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Seagrasses in the Mississippi and Chandeleur Sounds and Problems Associated With Decadal-Scale Change Detection

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Seagrass mapping data from a multitude of previous projects in the Mississippi and Chandeleur sounds were gathered and combined to provide information on seagrass change from 1940 to 2011. Seagrasses generally occur in three groups: (1) along the Mississippi mainland coastline dominated by *Ruppia maritima*, (2) on the north side of Mississippi Sound barrier islands dominated by *Halodule wrightii*, and (3) on the west side of the Chandeleur Islands dominated by *Thalassia testudinum* co-occurring with other seagrass species. The study area generally lost seagrasses over the 71-yr period, ostensibly due to loss or reduction of protective island barriers and reductions in water quality. An example of how the time series of maps generated in this project can be utilized to further investigate seagrass change was demonstrated with data from Horn Island, including problems associated with calculating change in seagrass area using data from previous investigations. Comparisons of seagrass area among various studies that used different mapping methods (seagrass extent vs. seagrass coverage vs. vegetated seagrass area) can result in overestimation of area change and misleading conclusions.

Seagrasses are submerged aquatic angiosperms that are found in shallow, coastal marine environments worldwide with the exception of Antarctica (Green and Short, 2003). Species found in the Mississippi and Chandeleur sounds and the northern Gulf of Mexico (GOM) are classified biogeographically into the Caribbean seagrass flora and include *Halodule wrightii* Asch. (shoal grass), *Halophila baillonis* Asch. (clover grass), *Halophila decipiens* Ostenf. (paddle grass), *Halophila engelmannii* Asch. (star grass), *Halophila johnsonii* Eiseman (Johnson's seagrass), *Ruppia maritima* L. (widgeon grass), *Syringodium filiforme* Kütz. (manatee grass), and *Thalassia testudinum* Banks ex König (turtle grass) (Phillips and Meñez, 1988). Most seagrass meadows are comprised of monospecific patches, especially in temperate regions, but can include a mixture of species, especially in subtropical and tropical regions (Hemminga and Duarte, 2000). Seagrasses provide key ecosystem services via carbon and nutrient cycling and sediment stabilization, as well as nursery habitat and refugia for invertebrates, finfish, and shellfish, and a food source for birds and marine endangered species (e.g., dugongs *Dugong dugon*, manatees *Trichechus spp.*, and green turtle *Chelonia mydas*) via trophic transfers to adjacent habitats (Orth et al., 2006; Waycott et al., 2009). Along with coastal ecosystems in general, seagrasses are subjected to numerous stressors such as direct physical damage to seagrass habitats, nutrient and sediment pollution, the introduction of exotic species, and global climate change (Orth et al., 2006; Lirman et al., 2008).

Seagrass decline.—The loss of seagrasses has been documented from local and regional studies to worldwide assessments (Kemp et al., 1983; Orth and Moore, 1983; Robblee et al., 1991; Duke and Kruczynski, 1992; Thayer et al., 1994; Green and Short, 2003; Waycott et al., 2009). Waycott et al. (2009) estimated that globally, seagrass decline accelerated from a pre-1940 median rate of 0.9% per year to 7% per year since 1990. Kemp et al. (1983) and Orth and Moore (1983) reported that declines in submerged aquatic vegetation (SAV), including *Zostera marina* L. (eelgrass), in Chesapeake Bay started from the 1960s, and then accelerated during the 1970s to present. Robblee et al. (1991) and Thayer et al. (1994) documented the die-off of *T. testudinum* and plant community changes in Florida Bay seagrass meadows during the late 1980s. Duke and Kruczynski (1992) reported 20–100% seagrass losses in areas of the northern GOM over the past 50 yr. Fifteen years later, Handley et al. (2007) reported that loss of seagrasses in Texas, Louisiana, Mississippi, Alabama, and Florida was much greater than gains during 1940–2002. Although seagrass loss in many parts of the GOM has occurred since 1940, there are areas where seagrass loss has not been as dramatic and increases in cover have actually been recorded. Lewis et al. (2008) reported a less severe decline in seagrass area in 1980–2003 than in the preceding 1960–80 time period for the Pensacola Bay system, with some increases observed in Pensacola Bay and Santa Rosa Bay from 1992 to 2003. In Mobile Bay and adjacent waters, Vittor

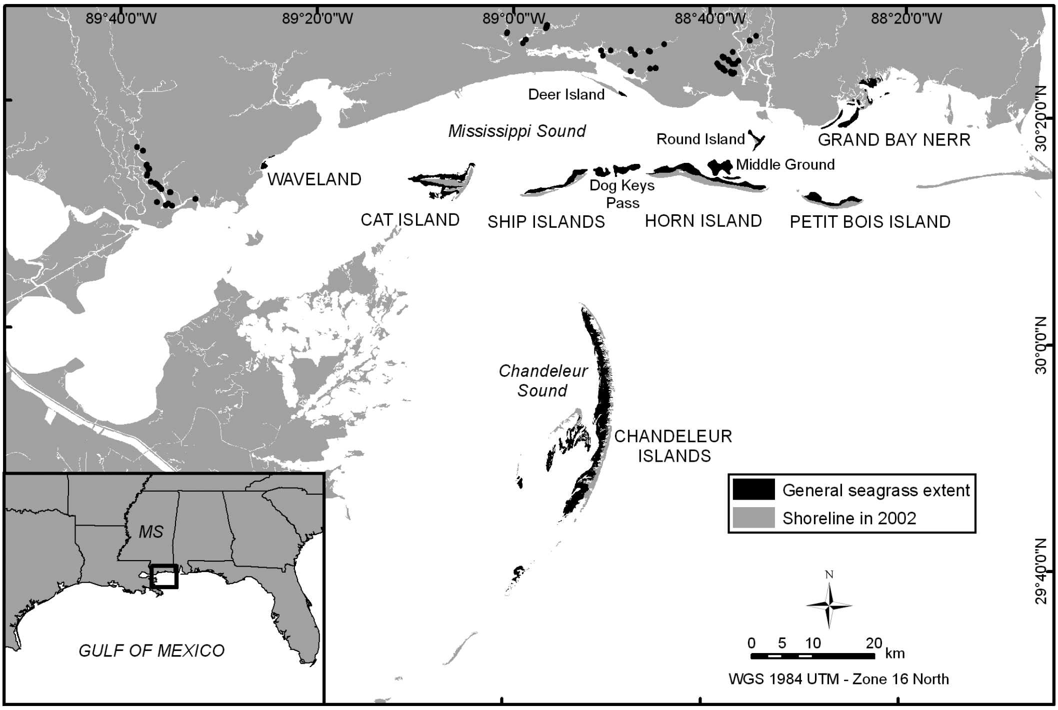

Fig. 1. Study area, which includes the Mississippi mainland coastline (Group 1), the five barrier islands in the Mississippi Sound (Group 2), and the northern Chandeleur Islands (Group 3). General seagrass extent (in black) for all years (1940–2011) was delineated by the outermost border of all historical occurrences; land is in grey. Black dots are point locations of submerged aquatic vegetation found along the Mississippi mainland.

and Associates, Inc. (2004, 2005, 2009) found substantially reduced seagrass area in 2002 compared to 1940, 1955, and 1966. According to their study, an increase in seagrass area found from 2002 to 2008, or from 2002 to 2009 in some of the quadrangles in the northeastern Mississippi Sound, must be considered together with a change in species composition, from monospecific beds of *H. wrightii* in 2002 to mixed beds of *H. wrighitii* and *R. maritima* (an opportunistic species) in 2008–09. Overall, this compendium of results suggests that a drastic decline in seagrasses at global, regional, and local scales has occurred from the mid-20th century to the present.

Seagrass mapping in the Mississippi Sound.—Seagrasses in this study follow an inshore to offshore gradient, and generally occur in three groups: (1) along the Mississippi mainland coastline dominated by *Ruppia maritima,* (2) on the north side of Mississippi Sound barrier islands dominated by *Halodule wrightii,* and (3) on the west side of the Chandeleur Islands, Louisiana, dominated by *Thalassia testudinum* co-occurring with other seagrass species. In the state of Mississippi, the Mississippi Sound (Fig. 1) is the primary body of water that supports seagrasses, whereas the Chandeleur Islands support the most important seagrass resource in Louisiana (Poirrier, 2007). Mississippi Sound is a lagoon formed by a chain of barrier islands that extends 130 km along the Alabama and Mississippi coastlines. With a 3-m mean low tide depth and a small diurnal tidal range of 0.5 m (Kjerfve, 1986), the Mississippi Sound connects hydraulically with Lake Borgne westward and Mobile Bay eastward. Salinity generally varies from 20 to 35 parts per thousand (ppt) (Eleuterius, 1976; Kjerfve, 1983, 1986).

Information and maps of Mississippi Sound seagrasses (Group 1 and Group 2 as defined above) are available from a multitude of previous studies, but do not provide common methods or mapping units, complicating comparisons of change over time. Submerged flowering plants were reported in the Mississippi Sound as early as the 1950s (Humm and Caylor, 1955; Humm, 1956). It was not until the 1970s that the first map of Mississippi Sound seagrass was published (Eleuterius, 1973) based on fieldwork conducted during the spring and summer of 1969, just prior to Hurricane Camille (17–18 Aug. 1969). In that study, a series of north–south transects were run across the Mississippi Sound with stations that were ≤3.2 km (2 miles) apart. Seagrass extent was then mapped by manually connecting observation points and recording the general species composition of the seagrass beds. Later, Eleuterius included seagrasses in his 1978 vegetation maps of Horn and Petit Bois islands (Eleuterius, 1979). During the 1990s, the United States Geological Survey–National Wetland Research Center (USGS–NWRC, 1998b) published a map of SAV in Mississippi by interpreting June 1992 natural-color aerial photography. This was part of the northeastern GOM seagrass mapping project; the classification system was based on percentage of ground cover of patches within the delineated area and consisted of five classes of seagrass cover, from very sparse patchy seagrass to dense continuous seagrass beds (Handley, 2007). Seagrasses were also included when the USGS–NWRC (1999) mapped coastal Mississippi habitats using March 1996 color-infrared aerial photography as the primary data source for identification of wetland and upland vegetation classes. Moncreiff et al. (1998) published the first report on changes in seagrass area and potential seagrass habitat (''PSGH'' in their publication) in Mississippi based on comparisons of mapping data from 1969 and 1992 (Eleuterius, 1973, and USGS–NWRC, 1998b, respectively). In 1992, PSGH was delineated from the 2-m depth contour applied to the USGS–NWRC map. Moncreiff et al. (1998) reported a decline in seagrass area from 5,252 ha to 809 ha (84.6%) but a reduction of only 19.6% in PSGH from 1969 to 1992. In Jan. 1999, natural-color aerial photography of the Mississippi barrier islands was collected for a National Park Service project and then photo-interpreted by USGS–NWRC (2003) using protocols similar to the 1992 study. Moncreiff (2007a) combined these 1999 data with the previous 1998 report (Moncreiff et al., 1998) to update seagrass status and trends, and suggested a slow increase in seagrass area throughout the Mississippi Sound between 1992 and 1999. The 2007 paper, however, did not include information on changes to PSGH.

Subsequently, the vegetated seagrass area (VSA) on the Mississippi barrier islands (Group 2) spanning the 1940–2007 period was recalculated by Carter et al. (2011) from analysis of high-spatial-resolution (0.3 m to 2.4 m) aerial photographs or digital spectral image data. Only historical imagery that had been acquired in the fall when water clarity appeared to be high, as evidenced by seafloor visibility, were selected for analysis. This increased the likelihood that individual seagrass patches would be delineated clearly in the imagery and that their spatial extent and foliar density would be near-maximum for the given year. For the more recent years in which multispectral or hyperspectral image data were acquired, only data from a single green band (500–600 nm wavelength) extracted from the full spectral data set were used in the analysis. Vegetated patches were classified based on a pixel edge solution that was modified from Urbanski (2006), with individual seagrass patches being mapped at spatial resolutions from 0.5 m to 2.4 m. The earliest seagrass maps by Carter et al. (2011) were developed from 1940 images of Horn and Petit Bois islands, 1963 images of Ship Island, and a 2003 photomosaic of Cat Island. Comparing between results obtained from their recently generated data and those of earlier mapping products, Carter et al. (2011) suggested that conclusions regarding temporal change in seagrass coverage should be made with caution because survey objectives and methods, including spatial resolution, can vary appreciably among studies. Most recently a survey of the seagrasses on the five Mississippi barrier islands was completed by Vittor and Associates, Inc. (2014) based on aerial imagery and complementary ground-truthing in 2010, but cannot be compared directly with maps by Carter et al. (2011) due to the very different minimal mapping units of 404 m^2 (0.1 acre) versus 1–2 m^2, respectively.

Field and remotely sensed data suitable for mapping seagrasses along the mainland coast of Mississippi (Group 1) are scarce relative to those available for the Mississippi barrier islands (Group 2). Due to high water turbidity, data used for mapping were obtained primarily in the field as individual geo-location points, and polygon data are available only for a few years. The two main areas supporting seagrasses are Waveland (near Buccaneer State Park) in the western Mississippi Sound and Grand Bay National Estuarine Research Reserve (GNDNERR) in the eastern Mississippi Sound. Seagrasses in Waveland were previously mapped only twice (Eleuterius, 1973; Moncreiff et al., 1998). GNDNERR seagrasses have been mapped more frequently and recently by the USGS–NWRC (1998b, 1999) and Sanchez-Rubio (2004), who updated the presence/absence as well as total area of the GNDNERR seagrass beds mapped previously by Eleuterius (1973) and Moncreiff et al. (1998). Sanchez-Rubio (2004) located seagrass beds by snorkeling in June 2002 based on a field survey grid of 5-sec latitude and longitude intervals, and subsequently area of the beds was estimated from aircraft video camera imagery collected on 29 Sept. 2003.

Later, May and other GNDNERR staff (C.A. May, pers. comm.) organized intensive fieldwork involving snorkeling, rake surveys, and visual identification to map seagrasses in the reserve during June–Aug. 2005 and 2006. They collected global positioning system (GPS) points using a Trimble GeoXT unit (Trimble, Sunnyvale, CA) set to 1.5 m geospatial accuracy and later connected those points to form polygons representing the extent of the seagrass beds. Strange and May (2009) used 2009 aerial imagery to update the size and location of seagrass beds determined in the earlier 2005 survey. Most recently, some of the seagrass beds in Point aux Chenes Bay (northwestern GNDNERR) were mapped in July 2011 and July 2012 using side-scan sonar, which was found to be an effective technique in these highly turbid and shallow waters (Hendon, 2013).

Seagrass mapping in the Chandeleur Sound.—Johnston and Handley (1990) mapped Chandeleur Sound seagrasses (Group 3) from aerial photography acquired in 1978, 1982, and 1987. Poirrier and Handley (2007), in their paper discussing status and trends of seagrasses on the islands, provided additional maps for April 1969, Oct. 1969, April–June 1992, and Nov–Dec. 1995. More recently, Bethel et al. (2006) mapped seagrasses on the northern part of the Chandeleur Islands using April 1999, Nov. 2000, and Nov. 2002 aerial photography. Bethel and Martinez (2008) studied the impacts of Hurricane Katrina (28–29 Aug. 2005) on seagrass area using imagery acquired in Jan. and Oct. 2005. Most of these studies combined image interpretation with ground observations to verify the presence of seagrasses. Additional photography was obtained following the Deepwater Horizon oil spill (April–July 2010), and the number of seagrass maps completed by USGS for the Chandeleur Islands increased to 14 by Feb. 2012 (L. R. Handley, pers. comm.). However, only the 1992 map (USGS–NWRC, 1998a), which used Nov. 1992 color infrared aerial photography as the primary data source and Jan. 1992 natural-color aerial photography as supplemental data for photo interpretation, is currently publically available. A common theme resulting from these maps is that erosion during hurricanes and lesser storms has periodically reduced the Chandeleur Island land and seagrass area, with recovery of land area and seagrass cover occurring during the relatively calm intervals between storms.

Objectives.—This paper presents an updated and comprehensive evaluation of decadal-scale changes to the seagrass area found in the Mississippi and Chandeleur sounds. Specific objectives were to (1) combine all available data that were acquired in both sounds from 1940 to 2011 to develop maps showing the general distribution of seagrasses over time, and (2) determine interannual and decadal-scale changes in seagrass area for the three groups (Mississippi mainland, Mississippi Sound barrier islands, and Chandeleur Island) within the Mississippi and Chandeleur sounds.

MATERIALS AND METHODS

Study area and base map.—The study area encompassed coastal Mississippi and the Chandeleur Islands in Louisiana (Fig. 1). Study sites were placed into three groups representing an inshore to offshore gradient: Group 1 is the Mississippi mainland coastline, specifically the GNDNERR and Waveland locations dominated by *R. maritima*; Group 2 includes the Mississippi barrier islands (Cat, West and East Ship, Horn, and Petit Bois islands) dominated by *H. wrightii*; and Group 3 comprises the northern Chandeleur Islands (NCI) dominated by *T. testudinum* co-occurring with other seagrass species.

Seagrass species composition differs among the three study groups following this inshore to offshore gradient. *Ruppia maritima* occurs in soft muddy bottoms and can tolerate brackish to hypersaline waters. *Halodule wrightii*, *Halophila engelmannii*, *T. testudinum*, and *S. filiforme* grow on sandy or sandy-mud substrates with high salinity and relatively clear water. On the mainland in Group 1, *R. maritima* dominates at Waveland and coexists with some *H. wrightii* in GNDNERR. Mississippi barrier islands in Group 2 have mainly supported *H. wrightii* since 1978 (Eleuterius, 1979), even though *T. testudinum*, *S. filiforme*, and *H. engelmannii* were documented there in 1969 and earlier (Humm and Caylor, 1955; Humm, 1956; and Eleuterius, 1973). *Syringodium filiforme* individuals were encountered on Horn and Petit Bois islands in 1993 and 2005 but only in very small areas (Heck et al., 1994; Heck and Bryon, 2006; Moncreiff, 2007a). A small population of *T. testudinum* still persists on Horn Island in a brackish lagoon named Ranger Lagoon. All of the five seagrass species mentioned above occur in Group 3 within the Chandeleur Sound.

The base map of the region was developed using geographic information system (GIS) layers for the coastal hydrographic area (USGS, 1999) and shorelines (MS DEQ, 2004; Carter et al., 2011). The most current shoreline available for the whole study area is from 2002, therefore, it was chosen for the base map. Other shorelines dated back to 1850 with gaps among years; in some

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years, data were only available for certain portions of the coast. Historical data that were utilized when displaying a specific seagrass layer for a single year include the shoreline closest in age to that specific seagrass layer and topologically integrated geographic encoding and referencing (TIGER) census geographic data (U.S. Department of Commerce, 2009), primarily roads, which were used for image georectification. All GIS files were downloaded from the Mississippi Geospatial Clearinghouse Portal website (MS DEQ et al., 2003).

Seagrass mapping data.—An overview of the data sources used in the development of the seagrass distribution maps is provided in Table 1. Paper maps for 1969 (Eleuterius, 1973) and 1992 (Moncreiff et al., 1998) were scanned at a resolution of 600 dots per inch (dpi) and saved as TIFF image files. These digital files were then geo-referenced in ArcGIS version 9.3 (ESRI, Redlands, CA) using 1950 and 1993 shorelines, respectively. The images were then georectified to World Geodetic System (WGS) 1984, Universal Transverse Mercator (UTM) zone 16 North projection. Seagrass areas in the georectified images were then manually delineated on the computer screen by tracing along the seagrass polygon edges using digitizing tablets.

Digital GIS files of USGS–NWRC's maps (1992, 1996, and 1999 for Mississippi Sound; 1992 for the Chandeleur Islands) were used in this project, but note that these maps are also available as hard copies. Data were downloaded as ArcInfo interchange files (.E00), imported to ArcGIS using ''Conversion Tools,'' and then transformed to the map coordinate system (WGS 1984 UTM 16N). The USGS–NWRC (1998b) map provided the primary data for 1992, only the Waveland section of the paper map (Moncreiff et al., 1998) was ultimately used because that area was not covered in the former map. However, the map by Moncreiff et al. (1998) contains inaccuracies in both seagrass extent and geo-location at Waveland because they were hand-drawn based on the general and inaccurate location of seagrass patches indicated in the previous 1969 paper map. In the USGS–NWRC's 1996 habitat map, only the features identified as E2AB3L, which are ''estuarine intertidal aquatic beds—rooted vascular'' and are equivalent to our definition of seagrasses, were extracted. The 1996 seagrass data were discovered to be exactly identical to the 1992 map (USGS–NWRC, 1998b) and, therefore, were excluded from the final maps. Other digital data for GNDNERR (Sanchez-Rubio, 2004; May, 2006; Strange and May, 2009), the Mississippi barrier islands (Carter et al., 2011), and the Chandeleur Islands (Bethel et al., 2006; Bethel and Martinez, 2008) were obtained in polygon vector and/or raster formats, and only map projection transformation was needed.

Additional efforts were spent on creating new GIS data for Waveland, which is a historically understudied, yet important, seagrass resource along the mainland coastline of Mississippi. Three complementary approaches were used to fill this critical gap: (1) recent ground-truthing, (2) historical herbarium specimen geolocations, and (3) aerial photograph interpretation. From 2006 to 2014, the authors conducted ground-truthing on a yearly basis of any seagrasses present at this site. Days in November and December with extreme low tides were considered the best time to spot the sparse coverage and short *R. maritima* plants at Waveland, which are otherwise not readily apparent due to the very turbid waters during the warmer months of the year. GPS coordinates of the approximate centroid of all seagrass patches were recorded. Additionally, if a patch was mappable (at least 0.5 m in diameter), a new polygon feature was created by walking along the patch edge with a Trimble GeoExplorer 2008 Series XT GPS unit. These point and polygon data were then transferred, differentially corrected to increase spatial accuracy of the raw data, and exported to shapefiles using Pathfinder Office ver. 4.0 (Trimble). The second complementary but less precise approach was plotting coordinates associated with specimens of *R. maritima* in the Gulf Coast Research Laboratory Herbarium collected in the period from September 1974 to June 2001, prior to the annual ground-truthing visits. Our third method was to map seagrass patches from historical aerial photography. Out of the available aerial images containing the Waveland area, the image in Feb. 1998 downloaded from the Earth Resources Observation Systems-Earth Explorer data center website (1999) is the only one acquired during low tide when water was clear, resulting in a high contrast between relatively bright bottom sand and dark patches of vegetation. The image was geo-rectified using ground control points and TIGER transportation routes as outlined previously, and then digitized by manually outlining the seagrass patch boundaries. Field data notes and historical herbarium records were considered during the visual estimation of seagrass patches in the image.

Map generation and seagrass area calculations.—A map of seagrass distribution in the study area was created in ArcGIS version 9.3 by drawing outline boundaries of all historical and recent seagrass extents and including points of occurrence

TABLE 1. Citations of data sources obtained for the seagrass maps listed by location and year. Spatial resolution is in square meters but reported as pixel side dimension (m). NA indicates a previously completed mapping product (paper or digital) with unknown pixel resolution; NERR indicates National Estuarine Research Reserve. Source of data includes A, aerial imagery; G, GPS ground-truthed; and T, transects with points. Note that sources of vector-point data are not listed here.

Sites	Year	Spatial resolution	Source of data	References
Group 1: Mississippi mainland				
Waveland	1969	NA	T	Eleuterius, 1973
	1992	NA	A	Moncreiff et al., 1998
	1998	NA	A	This study
	2004–11	1 m	G	This study
Grand Bay NERR	1969	NA	T	Eleuterius, 1973
	1992	NA	A	Moncreiff et al., 1998
	1992	NA	A, G	USGS–NWRC, 1998
	2003	NA	A,T	Sanchez-Rubio, 2004
	2005, 2006	NA	G	May, 2006
	2009	NA	A,G	Strange and May, 2009
Group 2: Mississippi barrier islands				
Cat Island	1969	NA	T	Eleuterius, 1973
	1992	NA	A	Moncreiff et al., 1998
	1992, 1996, 1999	NA	A, G	USGS–NWRC, 1998, 1999, 2003
	2003, 2006, 2007	0.3 m, 1 m, 2 m	A	Carter et al., 2011
	2010	1 m	A,G	Vittor and Associates, Inc., 2014
East and West Ship islands	1963	1.5 m	A	Carter et al., 2011
	1969	NA	T	Eleuterius, 1973
	1975	0.5 m	A	Carter et al., 2011
	1992	NA	A	Moncreiff et al., 1998
	1992, 1996, 1999	NA	A,G	USGS–NWRC, 1998, 1999, 2003
	2003, 2006, 2007, 2008	0.3 m, 1 m, 1 m, 2.4 m	A	Carter et al., 2011
	2010	1 m	A,G	Vittor and Associates, Inc., 2014
Horn Island	1940, 1952	1 m, 0.5 m	A	Carter et al., 2011
	1969	NA	T	Eleuterius, 1973
	1971	2 m	A	Carter et al., 2011
	1978	NA	T	Eleuterius, 1979
	1992	NA	A	Moncreiff et al., 1998
	1992, 1996, 1999	NA	A,G	USGS–NWRC, 1998, 1999, 2003
	2003, 2006, 2007, 2008	1 m, 1 m, 2 m, 2.4 m	A	Carter et al., 2011
	2010	1 m	A,G	Vittor and Associates, Inc., 2014
Petit Bois Island	1940, 1952	1 m, 0.5 m	A	Carter et al., 2011
	1969	NA	T	Eleuterius, 1973
	1978	NA	T	Eleuterius, 1979
	1985	1 m	A	Carter et al., 2011
	1992	NA	A	Moncreiff et al., 1998
	1992, 1996, 1999	NA	A,G	USGS–NWRC, 1998, 1999, 2003
	2003, 2006, 2007, 2008	0.5 m, 1 m, 2 m, 2.4 m	A	Carter et al., 2011
	2010	1 m	A,G	Vittor and Associates, Inc., 2014
Group 3: Chandeleur Islands				
North Chandeleur Islands	1992	NA	A,G	USGS–NWRC, 1998
	1999, 2000, 2002	2 m, 2 m, 2 m	A,G	Bethel et al., 2006
	2005	2.4 m	A,G	Bethel and Martinez, 2008

where polygon data were not available (Fig. 1). All data were projected to a common coordinate system, WGS 1984 UTM zone 16 North. GIS data layers were stored separately by year and site. Each GIS file was accompanied with an attribute table of collection/mapping date, collector's names, location, area and perimeter (for polygons). Metadata, if not already available, were created

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TABLE 2. Seagrass area (ha) calculated for each site by year. Data from 1992 are calculated from two different sources based on the same original imagery: area calculated by USGS–NWRC (1998b) are on the top line and area calculated by Moncreiff et al. (1998) is listed below in parentheses. Values in bold are seagrass extent, values in italics are seagrass coverage, and all other values represent vegetated seagrass area. GNDNERR indicates Grand Bay National Estuarine Research Reserve.

Year	Waveland	GNDNERR	Cat Island	West Ship Island	East Ship Island	Horn Island	Petit Bois Island	North Chandeleur Islands
1940						76.7	54.1	
1952						45.7	15.2	
1963				30.4				
1969	**90.9**	**550.5**	**226.3**	**655.6**		**1,365.0**	**650.2**	
1971						19.2		
1978						**249.4**	**222.8**	
1975				1.8	1.6			
1985							17.6	
1992		*183.1*	*55.4*	*23.2*	*27.6*	*87.4*	*76.9*	*4994.5*
	(*9.6*)	(*122.3*)	(*58.3*)	(*26.2*)	(*45*)	(*134.3*)	(*95.0*)	
1996			*56.4*	*23.1*	*28.7*	*90.0*	*78.2*	
1998	27.9							
1999			*645.5*	*0.5*	*97.1*	*233.9*	*172.1*	*1,495.7*
2000								*1,545.1*
2002								*1,525.1*
2003		142.5	21.8	0.02	16.5	50.7	8.0	
2004	+[a]							
2005		214.5						(Jan) 1,193.3 (Oct) 895.0
2006	0	181.6	25.5	0.9	15.5	82.0	18.9	
2007	+[a]		71.2	1.7	14.0	38.1	16.7	
2008	+[a]			3.2	17.9	18.6[b]	7.3	
2009	+[a]	213.8 (199.6)						
2010	+[a]		**693**	**50.6**	**105.6**	**394.1**	**218.9**	
2011	0.0009							

[a] Ground-truthed data at Waveland indicating presence of *Ruppia maritima* that was not mapped or too small for polygon mapping.

[b] Area calculated for Horn Island in 2008 contains only 70% of the island and is missing the eastern third.

to the Federal Geographic Data Committee (FGDC) standard (FGDC and USGS 1999).

There are different definitions of seagrass area that have been used prior to this paper, which can result in confusion and difficulties in calculating change over time. Here we define three terms used to describe seagrass area in this study: (1) Seagrass extent is the area within the outline encompassing all seagrass on a map or in a field survey, such as was done in Eleuterius (1973) and Vittor and Associates, Inc. (2014), and includes potentially extensive nonvegetated areas between the seagrass patches. (2) Seagrass coverage is based on the area of polygons that each contain multiple seagrass patches (ranging from sparse to dense patch aggregation), such as in USGS–NWRC (1998b), and includes a small amount of nonvegetated area between the seagrass patches. (3) VSA is the sum of the area of all the seagrass patches. An individual seagrass patch is equivalent to an individual polygon as mapped by Carter et al. (2011); note that not all seagrass patches may be getting mapped (e.g., those with very sparse shoot density, or those that are in deeper water and cannot be distinguished readily from the background). It is clear that VSA is a subset of seagrass coverage, which in turn is a subset of seagrass extent, and that newer mapping methods have made the increase in spatial accuracy obtained by the VSA method possible. Finally, PSGH was defined by Moncreiff et al. (1998) as the area of everything shallower than the 2-m depth contour, and is generally a larger area than the seagrass extent. The ''true'' seagrass area is likely to be greater than the VSA but less than the area obtained from seagrass coverage calculations, and substantially lower than either seagrass extent or PSGH.

A revised estimate of seagrass area (Table 2) was obtained using the ''Calculate Geometry'' function in ArcGIS even if areas were reported previously (e.g., Eleuterius, 1973; Moncreiff et al., 1998; Moncreiff, 2007a) to minimize calculation errors that may occur by comparing results obtained from different geometric formulae.

Maps for 1969 (seagrass extent), 1992 (seagrass coverage), and 2006 (VSA) were chosen to represent changes in seagrass area due in part to the different mapping methods (Figs. 2a,b) as in those years data are available for most of the study sites. An exception was the use of 2004 data for Waveland and 2005 data for the NCI due to the lack of 2006 maps. Also, there were no 1969 data accessible to us for the Chandeleur Islands, even though they exist (Poirrier and Handley, 2007). The three time points illustrate some of the potential error associated with comparing directly different mapping techniques (seagrass extent vs. seagrass coverage vs. VSA) from different investigators over the decades.

Change analysis of seagrasses on Horn Island.—Seagrasses on Horn Island were studied in more detail to illustrate changes to island geomorphology and the potential influence on seagrass area during the study period from 1940 to 2008. The island's shoreline was digitized from aerial photography when we had access to the original images. Horn Island was divided into three equal sections based on the distance from the eastern tip to the western tip in a particular year. Seagrass extent was divided into thirds accordingly and seagrass area calculated for each third (eastern, middle, western) along with the percentage of the total seagrass area of the island in each year as shown in Figure 3.

RESULTS

General seagrass distribution in the Mississippi and Chandeleur sounds.—Seagrasses can be found primarily on the Mississippi barrier islands within the Gulf Islands National Seashore and along select portions of the Mississippi mainland coast, particularly in GNDNERR and Waveland, the two mainland areas where seagrasses are protected. The Chandeleur Islands support seagrasses on their western shoreline (Chandeleur Sound), and the Mississippi Sound barrier islands have seagrasses on the northern side (Mississippi Sound). In both sounds the seagrasses are on the lee side of the islands where they are protected from the higher wave energy of the open GOM (Fig. 1). Seagrasses mostly occur as beds of small vegetated patches in Mississippi Sound in contrast to continuous meadows on the Chandeleur Islands.

Decadal-scale changes in vegetated seagrass area.—Over the years included in this study, each group of sites has experienced changes in VSA at various rates (Table 2; Fig. 2). More data are available during 1990–2010 than in previous decades, a reflection of advances in geospatial technology (remote sensing and GIS), which promote increasingly accurate natural resource mapping. Horn and Petit Bois islands have the most consistently available information; only data for either the 1970s or 1980s are missing (Table 2). Most other sites do not have information prior to 1969 (Eleuterius, 1973), and this paper includes no mapping data prior to 1992 for the Chandeleur Islands (Table 2), even though earlier imagery does exist (Handley, 1994; Poirrier and Handley, 2007). Decadal-scale changes in seagrass area are demonstrated in Figure 2a,b using data from 1969, 1992, and 2005–06. The difference between the seagrass area estimated in the 1969 map and other maps in this paper is very large (Table 2; Fig. 2a). The 1992 and 1999 maps created by USGS–NWRC (1998b, 2003) also show substantially larger calculated seagrass area compared to maps in other years. These differences are largely the result of different investigators using different mapping criteria. Seagrass area was calculated in 2005–06 based on vegetated seagrass polygons, whereas in 1992 it was calculated from seagrass coverage, and in 1969 the data used measured seagrass extent.

Breaking down the temporal changes in seagrass area by study group yields some interesting findings. Seagrasses in Group 1 (Mississippi mainland coast) had different dynamics between east and west. In the western part of the state, the *R. maritima* population located near Buccaneer State Park in Waveland was first documented in the late 1960s. The seagrass beds were severely damaged by Hurricane Camille in 1969 and seagrass patches were not noticeable in the early 1970s (J. D. Caldwell, pers. comm.). There was no extensive seagrass survey in this area during the 1970s and 1980s. The beds were documented again in the late 1990s; photos from this time show that seagrass patches at Waveland were comparable in abundance and size to those on the Mississippi barrier islands in the 2000s. The *R. maritima* population was wiped out by Hurricane Katrina in 2005, and then remained almost completely absent with very few or sometimes no plants found in our yearly field surveys from 2006 to 2013. This population was decimated by Hurricanes Camille in 1969 and Katrina in 2005 and appears to take a long time to recover, presumably from seeds or fragments originating from nearby freshwater populations. In the eastern end of the state is GNDNERR, where a considerable amount of *H. wrightii* and *R. maritima* has been consistently found at four discrete locations: Middle Bay, Grand Bay, South Rigolets, and Grand Batture shoal (Fig. 2a).

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Seagrass area in GNDNERR showed an apparent decline from 1969 to 1992 (methodological differences may account for part of this decline), then fluctuated around 150–200 ha until 2009. Overall, the eastern end of the Mississippi mainland supported consistent seagrass coverage through the years, whereas *R. maritima* has fluctuated more dramatically in the western part of the state after strong hurricanes damaged the beds in 1969 and 2005.

Trends in seagrass area also differed among the five Mississippi Sound barrier islands in Group 2. Horn Island, as the largest island, has the largest seagrass area in this group whereas West Ship Island, the smallest island, generally had the least seagrass, depending on the year surveyed (Table 2). One of the biggest problems in determining temporal change in seagrass area for Group 2 is the large difference in area calculated by different investigators using different mapping techniques. Earlier publications (e.g., Eleuterius, 1973, 1979; but also Vittor and Associates, Inc., 2014) generally calculated seagrass area as seagrass extent, thereby greatly inflating the number of hectares reported by including substantial areas of unvegetated sand bottom (Table 2, values in bold). As mapping technology evolved and greater spatial accuracy was possible, publications tended to report area calculated from seagrass coverage with polygons representing large numbers of discrete seagrass patches with similar density (e.g., USGS–NWRC, 1998b; Bethel et al., 2006) which still results in some inflation of the number of hectares (Table 2, values in italics). Finally, the approach adopted by Carter et al. (2011) to delineate each patch as a separate polygon allows for the most accurate calculation of VSA, but may underestimate the ''true'' area where patches fail to get mapped (e.g., very sparse shoot density). To reduce bias introduced with the different mapping techniques used, the interpretation of temporal change in Group 2 will focus on the VSA technique, as it is the most accurate and covers the largest time domain.

Cat Island had around 55 ha (calculated from seagrass coverage) of seagrass in the 1990s but that declined to around 22 ha in the early 2000s before increasing to 71.2 ha in 2007 (both calculated from VSA), tripling the 2003 value (Table 2). Seagrass patches also had become more numerous on the western end of Cat Island in this period, and had declined along the northeastern shoreline (Fig. 2a). Seagrasses on Ship Island declined dramatically after 1969 when Hurricane Camille cut through the island and divided it into East Ship and West Ship islands. In 1963 there were 30.4 ha of VSA on Ship Island, whereas by 1975, there were only 3.4 ha of seagrasses left on these two islands with almost equal amounts on each (Table 2). During the 1990s seagrasses had recovered to pre-Camille levels (based on seagrass coverage) but then declined again and it was not until the late 2000s that the VSA on West Ship Island increased. On East Ship Island, VSA fluctuated around 16 ha in 2003–06 before reaching a peak of 17.9 ha in 2008. East Ship Island supports more seagrasses than West Ship Island, which has a Civil War–era fort (Fort Massachusetts) and regular tourist ferry service from March to Oct. At the beginning of the study period in 1940, Horn Island supported 76.7 ha of seagrasses. About 40% of this VSA was lost by 1952, and only 25% (19.2 ha) was left by 1971 (after Hurricane Camille). In the 2000s, Horn Island seagrasses had recovered with a higher VSA present in 2003 than in 1952. In 2006 (after Hurricane Katrina), VSA on Horn Island had the highest single observation (82 ha) in the 71-yr study period, 7% higher than in 1940. The data show a decline after 2006, as in 2007 the amount of VSA had shrunk back to only 50% of that in 1940. Petit Bois Island supported 54.1 ha of seagrasses in 1940. Only 30% of this area remained by 1952, followed by a slight increase to 17.6 ha VSA in 1985. In 2003, only 15% (8 ha) of the original 1940 VSA was found. In the 2000s, VSA on Petit Bois Island showed a similar trend as on Horn Island, which was an increase in the first half of the decade followed by a decline in the latter half. However, with 36% of the 1940 VSA existing in 2006, Petit Bois Island did not experience as dramatic a recovery as Horn Island did. In short, there was an overall decline in VSA on Mississippi barrier islands from 1940 to 2008. In the western Mississippi Sound, Cat Island experienced an increase in VSA from 2003 to 2007, while in the eastern Mississippi Sound on Horn and Petit Bois islands there was an increase in VSA in the first part followed by a decrease in the latter part of the same decade. The dataset for the 2000s decade also demonstrates how large interannual fluctuations in VSA are possible on a given island. This complicates interpretation of decadal-scale change in Group 2, as it is not known whether the single year of data in earlier decades represents an average or extreme value for VSA.

Among all study sites, the NCI (Group 3) had the greatest seagrass area, at nearly 5,000 ha in 1992 (Fig. 2b), and also experienced much higher loss (>80%) during the subsequent decades, although it is not clear how much bias associated with the different mapping techniques may have influenced this apparent loss

(Table 2). Seagrass area on the NCI in 1992 was 10 times higher than at all Mississippi sites combined when using the same mapping technique (seagrass coverage) for both locations (Figs. 2a,b). But in 2005–06 there was roughly twice as much when VSA is used as a common technique to calculate area. In 1999–2002, the seagrass coverage on the NCI remained stable and fluctuated around 1,500 ha. Comparison of VSA in Jan. 2005, before Hurricane Katrina, with Oct. 2005 showed a decline of 25% in a single year. The lack of consistent mapping techniques for the Chandeleur Sound complicates understanding of decadal-scale changes in seagrass area.

In summary, seagrasses have continued to be supported in all the locations that were first mapped in 1969, except for Waveland on the mainland. There was an overall decline in VSA from 1940 to 2011 in the Mississippi–Chandeleur Sound region. The Chandeleur Islands, which are farthest offshore, are home to a much greater area and diversity of seagrasses when compared with the Mississippi sites, but may have also experienced the largest decline due to protective barrier island erosion and loss.

Decadal-scale changes in seagrass using Horn Island as a case study.—To demonstrate habitat change and the subsequent shift in location and total area of seagrass beds at a particular site, Horn Island was chosen as a case study. A set of seagrass maps on Horn Island spanning the study period from 1940 to 2008 is shown in Figure 3. The island underwent thinning in the north–south and shortening in the east–west direction over time. The 1940 seagrass area showed the farthest offshore distribution of vegetated patches in the north–south axis (data from 1969 are of insufficient spatial resolution to be considered very accurate), whereas the 2006–08 seagrass area showed a shift onshore into shallower waters compared to the earlier data. There was land loss on the eastern end at a much higher rate than land gain on the western end of the island. Horn Island is gradually moving westward and the shape of the eastern tip keeps changing. Seagrass distribution on Horn Island shrunk in both north–south and east–west directions mirroring the geomorphological changes of the island shoreline.

Comparing among years using the VSA data only (1940, 1952, 1971, 2003–08), maps show a decline from 76.7 ha in 1940 to 19.2 ha in 1971, followed by a recovery to a mean of 57 ha in the period of 2003–06 (Fig. 3). The year with the single greatest VSA was 2006 (82 ha), compared with 1,365 ha of seagrass extent in 1969 and 233.9 ha of seagrass coverage in 1999; the latter two values are both inflated by including unknown amounts of bare sand bottom. From west to east, VSA on each segment of Horn Island underwent different rates of change. In 1940s and 1950s, the accreting western third supported the largest seagrass area (21.7–38.1 ha), following by the eroding eastern third (15.6–23.5 ha), then the middle third (8.3–15.2 ha). In 1971, post-Camille, the protected middle segment had the highest VSA (10.5 ha), the western part took the second place (8.3 ha), and the eastern part had the lowest (0.3 ha). Since 2003, the highest VSA occurred on the accreting western third (17.5–37.3 ha) and the eroding eastern third had the lowest (8.4–15.2 ha).

A correction for bias in area calculated by the different methods (seagrass extent vs. seagrass coverage vs. VSA) can be attempted by comparing the percentage of the total seagrass in a given year found on each third of the island. Comparing percentage of total seagrass from maps for VSA (1940, 1952, 1971, 2003–08) shows the accreting western third of the island has remained consistent over time with 43.5–49.6% of the total seagrass, whereas the eroding eastern third has dropped from >30.6% in 1940–52 to <23.4% in 2003–07, and the more stable midsection has increased from around 19% in 1940–52 to around 33% in 2003–07 (Fig. 3). Dramatic departures from these proportions were found in 1971, after Hurricane Camille, with the stable midsection having 54.8%, and the eroding eastern third supporting only 1.7% of the total seagrass for that year (Fig. 3). Maps based on seagrass coverage, from the USGS–NWRC projects in the 1990s, suggest a higher proportion of the total seagrass was found on the accreting western third (51.7–71.6%) than on the eroding eastern third (6.4–22.4%).

In summary, the accreting western side of the island consistently had the largest amount or percentage of seagrass over the years, whereas the eastern side kept losing seagrasses as this end of the island eroded (Fig. 3). Comparing the 1940 map with the data gathered during the 2000s, the accreting western third of the island had the largest VSA with a stable percentage (45–50%), the stable middle third of the island showed the smallest decline in VSA and actually an increase in the percentage, while on the eroding eastern section of Horn Island VSA and percentage decreased over this time period.

DISCUSSION

Spatial distribution of seagrass in the Mississippi and Chandeleur sounds.—Principal factors responsible

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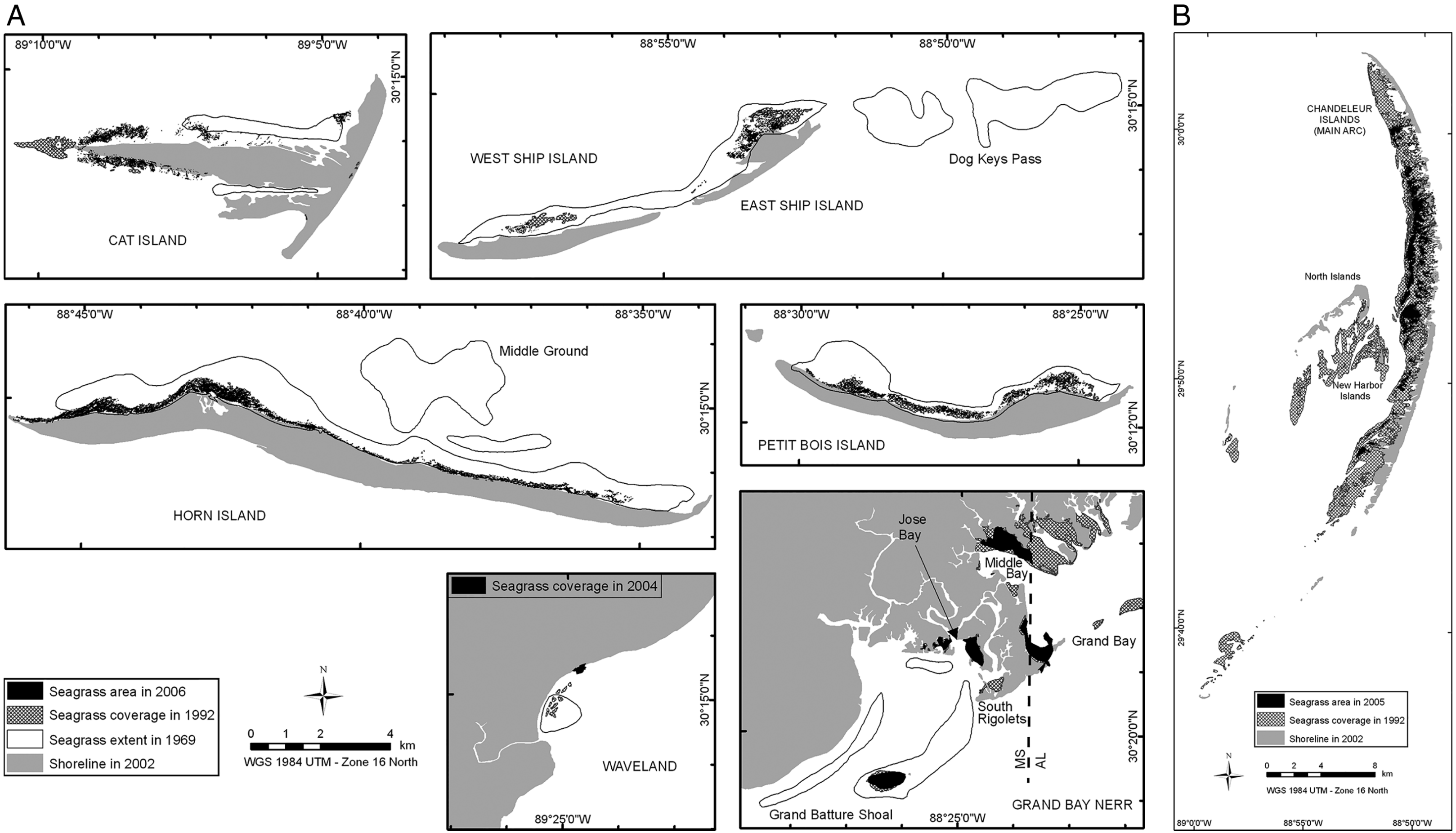

Fig. 2. (A) Change in seagrass in the Mississippi Sound (Groups 1 and 2) from 1969 to 2006. Dog Keys Pass and Middle Ground data were included only in the 1969 map and were not present in later maps. The 2004 map of Waveland is included because of the lack of 2006 data. The apparent location shift of seagrasses at Waveland is due to a mapping error in the early paper maps rather than a geolocation change. The Mississippi–Alabama state line is indicated as a dotted line in the Grand Bay National Estuarine Research Reserve map. (B) Change in seagrass on the Chandeleur Islands (Group 3) from 1992 to 2005. Data from 1969 were not available for the Chandeleur Islands. Data for the North Islands and New Harbor Islands, as well as the southern portions of the island were not available for 2005.

for the observed pattern of seagrass distribution in the Mississippi and Chandeleur sounds include water depth, salinity, type of substrate, and protection from wind and waves. Because of low light levels in the turbid waters, seagrasses do not currently colonize depths greater than about 2 m in the Mississippi Sound (Heck et al., 1994, 1996), but historically grew down to 6 m or more in the clearer water of the Chandeleur Sound (Eleuterius, 1987). Seawall construction from Biloxi to Gulfport in the 1930s and artificial beach maintenance since then have resulted in continuously shifting sandy sediments that are unsuitable for seagrass establishment, accounting for the large gap in seagrass distribution evident along the mainland coastline between Waveland and GNDNERR. *Ruppia maritima* is found in muddy sediments in brackish waters only in two areas along the mainland: (1) Waveland, where part of the beach was intentionally not renourished after the 1980s to protect this SAV, and (2) GNDNERR, where saltmarshes dominate the shoreline of the eroding former delta of the Escatawpa River. Additional species of SAV occur in brackish to freshwater in the river deltas and bayous along the mainland (Fig. 1) including *Vallisneria americana, Najas guadelupensis, Zannichellia palustris,* and *Potamegeton* spp. (Cho et al., 2010, 2012). The seagrass *H. wrightii* occurs on sand to sandy mud bottoms, and in relatively clear waters with a salinity of 20 ppt or more (Eleuterius, 1987) and is most prevalent in the shallow waters along the Mississippi Sound barrier islands. However, *H. wrightii* can also be found in the southern parts of GNDNERR on the submerged shallow sandbanks of the former Grand Batture Islands, which eroded away due to lack of riverine sediment supply, storm damage, and constant wave energy from the prevailing southeasterly summer winds. The prevailing winds stirring up the fine sediments in the nearshore shallows are a major reason why the Mississippi mainland coast does not support seagrasses, except for in protected bays, bayous, marshes, and ponds. No seagrasses are found on the high-wave-energy Gulf-facing southern beaches of West Ship, East Ship, Horn, and Petit Bois islands. The uniquely T-shaped Cat Island supports seagrasses on both the north and south shores as they are protected from the southeast summer winds by its north–south-oriented sand spit at the east end of the island. The Chandeleur Islands also stretch in a north–south direction, with seagrasses established on the protected western side, but SAVs are not found along the eastern beaches exposed to the open GOM. In the Chandeleur Sound to the lee (west) of the islands, substrates change from sandy offshore to more muddy inshore, supporting all five species of seagrasses, with *T. testudinum, S. filiforme,* and *H. wrightii* occurring more offshore, whereas *R. maritima* and *H. engelmannii* are found in the nearshore shallows (Pham and Biber, 2013).

Temporal changes in seagrass area in the Mississippi and Chandeleur sounds.—There are several factors thought to be responsible for changes in seagrass area in the Mississippi Sound over time. Eleuterius (1989) discussed hurricanes, salinity depression, low winter water temperatures, and sand bar movement as obvious causes of seagrass decline. Moncreiff (2007a, 2007b) indicated that the overall decline in water quality, from cumulative effects of human activities in the coastal environment, was also potentially responsible for the apparent ongoing reduction in seagrass area in the Mississippi Sound between 1969 and the late 1990s. More recently available data suggest that loss of land area on the Mississippi Sound barrier islands and the Chandeleur Islands also has an important impact resulting in reductions to both PSGH and VSA, for example the case of Petit Bois Island presented in Carter et al. (2011).

Change of species composition: One of the main reasons cited for widespread loss of *T. testudinum* and *S. filiforme* along the Mississippi barrier islands (Group 2) was severe salinity depression following increased rainfall and 10 openings of Bonnet Carré Spillway (28 Jan.–16 March 1937, 23 March–18 May 1945, 10 Feb.–19 March 1950, 8 April–21 June 1973, 14–26 April 1975, 17 April–31 May 1979, 20 May–23 June 1983, 17 March–17 April 1997, 11 April–8 May 2008, and 9 May–20 June 2011) designed to protect the city of New Orleans, LA, from river flooding. Even though overflow of freshwater from the Mississippi River via Lake Pontchartrain and Lake Borgne into the western Mississippi Sound was a historically natural phenomenon, Eleuterius (1987) argued that the spillway acted as a concentrated point of large volumes of freshwater discharge, which caused a more dramatic salinity perturbation than previous natural distributions of freshwater. Salinities in the Mississippi Sound, especially westward, can remain depressed for months after the openings of the spillway (Moncreiff, 2007a). The four halophilic seagrass species, *Halophila engelmannii, Halodule wrightii, S. filiforme,* and *T. testudinum,* which were found historically in the Mississippi Sound (Humm, 1956; Eleuterius, 1973), require a relatively high salinity of at least 15–20 ppt for survival. Their demise in the Mississippi Sound was highly correlated with the frequent openings

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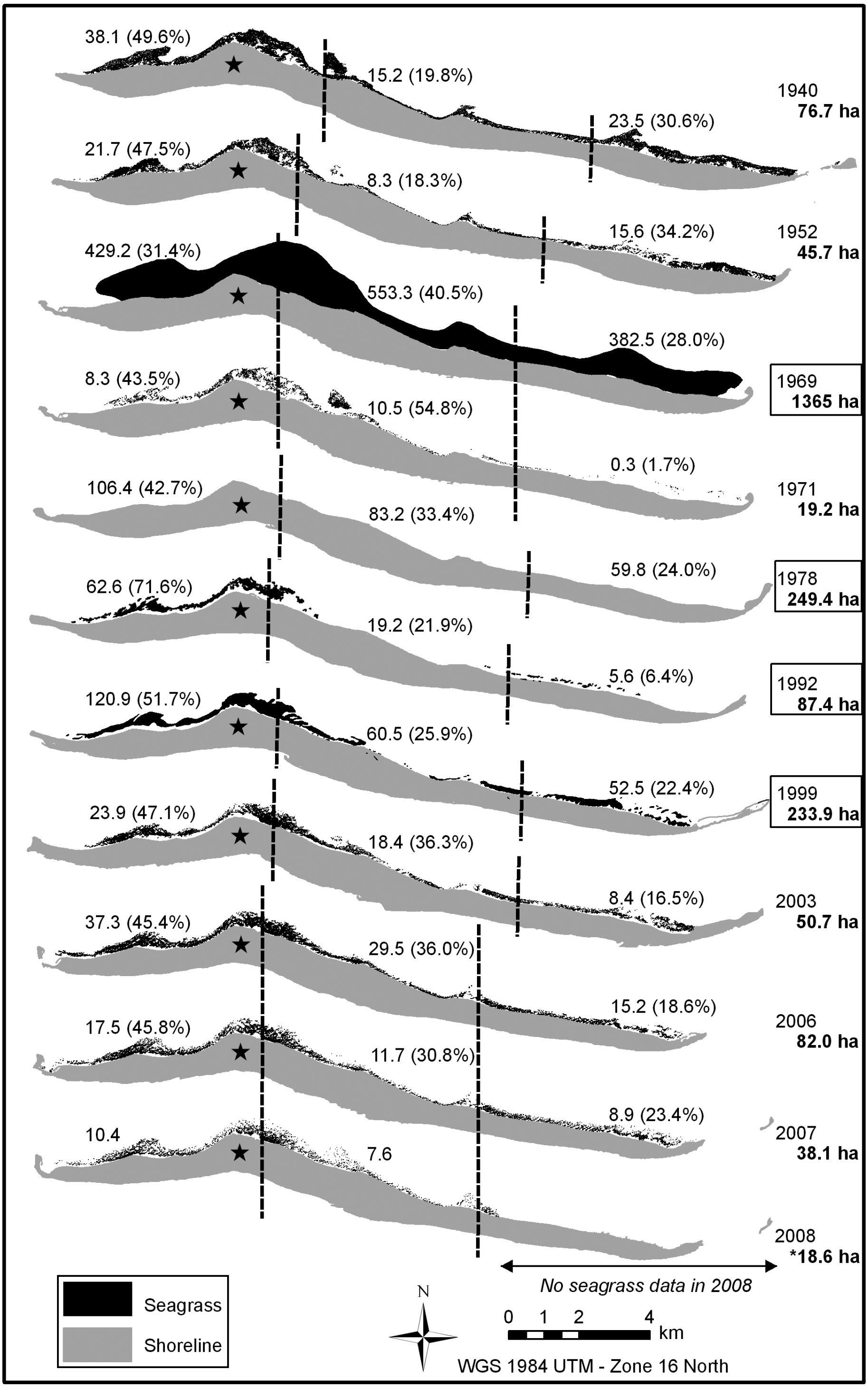

Fig. 3. Time-series maps showing changes in seagrass and island size of Horn Island from 1940 to 2008. The star indicates a common geo-reference in all years. Map dates and the associated total seagrass area (ha) are shown on the right. The 4 yr (1969, 1978, 1992, and 1999) indicated in boxes are based on coarse polygon maps of seagrass extent or coverage and highlight the potential inflation of the total area calculated compared to vegetated seagrass area in other years. The island and adjacent seagrass habitat were divided at the dotted lines into three equal segments based on the distance from its eastern to western tips for that year. Seagrass area (ha) and

of Bonnet Carré Spillway during 1973–83 following damage caused by Hurricane Camille in 1969 (Eleuterius, 1987; Moncreiff 2007a). Among these species, *H. engelmannii* is the most sensitive to disturbance and has not been reported to occur in the Mississippi Sound since 1972 (Eleuterius, 1989). *Syringodium filiforme* and *T. testudinum* were once abundant in the Mississippi Sound and have almost completely disappeared except for a few small patches on the north shore of Petit Bois Island and in Ranger Lagoon on Horn Island. *Halodule wrightii* is currently the predominant species remaining in the Mississippi Sound, in large part as a result of its rapid growth and tolerance to a wide range of salinity (Eleuterius, 1989).

Seagrass communities in the mainland (Group 1) and NCI (Group 3) did not experience species loss but change in species composition has also been documented. Cho et al. (2009) reported a relative increase in the opportunistic *R. maritima* at the expense of *H. wrightii* at GNDNERR in 2006 and 2007 following Hurricane Katrina, although it does not appear that this was a permanent change. At Waveland, Eleuterius (1973) initially described an *H. wrightii* population but only *R. maritima* was recorded in subsequent years. It seems likely that salinities in these waters are actually too low (Eleuterius, 1976) to support *H. wrightii* and that the earlier report of its presence at Waveland resulted from an error in species identification. Though less information is available, NCI seagrass meadows are also suspected to have undergone changes in the relative abundances of the five species due to salinity depression following high rainfall and the openings of Bonnet Carré Spillway.

Change of seagrass habitat and seagrass area: The seagrass area and suitable habitat have changed at all study sites but apparently for different reasons. In Group 1 at Waveland, the area where seagrass occurred has been excluded from beach renourishment since the 1980s. Importantly, the location shift of the seagrass polygons in the Waveland maps does not indicate a true change in the geolocation of suitable habitat and seagrass beds. Although the 1969 map indicates the general location where seagrasses were thought to have occurred by a single large polygon, the 1992 map shows multiple polygons to denote the patchy coverage. The smaller 1992 polygons also did not indicate the exact number or locations of patches (J. D. Caldwell, pers. comm.); rather, they were meant to convey that seagrass was less abundant than in 1969. The 1998 Waveland seagrass map created in this study was correctly geo-referenced and shows the true location of the seagrass patches, rather than the previously incorrect representations of location shown in the hand-drawn 1969 and 1992 maps (Eleuterius, 1973; Moncreiff et al., 1998). Obviously, any determinations of VSA in Waveland from the hand-drawn 1969 and 1992 maps are inaccurate. Toward the east in GNDNERR, seagrasses at the South Rigolets and Grand Batture sites were once protected by the Grand Batture Islands. However, by 1980, all remnants of this island chain were gone (Otvos, 2007), exposing the shoreline to increased wave erosion, which partly helps to explain the reduction in seagrass habitat from 1969 to 1992 in GNDNERR. Again, no accurate calculations of VSA can be made from these two mapping efforts due to the generalized nature of the polygons that were hand-drawn on paper maps.

The Mississippi Sound barrier islands in Group 2 have continued their historical trend of westward movement and continual land loss (Otvos and Carter, 2013), which in turn has caused changes in potential seagrass habitat and VSA. The three most important morpho-dynamic processes associated with barrier island translocation are (1) unequal lateral transfer of sand related to greater up-drift erosion compared to down-drift deposition, (2) barrier island narrowing resulting from erosion of both the GOM- and sound-side shores, and (3) island segmentation related to storm breaching, as with the division of Ship Island into East and West Ship islands since 1969 (Morton, 2007, 2008).

Firstly, the dominant westward alongshore littoral sediment transport results in net erosion on eastern ends and net accretion on western ends of the Mississippi barrier islands, with the exception of Cat Island. The erosion rate on the eastern ends exceeds the accretion rate on the western ends, leading to a progressive land loss and westward movement of the islands (Fig. 3). When there is no longer adequate substrate supply to maintain the eastern tip, seagrass decline is rapid along this portion of the island. On the western ends, seagrass establish-

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percentage of total area for each third is shown above that segment. * Note that the 2008 data cover only 70% of the island length, as seagrass survey data were not collected from the eastern portion, therefore no percentage of total area was calculated for that year.

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ment and growth does not stabilize new sediment deposits quickly enough to match rates of seagrass loss on the eastern end. Thus, over time, there is a net loss not only of PSGH but also of VSA, as illustrated by the Horn Island case study. Continued habitat loss in the eastern segment, a relatively low rate of habitat gain on the western end, and the relatively stable middle part of Horn Island help to explain the observed decadal-scale changes in VSA (Fig. 3). Human activities, such as dredging navigational channels to accommodate increasingly larger vessels, may disrupt alongshore sediment transport by trapping sand (Morton, 2007, 2008). These channels require continuous maintenance-dredging. For example, Petit Bois Island continues to shorten in the east–west direction but has stopped migrating because westward littoral drift falls into the Pascagoula Ship Channel adjacent to its western end (Morton, 2008). Decline in seagrass on Petit Bois Island since 1940 corresponds with a decline in above-water island land area (Carter et al., 2011).

Secondly, under the effects of summer tropical cyclones and winter cold fronts, Mississippi barrier islands have been progressively narrowing as a result of long-term beach erosion on both the GOM and sound sides. The apparent southward movement of seagrass beds, e.g., on Horn Island (Fig. 3), is partly because this north–south narrowing process. Thirdly, storm impacts on shoreline fragmentation depend on the orientation and other geomorphological characteristics of each island. In the Mississippi Sound, Ship Island is the most vulnerable to storm-driven land losses as topographic and bathymetric boundary conditions focus wave energy onto the island (Morton, 2007, 2008). Ship Island was breached into East Ship Island and West Ship Island after Hurricane Camille in 1969, which explains a steep drop in VSA in 1975 (Table 2). This breach was substantially widened during Hurricane Katrina in 2005. Currently the U.S. Army Corps of Engineers plans to close this breach by pumping large volumes of sediment into the gap (Vittor and Associates, Inc., 2014). It remains to be seen whether seagrasses will reestablish once the rejoined island is stabilized.

In Group 3, the Chandeleur Islands form a low-profile island chain that undergoes breaching, thinning in an east–west direction, and erosion on the northern and southern tips; all of these geomorphic processes affect the area of seagrass habitat and the location of the seagrass beds. Tropical cyclone frequency is thought to dominate the long-term evolution of the Chandeleur Islands (Fearnley et al., 2009), with a high return frequency causing faster rates of land loss. Although the GOM and sound shorelines are both migrating landward, the GOM shoreline is migrating twice as fast as the sound side, causing net deterioration of the island arc (McBride et al., 1992). The lack of new riverine sediments to help naturally renourish the islands is likely to be the cause for their ultimate demise in the future, much like what has already occurred to the former Grand Batture Islands at GNDNERR, with the attendant loss of extensive seagrass meadows.

The effect of hurricanes on seagrass, however, may not necessarily be devastating. Cho et al. (2009) reported that both *R. maritima* and *H. wrightii* at GNDNERR were more abundant in 2006 than any other years in the study period of 2005–2008; they suggested that physical disturbance by Hurricane Katrina in 2005 might have helped to expose the deep-buried seeds and promote their germination. Additionally, Anton et al. (2009) found no effect of Hurricane Katrina on *H. wrightii* leaf density and biomass 2 wk and 1 yr after landfall at the nearby Sandy Bay, Alabama. Also on the Mississippi barrier islands, Eleuterius (1971) found that Hurricane Camille eroded and destroyed all the seagrass in the island passes, but the seagrass beds on the north side of the islands were not significantly disturbed and grew more robustly during the summer following the hurricane than in the year prior to the hurricane. He suspected that wind and waves disrupted the organic sediments and inland rains brought down more nutrients than normal, stimulating seagrass growth. Carter et al. (2011) found no apparent impact of Hurricanes Camille and Katrina on VSA. Even though Hurricane Katrina's extreme storm surge caused temporary flooding of the entire Mississippi barrier island chain that resulted in massive erosion and local accretion of terrestrial sediments (Fritz et al., 2007), it did not seem to devastate the seagrass beds (Heck and Byron, 2006). The effect of hurricanes and tropical storms on seagrasses deserves further study in this region.

Potential problems when comparing maps from various sources.—There are numerous possibilities for misinterpretation when comparing among seagrass maps from different sources. For a given site, seagrass occurrence in one map but not in the others may be due to lack of survey information rather than any seagrass loss or gain. This is the case for Deer Island, Dog Keys Pass, Round Island, Middle Ground (included only in the 1969 map of Mississippi Sound), North Islands, and New Harbor Islands (only in the 1992 map of Chandeleur Islands). Since there were no comparable data available in later maps, these sites were excluded from area calculations

(Table 2). It is not clear whether the lack of seagrass in later maps is because those areas were just not surveyed, or whether there was indeed a complete loss of seagrasses. With respect to seagrass data for the GNDNERR, Eleuterius (1973) did not survey at the more eastern locations in Middle Bay and Grand Bay, but survey data for these two locations are included in later maps. Depending on the investigator, GNDNERR seagrass maps may include only those areas that fall within the GNDNERR reserve boundaries, or they may extend eastward beyond the Mississippi–Alabama state line boundary. Thus, attention should be paid to discrepancies between political boundaries and actual seagrass range when comparing among maps to determine change over time. Seagrass coverage in northeastern Grand Bay was not included in area determinations because of this surveying problem (Table 2).

A less obvious, but potentially major source of misinterpretation, is due to differences in mapping objectives and methods among studies. Eleuterius (1973, 1979) and Vittor and Associates, Inc., (2014) generated maps of seagrass extent, whereas Moncreiff et al. (1998) and USGS–NWRC (1998a, 1998b, 2003) generated maps of seagrass coverage; both approaches mapped general seagrass locations using relatively coarse-scale polygons that included unspecified large areas of unvegetated sand bottom. This approach may generally be more appropriate for estimating the extent of seagrass habitat rather than VSA and does not allow for the quantification of patch size and shape. More recent studies (e.g., Carter et al., 2011) have employed object-based mapping with manual pixel editing to accurately identify the boundaries of individual seagrass patches from vertical aerial image data with a horizontal resolution of 1 m or better and enable calculation of VSA. Such present-day methods, enabled by advances in computer processing power and software, are much more effective in quantifying the presence, shape, and area of the many small patches that often comprise a seagrass population. Direct comparisons of seagrass area among studies using the different techniques (seagrass extent vs. seagrass coverage vs. VSA) may yield conclusions of dramatic change over time (e.g., compare between 1969 and 1971 Horn Island data, Table 2), simply because of the various mapping methods employed. However, such conclusions may be primarily a consequence of improper comparisons between, for example, the seagrass extent compared to VSA on Horn Island in 1969 and 1971, respectively. The problem may be somewhat reduced with respect to the continuous seagrass meadows on the Chandeleur Islands vs. the more patchy seagrass beds on the Mississippi islands. This issue has also been considered for seagrass mapping in Florida (Dixon and Perry, 2003) and New South Wales, Australia (Meehan et al., 2005). Resampling from the original aerial imagery and a common definition of the mapping unit and the study object will be required to make maps at different scales and resolutions comparable. Also important is defining a threshold, such as an a priori minimum difference (e.g., 5–10%) between time points, to distinguish between real changes in VSA and potential mapping errors (Meehan et al., 2005).

Yet another source of error comes from comparing data collected in different seasons, as leaf biomass and shoot density can vary substantially during the year. For instance, seagrasses on the barrier islands proliferate from May to Oct. and are at their peak canopy density during the late summer and fall months. *Ruppia maritima* along the Mississippi mainland coast exhibits bimodal peaks in density in late spring and late fall (Moncreiff, 2007b), although other investigators have noted that late fall biomass can be dominated by *H. wrightii* in certain locations. Late fall, with high leaf biomass and relatively high water clarity, is considered the best time for mapping seagrasses in the Mississippi Sound. For the purposes of decadal-scale change detection, it is important to compare maps only within-season so that changes in VSA among years are not confounded with seasonal biomass changes.

In summary, studies in the Mississippi Sound indicate both seagrass loss and gain depending on location, but decline has remained the major overall trend consistent with earlier reports (Eleuterius, 1979; Heck et al., 1996; Moncreiff et al., 1998; Moncreiff, 2007a; Carter et al., 2011). The early 1970s was suggested as the beginning of seagrass decline in the Mississippi Sound, largely due to prolonged low-salinity incursions from frequent Bonnet Carré Spillway openings. Eleuterius (1989) estimated that only about 30% of the vegetated area found in 1969 remained in 1989, despite similar amounts of PSGH. The 1992 estimate of seagrass coverage (809 ha) by Moncreiff et al. (1998) represented an 84.6% loss when compared to the prior 1969 estimates (5,252 ha) by Eleuterius (1973), but this is confounded by the inaccurate comparison of seagrass coverage in 1992 with seagrass extent in 1969. Moncreiff et al. (1998) reported a 19.6% reduction in PSGH based on a 2-m depth limit. Moncreiff (2007b) already noticed that the methodological differences in the two maps prepared by Eleuterius (1973) and by the USGS–NWRC (1998b) precluded any direct

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comparisons outside of the loss of species and estimates of decline in seagrass habitat.

The compilation of various data in this study confirms the previously reported trend of seagrass decline (both in potential habitat and seagrass area), but the rate of change is not as high as reported previously based on inappropriate comparisons of maps created using different mapping methods. Change in seagrass area varies dramatically among the three study groups and even among islands within Group 2, where the best data are currently available. On the one hand, as shown in our case study of Horn Island, direct estimation of seagrass area change can be highly misleading if accepted prima facie without understanding the different mapping techniques used. Two examples of this problem are the incorrect statements in the literature, based on the study by Moncreiff et al. (1998), that ‘‘seagrasses in Mississippi suffered a decline of between 85 and 89 percent over 23 years’’ (Onuf et al., 2003), and that ‘‘the Mississippi Sound, Miss., has lost nearly all of its seagrasses—over 4,500 of 5,250 ha (11,120 of 12,973 acres) of seagrasses—since 1969’’ (Beck et al., 2007). On the other hand, development of new mapping techniques allows us to more thoroughly analyze patch fragmentation and obtain more accurate rates of change in VSA over time, which is needed for better management of this declining natural resource.

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