (1) (without averaging the values of different shoreline blocks).

Property damage offset values were significantly related to dune variables, but only in the two zones closest to the shore. The closest zone (Model 5) had a relatively lower p value for the dune vegetation area term and the middle zone (Model 6) had a relatively lower p value for the dune sediment volume term, hence the stepwise retention of each term in its respective model. Both terms had negative coefficients, indicating that larger and/or more vegetated dunes reduced the dollar value of landward property damage. Hierarchal partitioning indicated that the explanatory power of dunes in mitigating home damage diminished as homes were set back farther from the shoreline. In the closest shoreline zone (Model 5), ecological dune variables accounted for 27.3% of the model's explained variation, trailing off to 19.0% for the middle zone (Model 6) and 3.2% for the farthest zone (Model 7). The difference between dune volume and dune vegetation was negligible for all shoreline zones.

Geographic variables showed a similar pattern of diminishing importance for homes set back farther from the shoreline. Specifically, the shoreline setback distance decreased in importance (closest zone, Model 5, 34.8%; middle zone, Model 6, 8.0%; and farthest zone, Model 7, 0.4%) while the distance of a home from the eye of the storm increased in importance (closest zone, Model 5, 1.5%; middle zone, Model 6, 12.4%; and farthest zone, Model 7, 17.1%). Built variables show the opposite pattern, becoming more important for homes farther from the shoreline. For the built category, building age was the dominant variable affecting sustained damage across all shoreline zones.

DISCUSSION

This study presents evidence that coastal sand dune ecosystems have significant and meaningful economic value when it comes to storm protection. Both dune vegetation and sediment variables showed a negative relationship with property damage, though these predictor variables were collinear. This collinearity could have been caused by a variety of factors. First, the cross-shore width of a dune field largely determines each of the variables (all dune regions had the same alongshore length). When the cross-shore width is larger, there is both a larger potential area for vegetation growth and a larger area component for the sediment volume calculation. Second, there is already an established linkage between vegetation and sediment accretion (Buckley, 1987; Luna *et al.*, 2011; Mendelssohn *et al.*, 1991). Vegetation traps wind-blown sediments, gradually building dunes in the process. Eventually, areas with the most vegetation naturally tend to become volumetrically large.

The dune sediment value ranged from \$12.13 per cubic meter for Bolivar to \$51.83 per cubic meter for Galveston. Dune vegetation value ranged from \$43.87 per square meter for

Table 4. *Galveston regression models divided by shoreline section.*

Models†	Model 5: Galveston Homes 48–135 m from Shore	Model 6: Galveston Homes 136–187 m from Shore	Model 7: Galveston Homes 187–300 m from Shore
Ecological Variables			
Dune vegetation area (10^4 m^2)	−3.597** (1.244)	ns	ns
Dune sediment volume (10^4 m^3)	ns	−1.907* (0.7929)	ns
Geographic Variables			
Home distance from shore (10^2 m)	−3.444*** (0.4389)	−4.528** (1.742)	ns
Home distance from eye of storm (km)	ns	ns	−0.09553* (0.03687)
Built Variables			
Age of home (y)	0.05397*** (0.009296)	0.1645*** (0.02752)	0.1273*** (0.01473)
Value of home (log transformed)	ns	1.841*** (0.4863)	ns
Intercept	12.23*** (0.5321)	−10.60(6.826)	5.870*** (1.190)
r^2	0.2402	0.3225	0.2215
AIC	1945.84	1153.57	1170.18
BIC	1966.28	1173.91	1183.74
n (total homes)	440	219	219
Shoreline blocks	53	44	37

†*Values outside parentheses indicate the slope coefficient (values inside parentheses indicate standard error). The hierarchal partitioning of variance for these models is summarized in Figure 6.*
***$p \le 0.001$, **$p \le 0.01$, *$p \le 0.05$, †$p \le 0.1$.
ns = p *was not significant, variable removed stepwise.*

Bolivar to $139.25 per square meter for Galveston. Because dune sediment volume and vegetation area were highly collinear, these two variables should not be summed for a total dune value. The reason for the relatively higher value for vegetation is the nature of area *vs*. volume calculations for a region: volume is always larger than area if the average elevation is greater than 1 (as was the case, typically, for this study area). These results should not be interpreted as supporting the notion that dune vegetation is "more valuable" than dune sediment. The two variables are interchangeable from a modeling perspective and simply operate on slightly different scales because of their area- or volume-based nature.

Figure 5 illustrates the spatial variability of dune worth within Galveston and Bolivar. Understanding this variability is a useful application of dune modeling in that investment in certain critical areas along a coastline could yield a higher return on dune investment. Many areas in Figure 5 have fairly low per unit values of investment. However, investment in dunes for certain areas, particularly in the middle of Galveston, where heavy shoreline retreat has been occurring for years (Paine, 2012), would, in concept, yield a high return. This is because homes in these blocks have small dunes seaward of them, are close to the shoreline, are older, are highly numerous or valuable, or are a combination of these factors. Strategic targeting of these areas for dune construction and restoration projects could have mitigated a substantial amount of property damage during Hurricane Ike. Future planning along these same lines could be an effective means to reduce damage for the next hurricane. However, it is imperative that paradoxical and nonsustainable coastal planning is avoided: dune value is conceptually bolstered in areas with highly valuable or a large number of homes that justifies investment in better dune protection, which then leads to the construction of additional homes in the area because it is better protected, and so on.

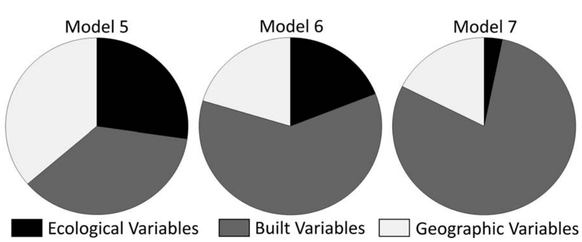

Figure 6. Hierarchal partitioning of variance for Models 5–7, grouped by variable category.

By some estimates, coastal marshes provide between roughly $2000 and $10,000 (these values were converted to 2015 U.S. dollars for consistency) of storm protection per hectare per year, depending on location and method of analysis (Costanza, Farber, and Maxwell, 1989; Costanza *et al*., 2008). From the models' estimates, vegetated dunes offered roughly $1.23 million of storm protection per hectare during Hurricane Ike along Galveston and Bolivar. Examining the frequency of storms for this area over the last 115 years, in which 0.07 hurricanes per year directly hit Galveston over this period (Roth, 2010), this equates to roughly $86,000 per hectare per year for this concentrated buffer ecosystem. This dune value is only based on one storm in one area, whereas wetland evaluations typically rely on multiple storms or numerical models of shoreline retreat and surge propagation (Costanza, Farber, and Maxwell, 1989; Costanza *et al*., 2008). Additional assessments of other dune systems and storms would be necessary to determine whether the dune value found in this paper for the Texas coast during Hurricane Ike was typical. These values are mentioned not to downplay the importance of wetlands, which offer many critical ecosystem services that dunes do not (*e.g.*, nursery habitat for fishing industries, water filtration, and carbon sequestration) but rather to acknowledge the critical importance of dune ecosystems in coastal management and hazard mitigation in conjunction with wetlands.

The total value of dunes for this entire region was estimated by using the minimal dune state comparison [Equations (2)–(4)] on Models 1 to 4. This technique estimates the amount of damage that was mitigated by the presence of dunes—in other words, how much more damage would have occurred if dunes had been removed (or put to a minimal state) before the storm. After averaging the total values of both dune variables (because of collinearity of sediment volume and vegetation), this equates to \$8.43 million in total dune storm protection value across the entire study area. For the average homeowner living in these areas, the presence of dunes mitigated roughly \$8200 of damage to their home. An additional 321 homes on Galveston and 975 homes on Bolivar within 300 m of the shore were also protected by dunes but were either between shoreline blocks or outside the range of the aerial photography, suggesting that the total value of dunes could be even higher.

The extent of Hurricane Ike damage mitigation provided by dunes may be somewhat surprising, because dunes along Galveston and Bolivar were breached and all but obliterated (Williams *et al*., 2009). However, even a breached dune possesses value, because any time that a dune takes to erode during a storm delays the exposure of landward homes to hazardous conditions. Moreover, an eroded dune still can provide protection by dissipating wave energy due to sediment deposition in the nearshore zone. Sediment transported offshore by storm waves may create a submerged bar feature and elevated offshore profile that causes waves to break and dissipate their energy farther from the shoreline. Even in the occurrence of a dune breach, a coastline can be extensively modified to a point where wave energy reaching residential areas is substantially reduced. This point again emphasizes the importance of having both well-vegetated and volumetrically large dunes. Well-vegetated dunes reduce the rate of erosion (Sigren, Figlus, and Armitage, 2014) and prolong the time until breaching (Kobayashi, Gralher, and Do, 2013; Silva *et al*., 2016), while volumetrically large dunes take longer to erode and provide a more dissipative shore profile after redistribution of sediment by storm hydrodynamics.

Models 5 to 7 break down Galveston by quartile zones of different distances to the shoreline, showing that dunes diminish in importance for homes set back farther from the shore. The only model in Table 4 in which dunes were not a significant or meaningful variable was the quartile zone of homes farthest from the shoreline, where dunes only accounted for 3.2% of the model's explained variation (Model 7). This could represent the "reach" of dune protection during Hurricane Ike for Galveston. Because these homes were the farthest from the shoreline, they were less likely to be influenced by storm surge and therefore any protective value of dunes. This was also the only model to find the distance from the eye of the storm to be a significant determinant of sustained damage. This implies that perhaps a wind gradient along Galveston (Overpeck, 2009) could have played a larger role for damage in this zone of homes.

Sediment volume as a predictor of dune storm protection capabilities has limitations. Hypothetically, dune protection increases with dune volume, but this is not necessarily the case. Figlus *et al*. (2011) demonstrated that volumetrically similar dunes with different morphologies possess differing breaching rates and protective capabilities. This finding can be attributed to differences among dune morphologies in terms of wave energy dissipation; the positioning of sand in front of the main dune (in the form of foredunes, a protective seaward berm, or simply a multiridged dune) dissipates wave energy more efficiently. Therefore, volumetrically similar dunes could behave differently in terms of protection and storm damage mitigation. Inclusion of dune morphology categorization could refine the method of multivariate analysis in future studies. In addition, the dune volume quantification technique used for this analysis depends on the way the area of the dune region is defined (*i.e*. the slope threshold that is used), as well as how the volume of sediment is vertically sliced above the beach. How these two parameterization techniques play out can drastically alter the quantity of dune sediment and therefore the per unit value of that quantity. This issue is discussed in greater detail in the authors' previous methods paper (Sigren *et al*., 2015).

The total vegetated area of a dune also has limitations as a predictor to dune stability and storm resistance. Though dune vegetation in general will likely improve dune sediment aggregation, shearing resistance (Figlus *et al*., 2014), wave energy dissipation, and erosion resistance in general (Sigren, Figlus, and Armitage, 2014; Silva *et al*., 2016), different kinds (*i.e*. species and morphotypes) of vegetation would likely affect these processes in different ways. Such discrepancies in wave resistance and erosion control among different kinds of vegetation have been observed in other coastal and transitional ecosystems (Burri, Gromke, and Graf, 2013; Coops *et al*., 1996; De Baets *et al*., 2008; Leonard and Luther, 1995; Ysebaert *et al*., 2011). In other words, the analysis treated all vegetation as being equal with regards to storm protection when in all likelihood it is not. This technique could be improved by collecting plant community data, in conjunction with aerial photography, to associate spectral signatures to different types of vegetation. Then, a similar analysis could determine whether certain types of dune vegetation make greater contributions to storm protection. Furthermore, all sediment volume and vegetation area calculations were based on LIDAR and aerial photography datasets that were collected 2 years before Hurricane Ike. Any accretion or erosion that took place in those 2 years would have added noise to the model.

There is the additional limitation that the overarching methodology used in this paper in not necessarily applicable to all dune systems. This evaluation methodology depends on using variation in the volume and vegetation area of dune systems to create a model. This approach works best for areas with naturally variable dune systems or where there is a combination of large restored dunes and natural systems. However, in locations with large uniform dunes, such variation along a shoreline in dune parameters may not exist and any attempt at modeling that dune's value would have little resolution. For a uniform dune system that is sufficiently large to not be breached during a storm, an alternative or replacement cost analysis (Barbier, 2007) could be a more appropriate evaluation technique. However, dunes tend to morph under natural Aeolian and hydrological processes, potentially generating volume and vegetation variation over time for uniform dune systems. This natural tendency toward variability could allow modeling of initially uniform dunes, given enough time has elapsed since construction. Furthermore, modeling storm damage by non-dune-related variables can still provide useful insights for coastal management.

CONCLUSIONS

Coastal sand dunes, in regards to both vegetation area and sediment volume, significantly reduced sustained property damage for portions of the Texas coast during Hurricane Ike. The total property damage offset worth of coastal dunes within the analyzed shoreline blocks during Hurricane Ike was in excess of $8 million and potentially more if considering dunes around other portions of the Gulf of Mexico that encountered the broadly distributed surge. The covariates of home age, value, and shoreline setback were also significant predictors of sustained damage. These covariates, along with dune variables, characterize the prestorm state of a coastal area and can inform predictions about how much damage it will sustain during a storm. This prestorm state also determines the cost efficacy of investing in dunes for a particular area, potentially allowing strategic hazard mitigation planning. The results indicate that dunes should play an integral role in coastal hazard mitigation strategies and offer a unique opportunity of bioengineering green infrastructure as an alternative to hard coastal structures.

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LITERATURE CITED

Aerials Express Staff, 2006. *2006 USGS Southeast U.S. Imagery*. Charleston, South Carolina: National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management.

Barbier, E.B., 2007. Valuing ecosystem services as productive inputs. *Economic Policy,* 22, 177–229.

Barone, D.A.; McKenna, K.K., and Farrell, S.C., 2014. Hurricane Sandy: Beach–dune performance at New Jersey beach-profile network sites. *Shore and Beach,* 82(4), 13–23.

Berg, R., 2009. *Tropical Cyclone Report: Hurricane Ike*. Miami, Florida: National Hurricane Center, 55p.

Blake, E.S.; Landsea, C.W., and Gibney, E.J., 2011. *The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2010 (and Other Frequently Requested Hurricane Facts)*. Miami, Florida: National Hurricane Center, *NWS NHC-6,* 49p.

Brody, S.D.; Highfield, W.E., and Kang, J.E., 2011. *Rising Waters: The Causes and Consequences of Flooding in the United States*. Cambridge, United Kingdom: Cambridge University Press, 194p.

Buckley, R., 1987. The effect of sparse vegetation on the transport of dune sand by wind. *Nature,* 325(6103), 426–428.

Burby, R., 1985. *Flood Plain Land Use Management: A National Assessment*. Boulder, Colorado: Westview Press, 249p.

Burby, R., 1998. *Cooperating with Nature: Confronting Natural Hazards with Land-Use Planning for Sustainable Communities*. Washington, D.C.: National Academies Press, 337p.

Burri, K.; Gromke, C., and Graf, F., 2013. Mycorrhizal fungi protect the soil from wind erosion: A wind tunnel study. *Land Degradation & Development,* 24(4), 385–392.

Chevan, A. and Sutherland, M., 1991. Hierarchical partitioning. *The American Statistician,* 45, 90–96.

Cochard, R.; Ranamukhaarachchi, S.L.; Shivakoti, G.P.; Shipin, O.V.; Edwards, P.J., and Seeland, K.T., 2008. The 2004 tsunami in Aceh and Southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability. *Perspectives in Plant Ecology, Evolution and Systematics,* 10(1), 3–40.

Coops, H.; Geilen, N.; Verheij, H.J.; Boeters, R., and Velde, G.V.D., 1996. Interactions between waves, bank erosion and emergent vegetation: An experimental study in a wave tank. *Aquatic Botany,* 53(3–4), 187–198.

Costanza, R.; Farber, S.C., and Maxwell, J., 1989. Valuation and management of wetland ecosystems. *Ecological Economics,* 1(4), 335–361.

Costanza, R.; Mitsch, W.J., and Day, J.W., 2006. A new vision for New Orleans and the Mississippi delta: Applying ecological economics and ecological engineering. *Frontiers in Ecology and the Environment,* 4(9), 465–472.

Costanza, R.; Pérez-Maqueo, O.; Martinez, M.L.; Sutton, P.; Anderson, S.J., and Mulder, K., 2008. The value of coastal wetlands for hurricane protection. *Ambio,* 37(4), 241–248.

De Baets, S.; Poesen, J.; Reubens, B.; Wemans, K.; De Baerdemaeker, J., and Muys, B., 2008. Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. *Plant and Soil,* 305(1–2), 207–226.

DeBlasio, S.M., 2008. *Hurricane Ike Impact Report by the State of Texas*. Washington, D.C.: Federal Emergency Management Agency, 64p.

Doran, K.S.; Plant, N.G.; Stockdon, H.F.; Sallenger, A.H., and Serafin, K.A., 2009. *Hurricane Ike: Observations and Analysis of Coastal Change*. Reston, Virginia: U.S. Geological Survey, *2009-1061,* 43p.

Elko, N.; Brodie, K.; Stockdon, H.; Nordstrom, K.; Houser, C.; McKenna, K.; Moore, L.; Rosati, J.; Ruggiero, P.; Thuman, R., and Walker, I., 2016. Dune management challenges on developed coasts. *Shore and Beach,* 84, 15–28.

Feagin, R.A.; Barbier, E.B.; Koch, E.W.; Silliman, B.R.; Hacker, S.D.; Wolanski, E.; Primavera, J.; Granek, E.F.; Polasky, S.; Aswani, S.; Cramer, L.A.; Stoms, D.M.; Kennedy, C.J.; Bael, D.; Kappel, C.V.; Perillo, G.M.E., and Reed, D.J., 2008. Vegetation's role in coastal protection. *Science,* 320(5873), 176–177.

Feagin, R.A.; Figlus, J.; Zinnert, J.C.; Sigren, J.; Martínez, M.L.; Silva, R.; Smith, W.K.; Cox, D.; Young, D.R., and Carter, G., 2015. Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. *Frontiers in Ecology and the Environment,* 13(4), 203–210.

Feagin, R.A.; Lozada-Bernard, S.M.; Ravens, T.M.; Möller, I.; Yeager, K.M., and Baird, A.H., 2009. Does vegetation prevent wave erosion of salt marshes? *Proceedings of the National Academy of Science,* 105(25), 10109–10113.

FEMA (Federal Emergency Management Agency), 1988. Flood insurance program: Flood plain management standards. *Federal Register,* 53(88), 16268–16273.

Figlus, J.; Kobayashi, N.; Gralher, C., and Iranzo, V., 2011. Wave overtopping and overwash of dunes. *Journal of Waterway Port Coastal and Ocean Engineering—ASCE,* 137(1), 26–33.

Figlus, J.; Sigren, J.; Armitage, A.R., and Tyler, R.C., 2014. Erosion of vegetated coastal dunes. *In*: Lynett, P. (ed.), *Proceedings of 34th Conference on Coastal Engineering* (Seoul, South Korea, ASCE), pp. 1–13.

Gedan, K.B.; Kirwan, M.L.; Wolanski, E.; Barbier, E.B., and Silliman, B.R., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. *Climatic Change,* 106(1), 7–29.

Highfield, W.E.; Norman, S.A., and Brody, S.D., 2013. Examining the 100 year floodplain as a metric of risk, loss, and household adjustment. *Risk Analysis,* 33(2), 186–191.

Highfield, W.E.; Peacock, W.G., and Van Zandt, S., 2014. Mitigation planning why hazard exposure, structural vulnerability, and social vulnerability matter. *Journal of Planning Education and Research,* 287–300.

Houston and Galveston, TX, Weather Forecast Office Staff, 2008. *Hurricane Ike (September 2008): Storm Surge Estimates from Damage Surveys*. Dickinson, Texas: National Weather Service,

Houston and Galveston, TX. http://www.crh.noaa.gov/hgx/?n=projects_ike08_storm_surge_overview.
Huber, P.J., 1967. The behavior of maximum likelihood estimates under non-standard conditions. *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability,* 1, 221–223.
Hurricane Research Division Staff, 2014. *The Thirty Costliest Mainland United States Tropical Cyclones 1900–2013*. Miami, Florida: National Oceanographic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory. http://www.aoml.noaa.gov/hrd/tcfaq/costliesttable.html.
Kobayashi, N.; Gralher, C., and Do, K., 2013. Effects of woody plants on dune erosion and overwash. *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 139, 466–472.
La Peyre, M.K.; Humphries, A.T.; Casas, S.M., and La Peyre, J.F., 2014. Temporal variation in development of ecosystem services from oyster reef restoration. *Ecological Engineering,* 63, 34–44.
Larson, L. and Plasencia, D., 2001. No adverse impact: New direction in floodplain management policy. *Natural Hazards Review,* 2(4), 167–181.
Leonard, L.A. and Luther, M.E., 1995. Flow hydrodynamics in tidal marsh canopies. *Limnology and Oceanography,* 40(8), 1474–1484.
Long, W.C.; Grow, J.N.; Majoris, J.E., and Hines, A.H., 2011. Effects of anthropogenic shoreline hardening and invasion by *Phragmites australis* on habitat quality for juvenile blue crabs *(Callinectes sapidus)*. *Journal of Experimental Marine Biology and Ecology,* 409(1–2), 215–222.
Løvås, S.M. and Tørum, A., 2001. Effect of the kelp *Laminaria hyperborea* upon sand dune erosion and water particle velocities. *Coastal Engineering,* 44(1), 37–63.
Luna, M.C.M.D.; Parteli, E.J.R.; Duran, O., and Herrmann, H.J., 2011. Model for the genesis of coastal dune fields with vegetation. *Geomorphology,* 129(3–4), 215–224.
MacArthur, B.; Coulton, K.; Dean, B.; Hatheway, D.; Honeycutt, M.; Johnson, J.; Jones, C.; Komar, P.; Lu, C.C.; Noble, R.; Ruthven, T., and Seymour, D., 2005. *Event-Based Erosion: FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report*. Washington, D.C.: Federal Emergency Management Agency, 84p.
Mendelssohn, I.A.; Hester, M.W.; Monteferrante, F.J., and Talbot, F., 1991. Experimental dune building and vegetative stabilization in a sand-deficient barrier-island setting on the Louisiana coast, USA. *Journal of Coastal Research,* 7(1), 137–149.
Morton, R.A. and Paine, J.G., 1985. Beach and vegetation-line changes at Galveston Island, Texas: Erosion, deposition, and recovery to Hurricane Alicia. *Geological Circular,* 85(5).
Navarro, M., 2012. Resisted for blocking the view, dunes prove they blunt storms. *The New York Times,* December 4, A1.
Office of Coastal Management Staff, 2007. *2006 Texas Water Development Board (TWDB) LIDAR: Galveston County*. Charleston, South Carolina: National Oceanic and Atmospheric Administration's National Ocean Service, Office for Coastal Management.
Overpeck, S., 2009. *Hurricane Ike Wind Speed Analysis for Southeast Texas*. Dickinson, Texas: National Oceanic and Atmospheric Administration and National Weather Service. http://www.crh.noaa.gov/hgx/?n=projects_ike08_wind_analysis.
Paine, J.G., 2012. Historical shoreline change through 2007, Texas Gulf coast: Rates, contributing causes, and Holocene context. *Gulf Coast Association of Geological Societies Journal,* 1, 13–26.
Piazza, B.P.; Banks, P.D., and La Peyre, M.K., 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. *Restoration Ecology,* 13(3), 499–506.
Pielke, R.; Gratz, J.; Landsea, C.; Collins, D.; Saunders, M., and Musulin, R., 2008. Normalized hurricane damage in the United States: 1900–2005. *Natural Hazards Review,* 9(1), 29–42.
Pilkey, O.H. and Wright, H.L., 1988. Seawalls versus beaches. *In*: Kraus, N.C. and Pilkey, O.H. (eds.), *The Effects of Seawalls on the Beach*. *Journal of Coastal Research,* Special Issue No. 4, pp. 41–64.
Roth, D., 2010. *Texas Hurricane History*. Camp Springs, Maryland: National Weather Service, 83p.
Sebastian, A.; Proft, J.; Dietrich, J.C.; Du, W.; Bedient, P.B., and Dawson, C.N., 2014. Characterizing hurricane storm surge behavior in Galveston Bay using the SWAN+ADCIRC model. *Coastal Engineering,* 88, 171–181.
Sigren, J.M.; Figlus, J., and Armitage, A.R., 2014. Coastal sand dunes and dune vegetation: Restoration, erosion, and storm protection. *Shore and Beach,* 82(4), 5–12.
Sigren, J.M.; Figlus, J.; Highfield, W.; Armitage, A.R., and Feagin, R.A., 2015. Methods evaluating the economic effects of coastal dunes in reducing storm-induced property damage: Hurricane Ike and Texas coast case study. *Proceedings of the Coastal Structures & Solutions to Coastal Disasters Joint Conference* (Boston, Massachusetts).
Silva, R.; Martínez, M.L.; Odériz, I.; Medoza-Baldwin, E., and Feagin, R.A., 2016. Response of vegetated dune–beach systems to storm conditions. *Coastal Engineering,* 109, 53–62.
Thampanya, U.; Vermaat, J.E.; Sinsakul, S., and Panapitukkul, N., 2006. Coastal erosion and mangrove progradation of Southern Thailand. *Estuarine, Coastal and Shelf Science,* 68(1–2), 75–85.
Walsh, C. and Mac Nally, R., 2013. *Hier.part: Hierarchal Partitioning*. R package version 1.0-4. Vienna, Austria: R Foundation for Statistical Computing.
Wamsley, T.V.; Cialone, M.A.; Smith, J.M.; Atkinson, J.H., and Rosati, J.D., 2010. The potential of wetlands in reducing storm surge. *Ocean Engineering,* 37(1), 59–68.
White, G.F., 1945. Human Adjustment to Floods: A Geographical Approach to the Flood Problem in the United States. Chicago, Illinois: University of Chicago, Ph.D. dissertation, 225p.
Williams, A.; Feagin, R.; Smith, W.K., and Jackson, N.L., 2009. *Ecosystem Impacts of Hurricane Ike on Galveston Island and Bolivar Peninsula: Perspectives of the Coastal Barrier Island Network (CBIN)*. Galveston, Texas: Coastal Barrier Island Network, 17p.
Wooldridge, J.M., 2000. *Introductory Econometrics: A Modern Approach*. Cincinnati, Ohio: South-Western College, 912p.
Yang, S.L.; Shi, B.W.; Bouma, T.J.; Ysebaert, T., and Luo, X.X., 2012. Wave attenuation at a salt marsh margin: A case study of an exposed coast on the Yangtze Estuary. *Estuaries and Coasts,* 35(1), 169–182.
Ysebaert, T.; Yang, S.L.; Zhang, L.; He, Q.; Bouma, T.J., and Herman, P.M.J., 2011. Wave attenuation by two contrasting ecosystem engineering salt marsh macrophytes in the intertidal pioneer zone. *Wetlands,* 31(6), 1043–1054.
Zeileis, A., 2004. Econometric computing with HC and HAC covariance matrix estimators. *Journal of Statistical Software,* 11(10), 1–17.