Catastrophic storm impact and gradual recovery on the Mississippi-Alabama barrier islands, 2005-2010: Changes in vegetated and total land area, and relationships of post-storm ecological communities with surface elevation

Gregory A. Carter[a,b]*, Ervin G. Otvos[c], Carlton P. Anderson[a,b], William R. Funderburk[b], and Kelly L. Lucas[d]

[a]Department of Geography and Geology, School of Biological, Environmental, and Earth Sciences, University of Southern Mississippi, 730 E. Beach Blvd., Long Beach, MS 39560

[b] Gulf Coast Geospatial Center, University of Southern Mississippi, 730 E. Beach Blvd., Long Beach, MS 39560

[c]Division of Coastal Sciences, School of Ocean Science and Engineering, University of Southern Mississippi, Ocean Springs, MS

[d]Thad Cochran Marine Aquaculture Center, University of Southern Mississippi, Ocean Springs, MS

*Corresponding Author

E-mail addresses: greg.carter@usm.edu (G.A. Carter); ervin.otvos@usm.edu (E.G. Otvos); carlton.p.anderson@usm.edu (C.P. Anderson); william.funderburk@usm.edu (W.R. Funderburk), and kelly.lucas@usm.edu (K.L. Lucas).

ABSTRACT

One of the most destructive tropical cyclones ever to strike the U. S., Hurricane Katrina made landfall along the Mississippi coast on 29th August 2005. The Mississippi-Alabama (MS-AL) barrier islands were subjected to storm breaching, area reduction, and vegetation loss caused by a number of parameters including salt spray, saltwater flooding, mechanical damage (e.g., ablation of bark from tree trunks), removal of plants and their soil substrate by scouring, burial under sand, and a 10-month, post-storm period of low rainfall. Repeated acquisitions of remotely-sensed data served as an essential tool in quantifying vegetated and total land area before and after the storm, and post-storm ecological community type and topographic elevation. Vegetated land area continued to decline on some islands in the first year following the storm. However, by November 2007, only 2.2 years after the storm, total vegetated land area had recovered to 72, 96, 77, 93, and 82 percent, and total subaerial land area to 97, 94, 33, 100, and 104 percent, of pre-Katrina values on Cat, W. Ship, E. Ship, Horn, and Petit Bois islands by natural re-growth and sediment accretion, respectively. Comparing ecological community-type maps that were developed from field and remotely-sensed data with LiDAR-derived digital elevation models determined that year 2010 ecological community type changed distinctively at the decimeter scale as mean surface elevation ranged from 0.1 m to 1.2 m. Storm-related changes in ecological community type included subtidal to supratidal sand flat, low marsh to wet or dry herbland, and woodland to wet herbland/shrubland.

Keywords: Gulf of Mexico; Hurricanes; Barrier island; Microtopography

1. Introduction

As generally low-elevation landforms composed almost entirely of sand, barrier islands are highly sensitive indicators of global climatic change and sea level rise (Pilkey, 2003). Indeed, the existence of some islands may be threatened in the present century by an expectedly greater frequency and intensity of tropical cyclones (Knutson et al., 2010), effects of relative sea-level rise (eustatic plus local subsidence), and human influences on sediment availability (e.g., Morton, 2008). After a storm, the level of island reconstruction by natural processes depends on sediment availability (Leatherman, 1979; Hesp, 2002; Psuty, 2004) and the stabilizing influence of vegetation (Hesp, 1991; Snyder and Boss, 2002; Feagin et al., 2015). The latter depends strongly on species adaptations to sediment erosion, movement, and deposition (Moreno-Casasola and Espejel, 1986; Hesp, 2002; Stallins and Parker, 2003; Stallins, 2005; Feagin et al., 2015), salt spray, low nutrient availability, and flooding (Oosting, 1954; Hesp, 1991; Carter and Young, 1993; Shao et al., 1996). For example, dunes allow the formation of more stable backdune plant communities because they reduce overwash and the windborne transport of sand and salt spray toward the island interior (Hayden et al., 1995; Stallins, 2005). In particular, saltwater flooding greatly affects the distribution of woody plant species because it inhibits seed germination and is often lethal (Lantz et al., 2015).

On 29th August 2005, the Mississippi-Alabama (MS-AL) barrier islands in the northern Gulf of Mexico, including Cat, W. Ship, E. Ship, Horn, W. Petit Bois (formerly named Sand Island), Petit Bois, and Dauphin islands (**Fig. 1**), were impacted severely by Hurricane Katrina (NOAA, National Hurricane Center, https://www.nhc.noaa.gov/data/tcr). The eye of the storm passed 50 – 150 km west of the islands, producing storm tide depths which ranged generally from 9 m on the westernmost islands (Cat and W. Ship islands) to 3.5 m on Dauphin Island (Fritz et al., 2007; 2008), with a maximum of 12 m on W. Ship Island (Morton, 2010). Maximum 1-min. average wind speeds ranged from 200 km h^{-1} on Cat Island to 140 km h^{-1} on Dauphin Island (Powell and Reinhold, 2007). Island geomorphic features were substantially altered (Feagin and Williams, 2008; Morton, 2008; 2010; Otvos and Carter, 2008; Lucas and Carter, 2013; Jones, 2015; Eisemann et al., 2018), while vegetation was decimated by wind, salt spray, erosion, sand overwash, saltwater flooding and several months of low rainfall following the storm (Hughes, 2008; Otvos and Carter, 2008; Lucas and Carter, 2013). Decadal-scale variability in the MS-AL barrier chain, and land area changes caused by Katrina in the context of long-term trends, were addressed earlier (e.g., Morton, 2008; Otvos and Carter, 2008; Jones, 2015).

Fig. 1. Landsat 5 Thematic Mapper (TM5) natural color image of the MS-AL barrier islands and mainland coast acquired on 16th September 2005, approximately two weeks after the 29th August 2005 Mississippi landfall of Hurricane Katrina. By acting as sediment traps, ship navigation channels (solid white lines) extending from Mobile Bay and west of Petit Bois and W. Ship islands have increasingly reduced the volume of westward-directed net longshore sediment transport since the late 19th century (Morton, 2008). Erosional conversion of most of the Chandeleur Islands, Louisiana to sandy shoals (Otvos and Carter, 2013; Moore et al, 2014; Otvos, 2018; in press) rendered them barely visible at bottom-left in the image. The dashed vertical white line on Dauphin Island indicates longitude 88.2º W, the eastern limit of the study area.

From the time of Hurricane Katrina's impact through summer 2010, when boulder placement reconnected central Dauphin Island with the developed eastern portion of the island, vegetation and geomorphic features on the MS-AL barriers west of longitude 88.2º W had undergone only naturally-occurring changes. These included limited erosion by Hurricane Gustav, which made landfall on 1st September 2008 near Cocodrie, Louisiana, approximately 150 – 200 km west of the MS islands and 230 km west of Dauphin Island, exposing the MS-AL islands to tropical-storm force winds (Doran et al., 2009; NOAA, National Hurricane Center, https://www.nhc.noaa.gov/data/tcr). Frequent acquisitions of remotely-sensed data by government and commercial organizations facilitated quantitative assessment of vegetation reestablishment and habitat change on the islands (Lucas and Carter, 2013). In combination with remotely-sensed data, ground observations from a 2010-2011 field survey (Carter et al., 2016) were incorporated to address post-Katrina changes in vegetation and geomorphic features, and decadal-scale resilience of the islands to relative sea-level rise, sediment deprivation, and storms (Anderson et al., 2016; Funderburk et al., 2016; Jeter and Carter, 2016). These studies considered either one large island (Cat or Horn Island) or two small islands (E. Ship and W. Petit Bois islands) at remote-sensing spatial resolutions as fine as 1 m ground sample distance (GSD), or ground pixel size. Their results indicated a strong dependence of plant survival and ecological community-type development on microtopographic (< 1 m) variations in surface elevation.

In contrast with the earlier studies of the impacts of Hurricane Katrina on island vegetation, the present study was more extensive geographically, addressing the entire uninhabited portion of the MS-AL barrier chain from Cat Island eastward to western and central Dauphin Island. Repeated acquisitions of remotely-sensed data served as an essential tool in identifying and mapping vegetated and total land area, ecological community type, geomorphic features and topographic elevation. Data were combined among the MS islands to describe the relationship between ecological community type and decimeter-scale surface elevation in the MS portion of the barrier chain at a 10 m GSD. Multispectral image data acquired prior to and following Hurricane Katrina in 2004-2005 and 2005-2010, respectively, were classified to produce maps of general land cover (total vegetation, unvegetated or sparsely-vegetated sand, and lagoons and ponds). This enabled quantification of land cover for image acquisition dates that occurred prior to the storm, approximately one and two weeks after landfall, and periodically within the subsequent five post-Katrina years. RADAR, LiDAR, and multispectral image data acquired in 2010 were used to map ecological community types and assess their relationship with surface elevation across the MS portion of the barrier chain. Specific objectives included: 1) determination of total land and total vegetated land area at a GSD of ~ 2 m to 4 m; 2) mapping the 2010 distribution of ecological community types at 10 m GSD, and 3) comparison of ecological community type with surface elevation at 10 m GSD on the MS portion of the barrier chain.

2. Study area

The ~105 km-long MS-AL barrier island chain marks the southern limit of the Mississippi Sound. Mean elevation of the MS islands, excluding W. Petit Bois Island, is ~ 0.9 m above mean sea level (± 0.6 m std. dev.; range 7.6 m) (data from present study). Prevailing southeasterly surface winds and waves produce an east-to-west longshore sediment transport along the Mississippi Sound islands (Byrnes et al., 2013). Longshore sediment transport and minor cross-shelf onshore sediment transport nourishes the islands. Sediment is transported from the large Mobile Bay ebb-tidal delta and sources in the SE Alabama and NW Florida coastal and nearshore region (Otvos, 1979, 1981, 2018). Navigation channels (**Fig. 1**) also continue to interfere with and reduce the westward-directed net sand transport to down-drift islands (Morton, 2008). The general characteristics and history of each island is described in Otvos and Carter (2008)

Except for eastern Cat Island, the MS portion of the island chain is under the stewardship of the U.S. National Park Service, Gulf Islands National Seashore (GUIS). Horn and Petit Bois islands are designated wilderness areas. The narrow western and central portions of Dauphin Island remain undeveloped since Hurricane Katrina. The first post-Katrina erosion mitigation effort on the MS islands began in August, 2011, with Phase I of the West Ship Island North

Shore Restoration project. This entailed beach nourishment of the island's northwestern shore in the vicinity of Fort Massachusetts (Mississippi Dept. of Marine Resources).

The barrier chain emerged originally by vertical aggradation on a narrow subtidal sand shoal platform that formed westward, down-drift, of the ancient core of eastern Dauphin Island. The island core is a large and high barrier ridge sector developed during the late Pleistocene Last Interglacial (Sangamonian) marine highstand along the Gulf coastal plain. Surrounded and covered by sands of the Holocene transgression, including massive sand dunes, it outcrops along the Gulf beach of eastern Dauphin Island. The sand platform on which the modern barrier islands emerged once extended as far west as present-day Orleans Parish, LA. Absolute dates from that area (Otvos, 1978, 1981, 2012; Otvos and Giardino, 2004; Otvos and Carter, 2013; Miselis et al., 2014) indicate that the earliest island generation was established by ~ 5.3-5.1 ka. Island growth involved construction of a series of southward-prograding, semi-parallel strandplain (synonymous with beach ridge, cf. Otvos, 2018) ridges. Their development was guided by the predominant southeasterly wave approach and consequent westward net longshore sediment transport. Strandplain-covered, higher and wider island sectors in several of the islands alternate with narrow, low, spit-like, easily-overwashed island segments. The original islands, just as the modern barriers, were eroding on their eastern ends and concurrently prograded from their western ends in downdrift direction. Storm erosion, associated with island degeneration and recovery cycles, was equally critical in island development (Morton, 2008; Otvos and Carter, 2008). Partial or complete island burial was related to the growth of a Mississippi - St. Bernard subdelta lobe that started to develop after ~3.8 ka and ended its active existence by ~ 1.8 ka (Otvos and Giardino, 2004; Otvos and Carter, 2013). Delta advance overwhelmed all pre-existing barrier islands west of Cat Island. On Cat Island, swales (shallow, narrow valleys) located between strandplain ridges in the E-W-trending original body of the island are gradually filling with sea water (Otvos and Giardino, 2004; Otvos, 2018). This resulted in the fragmentation and complete immersion of certain marginal island areas. Gradual immersion is related to the island's location on the fringes of the subsiding Mississippi Delta Complex. The northern and southern ridge sets have been the most impacted. Sand on the eastern strandplain of Cat Island has been reworked by shore erosion and incorporated into two spit-like landforms. These extend northeastward and southwestward, nearly perpendicular to the original island body, and have gradually reduced in area and retreated westward (Otvos and Giardino, 2004). Underlain by the thick Holocene shoal platform sands, the MS-AL barriers are associated with larger and more extensive sand resources than the barrier island chains that occur along the nearby relict Mississippi delta lobes. The thin, low, and narrow deltaic barrier sand bodies, such as the Chandeleur chain (**Fig. 1**), are composed predominantly of fine rather than medium-grained sand and are more vulnerable to storms (Otvos, 2018). Despite periodic regeneration of the Chandeleurs, the expected overall life-spans of deltaic barrier islands, in particular the two Timbalier islands and Last Islands (Isles Dernieres) along the southern shore of the late Holocene Mississippi Delta Complex, are significantly shorter in comparison with the coastal plain barriers (Otvos and Carter, 2013; Moore et al., 2014; Otvos, 2018).

3. Methods

3.1 General approach

The impacts of Hurricane Katrina on vegetated and total land area and gradual regrowth over a post-Katrina period of approximately five years were inferred from the unsupervised classification of aerial or satellite multispectral image data. Prior to Katrina, high spatial resolution (small GSD) remotely-sensed imagery had been acquired only sporadically for the MS-AL islands. Such data were acquired more frequently in years following the storm. The best-available pre-Katrina image data were acquired in 2004-2005 on dates that ranged from 1.5 months (for Petit Bois Island) to 6.7 months (for Cat and Horn islands) after the 16th September 2004 landfall of Hurricane Ivan at Gulf Shores, Alabama (NOAA, National Hurricane Center, https://www.nhc.noaa.gov/data/tcr) (**Fig 2**; **Table 1**). Although spits on island ends, which are typically bare of vegetation, were eroded by Ivan on the MS islands, and western and central Dauphin Island was subjected to washover and erosion, the barrier cores of the MS islands were unmodified by Ivan (Morton, 2007). This conclusion was supported additionally by field observations made from November 2004 through May 2005 during an earlier study on Horn Island (Lucas and Carter, 2010). Furthermore, the pre-Katrina image data were acquired 3 months (for Cat and Horn islands) to 8 months (for Petit Bois Island) before Tropical Storm Cindy moved inland across the MS coast and continued its northeasterly path on 6th July 2005. A short-lived storm which reduced to a Tropical Depression in southern MS, Cindy produced a storm surge of 1.2 m to 1.8 m along the MS coast, compared with the generally 7 m to 9 m surge (ranging to 12 m on W. Ship Island) produced by Katrina (NOAA, National Hurricane Center, https://www.nhc.noaa.gov/data/tcr). Thus, the 2004-2005 post- Hurricane Ivan, pre- Tropical Storm Cindy images were considered to be a valid source of pre- Hurricane Katrina reference data for the MS-AL islands. Post-Katrina acquisitions of remote imagery began on 7th September 2005 for all islands, and continued periodically through dates in 2010 that were 4.6 years (for western and central Dauphin Island) or 4.9 years (for all other islands) after the storm (**Table 1**).

Image analysis was supplemented by field survey data acquired in earlier studies of post-Katrina tree mortality in 2007 (Hughes, 2008), and land cover in 2010-2011 (Carter et al., 2016) (**Fig. 2**). Finally, the 2010-2011 land cover data were used as training data in the supervised classification of 2010 synthetic aperture radar (SAR) plus satellite multispectral image data to island ecological community type. Ecological community type then was correlated with mean (spatially-averaged) surface elevation (MSL) derived from a 10 m grid digital elevation model (DEM) that was developed from 2010 LiDAR data (**Fig. 2**). On Horn Island only, the establishment of photographic vantage points by means of GPS positioning prior to Hurricane Katrina (Lucas and Carter, 2010) allowed a visual comparison of pre-Katrina (2004-2005) versus post-Katrina (2010) ecological communities.

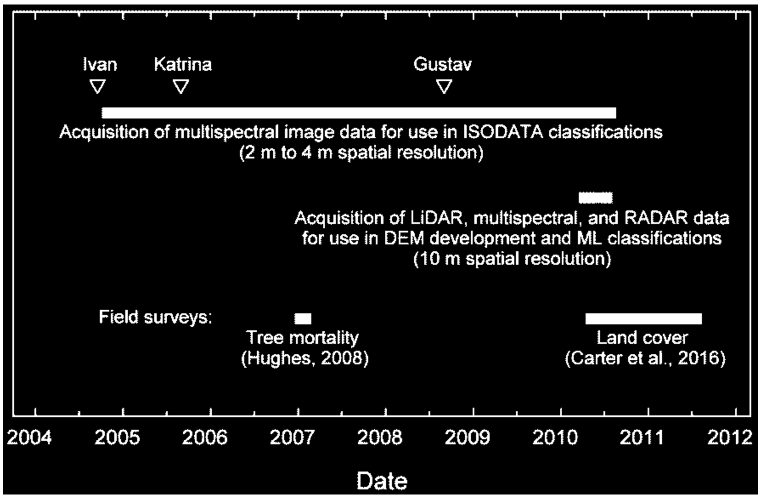


Fig. 2. Time periods for acquisitions of data used in the present study.

3.1.1 Determination of land area and vegetated area changes during Hurricane Katrina and through 2010 at ~ 2 m to 4 m GSD

For each island, total areas of land, vegetation, ponds and unvegetated/sparsely-vegetated sand were determined at high spatial resolutions (~ 2 m to 4 m) from the pre-Katrina and post-Katrina aerial or satellite multispectral imagery (ENVI v4.3, ITT Visual Information Solutions, Boulder, CO). Pre-Katrina image data were acquired less than one year prior to Katrina by the QuickBird (QB) satellite imager (2.4 m resolution, Digital Globe, Inc.). Post-Katrina data acquisition began with IKONOS (IK) satellite imagery (4 m, Space Imaging, Inc.) acquired 7th September 2005, 9 days after Katrina's Mississippi landfall. QB data along with CASI (1.5 m, model 1500, ITRES Research, Inc.), UltraCamX (UCX) (Vexcel Imaging, Inc., resampled to 2 m), and National Agriculture Imagery Program (NAIP) multispectral airborne system imagery (resampled to 2 m; https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs) provided island image coverage for the later dates (**Table 1**) (see Jensen, 2016, for detailed summaries of sensor characteristics). In three cases, including the pre-Katrina imagery of western and central Dauphin Island, imagery recorded for the majority of an island on a primary acquisition date was supplemented, if necessary, with data from 1-2 other acquisition dates to produce a complete island image (see **Table 1** footnotes).

The georectification of each image was compared with known map features. Small adjustments were made if necessary to improve accuracy. Portions of the image which represented waters of the Mississippi Sound or Gulf of Mexico were excluded by masking, so that only the subaerial island, but including island lagoons and freshwater ponds, remained for subsequent analysis. The Normalized-Difference Vegetation Index (NDVI) was computed from near-infrared (NIR) and red band brightness values as: $\mathrm{NDVI} = (NIR - Red)/(NIR + Red)$ for inclusion as a data layer in the multispectral image file. The NDVI, or frequently the NIR band alone, was particularly effective in discriminating among vegetated surface, unvegetated or sparsely-vegetated soil (mostly sand), and water (lagoon or pond). An unsupervised Iterative Self-Organizing Data Analysis Technique (ISODATA) classifier (Jensen, 2016) was applied to the multiband file and three classes, including vegetated surface, unvegetated to sparsely-vegetated sand, and lagoon/pond, were produced. A wet-dry line approach (Hapke et al., 2011) was used to determine the shoreline at the time of image acquisition by digitizing the land-water boundary observed in the multiband imagery. For all but one sampled year, this was facilitated by the typically strong contrast in the NIR band between relatively bright sand or vegetation versus water, which is nearly black in the image owing to almost complete absorption of NIR radiation by water depths of a few cm or greater (Jensen, 2016). The only exception was that year 2009 shorelines of W. Ship, E. Ship, Horn, and Petit Bois islands were digitized using RGB true color imagery because the 2009 NAIP imagery did not included a NIR band.

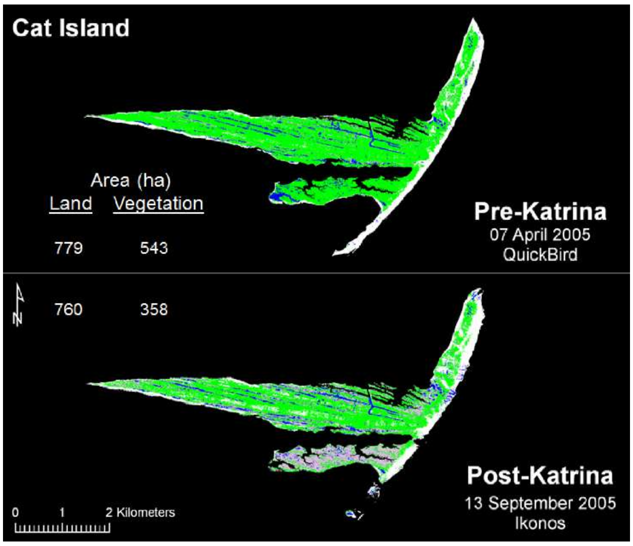


Fig. 3. ISODATA classifications of pre-Hurricane Katrina and post-storm imagery of Cat Island, MS. Such classified maps were used to quantify projected areas of the subaerial island, vegetated surface (green), unvegetated to sparsely-vegetated sand (white), and lagoons/ponds (blue) as they varied from pre-Katrina dates in 2004 or 2005 through July, 2010 (**Table 1**).

Total projected areas (ha) of subaerial land, vegetated surface and lagoons/ponds were determined from the number of image pixels representing the class and GSD as defined by sensor characteristics and image georectification. The area of unvegetated to sparsely-vegetated sand was determined by subtraction as the portion of total island land area not classed as vegetation or lagoon/pond (**Fig. 3**). Under non-storm conditions, the effect of tidal range on the projected subaerial island land areas measured by remote sensing would be expectedly small, on the order of 1 percent or less, for this low-microtidal region (see Results).

3.1.2 Ground Survey of Tree Mortality (2007)

After the first full post-Katrina growing season (2006), mortalities in slash pine (*Pinus elliottii* Engelm.) and sand live oak (*Quercus geminata* Small) on Horn Island were sampled on 9th January – 2nd February 2007, by counting live and dead trees within 25, 2 m x 30 m field quadrats (Hughes, 2008). Some authors consider sand live oak to be synonymous with live oak, *Q. virginiana* Miller, found commonly on the mainland (Radford et al., 1968). Sampling points representing the starting corner of each quadrat (for review of vegetation sampling methods see Barbour et al., 1999) were pre-positioned at random locations within woodland areas containing live or dead trees represented in a 2nd February 2006, QuickBird image of Horn (ENVI v. 4.3). In the field, a Trimble GeoXT model GPS receiver (Trimble, Sunnyvale, CA) was used to navigate to the corner point. Quadrat azimuth direction from the point was assigned by random number (0-359 degrees) and adjusted as necessary to ensure that it would sample a woodland area rather than a treeless community (e.g., marsh or beach backshore dune areas). Tree mortality was sampled by holding a 2 m pole horizontally and perpendicularly to the right side of the azimuth line while walking in the azimuth direction. Trees touched by the pole were counted as alive (green leaves present) or dead (green leaves absent). Percent mortality was computed as (number of dead trees x 100)/total number of trees sampled. Cumulative mortality for each species was determined by re-computing mortality based on data combined among all quadrats as each additional quadrat was sampled. Pine mortality in the much less extensive tree populations of W. Ship, E. Ship and Petit Bois islands was determined by visual inspection during the same time period to be 100%.

3.1.3 Mapping year 2010 ecological communities at 10 m GSD

A map of ecological community types present in 2010 was developed for each island by supervised classification of 10 m GSD, 3-band image data (ENVI v4.8, Exelis Visual Information Solutions, Boulder, CO). The image file was constructed by fusing 10 m NIR and red spectral data from the SPOT 5 HVNIR sensor (SPOT Image Corp.) with the horizontal-send, vertical-receive (HVHV) cross-product derived from L-band Synthetic Aperture Radar (UAVSAR, NASA, JPL). The HVHV band was selected because of its sensitivity to vegetation features (e.g., Jensen, 2016). The Maximum Likelihood (ML) classifier was used to produce the ecological community-type map of each island because of its accuracy and broad acceptance among users (Jensen, 2016). Selection of training (ground truth) pixels for the ML procedure was based on the 2010-2011 ground survey (Carter et al., 2016). At least five 10 m pixels were selected per ground truth sample point to become training data in the ML procedure. Class names followed or were modified from those described by the Mississippi Natural Heritage Program (2006):

- Unvegetated/sparsely-vegetated sand

This broad class includes areas in which the sky-exposed ground surface is comprised of quartz sand that may be mixed with shells, shell fragments, dark heavy mineral-enriched sand, or organic debris. It also incorporates sparsely-vegetated community types such as dry herblands, i.e., community types that are characterized by a low density of live plants per unit ground area and a sky-exposed surface that is more unvegetated than plant-covered. More specifically to the present study, the class was defined by image pixel brightness values, each representing the average brightness of a ground area defined by GSD (e.g., 4 m for IKONOS or 10 m for SPOT 5). Thus, the unvegetated/sparsely-vegetated class included ground areas that were covered partially by vegetation, but given the pixel GSD, remained spectrally indistinguishable from bare quartz sand, or mixtures of quartz sand with dark mineral sand, other non-plant materials, or organic debris. Such areas were assigned to the unvegetated/sparsely-vegetated sand class by either the unsupervised ISODATA or supervised ML algorithm. Pixel brightness values representing unvegetated sand or the following community types could be similarly high. Thus, they all were assigned to the unvegetated/sparsely-vegetated sand class because they could not be distinguished from each other consistently throughout the barrier chain when the same classification procedure was applied for all islands at 10 m GSD.

- Dry herblands are found generally on the highest, oldest interior ridge plains. Dominant plant species include woody goldenrod (*Chrysoma pauciflosculosa* [Michx.] Greene), rockrose (*Helianthemum arenicola* Chapm.), and beach rosemary *(Ceratiola ericoides* Michx.). These herblands include the stable dune community type described earlier for Horn Island (Lucas and Carter, 2008; 2010; 2013; Lucas et al., 2010).

- Backshore herblands include sparsely-vegetated foredune and backshore dune ridges, backshore and interior sand plains of eolian and washover origin, washover fans and emerged supratidal sand flats. Dominant species include sea oats (*Uniola paniculata* L.), beach morning glory (*Ipomoea imperati* [Vahl] Griseb.), rockrose, and gulf bluestem (*Schizachyrium maritimum* [Chapm.] Nash) along with occasional wax myrtle (*Morella cerifera* [L.] Small). This community type includes the beach dune and beach-dune complex types described earlier for Horn Island (Lucas and Carter, 2008; 2010; 2013; Lucas et al., 2010).

- Intertidal sand flats form after shoal areas aggrade to intertidal level, and later to above high tide (Otvos and Carter, 2008). These occurred on W. and E. Ship, Horn, Petit Bois and Dauphin islands. Because they usually are colonized by algae, occasionally they are designated as algal flats (e.g., Anderson et al., 2016). A cyanobacterial film on an emerging Frisian Coast barrier island in northwest Germany (Wehrmann and Tilch, 2008) was shown to contribute to the stabilization of low intertidal-supratidal sand flats.

- Woodland

Woodlands are dominated by slash pine with occasional sand live oak (*Quercus geminata* Small), eastern baccharis *(Baccharis halimifolia* L.), wax myrtle, yaupon (*Ilex vomitoria* Aiten), and torpedo grass (*Panicum repens* L.), along with occasional marsh elder (*Iva frutescens* L.). They occur in the WNW-trending, old strandplain ridges of Cat Island and in the beach ridge plains of inactive dune ridges on Horn, as well as high dunes along the landward margin of the backshore herbland zone of northeastern Cat. Flooding and mechanical damage from Hurricane Katrina and low rainfall amounts for several months after the storm temporarily eliminated the woodland community type from E. Ship and Petit Bois.

- Wet herbland/shrubland

Wet herbland/shrubland is predominant in island interiors above high tide level in low areas between the oldest northern and central strandplain ridges on Cat, W. Ship, Horn and Petit Bois islands, and low areas landward of the elevated backshore zone on these islands. Dense stands of saltmeadow cordgrass (*Spartina patens* [Aiton] Muhl.) and torpedo grass dominate while stands of eastern baccharis, yaupon, and wax myrtle are widespread and vary greatly in density. Cattail (*Typha spp.*) occurs around interior freshwater ponds. Wet herbland/shrubland includes the moderately wet, transitional meadow category described earlier for Horn Island (Lucas and Carter, 2008; 2010; 2013; Lucas et al., 2010) and the high marsh category described earlier for Cat Island (Funderburk et al., 2016). A narrow, dense zone, typically composed of eastern baccharis and yaupon, occasionally with wax myrtle and marsh elder, skirts the inland, high-tide margins of low marshes and occasionally of the backshore zone. As the marsh expands, its shrubland fringe shifts toward the island interior. The process is reversed when sediments fill marshes. Sand accumulation due to eolian and overwash processes, particularly in backshore and wet herbland areas, raises surface elevation and initiates or expands shrub vegetation. Landward expansion of shrub-edged backshore zones results in a widened shrubland belt.

- <u>Low (saline to brackish) marsh</u>

Low (saline to brackish) marshes skirt lagoons connected to the Mississippi Sound (e.g., northern Horn Island and east, southeast-trending dune-swale system on Cat Island). Smooth cordgrass (*Spartina alterniflora* Loisel) occupies the lower elevation land-water interface. Needlegrass rush, known also as black needle rush (*Juncus roemerianus* Scheele) replaces smooth cordgrass as distance from shoreline and elevation increase. Saltmeadow cordgrass (*S. patens* [Aiton] Muhl.), preferring less salty areas and more access to fresh water, occurs at higher elevations and invades shrublands and woodlands. *S. patens* grass plains dominate the subsiding E-W and WNW-ESE-trending relict dune ridges in the northern and southernmost Cat Island strandplain areas. The narrow banks of parallel intervening flooded swale-embayments (**Fig. 4;** see also Funderburk et al., 2016, journal cover photo and caption, to view a more extensively flooded condition and a description of the plant community zonation) are also overlain by a very narrow and low smooth cordgrass zone. Initiating the transition and habitat conversion to higher elevation marginal shrubland, sediment delivered by occasional storm- or daily flood-tide and wave-related processes may fill the low marshes.

- Lagoon/pond

Island lagoons and ponds were established usually in elongated swales located between semi-parallel beach ridges. The most recently-formed swales frequently remain connected to open water by tidal passes on northern and southern island shores formed by relatively recent intertidal-supratidal beach ridge growth driven by longshore sediment transport. Shore erosion may gradually shift active foredune ridges toward island interiors by inland-directed overwash and wind processes that fill backshore lagoons and ponds in the rear. Unless the opposite (lagoonal, respectively, oceanic) shore is simultaneously undergoing progradation, the retreat would result in narrower barrier islands. Ponds in island centers contain fresh water. The long, narrow, semi-parallel, locally disintegrating brackish embayments in central and western Cat Island, located on the flank of the subsiding Mississippi – St. Bernard subdelta, originated as marshy inter-ridge swales that were gradually invaded by the sea and drowned (**Fig. 4**). Where isolated and exposed to higher waves, these landforms were subjected to severe shore erosion.

Fig. 4. Eastward view of a subsiding inter-ridge swale, central Cat Island strandplain at low tide, July 12, 2013. The swale was invaded and partially filled by seawater. Both banks display ecological community zonation: (1) lagoon/pond; (2) low (saline to brackish) marsh; (3) wet herbland/shrubland; (4) woodland, and (5) unvegetated/sparsely-vegetated sand. Photograph by G. Carter.

3.2 Determining the relationship of ecological community type with surface elevation at 10 m GSD.

The method of comparing ecological community type with ground surface elevation largely followed Gibeaut et al. (2003). Digital elevation models (DEM) were constructed for the MS islands from 1 m GSD, multiple-return, 1064 nm wavelength LiDAR data (LAS 1.2 format, SHOALS 3000T, OpTech, Inc.) that were resampled to match the 10 m resolution of the ecological community classification maps (ArcGIS v10.0, ESRI, Redlands, CA). Point clouds were created using laser returns classified as ground returns. The ground-return point cloud then was converted into a 10 m resolution DEM in raster format by computing mean elevation per 10 m grid cell. Any data voids which resulted from extracting only ground returns were filled using the mean value within a 5 x 5 nearest-neighbor moving window in multiple separate iterations (Funderburk et al., 2016). A DEM for western and central Dauphin Island was not constructed because year 2010 LiDAR coverage for the island was not available at the time of analysis.

Individual island ecological community-type maps were co-registered with their respective 2010 DEM (ArcGIS v10.2). For each island, elevation bins of 0.3 m increments were created and random sample points were assigned at a density of one point per ha of land area associated with a given bin. For example, a 0.0 m – 0.3 m elevation bin representing 500 ha of land area would be assigned 500 random sample points. Random sample points were then classified by their corresponding ecological community type and an elevation determined from the underlying DEM. This procedure ensured no over- or under-sampling of any particular ecological community type. A total of 2665 points were sampled throughout the MS barrier chain (Cat, E. and W. Ship, Horn, and Petit Bois islands).

4. Results

4.1 Total land and total vegetated land areas prior to and after Hurricane Katrina through 2010

4.1.1 Inferred storm impact and the initial three years after Katrina

In Hurricane Katrina, the MS islands and western and central Dauphin Island were exposed to hurricane-force winds of several hours in duration, and submersion under historically unprecedented storm tides (Fritz et al., 2007; 2008). Comparisons of pre-Hurricane Katrina classified imagery with the 13th September 2005 post-storm data indicated net erosion of land area from all islands except Petit Bois, which was greater in area by 4 ha, or one percent, of its pre-storm area (**Table 1, Fig. 5**). The greatest immediate loss in land area, 77 percent, occurred on E. Ship Island (**Fig. 5**). Details regarding post-storm erosional features have been described elsewhere (Feagin and Williams, 2008; Morton, 2008; 2010; Otvos and Carter, 2008; Eisemann et al., 2018). Vegetation cover was reduced on all islands, with initial reductions ranging from

11% on W. Ship Island to 37% on Petit Bois Island. Lagoon/pond areas had increased on most islands two weeks after the storm, while they decreased on E. Ship and Horn islands. Areas of unvegetated/sparsely-vegetated sand increased on the larger islands, but were reduced on the smaller western and central Dauphin and W. and E. Ship islands.

Tidal range along the MS-AL coast is classified as low-microtidal; 0.5 m is a reasonable approximation. A simple geometric model indicates that given a foreshore slope of 10 percent, the water line would move 5 m inland with a 0.5 m rise in water level. For a 50 ha rectangle, approximately the area of post-Katrina E. Ship Island (**Table 1**), this change would reduce the projected subaerial area of the island by 0.7 ha, or 1.4 percent of the total island area. For a 1,300 ha rectangle, approximating the area of pre-Katrina Horn Island, the same water level rise would reduce island projected subaerial area by 3.6 ha, or only 0.3 percent of island total area. Foreshore slopes greater than 10 percent would result in even smaller water-level-induced changes in subaerial land area. In comparison, the total land areas of Cat, W. Ship, E. Ship, Horn, Petit Bois, and western and central Dauphin islands were 2, 7, 6, 2, 5, and 3 percent less, respectively, on 7th September than on 13th September 2005 (**Table 1**). This indicated that each island remained partially flooded for at least nine days after the storm.

February 2006 imagery was available only for Cat, W. and E. Ship and Horn islands. However, its classification indicated that in the first five months after the storm, the vegetated area continued to decline on Cat, W. Ship and E. Ship islands while it increased on Horn Island (**Table 1**). In the same period, the land area was 26 percent of the pre-storm area on E. Ship Island but exceeded 90 percent in Cat, W. Ship and Horn islands (**Fig. 5**). Simple regressions (y = a + bx) of **Table 1** data combined among all islands and sample dates indicated linear relationships with island total land area (x) when: y = unvegetated/sparsely-vegetated sand area

($r^2 = 0.87$, a = 36.89, b = 0.42, and standard deviation of the regression, $s = 67.42$ ha); y = lagoon/pond area ($r^2 = 0.89$, a = -12.59, b = 0.09, and $s = 13.52$ ha), and y = vegetated land area ($r^2 = 0.91$, a = -24.56, b = 0.49, and $s = 62.98$ ha).

Table 1

Pre- and post- Hurricane Katrina areas of unvegetated/sparsely-vegetated sand, lagoons and ponds, vegetated land, and total land on the MS-AL barrier islands, along with image acquisition date, sensor system, and time elapsed (Δt) since Hurricane Katrina's Mississippi landfall on 29th August 2005. Areas were determined by image georectification and the ISODATA classification procedure.

			Area (ha)			
Image date	Sensor	Δt (y) from 2005-08-29	Unvegetated/sparsely-vegetated sand	Lagoon/pond	Total vegetation	Total land
			Cat Island			
2005-04-07	QB	-0.39	185.9	50.6	542.6	779.2
2005-09-07[a]	IK	0.02	-------	------	-------	749.6
2005-09-13	IK	0.04	344.5	58.7	357.5	760.7
2006-02-02	QB	0.43	359.6	72.4	328.9	760.9
2007-11-10,12	CASI	2.20	312.8	47.1	392.5	752.4
2008-09-16	QB	3.05	188.3	69.3	462.8	720.4
2010-07-28	UCX	4.91	171.9	46.0	500.7	718.5
			West Ship Island			
2005-01-25	QB	-0.59	122.7	1.8	82.5	207.9
2005-09-07[a]	IK	0.02	-------	-----	-------	163.8
2005-09-13	IK	0.04	95.9	6.0	73.4	175.8
2006-02-02	QB	0.43	118.2	7.3	65.6	191.8
2007-11-13	CASI	2.21	109.9	6.5	79.3	196.4
2008-07-24[b]	QB	2.90	99.5	4.3	83.3	187.9
2009-08-24[c]	NAIP	3.99	-------	----	------	188.4
2010-07-28	UCX	4.91	100.4	3.4	76.7	181.3
			East Ship Island			
2005-01-25	QB	-0.59	171.8	8.6	18.3	198.7
2005-09-07[a]	IK	0.02	-------	-----	------	42.9
2005-09-13	IK	0.04	26.4	5.5	13.8	45.6
2006-02-02	QB	0.43	37.7	4.5	9.7	52.0
2007-11-13	CASI	2.21	48.9	3.6	14.1	66.5
2008-07-24	QB	2.90	47.3	2.5	15.6	65.4
2009-08-24[c]	NAIP	3.99	-------	-----	------	79.1
2010-07-28	UCX	4.91	61.8	7.6	6.2	75.7
			Horn Island			
2005-04-07	QB	-0.39	524.7	156.7	637.1	1318.5

2005-09-07[a]	IK	0.02	-------	-------	------	1251.5
2005-09-13	IK	0.04	689.4	87.5	501.2	1278.0
2006-02-02	QB	0.43	616.3	102.6	557.0	1275.9
2007-11-16	CASI	2.21	618.3	107.1	592.1	1317.5
2008-07-01[d]	QB	2.84	614.7	93.1	600.1	1307.9
2009-06-20[c]	NAIP	3.81	-------	-------	-------	1265.4
2010-07-28	UCX	4.91	614.3	91.6	556.3	1262.2
Petit Bois Island						
2004-10-27	QB	-0.84	213.3	10.0	173.2	396.5
2005-09-07[a]	IK	0.02	-------	-------	-------	382.2
2005-09-13	IK	0.04	278.9	12.4	109.2	400.4
2007-11-16,19	CASI	2.21	256.1	14.1	142.3	412.5
2008-05-08	QB	2.69	207.7	16.6	144.4	368.8
2009-06-20[c]	NAIP	3.81	-------	------	-------	363.8
2010-07-28	UCX	4.91	232.4	11.3	136.8	380.5
Western and Central Dauphin Island						
2004-12-15[e]	QB	-0.70	284.4	4.8	100.1	389.2
2005-09-07[a]	IK	0.02	-------	------	-------	317.6
2005-09-13	IK	0.04	237.4	15.9	75.5	328.8
2008-05-31	QB	2.75	246.6	6.3	102.2	355.0
2010-04-09	CASI	4.61	244.8	5.9	92.4	343.0

Date: yyyy-mm-dd

[a] Only total land area is shown for 7th September 2005, nine days after the Mississippi landfall of Hurricane Katrina, because each island remained partially flooded. Subaerial land area on Cat, W. Ship, E. Ship, Horn, Petit Bois, and western and central Dauphin islands was 2, 7, 6, 2, 5, and 3 percent less, respectively, on 7th September than on 13th September 2005.

[b] QB data acquired on 24th July 2008 covered 85% of the island area. QB data acquired on 16th September 2008 were used to cover the remaining 15% of total land area.

[c] Only total land areas were determined because the image data did not include a near-infrared band.

[d] QB data acquired on 1st July 2008 covered 79% of the island area. QB data acquired on 8th February 2008 were used to cover the remaining 21% of total land area.

[e] QB data acquired on 15th December 2004 covered 76% of the island area. Data acquired by QB on 8th May 2005, and by Landsat 5 TM on 27th May 2005, were used to cover the remaining 21% and 3%, respectively, of total land area.

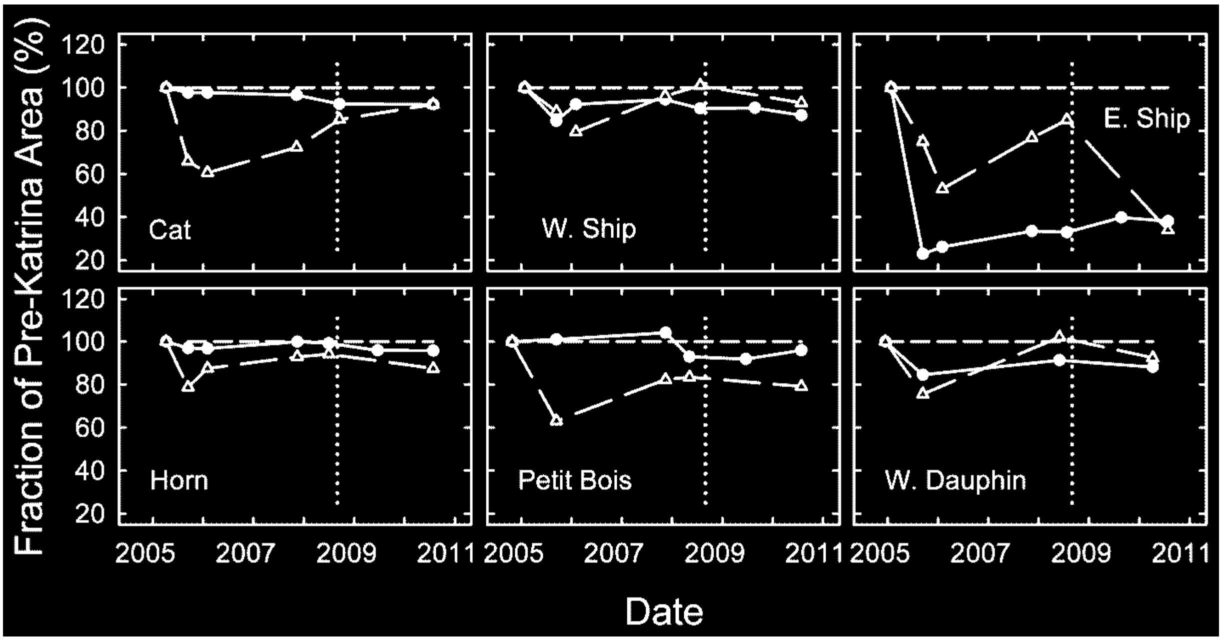


Fig. 5. Island total land (closed circles) and vegetated (open triangles) areas as percentages of pre-Katrina values for the 2004-05 to 2010 period. The horizontal dashed line in each graph represents the pre-Katrina reference value of 100%. The vertical dotted lines indicate the 1st September 2008 landfall date of Hurricane Gustav.

With respect to island total land area, the greatest mean rate of change (i.e., rate of change over the given elapsed time, **Table 2**) during the 0.39 years from 13th September 2005 to 2nd February 2006 occurred on the smallest islands, W. and E. Ship. Overall minimum and maximum mean rates of change for the period were represented by the -188 ha/y loss in unvegetated/sparsely-vegetated sand, and the 144 ha/y gain in vegetated area on Horn Island. Due to the unavailability of February 2006 imagery, rates of change over this period could not be computed for Petit Bois and western and central Dauphin islands.

The January 2007 field surveys indicated post-storm slash pine mortalities of 80% on Horn Island by quadrat sampling (**Fig. 6**) and 100% in the much less extensive tree populations of W. Ship, E. Ship and Petit Bois islands by visual inspection. Tree loss, and vegetation loss in general, could have been caused by any number of parameters or their combination, including salt spray, saltwater flooding, direct mechanical damage such as defoliation, breakage of limbs and main trunks, and bark ablation by floating debris (Fritz et al., 2007; 2008), removal of plants along with the soil substrate by scouring, burial under sand, a floodwater persistence of at least nine days on some portions of the islands (see **Table 1** footnote regarding 7th September 2005 land areas), and a 10-month, post-storm period of low rainfall (**Fig. 7**). On Horn Island, cumulative slash pine mortality reached a nearly constant value of 80% once the 19th quadrat had been sampled (*n*=178 trees), indicating an adequate sample size (Barbour et al., 1999). Nevertheless, sampling continued until 25 quadrats had been sampled. Sand live oak mortality reached a value of 27% when quadrat 25 was sampled (**Fig. 6**). However, relatively few oaks, only approximately one for every 18 pine trees, were encountered. Whereas 24 of the 25 quadrats included pines (*n*=196), only four quadrats included sand live oak (*n*=11 trees). Thus, 25 quadrats were not adequate for sampling the mortality of sand live oak. Assuming the same mean frequency of 0.44 oaks per quadrat, and that, as in pine, a sampling of 178 oaks would have been required to reach a constant mortality value, 405 quadrats would have been required to provide a more reliable estimate of mortality in sand live oak. Furthermore, the assessment of sand live oak mortality by its appearance can be deceptive. In contrast to slash pine, which does not sprout new shoots from roots or stems after it is damaged (see Del Tredeci, 2001, for a review of sprouting), some of the sand live oak trees on E. Ship Island which remained leafless for 1-2 years after the storm eventually sprouted new foliage from roots, the main trunk and limbs, often yielding a shrub-like growth form early in the re-growth period.

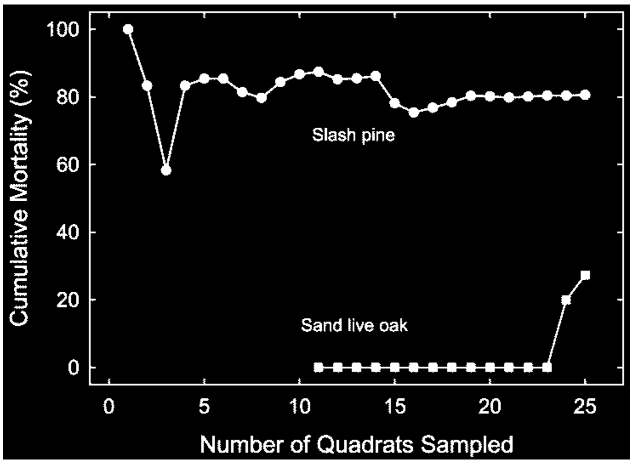


Fig. 6. Slash pine and sand live oak mortality on Horn Island during the period of 9th January – 2nd February 2007, approximately 1.4 y after Hurricane Katrina (Hughes, 2008). Live trees (green needles present) and dead trees (needles brown or absent) were counted within each of 25 randomly-positioned, 2 m x 30 m quadrats.

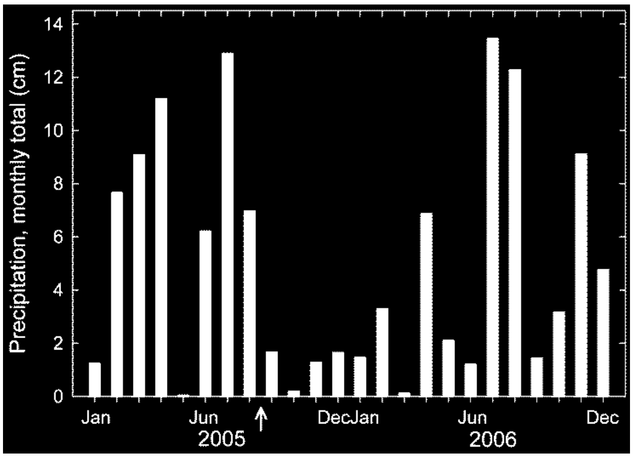


Fig. 7. Total monthly precipitation (rainfall) indicating low rainfall along the MS coast in the first 10 months following Hurricane Katrina, 2005-06. Data from Keesler Air Force Base, Biloxi, MS (http://www.wunderground.com/history/airport/kbix), accessed 5th October 2017). Arrow along horizontal axis indicates 29th August 2005, the landfall date of Hurricane Katrina.

By November 2007, 2.2 years after Hurricane Katrina, land area had grown to 97, 94, 33, 100, and 104 percent of pre-Katrina values on Cat, W. Ship, E. Ship, Horn, and Petit Bois islands, respectively. This growth occurred by natural accretion processes, including onshore and alongshore sediment transport by waves and currents and storm overwash action. This did not include any man-made area enhancement by dredged sand placement. In the same period, vegetated area had increased to 72, 96, 77, 93, and 82 percent of pre-Katrina values. Mean rates of change from 13th September 2005 to November 2007 were greatest on Horn Island (**Table 2**). Lagoon/pond, vegetated, and total land areas grew at 9.0, 41.8, and 18.1 ha/y, while unvegetated/sparsely-vegetated sand declined at -32.7 ha/y. High rates of vegetation increase and decline in unvegetated/sparsely-vegetated areas were likely a result of vegetation re-growth in overwashed areas, with absolute magnitudes in re-growth rates expectedly greatest on Horn, the largest of the MS islands.

In the period from approximately 2.5 – 3 y after Hurricane Katrina, and prior to the 1st September 2008 landfall of Hurricane Gustav 150 km – 200 km west of the MS islands, QB data provided complete 2008 coverage of all islands except W. Ship and Cat (**Table 1**). Partial coverage of W. Ship Island and complete coverage of Cat Island was acquired after Hurricane

Gustav on 16th September 2008. The 2008 data indicate that vegetated land area had increased steadily from late 2005-early 2006 until the respective 2008 sampling date for each island (**Table 1, Fig. 5**). However, vegetated land area had grown to equal or exceed pre-Katrina vegetated area only on W. Ship and western and central Dauphin, at mean growth rates of 3.5 ha/y and 9.8 ha/y, respectively (**Fig. 5, Table 2**). In contrast, land areas in 2008 had changed more erratically than did vegetated area, and never reached pre-Katrina values (**Tables 1, 2; Fig. 5**).

Table 2

Post- Hurricane Katrina mean rate of change in unvegetated/sparsely-vegetated sand, lagoon/pond, vegetated land, and total land areas on the MS-AL barrier islands, given image acquisition date and time elapsed (Δ*t*) since the 13th September 2005 acquisition date.

		Mean Rate of Change since 2005-09-13 (ha/y)			
Image date[a]	Δ*t* (y) from 2005-09-13	Unvegetated/sparsely-vegetated sand	Lagoon/pond	Vegetated land	Total land
		Cat Island			
2006-02-02	0.39	39.0	35.1	-73.6	0.5
2007-11-10	2.16	-14.7	-5.4	16.2	-3.8
2008-09-16	3.01	-51.9	3.5	35.0	-13.4
2010-07-28	4.87	-35.4	-2.6	29.4	-8.7
		West Ship Island			
2006-02-02	0.39	57.4	3.3	-20.0	41.1
2007-11-13	2.17	6.5	0.2	2.7	9.5
2008-07-24	2.86	1.3	-0.6	3.5	4.2
2009-08-24	3.95	*	*	*	3.2
2010-07-28	4.87	0.9	-0.5	0.7	1.1
		East Ship Island			
2006-02-02	0.39	29.2	-2.4	-10.4	16.4
2007-11-13	2.17	10.4	-0.9	0.2	9.7
2008-07-24	2.86	7.3	-1.1	0.6	6.9
2009-08-24	3.95	*	*	*	8.5
2010-07-28	4.87	7.3	0.4	-1.5	6.2
		Horn Island			
2006-02-02	0.39	-188.0	38.8	143.6	-5.6
2007-11-16	2.17	-32.7	9.0	41.8	18.1
2008-07-01	2.80	-26.7	2.0	35.4	10.7
2009-06-20	3.77	*	*	*	-3.4
2010-07-28	4.87	-15.4	0.8	11.3	-3.3
		Petit Bois Island			
2007-11-16	2.17	-10.5	0.8	15.2	5.6
2008-05-08	2.65	-26.9	1.6	13.3	-12.0

2009-06-20	3.77	*	*	*	-9.7
2010-07-28	4.87	-9.5	-0.2	5.7	-4.1
Western and Central Dauphin Island					
2008-05-31	2.71	3.4	-3.5	9.8	9.7
2010-04-09	4.57	1.6	-2.2	3.7	3.1

Date: yyyy-mm-dd

[a] See image date footnotes, **Table 1**.

* Values were not determined because near-infrared data were not available.

4.1.2 Impact of Hurricane Gustav (2008)

Hurricane Gustav exposed the MS-AL islands to tropical storm-force winds on 1st September 2008 (Doran et al., 2009; Anderson et al., 2016). With the exception of a 122 m mean retreat on E. Ship Island, mean shoreline retreat generally ranged 8 – 15 m between W. Ship Island and Petit Bois islands (Stockdon et al, 2010). However, shoreline change was highly variable, and locations of erosion, accretion and no-change were observed on each island (Stockdon et al., 2010). Overall, this resulted in small net effects on island land areas measured from post-Gustav image data (**Table 1, Fig. 5**). While land area did not change on W. Ship Island, it decreased on the remaining islands and increased on E. Ship (Anderson et al. 2016; Eismann et al., 2018). Also following Gustav, vegetated area had increased on Cat but declined on all other islands. Although E. Ship gained total land area, approximately 90 percent of its low-elevation beach dune herbland area was lost due to erosion and overwash (Anderson et al., 2016).

4.1.3 Five years after Hurricane Katrina and two years after Hurricane Gustav

By five years after Hurricane Katrina and two years after Hurricane Gustav (2010), total land area of Cat, W. Ship, E. Ship, Horn, Petit Bois and western and central Dauphin islands had recovered to 92, 87, 38, 96, 96 and 88 percent, and total vegetated land area to 92, 93, 34, 87, 79 and 92 percent of pre-Katrina values, respectively (**Fig. 5**). However, land and vegetated areas in April-July 2010 remained less than the peak values attained by natural accretion and re-growth prior to Gustav (**Table 1, Fig. 5**). The exception was Cat Island, where land area declined and vegetated area increased steadily in the period from 13th September 2005 through 2010.

Before Hurricane Katrina, the percentage of island land area covered by vegetation was greatest on Cat Island (70%) and least on E. Ship Island (9%) (**Fig. 8**). Values for W. Ship, Horn, Petit Bois, and western and central Dauphin islands were 40%, 48%, 44%, and 26%, respectively. After Katrina, vegetation declined generally. Unvegetated/sparsely-vegetated land became more extensive with respect to total island area. However, vegetation recovered until reaching nearly pre-Katrina values just prior to Hurricane Gustav, or in the case of Cat Island, shortly after Gustav. The exception was E. Ship Island, where vegetated and unvegetated/sparsely-vegetated land did not reach pre-Katrina percentages of total island land area until 4.9 years after Katrina. Percent of total island area represented by lagoons/ponds remained low and constant compared with percentage values of vegetated and unvegetated/sparsely-vegetated land (**Fig. 8**).

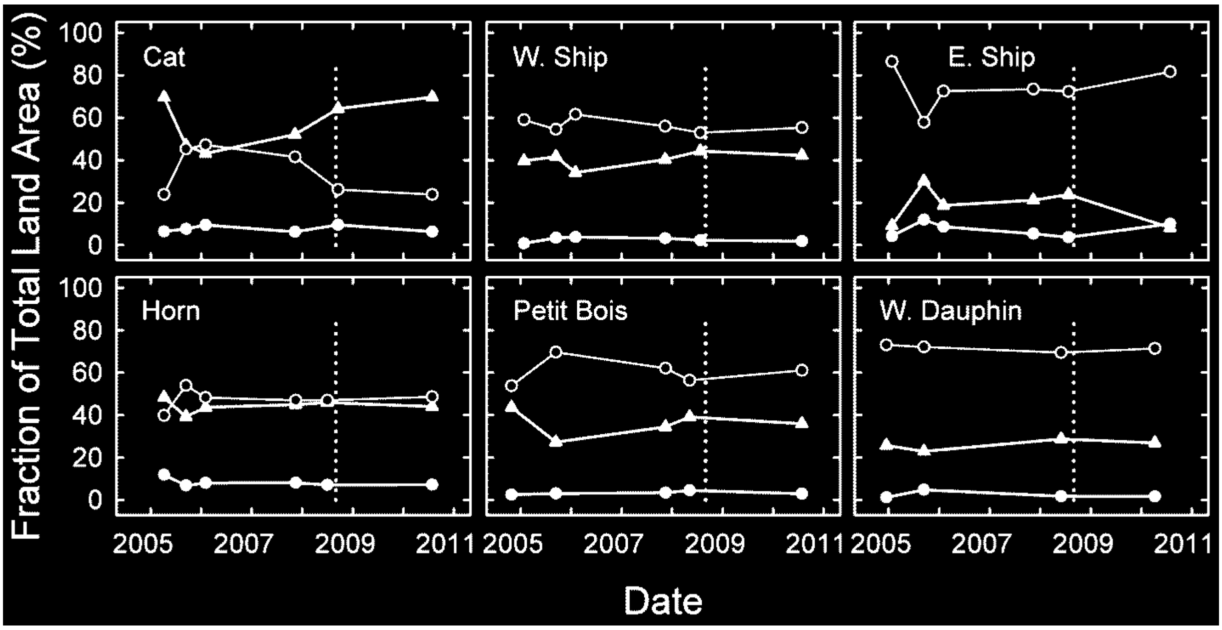


Fig. 8. Area of vegetated land (triangles), unvegetated/sparsely-vegetated sand (open circles), and lagoons/ponds (closed circles) shown as a percentage of island total land area on the given image date. The vertical dotted lines indicate the 1st September 2008 landfall date of Hurricane Gustav. The area of unvegetated/sparsely-vegetated sand was determined as total island area – (vegetated area + lagoon/pond area) (**Table 1**). Thus, because lagoon/pond area remained small, the percentages shown to represent the relative coverage by unvegetated/sparsely-vegetated sand tended to mirror those representing the relative coverage by vegetation.

4.2 Island ecological communities five years after Hurricane Katrina

The 2010, 10 m imagery was classified by the Maximum Likelihood procedure into the broad ecological community classes of unvegetated/sparsely-vegetated sand, woodland, wet herbland/shrubland, low (saline to brackish) marsh, and lagoon/pond (**Table 3; Fig. 9**).

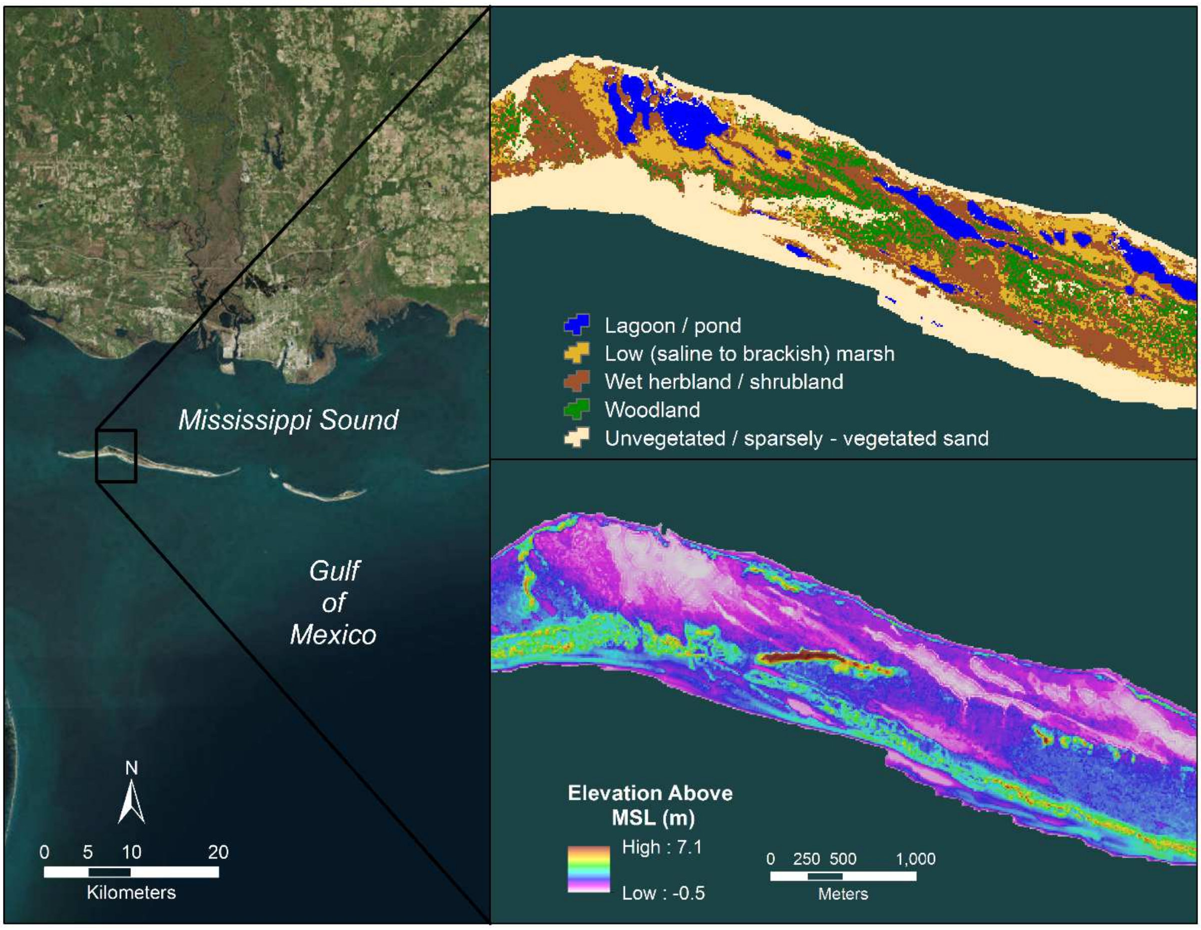


Fig. 9. Classification results for a segment of western Horn Island illustrating an ecological community-type map (upper right) and digital elevation model (DEM, lower right) produced at 10 m horizontal ground resolution (GSD). The community-type map was derived from Maximum Likelihood classification of fused SPOT 5 (red and near-infrared spectral bands) + UAVSAR data. The DEM was developed from LiDAR data.

Maximum Likelihood community-type classifications produced accuracies of 88, 98, 100, 81, 93, and 93 percent among the islands, respectively (**Table 3**). For the MS islands, median MSL elevations associated with these community classes ranged only from 0.1 m to 1.2 m. Community type changed distinctively with decimeter-scale changes in elevation (**Fig. 10**). Island lagoon/pond, low marsh, wet herbland/shrubland, woodland, and unvegetated/sparsely-vegetated sand were associated with mean elevations (+/- one standard deviation of the mean) of 0.1 (0.2) m, 0.6 (0.4) m, 0.9 (0.4) m, 1.0 (0.4) m, and 1.2 (0.7) m, respectively. Unvegetated/sparsely-vegetated sand communities were most variable in elevation, with geomorphic features ranging from intertidal sand flats to interior beach ridge plains. Photographs acquired during earlier field studies (Lucas and Carter, 2010; Carter et al., 2016) provide visualization of post-Katrina transitions in ecological community type (**Figs. 11, 12**).

Table 3

Ecological community-type coverage on the Mississippi-Alabama barrier islands in 2010 determined from ML classification of SPOT5+UAVSAR data.

	Area (ha)					
	Cat	W. Ship	E. Ship	Horn	Petit Bois	Dauphin
Community type						
Unvegetated/sparsely-vegetated sand	128.10	114.78	73.61	627.70	257.93	274.41
Woodland	151.93	*	*	91.55	*	*
Wet herbland/shrubland	196.46	73.84	7.21	393.87	94.82	65.35
Low (saline to brackish) marsh	241.52	*	*	130.86	34.59	6.43
Lagoon/pond	19.99	1.56	1.26	54.45	8.72	3.60
Total land	738	190.18	82.08	1298.43	396.06	349.79
Accuracy						
Overall	88.01	98.00	100	80.75	93.45	92.82
Kappa	0.84	0.97	1.0	0.75	0.87	0.86

* Not extensively present on the island.

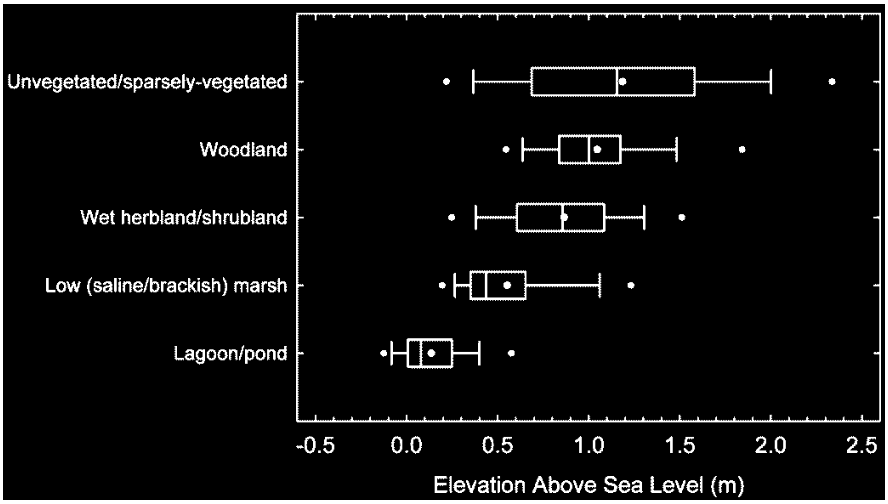


Fig. 10. Relationship of ecological community type with ground elevation above sea level along the Mississippi barrier chain from Cat to Petit Bois islands. Data sub-sampled from vegetation maps and corresponding digital elevation models (e.g., **Fig. 9**) were combined among all Mississippi barrier islands except W. Petit Bois Island. Elevation data for 2010 were not available for Dauphin Island at the time of analysis. The point and vertical line inside each box represent mean and median elevation, respectively, for the community type. The box represents the central 50% of data values. Error bars and outlier points represent the 10th and 90th and 5th and 95th percentiles, respectively, of the data. Island lagoon/pond, low marsh, wet herbland/shrubland, woodland, and unvegetated/sparsely-vegetated sand were associated with mean elevations (+/- one standard deviation of the mean) of 0.1 (0.2) m, 0.6 (0.4) m, 0.9 (0.4) m, 1.0 (0.4) m, and 1.2 (0.7) m, respectively.

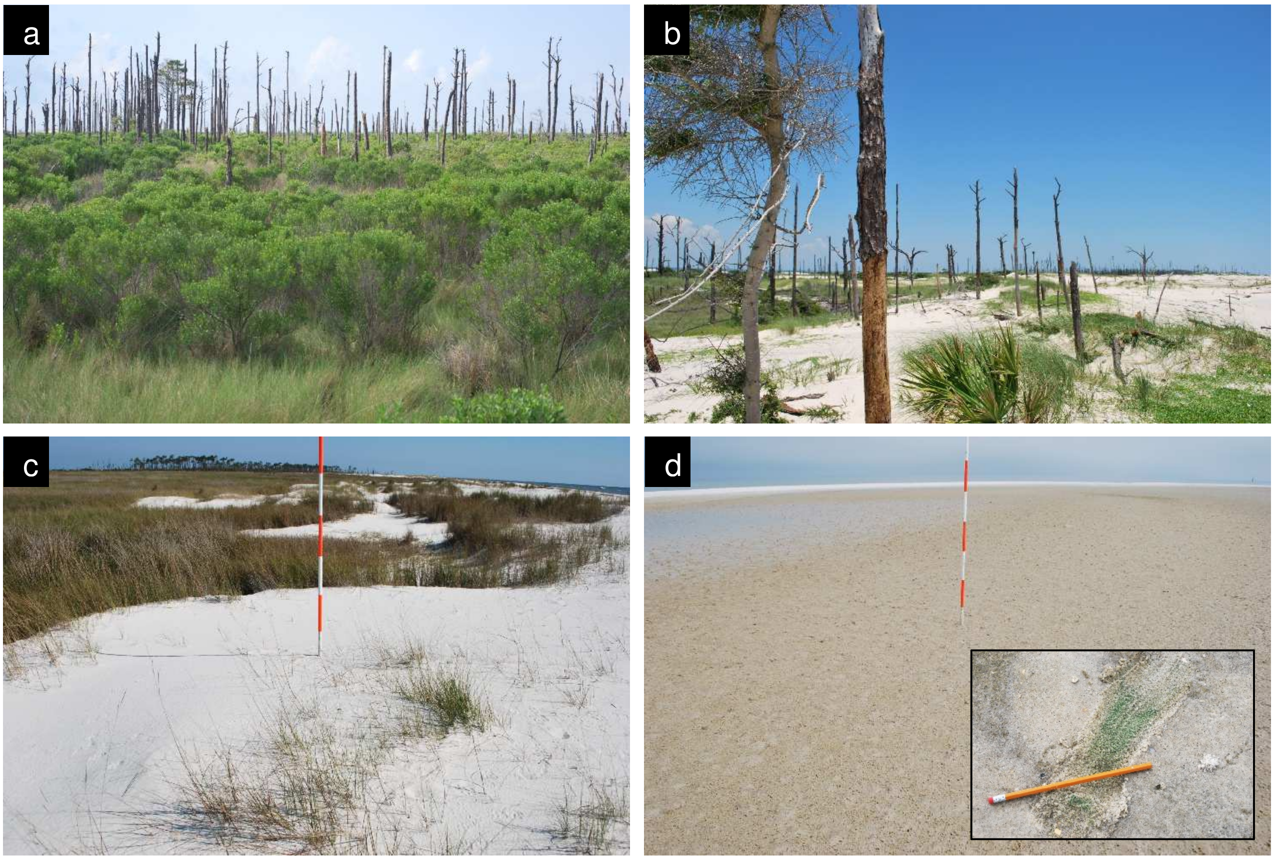


Fig. 11. Examples of post-Katrina changes in ecological communities on the MS-AL islands: (a) woodland to wet herbland/shrubland (Horn Island, 6th May 2010); (b) woodland (left two-thirds of photo) to unvegetated/sparsely-vegetated sand (backshore dry herbland, Horn Island, 9th June 2010); (c) low marsh to unvegetated/sparsely-vegetated sand (backshore dry herbland, Horn Island, 8th July 2010), and (d) submerged shoal to unvegetated/sparsely-vegetated sand (intertidal sand flat, (Cat Island, 28th January 2011). Intertidal sand flats (d) are sometimes referred to as algal flats because algae grow on or immediately beneath the sand surface and serve to stabilize sand (Wehrmann and Tilch, 2008) (inset shows pencil for scale and scraped

sand surface revealing blue-green-colored algae, E. Dauphin Island sand flat, 19th November 2010). In (c) and (d), the length of each orange or white segment of the range pole was approximately 0.3 m (1 ft.). Additional ground photos may be downloaded with the database described in Carter et al. (2016). Photographs by G. Carter.

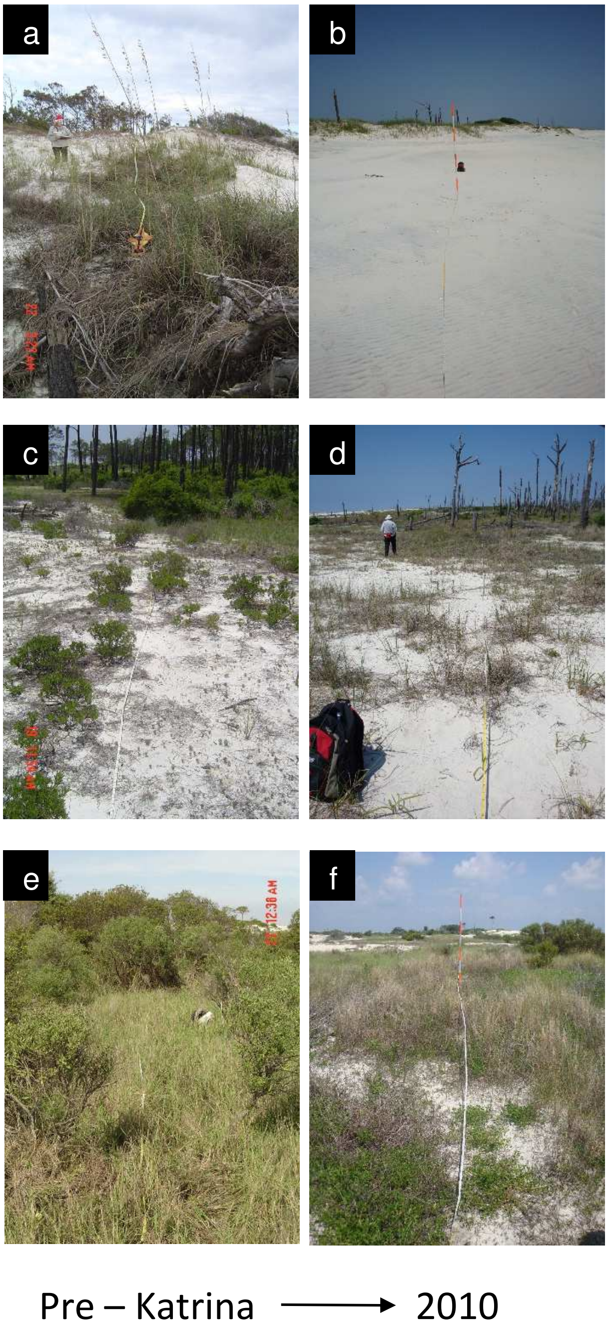


Fig. 12. Examples of change in Horn Island ecological communities photographed from vantage points that were established via GPS before Hurricane Katrina (Lucas and Carter, 2010). Shown, by row, are post-Katrina transitions from: (a,b) backshore dry herbland (22nd December 2004) to unvegetated beach backshore (14th July 2010); (c, d) woodland/dry herbland, interior ridge plain (19th May 2005) to backshore dry herbland (6 Jun 2010), and (e, f) wet herbland/shrubland (27th November 2004) to backshore dry herbland (10th June 2010). Photographs by K. Lucas.

5.0 Discussion and conclusions

5.1 Katrina's impact on vegetation and subsequent recovery

The impact of Hurricane Katrina on the MS-AL barrier islands inferred from analysis of remotely-sensed imagery was severe in terms of area reduction and the impact on vegetation. Nevertheless, by naturally-occurring regrowth, vegetation cover increased rapidly on the islands within the initial three post-Katrina years. In this respect, the vegetation was resilient, as often found on barrier islands in the aftermath of severe storms (Ehrenfeld, 1990; Johnson and Young, 1992; Young et al., 1995; Tolliver et al., 1997). A similar regrowth period was reported for nearby Santa Rosa Island, FL, following hurricanes Opal and Erin in 1995. Changes in species composition did occur, but constant levels of plant cover and species diversity were attained within three years of storm impact (Snyder and Boss, 2002).

On barrier islands, the development of vegetation depends on plant growth and reproductive responses to rapidly changing geomorphic features (Oosting, 1954; Godfrey et al., 1979; Stallins and Parker, 2003; Feagin et al., 2005). The development of minimum surface elevations required for the establishment and growth of dune vegetation depends on the competing processes of dune building versus erosion (Durán Vinent and Moore, 2015). A single disturbance event could be catastrophic, but on low island sections, high-frequency, low-magnitude storm events could be equally detrimental to vegetation survival (Durán Vinent and Moore 2015; Goldstein and Moore 2016). In either case, beyond a given level of erosion, vegetation cannot recover. The exact magnitude of this erosion threshold may vary among barrier islands and depends upon shoreline orientation, tidal range, storm frequency and the ability of native plants to bind sand (Roman and Nordstrom, 1988; Tsoar, 2005). Native dune species may actually benefit from disturbance because they are adapted to being uprooted or re-seeded when storms strike (Feagin et al., 2015). They are critical not only to the sand stabilization that enables dune formation, but also for continued sediment accretion which leads to further successional stages. Spreading herbaceous plants, rather than rigid and tall woody growth forms, promote sediment accretion and raise surface elevation (Feagin et al., 2015). In the progression from dune stabilization to the development of woodland communities, each successional stage induces stronger substrate stabilization (Ehrenfeld, 1990; Feagin et al., 2005; Tsoar, 2005). The importance of considering such ecological processes in the prediction of barrier island change has been emphasized recently (Zinnert et al., 2017).

5.2 Vegetation tolerance to stress during and following storms

Barrier island plant species are variously adapted to a broad range of stressors including drought, salt spray, and fresh or saltwater flooding (Oosting, 1954; Shao et al., 1996). Stress tolerance and the shelter from salt spray and flooding provided by dunes and other landforms, along with soil characteristics, depth to the water table, and groundwater salinity, determine the composition and spatial distribution of barrier island ecosystems (Hayden et al., 1995). Exposure to fresh or saline water is determined by the influence of surface elevation and topography on precipitation infiltration and runoff, and the likelihood of tidal flooding (Hayden et al., 1995). Thus, net erosion or accretion in a given community type will tend to induce transitions to a wetter or drier community type, respectively (**Figs. 9-11**, **Table 4**). Indeed, landscape position defined by elevation above sea level and distance from shoreline integrates a suite of environmental and biotic factors and identifies "habitat polygons" that can be characteristic for individual plant species (Young et al., 2011).

Each of the MS-AL islands supports a unique set of ecological community types owing to differences in island size, position, and local bathymetry, which affect exposure to wind, waves, and currents, and thus magnitudes of sediment flux and accretion. Historically, island width, elevation, nearshore bathymetry, and subaqueous boundary conditions have exerted greater influence over storm impacts than storm intensity (Morton, 2010). Vulnerability to storms is minimized on an island characterized by relatively high-elevation topography (e.g., Horn Island), whereas low barriers (e.g., E. Ship Island) are dominated by storm erosion, dune flattening and overwash, resulting in low sustained island elevations and the highest vulnerabilities to storms (Durán Vinent and Moore, 2015).

Table 4. Broad ecological community classes, their associated geomorphic framework, and potential transitional trends on the MS-AL barrier islands.

Ecological community classification[a]	Geomorphic framework[b]	Potential transitional trends	
		With erosion, shore retreat	With aggradation
Unvegetated/sparsely-vegetated sand	Dry herbland, old interior ridge plain	Beach backshore	Ridge accretion, woodland
	Dry herbland, beach backshore to foredune	Salt marsh with fringing shrubland	Interior dune ridge dry herbland, woodland
	Intertidal sand flat	Subtidal nearshore sand flat	Supratidal sand flat
Woodland	Interior barrier ridge plains and infrequently-flooded, inter-ridge swales	Dry herbland, beach backshore	Dune ridge and sand sheet accretion in woodland
Wet herbland/shrubland	Old ridge plain, backshore; low interior basin and inter-ridge swale	Salt marsh with fringing shrubland and beach swale wet herbland	Accreting dry herbland, woodland
Low (saline to brackish) marsh	Small intertidal inshore basin, basin fringe	Subtidal nearshore sand flat	Salt-marsh fringing shrubland, dry herbland
Lagoon/pond	Island pond or lagoon	Subtidal nearshore sand flat	Saline, brackish, or freshwater marsh

[a] After the Mississippi Natural Heritage Program (2006)

[b] Otvos (1981, 2012), Otvos and Carter (2008)

In those parts of a barrier island where surface aggradation (vertical accretion) by eolian or overwash processes cannot keep pace with rising sea level, the ground water table will be located closer to the land surface (Masterson et al., 2013). Following lateral intrusion of salt water from the surrounding sea, lagoon, and inlets, major changes in freshwater-adapted plant communities may occur. The dimension of the subsurface freshwater lens will diminish, and the extent of brackish ground water will increase steadily. This expands wetter ecological communities, reduces the extent of drier ones, and profoundly changes species diversity, community structure and ecosystem function (Ehrenfeld, 1990). From approximately the mid-1960s through 2010, sea-level rise along the northeastern Gulf coast of Florida and Alabama generally reflected a global eustatic rise of approximately 2 mm per year, while relative sea-level rise was faster and more variable, particularly westward of the Florida panhandle, due to subsidence (Donoghue, 2011; Otvos, 2018). Mean relative sea-level rise on Dauphin Island, AL and in Bay-Waveland, MS were approximately 4 and 5 mm per year during the 1966-2017 and 1978-2017 periods, respectively (http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml). On Horn Island, from 1940 to 2010, the relative land cover of marsh and shrubland communities increased while that of drier woodland and bare sand communities declined (Jeter and Carter, 2016). Similarly, on the Atlantic coast barrier islands of Virginia, shrublands became more prevalent while grassland and bare sand coverage declined between 1984 and 2011 (Zinnert et al., 2016). At 10 m image resolution in the MS-AL barrier chain in general (present study), and at 1 m resolution on Horn Island (Lucas and Carter, 2013) and E. Ship and W. Petit Bois islands (Anderson et al., 2016), decimeter-scale changes in elevation were associated with substantial change in ecological community type (Fig. 9). Recent experimental work has shown the importance of even centimeter-scale differences in overwash thickness in marsh grass (*Spartina alterniflora*) productivity. Burial depths of 5 cm to 10 cm were determined to be optimal for productivity, while greater burial depths, more frequent when storm frequency and intensity increase, caused reduced growth and increased plant mortality (Walters and Kirwan, 2016).

The future of barrier island ecological communities is being determined by sea-level rise, ground subsidence, storm frequency and intensity, and the volume and direction of longshore sediment transport and onshore sand transfer from inner shelf sand resources. Changes in the depth and width of subtidal platform sectors over which islands emerge, as well as in the configuration of passes and their consequent offshore sand transmission will be significant factors. The intensity of dune and sandsheet aggradation by wind, stabilization of sand by vegetation, and the growth and reproductive success of island vegetation, in turn, will also influence the areal extent and topographic elevations on the islands. Frequent acquisitions of remotely-sensed data, preferably of high spatial and spectral as well as temporal resolution, will be essential in quantifying these processes. In the present study, with the exception of total land area on E. Ship, the smallest, lowest-elevation island, interactions among these natural forces resulted in island vegetated and total land areas that approached pre-storm values two to three years following catastrophic impact by one of the most destructive hurricanes in U.S. history. In post-storm island development, remotely-sensed spatial distributions of ecological community type were associated with often subtle changes in remotely-sensed elevation.

ACKNOWLEDGMENTS

This research was sponsored by NOAA, Regional Geospatial Modeling Program, and the NASA Applied Sciences Program, and conducted under research permits from the U.S. National Park Service, Gulf Islands National Seashore. The funding agencies had no role in the study design, in the collection, analysis and interpretation of the data, in the writing of this report, or in the decision to submit this article for publication. We thank Alan Criss for the processing of image data and producing ISODATA classifications, and David Mooneyhan, Chris Brown and Les Graham for facility, data management and technological support. Our sincere thanks also to Cathleen Jones and the UAVSAR program at JPL/NASA for providing the Polarimetric SAR coverage of the MS-AL islands, George and Nathan Boddie and Walter Gaudin for their kind and enthusiastic support of our field work on Cat Island, Will Jeter for assistance with supervised classifications, Maggie Bell for proofreading, and Evan Goldstein, three anonymous reviewers, and Editor Andrew Plater for their valuable comments on the manuscript.

Data Availability

The 2010 – 2011 ground survey data including ground photos are publicly accessible for download via Carter et al., (2016) at http://www.mdpi.com/2306-5729/1/3/16).

References

Anderson, C.P., Carter, G.A., Funderburk, W.R., 2016. The use of aerial RGB imagery and LIDAR in comparing ecological habitats and geomorphic features on a natural versus man-made barrier island. Remote Sensing 8 (7), 602. http://dx.doi.org/10.3390/rs8070602.

Barbour, M.G., Burk, J.H., Pitts, W.D., Gilliam, F.S., Schwartz, M.W. 1999. Terrestrial plant ecology (3rd edition). Addison Wesley Longman, Menlo Park, CA. 649 pp.

Byrnes, M.R., Rosati, J.D., Griffee, S.F., Berlinghoff, J.L., 2013. Historical sediment transport pathways and quantities for determining an operational sediment budget: Mississippi Sound barrier islands. Journal of Coastal Research: Special Issue 63, Understanding and Predicting Change in the Northern Gulf of Mexico. 166-183.

Carter, G.A., and Young, D.R., 1993. Foliar spectral reflectance and plant stress on a barrier island. International Journal of Plant Sciences 154, 298-305.

Carter, G.A., Anderson, C.P., Lucas, K.L., Hopper, N.L., 2016. Land cover data for the Mississippi-Alabama barrier islands, 2010-2011. Data, 1 (16); http://dx.doi.org/10.3390/data1030016.

Del Tredeci, P., 2001. Sprouting in temperate trees: A morphological and ecological review. The Botanical Review, 67 (2), 121-140. https://doi.org/10.1007/BF02858075.

Donoghue, J.F. 2011. Sea level history of the northern Gulf of Mexico coast and sea level rise scenarios for the near future. Climate Change, 107, 17-33.

Doran, K.S., Stockdon, H.F., Plant, N.G., Sallenger, A.H., Guy, K.K., and Serafin, K.A., 2009. Hurricane Gustav: Observations of coastal change: U.S. Geological Survey Open-File Report 2009-1279, 35 p.

Durán Vinent, O, Moore, L.J., 2015. Barrier island bistability induced by biophysical interactions. Nature Climate Change 5(2), 158-162.

Ehrenfield, J.G., 1990. Dynamics and processes of barrier island vegetation. Reviews in Aquatic Sciences 2, 437-480.

Eisemann, E.R., Wallace, D.J., Buijsman, M.C., Pierce, T., 2018. Response of a vulnerable barrier island to multi-year storm impacts: LiDAR-data-inferred morphodynamic changes on Ship Island, Mississippi, USA. Geomorphology 313, 58-71. http://dx.doi.org/10.1016/j.geomorph.2018.04.001.

Feagin, R.A., Sherman, D.J., Grant, W.E., 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. Frontiers in Ecology and the Environment 3, 359-364.

Feagin, R.A., Williams, A.M., 2008. Sediment spatial patterns in a Hurricane Katrina overwash fan on Dauphin Island, Alabama, U.S.A. Journal of Coastal Research 24(4), 1063-1070.

Feagin, R.A., Figlus, J., Zinnert, J.C., Sigren, J., Martinez, M.L., Silva, R., Smith, W.K., Cox, D., Young, D.R., 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.

Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., Tate, B., 2007. Hurricane Katrina storm surge distribution and field observations on the Mississippi barrier islands. Estuarine, Coastal and Shelf Science 74(2007), 12-20.

Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., Tate, B., 2008. Hurricane Katrina storm surge reconnaissance, J. Geotechnical and Geoenvironmental Engrg., ASCE 134(5), 644-656. doi:10.1061/(ASCE)1090-0241(2008)134:5(644).

Funderburk, W.R., Carter, G.A., Anderson, C.P., 2016. Evaluating the influence of elevation and impact of Hurricane Katrina on radial growth in slash pine (*Pinus elliottii* var. *elliottii* Engelm) on Cat Island, Mississippi, U.S.A. Journal of Coastal Research 32(3), 483-489.

Gibeaut, J.C., White, W.A., Smyth, R.C., Andrews, J.R., Tremblay, T.A., Gutiérrez, R., Hepner, T.L., Neuenschwander, A., 2003. Topographic variation of barrier island subenvironments and associated habitats. Proceedings of the Fifth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes (Clearwater Beach, Florida), Coastal Sediments '03: Crossing disciplinary boundaries. CD-ROM, 10pp.

Godfrey, P.J., Leatherman, S.P., Zaremba, R., 1979. A geobotanical approach to classification of barrier beach systems. In: SP Leatherman (ed) *Barrier islands from the Gulf of St. Lawrence to the Gulf of Mexico*. Academic Press, NY, 99-126.

Goldstein, E.B., and Moore, L.J., 2016. Stability and bistability in a one-dimensional model of coastal foredune height. J. Geophys. Res. Earth Surf., 121, 964–977. http://dx.doi.org/10.1002/2015JF003783.

Hapke, C.J., Himmelstoss, E.A., Kratzmann, M.G., List, J.H., and Thieler, E.R., 2011. National assessment of shoreline change: Historical shoreline change along the New England and Mid-Atlantic coasts. U.S. Geological Survey Open File Report 2010-1118, 57 pp.

Hayden, B.P., Santos, M.C.F.V., Shao, G., Kochel, R.C., 1995. Geomorphological controls on coastal vegetation at the Virginia Coast Reserve. Geomorphology 13(1995), 283-300.

Hesp, P.A., 1991. Ecological processes and plant adaptations on coastal dunes. Journal of Arid Environments 21, 165–191.

Hesp, P.A., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48, 245–268.

Hughes, J., 2008. Tree mortality on Horn Island following Hurricane Katrina. Senior Honors Thesis, Department of Geography and Geology, The University of Southern Mississippi. 46pp.

Jensen, J.R., 2016. Introductory digital image processing: a remote sensing perspective, 4th Edition. Pearson, N.Y. 623 pp.

Jeter Jr., G.W., Carter, G.A., 2016. Habitat change on Horn Island, Mississippi, 1940-2010, determined from textural features in panchromatic vertical aerial imagery. Geocarto International 31(9), 985-994. http://dx.doi.org/10.1080/10106049.2015.1094527.

Johnson, S.R., Young, D.R., 1992. Variation in tree ring width in relation to storm activity for mid-Atlantic barrier island populations of *Pinus taeda*. Journal of Coastal Research 8, 99-104.

Jones, R., 2015. Quantifying extreme weather event impacts on the northern Gulf Coast using Landsat imagery. Journal of Coastal Research 31 (5), 1229-1240. http://dx.doi.org/10.10.2112/J COASTRES-D-14-0 006.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., Sugi, M., 2010. Tropical cyclones and climate change. Nature Geoscience 3(March 2010), 157-163.

Lantz, T.C., Kokelj, S.V., Fraser, R.H., 2015. Ecological recovery in an Arctic delta following widespread saline incursion. Ecological Applications 25(1), 172-185.

Leatherman, S.P., 1979. Barrier island dune systems: a reassessment. Sedimentary Geology 24, 1–16.

Lucas, K.L., Carter, G.A., 2008. The use of hyperspectral remote sensing to assess vascular plant species richness on Horn Island, Mississippi. Remote Sensing of Environment 112(2008), 3908-3915.

Lucas, K.L., Carter, G.A., 2010. Decadal changes in habitat-type coverage on Horn Island, Mississippi, U.S.A. Journal of Coastal Research 26(6), 1142-1148.

Lucas, K.L., Carter, G.A., 2013. Change in distribution and composition of vegetated habitats on Horn Island, Mississippi, northern Gulf of Mexico, in the initial five years following Hurricane Katrina. Geomorphology 199(2013), 129-137.

Lucas, K.L., Raber, G.T., Carter, G.A., 2010. Estimating vascular plant species richness on Horn Island, Mississippi, using small-footprint airborne LIDAR. Journal of Applied Remote Sensing 4(1), 043545. http://dx.doi.org/10.1117/1.3501119.

Masterson, J.P., Fienen, M.N., Thieler, E.R., Gesch, D.B., Gutierrez, B.T., Plant, N.G., 2013. Effects of sea-level rise on barrier island groundwater system dynamics – ecohydrological implications. Ecohydrology (2013), 8 pp. http://dx.doi.org/1002/eco.1442

Miselis, J.L., Buster, N.A., Kindinger, J.L., 2014. Refining the link between the Holocene development of the Mississippi River Delta and the geologic evolution of Cat Island, MS: Implications for delta-associated barrier islands. Marine Geology 355, 274-290.

Mississippi Natural Heritage Program, 2006. Ecological Communities of Mississippi. Museum of Natural Science, Mississippi Dept. of Wildlife, Fisheries and Parks, Jackson, MS, 9 pp.

Moore, L.J., Patsch, K., List, J.H., Williams, S.J., 2014. The potential for sea-level-rise-induced barrier island loss: Insights from the Chandeleur Islands, Louisiana, USA. Marine Geology 355, 244–259. http://dx.doi.org/10.1016/j.margeo.2014.05.022.

Moreno-Casasola, P., Espejel, H., 1986. Classification and ordination of coastal sand dune vegetation along the Gulf and Caribbean Sea of Mexico. Vegetatio 66 (3), 147–182.

Morton, R.A., 2007. Historical changes in the Mississippi-Alabama barrier islands and the roles of extreme storms, sea level, and human activities. U.S. Geological Survey Open File Report 2007-1161, 38 pp.

Morton, R.A., 2008. Historical changes in the Mississippi-Alabama barrier island chain and the roles of extreme storms, sea level, and human activities. Journal of Coastal Research 24(6), 1587-1600.

Morton, R.A., 2010. First-order controls of extreme-storm impacts on the Mississippi-Alabama barrier-island chain. Journal of Coastal Research 26(4), 635-648.

Oosting, H.J., 1954. Ecological processes and vegetation of the maritime strand in the southeastern United States. Botanical Review 20, 226-262.

Otvos, E.G., 1978. New Orleans-South Hancock Holocene barrier trends and origins of Lake Pontchartrain. Gulf Coast Association Geological Societies Transactions 38, 337-355.

Otvos, E.G., 1979. Barrier island evolution and history of migration, north-central Gulf Coast p. 291-319; in: Barrier Islands. Academic Press, Cambridge, MA, 325 pp.

Otvos, E.G., 1981. Barrier island formation through nearshore aggradation – stratigraphic and field evidence. Marine Geology 43(1981), 195-243.

Otvos, E.G., 2012. Coastal barriers – nomenclature, processes, and classification issues. Geomorphology 39, 39-52.

Otvos, E. G., 2018. Coastal barriers, northern Gulf - Last Eustatic Cycle; Genetic categories and development contrasts. A review. Quaternary Science Reviews 193, 212-243.

Otvos, E.G., in press. Barrier island formation and development; Last Interglacial; Eustasy and Sea Level; Gulf Shorelines, Last Eustatic Cycle; Beach ridges; Cheniers; Barrier island preservation and destruction, in Encyclopedia of Coastal Science, 2nd Edition (C. Finkl and C. Majewski, eds.), Springer Verlag, Berlin.

Otvos, E.G., Carter, G.A., 2008. Hurricane degradation – barrier development cycles, Northeastern Gulf of Mexico: Landform evolution and island chain history. Journal of Coastal Research 24(2), 463-478.

Otvos, E.G., Giardino, M.J., 2004. Interlinked barrier chain and delta lobe development, northern Gulf of Mexico. Sedimentary Geology 169(2004), 47-73.

Otvos, E.G., Carter, G.A., 2013. Regressive and transgressive barrier islands on the North-Central Gulf Coast – Contrasts in evolution, sediment delivery, and island vulnerability. Geomorphology 198, 1-19.

Pilkey, O.H., 2003. A Celebration of the World's Barrier Islands. Columbia University Press, NY. 309 pp.

Powell, M.D., Reinhold, T.A., 2007. Tropical cyclone destructive potential by integrated kinetic energy. Bulletin of the American Meteorological Society 88, 513-526.

Psuty, N.P., 2004. The coastal foredune: a morphological basis for regional coastal dune development. In: Martinez, M.L., Psuty, N.P. (Eds.), Coastal dunes ecology and conservation. Springer, New York, 11–27.

Radford, A.E., Ahles, H.E., Bell, C.R., 1968. Manual of the Vascular Flora of the Carolinas. The University of North Carolina Press, Chapel Hill. 1183 pp.

Roman, C.T., Nordstrom, K.F., 1988. The effect of erosion rate on vegetation patterns of an East Coast barrier island. Estuarine, Coastal and Shelf Science 26, 233-242.

Shao, G., Shugart H.H, Hayden, B.P., 1996. Functional classifications of coastal barrier island vegetation. Journal of Vegetation Science 7, 391-396.

Snyder, R.A., Boss, C.L., 2002. Recovery and stability in barrier island plant communities. Journal of Coastal Research 18(3), 530-536.

Stallins, J.A., 2005. Dune plant species diversity and function in two barrier island biogeomorphic systems. Plant Ecology 165(2002), 183-196.

Stallins, J.A., Parker, A.J., 2003. The influence of complex systems interactions on barrier island dune vegetation pattern and process. Annals of the Association of American Geographers 93, 13-29.

Stockdon, H.F., Doran, K.S., Serafin, K.A., 2010. Coastal Change on Gulf Islands National Seashore during Hurricane Gustav: West Ship, East Ship, Horn, and Petit Bois Islands. U.S. Geological Survey Open-file Report 2010-1090, 14 pp.

Tolliver, K.S., Martin, D.W., Young, D.R., 1997. Freshwater and saltwater flooding response for woody species common to barrier island swales. Wetlands 17, 84-92.

Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. Physica A 357(1), 50-56.

Walters, D.C., Kirwan, M.L., 2016. Optimal hurricane overwash thickness for maximizing marsh resilience to sea level rise. Ecology and Evolution 6(9), 2948-2956. http://dx.doi.org/10.1002/ece3.2024.

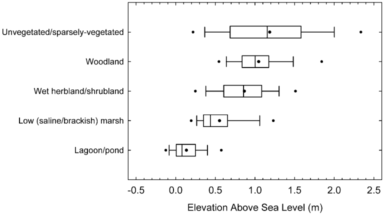
Wehrmann, A., and Tilch, E., 2008. Sedimentary dynamics of an ephemeral sand bank island (Kachelotplate, German Wadden Sea): An atlas of sedimentary structures. Senckenbergiana maritima 38 (2), 181–194.

Young, D.R., Shao, G., Brinson, M.M., 1995. The impact of the October 1991 northeaster storm on barrier island shrub thickets (*Myrica cerifera*). Journal of Coastal Research 11, 1322-1328.

Young, D.R., Brantley, S.T., Zinnert, J.C., Vick, J.K., 2011. Landscape position and habitat polygons in a dynamic coastal environment. Ecosphere 2(6), art71. http://dx.doi.org/10.1890/ES10-00186.1.

Zinnert, J.C., Shiflett, S.A., Via, S., Bissett, S., Dows, B., Manley, P., Young, D.R., 2016. Spatial-temporal dynamics in barrier island upland vegetation: The overlooked coastal landscape. Ecosystems 19 (2016), 685-697.

Zinnert, J.C., Stallins, A., Brantley, S.T., Young, D.R., 2017. Crossing scales: The complexity of barrier island processes for predicting future change. BioScience 67, 39-52. http://dx.doi.org/10.1093/biosci/biw154.


Unvegetated/sparsely-vegetated
Woodland
Wet herbland/shrubland
Low (saline/brackish) marsh
Lagoon/pond
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
Elevation Above Sea Level (m)