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WETLANDS RESTORATION

Use of Remote Sensing and Field Data to Quantify the Performance and Resilience of Restored Louisiana Wetlands

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Abstract
Typical goals of wetland restoration efforts are to conserve, create, or enhance wetland structure, and to achieve wetland function that approaches or exceeds natural conditions. Measuring wetland establishment, condition, and resilience can be difficult, especially because monitoring wetland function has traditionally been time-intensive, costly, and often required repeat field-based surveys. Remote sensing provides novel collections of data and facilitates rapid assessments of wetland landscapes, land cover, species/habitat composition, change detection, degradation, diversity, as well as system threats and pressures. A combination of remotely collected and in situ vegetation data were used in conjunction with landscape metrics and vegetative indices. These data were used to evaluate and compare changes and trends in condition, function and resilience of restoration sites and reference wetlands in southwest Louisiana, USA. Results of this work show the restored wetlands reached structural and functional equivalency to reference wetlands after approximately three to ten years post-construction. With adequate maturity, the restored wetlands outperformed the reference wetlands, having higher percentage of land, land aggregation, aboveground vegetation productivity and floristic quality. Supplementing traditional field-based methods with remote sensing applications provided enhanced metrics for inventorying and monitoring of wetland resources, forecasting of resource condition and stability, and adaptive management strategies.

Keywords Ecosystem restoration · Remote sensing · Goods and services · Wetland function · Landscape ecology

Introduction

Wetlands are among the most productive and beneficial ecosystems in the world. Wetlands provide a wide range of services, including regulation (i.e., floods and droughts), support (i.e., soil formation and nutrient cycling), provisions (i.e., food and fresh water); cultural (i.e., recreational and aesthetics), and ecosystem (i.e., biological productivity and critical habitat) (Millennium Ecosystem Assessment 2003; United States Army Corps of Engineers [USACE] 2013). With an increasing understanding of wetland importance, Federal and State governments in the USA enacted various policies, regulations, and incentive programs to directly and indirectly protect, maintain, and restore wetlands (Votteler and Muir 1996). Typical goals of wetland restoration efforts are to conserve, create, or enhance wetland structure, and to achieve wetland function that approaches natural conditions (Stagg and Mendelssohn 2010; Craft 2016). Although wetland structure and function are driven by many presses and pulses, the dominant factors include elevation, hydrology, sedimentation, and vegetation (Steyer et al. 2008a). For a constructed wetland, failure to adequately account for, or manage one of these elements, can have negative implications on other elements, and ultimately on overall wetland condition.

Landscape ecology is based on the premise that there are strong correlations between landscape pattern (configuration) and ecosystem function (Gustafson 1998). Furthermore, wetland condition has traditionally been evaluated using a system's structure and/or ability to perform a suite of functions

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(Cohen et al. 2004). Measures of wetland condition are used to assess and track wetland performance, resilience, and recovery. The monitoring of wetland condition can be time intensive and costly because it often requires repeat surveys with high precision data about the landscape. However, remote sensing-based assessments circumvent many of the field-based limitations and provide useful tools when general site-specific wetland ecological conditions are required (Patience and Klemas 1993; Klemas 2013; Willis 2015). Remote sensing-based wetland evaluations provide biological metrics and indices that measure or estimate wetland quantity, quality, and condition (Karr and Chu 1997).

Plants are excellent indicators of wetland function and condition because of their rapid growth rates and direct response to environmental stressors and disturbances (Smith et al. 1995; Fennessy et al. 2002; USEPA 2002; Cohen et al. 2004; Mack 2007). Plant species composition, cover, density, and biomass are structural components of wetlands that are commonly used to quantify vegetative characteristics and often serve as indicators of wetland condition (Chamberlain and Ingram 2012; Cretini et al. 2012). Although these structural components are useful for quantifying and comparing some wetland characteristics, they typically lack measures of quality. Wetland plant quality can be an essential metric of wetland function because it provides critical information related to habitats, effectiveness of restoration measures, as well as resilience to (and recovery from) disturbance events (USEPA 2002).

Many natural and anthropogenic-induced disturbances, such as storm energies, inundation, and salinity, can be catalysts for long-term impacts on wetland ecosystems (Steyer et al. 2007). Recent studies have shown linkages between disturbance events, wetland landscape configuration, and wetland loss (Liu and Cameron 2001; Suir et al. 2013; Couvillion et al. 2016). Extreme extratropical storms have contributed to extensive erosion, breaching, scouring, and compression of coastal wetlands (Meeder 1987; Morton and Sallenger 2003; Suir et al. 2011). Similarly, inundation (especially with increased depth and duration) and salinity fluxes can strongly influence establishment, distribution, competition, and switching of vegetation and habitat (Steyer et al. 2008b). The resilience of ecosystems, defined as the amount of disturbance a system can absorb and still return to a pre-disturbance state or domain (Leps et al. 1982; Holling 1996), is a critical factor underlying the sustained production of natural resources and ecosystem services (Gunderson and Holling 2002).

The overall goal of this study was to identify and utilize practical wetland monitoring and assessment metrics, including wetland change assessments (structural), aggregation index (AI, structural), normalized difference vegetation index (NDVI, functional), vegetation abundance and composition (functional), floristic quality index (FQI, functional and structural), and multi-metric trends (resilience). The assessment metrics were used to evaluate changes and trends in restored wetland condition, function and resilience, and compare restored wetlands to reference wetlands. The objectives were to utilize field and satellite-derived data, including landscape metrics and vegetative indices to: (1) evaluate and compare structural changes of restored wetlands to naturally occurring reference wetlands; (2) quantify the quality and functional changes of restored wetlands; and (3) assess the resilience and recovery of restored wetlands to short-term episodic events (i.e., tropical storms and salinity spikes).

Methods

Study Area

The study and reference sites consist of the Sabine Refuge Marsh Creation restoration project and surrounding areas (Fig. 1). These study and reference areas consist of primarily brackish wetlands located west of the Calcasieu Ship Channel near Hackberry, Louisiana, USA. This area experienced significant conversion from wetlands to open water between 1956 and 1978 due to hurricane impacts and altered hydrologic and salinity regimes (Barras et al. 2008; Miller 2014a; Couvillion et al. 2017). There was also a 1968 to 1988 shift in the study area vegetation from fresh and intermediate dominated marsh species to more brackish species (Miller 2014a). This shift was induced by the introduction of saltwater through the Calcasieu Ship Channel (Miller 2014a). Since 2002, the Sabine study area has undergone extensive wetland restoration. These restoration efforts were implemented as part of the Coastal Wetland Planning, Protection, and Restoration Act (CWPPRA) to provide direct and indirect structural and functional benefits within the Sabine Refuge and surrounding wetlands. Although CWPPRA is a large-scale restoration program, it also consists of a monitoring program which collects useful ecosystem-based information (e.g., vegetation species composition, relative abundance, and aboveground biomass data) (Steyer and Stewart 1992). Similarly, the Coastwide Reference Monitoring System (CRMS) is a network of approximately 390 monitoring sites in coastal Louisiana designed to collect, process, and analyze physical, chemical, biological, and geospatial data to characterize coastal wetland landscapes inside and outside of CWPPRA projects (Cretini et al. 2011).

The Sabine Refuge Marsh Creation restoration project consists of five separate creation sites ranging in size from 87 to 149 hectares [ha] within an open water area that was approximately 1200 ha in 2001 (Sharp 2011) (Fig. 1). The creation sites, known as Sites 1–5, were constructed in 2002 (Site 1), 2007 (Site 3, constructed before Site 2), 2010 (Site 2 and overflow), 2014 (Site 4), and 2015 (Site 5), respectively (Table 1). Approximately 3.3 million m^3 of dredged material

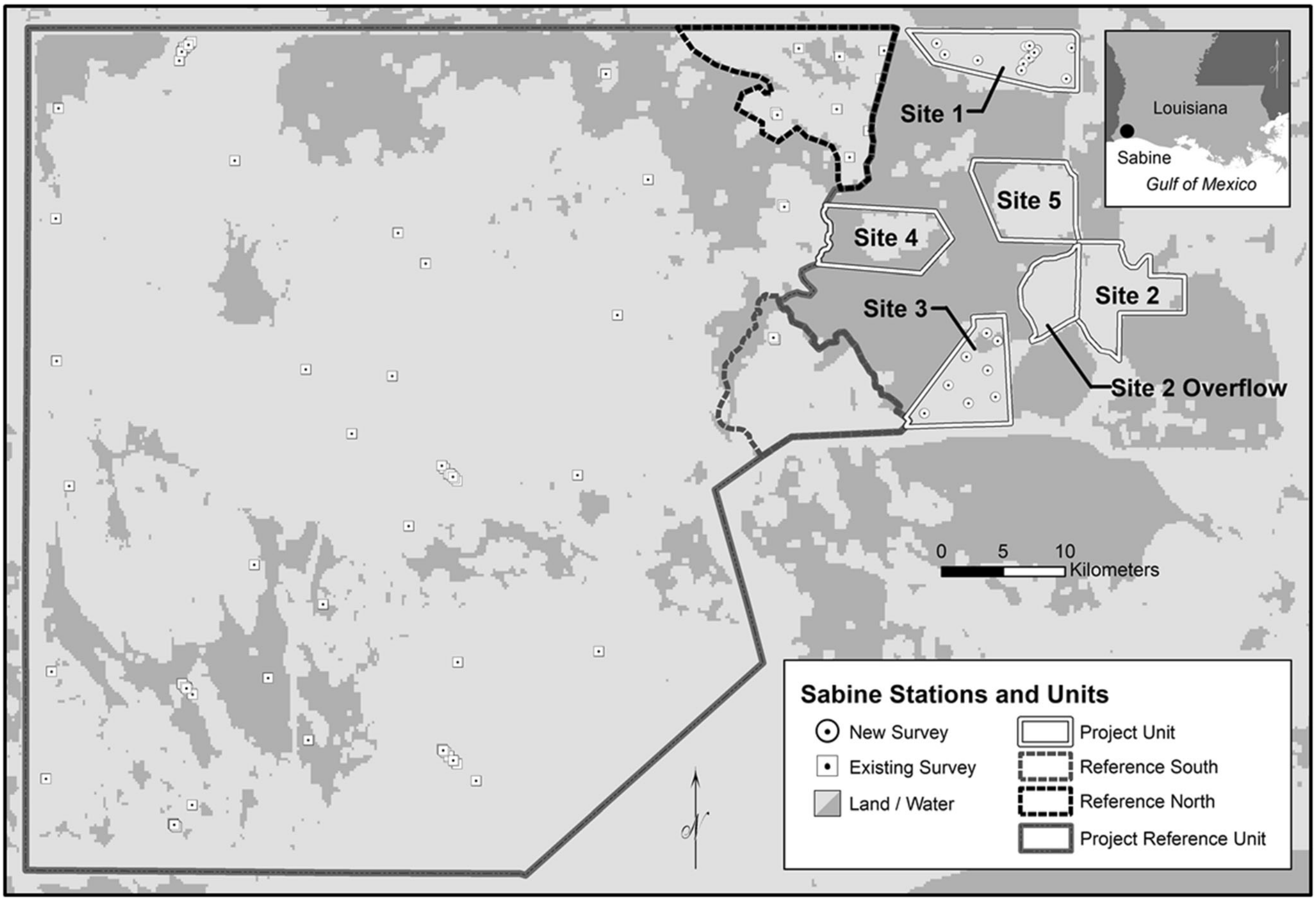

Fig. 1 Location map of the Sabine study area assessment units (Project Sites, Project Reference, Reference South, and Reference North) and data collection sites

were used to construct the sites to an initial height of +0.82 to +0.94 m North American Vertical Datum 1988 (NAVD88, Geoid 99). The material placed in Site 2 was allowed to overflow the western dike, resulting in a large "overflow area" that was used as a sixth project assessment unit (Fig. 1). After placement, the material within each site was allowed to consolidate and desiccate to a final target elevation of approximately +0.37 m NAVD88 (Sharp 2003; USACE 2005; Miller 2014a). Upon consolidation of the dredged material, the containment dike along one side of each site (except Site 2) was degraded and breached to allow for water movement and vegetation establishment, and to restore the area to more natural

Table 1 Construction data, area, and fill for Sabine restoration sites

Project Area	Constructed (date)	Area (hectares)	Fill (cubic meters)
Site 1	2002	87	637,957
Site 3	2007	94	633,638
Site 2/Overflow	2010	149	764,555
Site 4	2014	93	695,364
Site 5	2015	94	565,123

conditions (Louisiana Coastal Wetlands Conservation and Restoration Task Force [LCWCRTF] 2010). All sites were allowed to vegetate naturally, except for Site 1, which was planted with 36,000 *Spartina alterniflora* (saltmeadow cordgrass) plants around the perimeter and along constructed hydrologic channels (Sharp 2003; Miller 2014a). All sites vegetated within two growing seasons, except Site 2, which remained largely void of vegetation, even as late as 2013 (3 years after construction) (Miller 2014a). It is theorized that Site 2 remained unvegetated until the containment dikes were breached, allowing for the requisite hydrology (Miller 2014a; personal communication Robert Dubois). At the time of initial field sampling (September, 2014), only Sites 1, 3, and the overflow area of Site 2 contained nearly complete coverage by vegetation, and/or existing vegetation survey data. Therefore, Sites 2, 4, and 5 were only included in the remote sensing-based assessments (descriptions below).

Assessment Units

The assessment units used in this study consist of the Project and Project Reference (PR) units (Fig. 1). The Project units consists of the five project footprints and the Site 2 Overflow area where the Sabine Refuge Marsh Creation restoration projects were constructed. Reference wetland sites serve as standards against which others are evaluated, and therefore can be critical components of biological assessments (USEPA 2002). Although selection of appropriate or representative reference sites can be difficult, the use of multiple sites and scales can overcome some of the challenges of defining a reference standard for evaluating restoration performance (Matthews et al. 2009). The PR unit, which is an area in closest proximity to (but excluding) the Project sites, was selected due to its similar soil type, vegetation, and hydrology to the project area (Sharp, 2003). Satellite imagery was used to assess and compare changes in wetland area and vegetation biomass. However, due to limited coverage of higher resolution imagery in the PR unit, additional representative areas from within the reference unit were selected based on coverage and proximity to Project sites. These sub-units, which consist of the Reference North and Reference South units (Fig. 1), provide brackish and intermediate standards (Sasser et al. 2014), respectively, that the restored wetlands can be compared. The PR unit was used for moderate resolution imagery-based assessments, while the Reference North and South units were only used for high resolution imagery-based assessments.

Remote Sensing

Remote sensing assessments were performed using Landsat and DigitalGlobe imagery. Landsat Thematic Mapper (TM) and Operational Land Imager (OLI) images, which provide moderate spatial (resampled to 28 m) and temporal (16 day return) resolution imagery, were acquired using the Google Earth Engine (GEE) image service (Table 2). GEE provides Tier 1 surface reflectance imagery, those meeting geometric, radiometric, and atmospheric quality requirements (Kalnay et al. 1996; Chander et al. 2009; Schmidt et al. 2013). For Landsat imagery, all cloud-free “8-day” imagery across the Landsat collection period (1985 to 2015) were acquired. Cloud-free 32-day composites were also acquired when and where 8-day imagery were not available or were not cloud-free (Strahler et al. 1999). Images from the DigitalGlobe constellation of satellites provide high spatial (1.24 to 2.62 m multispectral) and temporal (1–3 day sensor returns) resolution data that are useful for estimating short-term landscape variation linked to disturbance events and/or prevailing environmental conditions (Suir et al. 2011). All cloud-free DigitalGlobe satellite imagery collected during the period of 2004 to 2016 (Table 2) were acquired using the Enhanced Viewer Web Hosting Service. The images were geometrically and atmospherically corrected and transformed to reflectance using the QUick Atmospheric Correction (QUAC) and Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm in ENVI 5.3 software (ITT 2009; Mutanga et al. 2012). This study also used other ancillary data (i.e., 1956 habitat data [Army Map Service, USGS 1997], 1978 land and water imagery [USGS, Hartley et al. 2000], and the 1998 digital color infrared orthophotos [Louisiana Oil Spill Coordinator’s Office 2009]), resampled to 28 m, to supplement the moderate resolution satellite-borne imagery and provide a longer period of analysis.

Land and Water Classification

The primary goal of wetland restoration in the Sabine Refuge was to create emergent marsh. Quantifying short- and long-term landscape structural changes can serve as an important precursor to understanding functional effects of wetland restoration and change (Tischendorf 2001). This study utilized space-borne data to classify land and water features and evaluate their changes over time. The standard procedures established for CRMS land-water classifications (Folse et al. 2014) was performed on all qualifying Landsat and DigitalGlobe imagery. This classification process utilized the Normalized Difference Water Index (NDWI) and NDVI, (method details provided in the vegetation section below) to identify water and land features, respectively. These indices were used in conjunction and separately to generate metrics useful for evaluating wetland structure and function. The modified NDWI and WorldView Water Index (WV-WI) were used for the Landsat and DigitalGlobe imagery, respectively (Mcfeeters 1996). The mNDWI normalizes a green band against a short-wave infrared (SWIR) band and the WV-WI normalizes a coastal band against a near infrared band. The mNDWI and WV-WI are calculated using the following equations:

$$\mathrm{mNDWI} = \frac{Green - \mathrm{SWIR}}{Green + \mathrm{SWIR}} \tag{1}$$

$$\mathrm{WV{-}WI} = \frac{Coastal - \mathrm{NIR2}}{Coastal + \mathrm{NIR2}} \tag{2}$$

A final land-water dataset is created by categorizing each independent variable (spectral bands and indices) into a land-water type (detailed methods in Folse et al. 2014).

Landscape Metrics

The FRAGSTATS landscape pattern analysis software (version 4.2) was used to compute landscape metrics using the high-resolution (i.e., DigitalGlobe) imagery-derived land and water data. The ratio and interface of land and water are some of the more important features and metrics of wetland landscapes (Suir and Sasser, 2019a). Therefore, the landscape metrics selected for use in this study were the percentage of landscape, edge density, and aggregation index. This study utilized land-water classified data to evaluate land area and edge changes and trends during select periods (i.e., post-restoration,

Table 2 Sources and specifications of study-related remotely sensed imagery

Source/Sensor	Date(s)	Spectral Bands	Spatial Resolution (scale)(m)	Swath Width (km)	Repeat Orbit (days)
Army Map Service Aerial Photography	1956	Panchromatic	1:20,000	–	–
USGS Aerial Photography	1978	RGB	1:65,000	–	–
Louisiana Oil Spill Coordinator's Office (1999) Aerial Photography	1998	RGB	1:40,000	–	–
USGS Landsat 5 TM	1985–2011	6 multispectral + pan + thermal	28	185	16
USGS Landsat 8 OLI	2013–2016	6 multispectral + pan + thermal	28	185	16
Digital Globe GeoEye-1	May 2009 May 2012 February 2014	4 multispectral + pan	1.84	15.2	2
Digital Globe QuickBird-2	June 2004 April 2005 November 2014	4 multispectral + pan	2.62	16.8	1–3.5
Digital Globe WorldView-2	January 2010 June 2012 September 2013 December 2014	8 multispectral + pan	1.8	16.4	1.1
Digital Globe WorldView-3	December 2015 July 2015 February 2016 September 2016	8 multispectral + pan + SWIR/CAVIS	1.24	13.1	1

disturbance period). The percentage of landscape is the proportional abundance of land within the landscape and is quantified using the equation:

$$PLAND = P_i = \frac{\sum_{j=1}^{n} a_{ij}}{A}\ (100) \tag{3}$$

where P_i is the proportion of the landscape occupied by patch type (class) i, a_{ij} is the area (m^2) of patch ij, and A is the total landscape area (m^2). Edge density provides a general measure of ecosystem function (Browder et al. 1985), and is quantified using the equation:

$$ED = \frac{E}{A}\ (10,000) \tag{4}$$

where, E is the total length (m) of edge in the landscape and A is the total landscape area (m^2). Typically, wetland edge density increases with time, as a result of structural change and wetland loss. Edge density increases to a maxima, then decreases as wetland loss continues, resulting in a curvilinear relationship between edge and wetland loss (Browder et al. 1985; Couvillion et al. 2016). AI provides a measure of landscape condition that positively correlate to wetland integrity and stability (Suir et al. 2013; Couvillion et al. 2016). AI has evolved as a primary metric for linking structure to ecosystem function and is defined as the frequency with which different pairs of patch types appear side-by-side in a landscape (McGarigal 2015). This index was used to assess landscape configuration changes over time using high resolution spaceborne imagery. The class-level aggregation index (AI) is derived as:

$$AI = \left[\sum_{i=1}^{n}\left(\frac{g_{i,i}}{\max\_g_{i,i}}\right)\right](100) \tag{5}$$

where $g_{i,i}$ is the number of like adjacencies between pixels of patch type i (class), $\max\_g_{i,i}$ is the maximum number of like adjacencies between pixels of patch type (class) i (He et al. 2000; McGarigal 2015).

Normalized Difference Vegetative Index

NDVI has well established correlations to photosynthetic activity, aboveground biomass, and leaf area index (Carle 2013). NDVI was used in this study to assess the establishment, health, and productivity of aboveground vegetation in restored and reference wetlands. NDVI assessments were performed using pre- and post-construction satellite imagery collected from Landsat and DigitalGlobe (i.e., GeoEYE, Quickbird, and WorldView) satellite sensors. NDVI data were created using the standard equation (Rouse et al. 1974):

$$\mathrm{NDVI} = \frac{NIR - Red}{NIR + Red} \tag{6}$$

which uses a ratio between a NIR and red band to measure an ecosystem's ability to capture solar energy and convert it to organic carbon or biomass (An et al. 2013).

NDVI values range from −1 to 1, where values between −1 and zero (0) are typical of non-vegetation features (i.e., water, cloud, and impervious surfaces), and those between 0.2 and 1.0 are typical of green vegetation (Datt 1999; Sims and Gamon 2002). Generally, the higher the NDVI value, the higher the biomass, productivity, and vigor of the vegetation. All non-marsh features within the study area were excluded from each image by removing all NDVI values less than zero (< 0) (Reif et al. 2011). ESRI ArcGIS 10.5 was used to calculate zonal statistics (i.e., mean, min, max, sum, and standard deviation) on values of each NDVI raster within the Sabine assessment units (ESRI 2015).

Vegetation Surveys

This study utilized existing (CWPPRA and CRMS; Fig. 1, white squares) and newly collected vegetation data (Fig. 1, white dots). Within the CRMS program, emergent vegetation are surveyed annually during the period of peak biomass (Folse et al. 2014). All existing vegetation data from CWPPRA and CRMS stations were acquired for the Project and PR sites. For new data collections, this study utilized 0.25 m^2 (0.5 m × 0.5 m) plots within the sites and reference areas. Sample location coordinates were determined and recorded using a Trimble GeoXH Differential Global Positioning System (DGPS) unit, and photographic and visual observations were conducted on all vegetation within plots. To assist with site identification and to minimize disturbance, all plots were marked with polyvinyl chloride (PVC) pipe. When accessible, the same plots were sampled on subsequent visits in the Fall of 2014, Summer 2015, and Fall 2015.

Previous and new vegetation-specific surveys consisted of species identification, percent cover, and vegetation height. Within each plot the vegetation cover of each species was visually estimated using the Braun-Blanquet scale (Braun-Blanquet 1932). Since the percent cover is estimated for each strata, the total vegetation cover (sum of all layers) can exceed 100%. Vegetation surveys were used to assess percent cover within each plot, which were subsequently used to calculate FQI for each Project and PR site.

Floristic Quality Index

The traditional FQI, developed by Swink and Wilhelm (1979), is a weighted metric that assesses the quality of native plant communities. The FQI is based on a measure of vulnerability, called the Coefficient of Conservatism (CC), together with the richness of a plant community (Gianopulos 2014). CC values range from zero (not conservative) to ten (conservative and highly ecologically sensitive), and are assigned to individual plant species within a local flora by a panel of experienced botanists, primarily based on their best professional judgment (Little 2013; Bourdaghs et al. 2006). Since the impact and function of plant species differ by locale, CC values are specific to a State or region (Little 2013). Table 3 provides the criteria that are typically used to assign CC values to individual plant species. Species are also assigned to general classes based on species characteristics. These classes include invasive plant species (CC value of 0), disturbance species (CC = 1–3), vigorous wetland communities (CC = 4–6), common species (CC = 7–8), and dominant wetland species (CC = 9–10).

This study used a modified FQI, which accounts for invasive plants and uses a two-pronged approach to account for sample units with vegetation cover that is less than or equal to 100%, or is greater than 100% (overlapping canopies). If the sum of species covers within a sample unit at time t is less than or equal to 100, the applicable formula is as follows:

$$\mathrm{FQI}_{\mathrm{mod}\ t} = \left(\frac{\sum(\mathrm{COVER}_{it} \text{ x } \mathrm{CC}_i)}{100} \right) \text{x } 10 \tag{7}$$

where $\mathrm{FQI}_{\mathrm{mod}\ t}$ is the modified floristic quality index (unitless), COVER_{it} is the percent cover (%) for species i at a sample unit, within a sample site, at time t, and CC_i is the Coefficient of Conservatism for species i (Table 3).

By using 100 in the denominator (instead of the actual sum of species covers), differentiation between wetlands of similar composition (e.g., vigorous wetlands) can be made using normalized biomass (estimated through cover) (Cretini et al. 2012). For consistency with other CRMS and CWPPRA metrics and indices, the FQI values were multiplied by 10 to scale the scores from 0 to 100 (Cretini et al. 2011).

If the sum of species covers within a sample unit at time t is greater than 100, the applicable formula is:

$$\mathrm{FQI}_{\mathrm{mod}\ t} = \left(\frac{\sum(\mathrm{COVER}_{it} \text{ x } \mathrm{CC}_i)}{\sum(\mathrm{TOTAL\ COVER}_t)} \right) \text{x } 10 \tag{8}$$

Table 3 General description and criteria for assignment of Coefficient of Conservatism (CC) scores to different plant species (based on Andreas et al. 2004; Cohen et al. 2004; Cretini et al. 2012; Swink and Wilhelm 1994)

General characteristics of species	Criteria	CC
Invasive plant species	Obligate to ruderal areas	0
Plants that are opportunistic users of disturbed sites	Occurs more frequently in ruderal areas than natural areas	1
	Facultative to ruderal and natural areas	2
	Occurs less frequent in ruderal areas than natural areas	3
Plants that occur primarily in less vigorous coastal wetland communities	Occurs much more frequently in natural areas than ruderal areas	4
	Obligate to natural areas (quality of area is low)	5
	Weak affinity to high-quality natural areas	6
Plants that are common in vigorous coastal wetland communities	Moderate affinity to high-quality natural areas	7
	High affinity to high-quality natural areas	8
Plants that are dominants in vigorous coastal wetland communities	Very high affinity to high-quality natural areas	9
	Obligate to high-quality natural areas	10

where TOTAL COVER$_t$ refers to the percent cumulative species cover (expressed as a percentage) within a sample unit (Cretini et al. 2012).

FQI scores provide estimates of vegetation condition and maturity. Low FQI values can be indicative of early successional vegetation communities, highly disturbed or early post-disturbance evolution, or other presses or pulses that are negatively impacting natural or managed wetlands. Conversely, high FQI values are more typical in mature, stable, and undisturbed wetlands.

For all established CWPPRA and CRMS stations within the Project and PR assessment units, the CRMS Data Download service was used to acquire all vegetation data (i.e., species composition, cover, FQI) from 1997 to 2015 (CPRA 2016). These data were appended with vegetation surveys performed as part of this study (surveys conducted in 2014 and 2015). FQI$_{mod}$ scores were calculated for each vegetation station within the Sabine Project and PR areas, using the Louisiana CC list and equations (Eqs. 7 and 8, incorporating invasive species) developed by Cretini et al. (2011, 2012). For species not on the Louisiana Coefficient of Conservatism list, established values from regional lists or neighboring states were used in conjunction with best judgement (Herman et al. 2006; Mortellaro et al. 2012; Gianopulos 2014).

Resilience

Ecosystem resilience was evaluated and compared within restored and reference wetlands by quantifying wetland structure (i.e., wetland area and aggregation index) and function (i.e., biomass, edge density, and floristic quality index) before, during, and after disturbance events. Tracking these metrics over time provides assessments of wetland resilience, and comparisons of restored to naturally occurring wetlands.

Statistical Analyses

The relationships among landscape metrics, vegetation characteristics, and wetland biomass were assessed using regression and correlation methods. The Statistical Analysis System software version 9.2 PROC GLM procedure was used to perform a one-way analysis of variance (ANOVA) and a means separation test (Tukey's, $\alpha = 0.05$) to evaluate significance of differences between attributes for each assessment unit.

Results and Discussion

Land and Water Trends

The land and water trends presented in Fig. 2 were computed using the moderate resolution Landsat imagery. The Project and PR units consisted of more than 90% land in 1956 (Fig. 2). By the year 2001, prior to wetland restoration activities in the Sabine area, those units were reduced to approximately 5% and 74% land, respectively. Approximately four years after construction, Sites 1 and 3 both regained and maintained percentages of land greater than 90%. The Site 2 overflow area, which experienced similar trends to Sites 1 and 3, achieved higher land percentages and gains than Site 2 proper (Fig. 2). This was primarily due to hydrologic restrictions to the Site 2 unit (containment dike gaps were not cut for hydrologic flow until 2014). Although only recently constructed, the early stages of platform consolidation and vegetation establishment within Sites 4 and 5 mimic those observed in Sites 1, 2, and 3.

During the restoration period (2002 to 2015) the PR unit exhibited a slight decrease in land area, while the Project units exhibited rapid increases in land area (due to wetland restoration measures) (Fig. 2). The performance of Project and

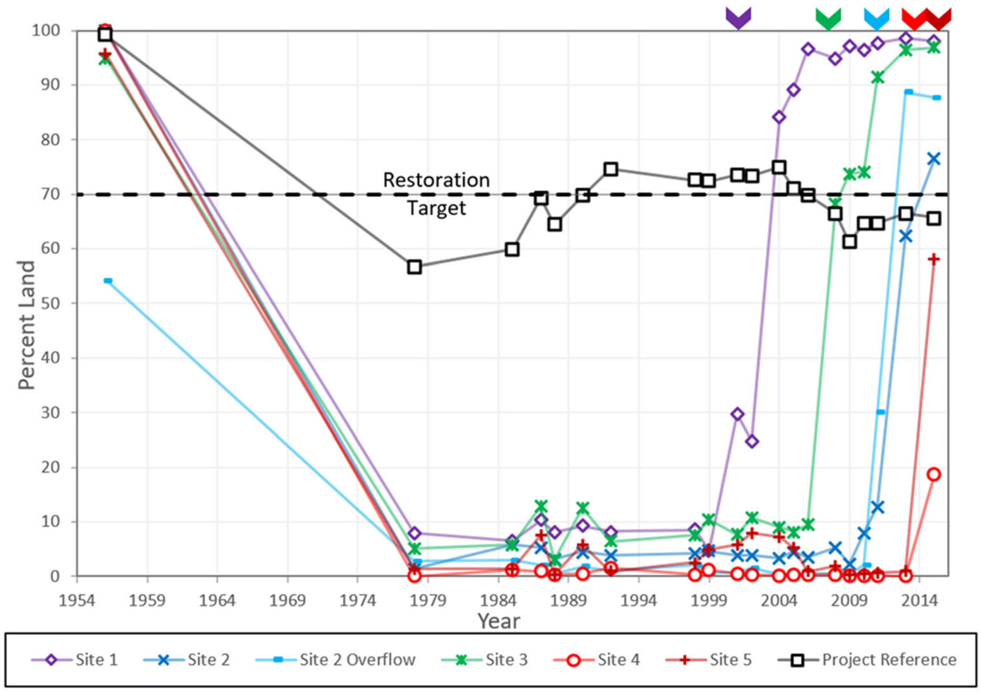

Fig. 2 Land change data (derived from moderate resolution imagery) within the Sabine assessment units from 1956 to 2016. Colored arrows represent end of construction for each associated restoration site

reference wetlands were compared to the 70% land target that is common for many wetland restoration projects in coastal Louisiana (Raynie and Visser 2002; USACE 2004) (Fig. 2). The older Sabine sites (1, 2, and 3) consist of more than 70% land, while the younger sites (4 and 5) are undergoing vegetative colonization and are expected to follow similar trajectories and eclipse the 70% target within four or five years of construction. In recent decades the land area percentages within the PR unit have primarily resided below the 70% target, and have experienced slightly decreasing trends since Hurricanes Rita (Category 3 storm, 24 September 2005) and Ike (Category 2 storm, 13 September 2008).

Aggregation Index and Spatial Integrity

Aggregation index values were computed for each assessment unit using the "land" class from 13 classified high-resolution images from 1998 to 2016 (Table 4 and Fig. 3). Table 4 provides the results of a one-way ANOVA with a post-hoc Tukey HSD test which shows the mean AI ranged from 84.8 ± 6.1 in Site 5 to 98.1 ± 2.0 in Sites 1 and Reference North. Figure 3 shows the starting AI values for Reference South and North were high and increased throughout the period of analysis. These values and trajectories are indicative of relatively stable landscapes with increasing spatial integrity. The starting AI values varied considerably for each of the Project sites. This is a result of the class-level computation of the AI and the fact that some Project sites contained land features prior to restoration. The more mature restoration units, Sites 1, 3, and 2, exhibited moderate starting AI values but experienced significant increasing trends, post-construction. The increasing AI values in Sites 1, 3, and 2 are indicative of vegetative establishment on newly constructed wetland platforms. It took approximately four to six years post-construction for the AI values in Sites 1, 3, and 2 to exceed those of the reference units (Fig. 3). The AI trends in Sites 4 and 5 were driven primarily by pre-construction vegetation, but did exhibit recent increases due to early vegetation establishment, post-construction. Overall, AI trends corresponded to observed land change trends in each assessment unit. Greater land area resulted in higher levels of aggregation and spatial integrity. This was more evident in the mature restoration sites and reference units.

Table 4 Class-level mean aggregation index values for project areas from 1998 to 2016

Project Area	Aggregation Index Mean ± std
Site 1	98.1 ± 2.0a
Site 2	92.0 ± 4.6b
Site 2 overflow	93.9 ± 4.3ab
Site 3	97.3 ± 2.9a
Site 4	91.5 ± 6.3ab
Site 5	84.8 ± 6.1c
Reference South	97.7 ± 1.0a
Reference North	98.1 ± 0.6a

Mean values within each column followed by the same letter(s) are not significantly different ($p > 0.05$) as analyzed by one-way ANOVA and the TUKEY test

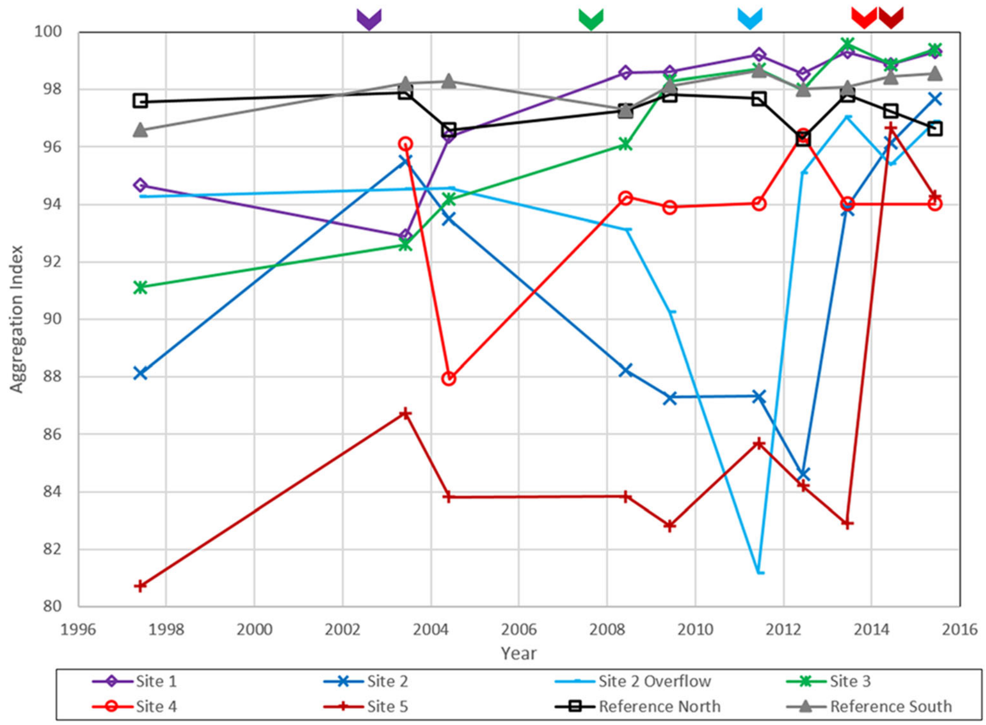

Fig. 3 Aggregation index data (derived from high resolution imagery) within the Sabine assessment units from 1998 to 2016. Colored arrows represent end of construction for each associated restoration site

Wetland Biomass

Figure 4 shows Landsat-derived mean NDVI values (per image) and trajectories within the Project sites and PR assessment unit. These represent all qualifying data, across two distinct periods, the pre-restoration (1985 to 2001) and restoration (2002 to 2015) periods. Mean NDVI values ranged from 0.03 for the Site 4 area in 2007 to 0.51 for the PR unit in 2014. Mean NDVI values by assessment unit were 0.26 ± 0.1, 0.19 ± 0.07, 0.18 ± 0.09, 0.22 ± 0.09, 0.1 ± 0.05, 0.13 ± 0.06, 0.35 ± 0.08, for the Site 1, Site 2, Site 2 overflow, Site 3, Site 4, Site 5, and PR assessment units, respectively. Mean NDVI values for each assessment unit were significantly different ($p < 0.05$), except for Site 2 and Site 2 overflow, which were

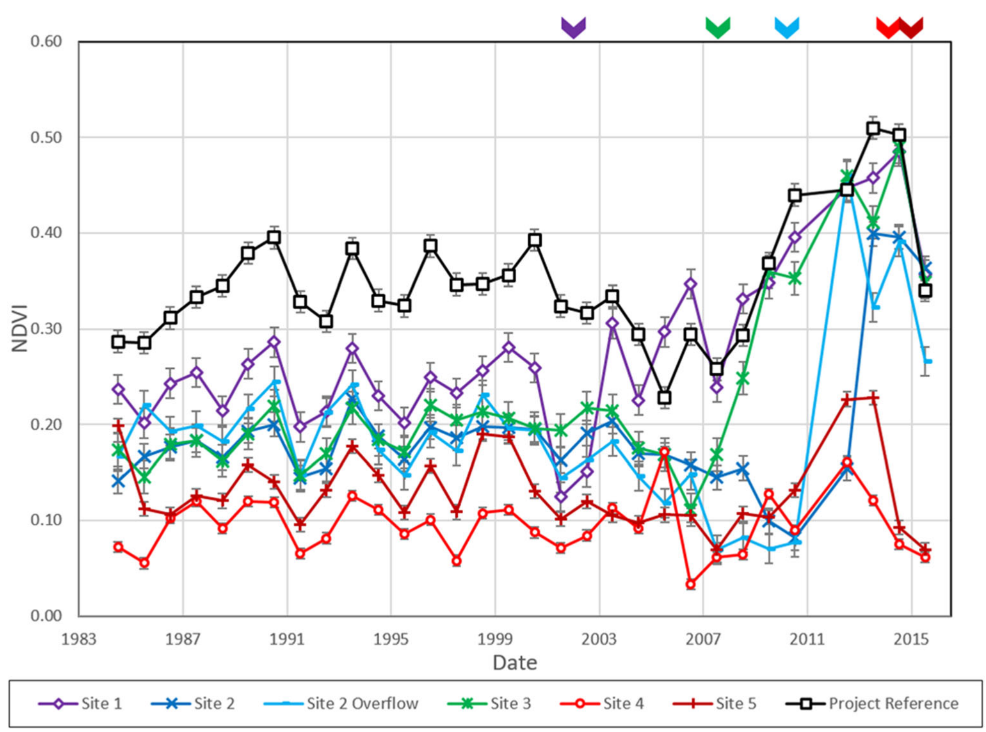

Fig. 4 Normalized difference vegetation index data (derived from moderate resolution imagery) within the Sabine assessment units from 1985 to 2016. Colored arrows represent end of construction for each associated restoration site

not significantly different from each other. These differences are primarily due to the age of restoration.

The pre-restoration period values for all assessment units were lower than those previously reported for brackish marsh (0.45) in the Calcasieu/Sabine watershed basin (Suir and Sasser 2019b). Lower mean NDVI values in the Project units, specifically during the pre-restoration period, are indicative of low biomass wetlands that were highly degraded by disturbance events (e.g., hurricanes). The earlier constructed sites, 1 and 3, experienced marked increases in NDVI values during the restoration period. These increases ranged from lows near 0.2 in 1985, to highs near 0.45 by the end of the restoration period. It took approximately ten years for Sites 1 and 3 to reach biomass equilibrium with the PR unit. The vegetation biomass trends within the Site 2 and Site 2 overflow units were similar to those observed in the early years of Sites 1 and 3. On the current trajectory, it is expected that the Site 2 units will also reach biomass equilibrium with the PR unit at approximately ten years after construction. Likewise, since Sites 4 and 5 were constructed similarly to Site 3 (natural establishment of trenasses and vegetation), they are expected to evolve and function similarly to Site 3 (i.e., biomass equilibrium within 10 years).

Increasing mean NDVI values were also observed in the PR unit. These increases are potentially due to combined impacts from restored hydrology and erosion control provided by the CWPPRA projects (increased nourishment in adjacent marshes and reduced open water fetch were CWPPRA project objectives; LCWCRTF 2010). Figure 4 illustrates some reductions in NDVI that were more than likely induced by Hurricanes Rita (2005) and Ike (2008). These downward trends in NDVI were succeeded by vegetative recovery, which typically occurs by the end of the next full growing season after a disturbance event (Steyer et al. 2013; Carle et al. 2015). Overall, the PR and more mature Project sites have recent vegetative biomass trends that correspond to the long-term Calcasieu basin mean NDVI (0.45; Suir and Sasser 2019b). These assessments show that with maturity, and when sediment deposition increases the marsh platform elevation to a range that promotes vegetation growth, the restored wetlands in this area can achieve, and potentially outperform, vegetative productivity of natural or minimally managed wetlands.

Vegetation Abundance and Composition

Figure 5 shows the average vegetation percent cover by species for all survey stations, separated by assessment unit and year. Figure 5 also groups and color codes all species based on Coefficient of Conservatism values (Table 3). There were 85 different plant species observed across all Sabine units and stations from 1999 to 2015. The first vegetation survey (2004) within the Project assessment unit (upper panel in Fig. 5) shows the edge planting (i.e., vegetation planted along the edge and trenasses of restoration units) as part of Site 1 construction (2002) stimulated early vegetation expansion, resulting in a *Spartina alterniflora* dominated landscape (57.5%) with a total cover of 59.5%. Hurricane Rita reduced the percent cover within Site 1 to 1.8% in 2005, but the unit recovered to 90% and 81.5% cover by 2006 and 2007, respectively. *Spartina alterniflora* remained the dominant species during this recovery, accounting for 90% and 76.6% of the total cover, respectively. By 2008 the *Spartina alterniflora* monoculture within the Project sites began to shift to a vegetative assemblage of common (CC = 7–8) and dominant (CC = 9–10) species. This was due in part to the construction (2007) and natural colonization of Site 3. From 2009 to 2015 the typical vegetation profile for Project sites had total cover values between 75% and 87%, and consisted primarily of *Spartina alterniflora*, *Distichlis spicata* (coastal salt grass), *Schoenoplectus robustus* (sturdy bulrush), *Borrichia frutescens* (bushy seaside tansy), *Iva frutescens* (Jesuit's bark), and nominal percentages of "other" species.

From 1999 to 2004 the average total cover of Project Reference stations ranged from 80% to 98% and consisted primarily of *Schoenoplectus americanus*, *Distichlis spicata, Spartina patens* (saltmeadow cordgrass), *Paspalum vaginatum* (seashore paspalum), and a range of other species (Fig. 5, lower panel). In 2005, the average total cover per site decreased to 44.4% and consisted of only two species, *Spartina patens* and *Paspalum vaginatum*. This change in cover was directly related to Hurricane Rita impacts. From 2006 to 2015, the PR sites exhibited a slow recovery and reestablishment of vegetation, with higher percentages of "other" class species initially, followed rapidly by increasing percentages of disturbance species (CC = 1–3), and more recently by vigorous wetland species (CC = 4–6).

Across the entire period of analysis, the Sabine Project sites generally experienced rapid vegetation establishment followed by a transition to higher diversity and colonization by common and dominant species. The PR unit consisted primarily of common and dominant species (i.e., *Distichlis spicata*, *Spartina patens*, *Schoenoplectus americanus, and Paspalum vaginatum*) prior to Hurricane Rita. However, the PR unit transitioned to dominant with disturbance and vigorous wetland plants.

Field-Based Floristic Quality Index

FQI_{mod} scores were calculated for survey sites within the Project and PR assessment units from 1999 to 2015 (Fig. 6). The Project sites (red dots), which consisted of Sites 1 and 3, were first surveyed in 2004 (post construction of Site 1) and last surveyed in 2015. The PR sites (green squares) were surveyed from 1999 to 2015. Figure 6 show the trajectories of FQI_{mod} values across each assessment unit's period of

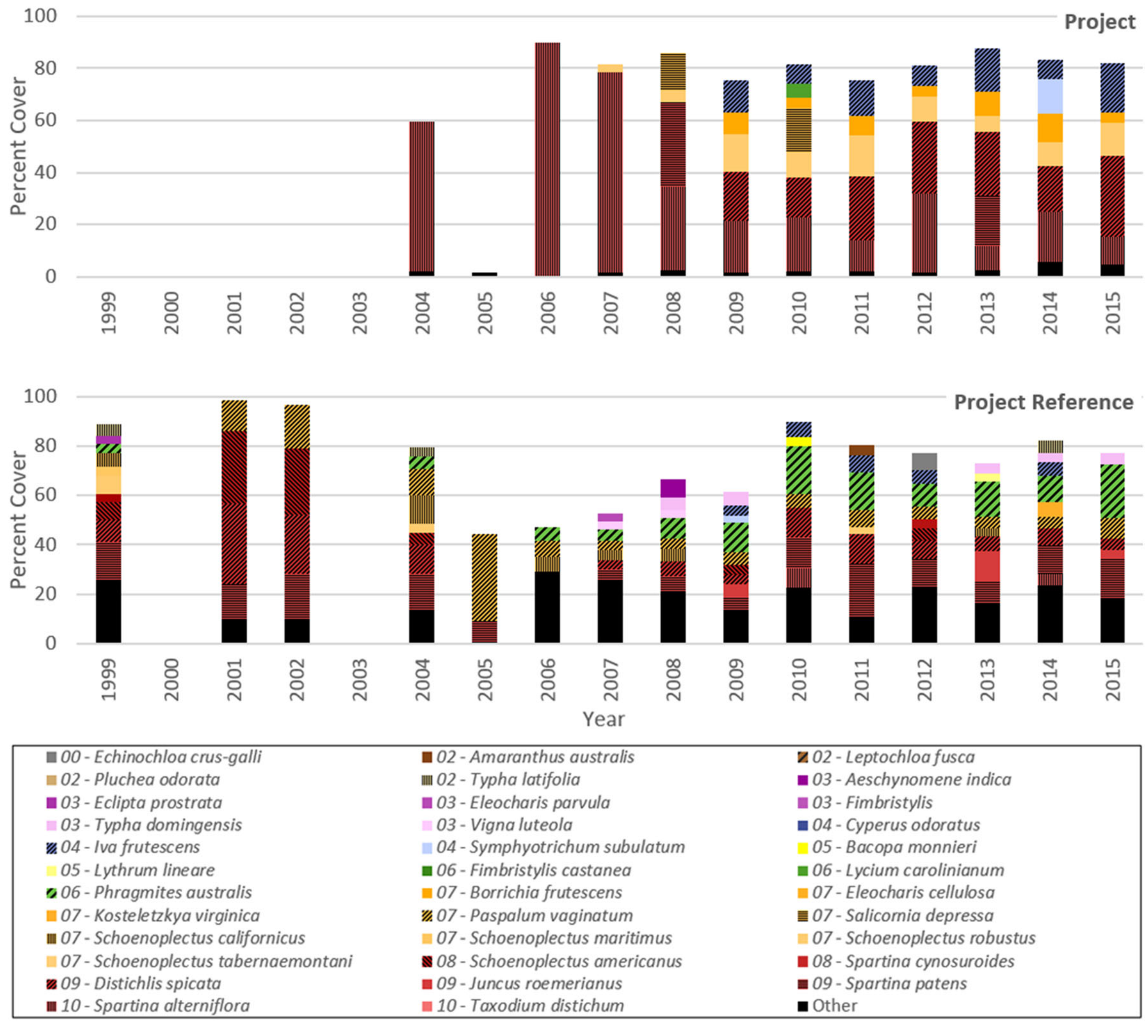

Fig. 5 Percent cover and Coefficient of Conservatism values for species within the Sabine Project and Project Reference assessment units

analysis. The Project Reference unit data and trends show a landscape with rapidly declining floristic quality during the Hurricane Rita and Ike disturbance period (2002 to 2009) and equally rapid increase in FQI during the recovery period (2010 to 2015). The Project and PR units also experienced moderate reductions in FQI scores in 2011 due to an exceptional salinity spike. This is indicative of a moderately susceptible system and corroborates previous studies that show significant wetland area and function loss due to hurricanes, high salinity events, increased water fluctuations, and tidal scouring (USEPA 2002; Barras 2005; Miller 2014b). In 2004 the newly constructed and vegetated Project unit plants returned an FQI score of 60, while the PR unit had an FQI score of 66. Hurricane Rita significantly reduced the FQI score in the immature Project Site 1, reducing the FQI from 60 in 2004 to 1.5 in 2005. However, the Site 1 wetland recovered quickly and along with vegetation establishment in Site 3, the Project sites maintained relatively stable FQI scores from 2006 to 2011. The Project unit FQI_{mod} data and trends are indicative of rapid colonization and vegetative growth common in newly constructed wetlands. The Project unit average FQI_{mod} score from 2006 to 2015 was approximately 80 (approaching upper functional limits for this system). This coincides with the ideal range for Chenier Plain brackish marsh reported by Cretini et al. (2012). Since construction, the Project units have primarily maintained higher floristic quality than the reference units.

Multi-Metric Resilience Assessment

To further test the resilience of restored marsh to disturbance events, comparisons of key ecosystem metrics were made between the Project Sites and the Reference North and South assessment units. Two principal energy-based disturbance events occurred within the Sabine study site during the disturbance period (2002 to 2009). These disturbances consisted of Hurricane Rita (landfall on 24 September 2005), with sustained winds of 47 m per second (m s-1) and a storm surge height of approximately 1.3 m; and Hurricane Ike (13 September 2008), with sustained winds of 42 m s-1,

Fig. 6 Floristic Quality Index (FQImod) scores for all survey stations within the Sabine assessment units by year. Grey arrows represent tropical storm (TS) activity (wind speed m s-1) and the black arrow represents a salinity spike

storm surge height of approximately 3 m, and major flooding and inundation. The disturbance period was followed by a period of recovery (2010 to 2016). Although the recovery period was not impacted by significant energy-based disturbances, it did contain one significant salinity spike. A high salinity event in 2011, with maintained salinity above 30 parts per thousand (ppt) from 26 August to 21 December (40.93 ppt salinity maxima on 3 November 2011), was observed within Site 1. Similar and relative salinity spikes were observed at hydrologic gages located within the Reference unit during the same period. The elevated salinity levels were likely due, in part, to a period of exceptional drought conditions (D4 on the drought intensity scale) that occurred between June and December, 2011 (National Drought Resilience Partnership, 2020), which caused reduced inflow of freshwater into adjacent wetlands. By comparison, the average salinity across the remainder of the recovery period was 7.37 ppt. Metrics of wetland condition during these periods provide measures of direct and indirect impacts from the disturbance events, and the recovery or resilience of Sabine wetlands.

Table 5 provides the mean, standard error, and change rates (slope) for each measure of resilience (i.e., percent land, edge density, aggregation index, NDVI, and FQI) by assessment unit across the disturbance and recovery periods of analysis. Sites 1 and 3 (those constructed during the disturbance period) experienced significant increases in wetland area during the disturbance period. The rates of change during this period were 3.31% and 11.99% per year, for Sites 1 and 3, respectively, for a Project average rate of 7.65% (Fig. 2 and Table 5).

The land change trends in the Reference South and Reference North units during the disturbance period were significantly lower than the more mature Project Sites. The Reference North and Reference South rates of change were 0.43% and −0.01% per year, respectively. The rate of loss in the Reference South unit, is indicative of wetlands that experienced direct disturbance impacts (e.g., plucked marsh and amorphous ponds due to hurricane). The percentage of land and land change rate in Sites 1 and 3 during the recovery period are indicative of landscapes that were approaching the upper land gain limits (> 90% land) and exhibited nominal negative impacts from the high salinity event. The land change rates within the Reference North and South units are indicative of landscapes with minimal recovery after hurricane-induced reductions in wetland area. It is theorized that the differences in land change rates between Project and Reference sites are largely due to the erosion protection that is provided by the containment dikes around the Project sites.

The landscape pattern metrics and trends selected for use in this assessment (edge density and aggregation index) provide measures of wetland structure and spatial integrity. In wetland landscapes that are predominantly land, decreasing rates of edge density and increasing rates of aggregation are indicative of water features that are converting to emergent marsh or where vegetation is establishing on newly construction wetland platforms. The opposite is true of landscapes with increasing edge density and decreasing aggregation. For the disturbance period, Site 1 experienced a high negative rate of change in edge density (−78.71) and a positive rate of

Table 5 Mean, standard error, and change rates (slope) of percent land, edge density, aggregation index, normalized difference vegetation index, and floristic quality index for the project, reference south, and reference north units across the disturbance (2002 to May 2009) and recovery (June 2010 to 2015) periods of analysis

		Percent Land			Edge Density			Aggregation Index			NDVI			FQI		
Site	Period	Mean	SE	Slope	Mean	SE	Slope	Mean	SE	Slope	Mean	SE	Slope	Mean	SE	Slope
Site 1	Disturbance	53.66	5.39	3.31	422.74	128.49	−78.71	95.95	1.66	0.97	0.230	0.017	0.025	64.97	13.49	8.50
Site 1	Recovery	66.40	0.34	0.41	265.64	12.65	−7.21	91.34	0.10	0.06	0.404	0.015	0.011	72.62	2.62	2.62
Site 2	Disturbance	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Site 2	Recovery	46.38	11.85	15.94	380.37	59.94	78.44	92.30	1.72	2.16	0.229	0.029	0.055	–	–	–
Site 2O	Disturbance	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Site 2O	Recovery	70.20	9.63	14.40	700.28	159.49	13.86	93.92	1.75	1.84	0.231	0.032	0.050	–	–	–
Site 3	Disturbance	24.58	18.63	11.99	215.90	139.85	89.77	94.29	1.01	0.64	0.197	0.011	−0.001	–	–	–
Site 3	Recovery	90.02	2.81	4.01	188.65	32.80	−23.60	98.99	0.20	0.19	0.396	0.016	0.010	79.39	1.12	−0.41
Site 4	Disturbance	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Site 4	Recovery	5.97	3.02	2.98	93.06	40.26	42.47	91.07	2.52	−0.85	0.105	0.010	−0.008	–	–	–
Site 5	Disturbance	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Site 5	Recovery	10.26	6.30	5.95	106.34	49.08	55.06	86.54	2.35	1.85	0.131	0.013	−0.001	–	–	–
Ref North	Disturbance	44.58	0.87	0.43	234.40	12.47	6.24	96.92	0.34	0.17	0.146	0.010	−0.009	63.87	7.09	−0.44
Ref North	Recovery	59.68	1.78	2.12	283.12	37.49	8.44	98.26	0.27	−0.06	0.236	0.017	−0.018	79.93	3.80	0.16
Ref South	Disturbance	70.68	0.02	−0.01	333.33	66.87	26.75	97.76	0.46	−0.18	0.217	0.011	−0.012	62.08	10.54	−4.28
Ref South	Recovery	79.73	1.04	1.19	262.80	15.88	−7.05	98.47	0.11	0.07	0.289	0.016	−0.015	71.75	13.79	−2.16

change in aggregation index (0.97) (Table 5). The rates of change were more moderate during the recovery period, −7.21 and 0.06, for edge density and aggregation index, respectively. These trends are indicative of a wetland landscape that was establishing, maturing, and resilient to episodic disturbance events. Site 3 experienced a change rate of 89.77 in edge density during the disturbance period. This increase in edge density is largely due to the northern half of the site desiccating, consolidating, and compacting to an elevation lower than the desired goal (elevation range of −62 cm to 25 cm), resulting in a fragmented wetland landscape. The Reference North site experienced nominal positive rates of change in both edge density and aggregation index, while the Reference South site experienced a moderate positive rate of change in edge density and nominal negative change rate in aggregation index during the disturbance period. These combinations are typical in wetland landscapes with increasing edge and decreasing aggregation (for Reference South) due to direct hurricane impacts (e.g., scouring and edge erosion). Recovery in the reference units were dissimilar, with moderate recovery in both structural metrics for Reference South and continued degradation in the Reference North unit.

The NDV and FQ indices provide measures of vegetative biomass and quality, both serving as indicators of wetland function and condition. Highly functioning wetlands typically have high NDVI and FQI values, while disturbed or low functioning wetlands have lower NDVI and FQI scores. The NDVI rates of change were negative for all qualifying assessment units during the disturbance period, except for Site 1 (Table 5). During the recovery period, the NDVI rates of change were negative for all but the more mature Project sites (1, 2, 2 overflow, and 3). The Site 1 NDVI and FQI rates of change during the disturbance and recovery periods were also significantly higher than the reference units ($p < 0.05$). Also, although the FQI rates of change in the Site 1 unit were positive during the disturbance (8.5) and recovery (2.62) periods, the rate was significantly higher in the disturbance period. This corresponds to a Site 1 landscape that was quickly vegetating during the disturbance period, and experienced an increasing FQI rate of change due to increasing vegetative establishment and cover. The lower FQI rate of change in Site 3 during the recovery period is likely due to functional limits (FQI near 80 during recovery period) and possibly some salinity impacts (drought-induced salinity spike in 2011). Both reference units experienced decreasing rates of FQI during the disturbance period, and only the Reference North site experienced a nominal increasing rate (0.16) of FQI during the recovery period. These are more typical trends in floristic quality rates, where vegetative quality and quantity are quickly reduced during and soon after disturbance events, followed by lower rates or recovery over subsequent growing seasons (Suir and Sasser 2017).

The measures of disturbance and recovery used in this study show restored wetlands largely experienced insignificant impacts from disturbance events, while the reference wetlands were significantly (for most measures) impacted. These differences are potentially related to the protection (containment dikes) and function (reduced fetch) that the large volume of placed sediments and subsequent vegetation provide. Ultimately, the restored wetlands were more resistant to disturbance events and more resilient across all assessment periods.

Conclusions

This study used vegetation survey data and satellite-derived data to generate landscape metrics (land area, edge density, and aggregation index) and vegetative indices (vegetation cover, normalized difference vegetative index, and floristic quality index) to evaluate changes and trends in restored wetland structure and function by comparison to reference wetlands. Across all measures, the restored brackish wetlands reached structural and functional equivalency to reference wetlands at approximately three to ten years after construction. With adequate maturity, the restored wetlands outperformed the reference wetlands in all applied metrics, having higher percentage of land, land aggregation (i.e., spatial integrity), aboveground vegetation biomass, and floristic quality. The restored brackish wetlands also demonstrated higher levels of stability, providing more resistance to disturbance events (i.e., hurricanes, inundation, and salinity events), and experiencing reduced levels of flux (e.g., transitional phases of invasive and disturbance species) during the recovery period.

The results of this study show the combination of remotely collected and in situ data provided enhanced measures of wetland performance (structure and function), and through a multiple lines of evidence approach, were able to reflect resilience to and recovery from disturbance events. Future work should include methods that provide additional continuous spatial data (combining vegetation quality and quantity), which would allow for more representative assessments over larger landscape areas. Ultimately, these data and methods provide advanced knowledge elements that contribute more efficient and comprehensive inventorying and monitoring of wetland resources which should improve forecasting of resource condition and stability, and adaptive management strategies.

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