ERDC/TN EMRRP-ER-25
August 2023

Selection of a Time Series of Beneficial Use Wetland Creation Sites in the Sabine National Wildlife Refuge for Use in Restoration Trajectory Development

by Brian D. Harris,[1] Kathleen E. Harris,[2] Navid H. Jafari,[3] Jasmine Bekkaye,[4] Elizabeth O. Murray,[5] and Safra Altman[6]

PURPOSE: The development of regional restoration trajectories of marsh creation and nourishment projects is key to improved design, management, and implementation of adaptive management principles. Synthesizing information from multiple marsh creation projects constructed at various times but with consistent site characteristics and borrow material sources, helps elucidate restoration success in a specific region. Specifically, this technical note (TN) documents the process of determining a suitable study area, construction methods, and the current state of establishing sites in the Louisiana Gulf Coast that could be used for restoration trajectory development. This investigation compiled information from the construction phases, Landset 8 satellite imagery, and the most recent digital elevation model (DEM) to investigate elevation and vegetation establishment within these sites.

INTRODUCTION: The Louisiana coastal zone is experiencing a land loss crisis driven by naturally occurring subsidence, relative sea-level rise, and deterioration due to storm impacts and anthropogenic disturbances (e.g., channelization, pipeline construction) (NRC 1992; Turner 1997; Day et al. 2000; Costa-Pierce and Weinstein 2002; Stagg and Mendelssohn 2011; Saleh and Weinstein 2016; Twilley et al. 2016; Harris et al. 2020a). This land loss has converted large swaths of once vibrant wetlands to shallow open water and eroded marsh expanses. In turn, this increase in open water is accelerating future marsh edge erosion by extending fetch lengths (Twilley et al. 2016). A common solution to replace lost land is the construction of new marshes by the beneficial use (BU) of hydraulically dredged sediment from waterway maintenance events (Harris 2020b). These BU placements of sediment support the Navigation, Flood Protection, and Ecosystem Restoration missions of the US Army Corps of Engineers (USACE) while offering an alternative to confined dredged disposal facilities.

[1] Research Civil Engineer, ERDC-CHL, Vicksburg, MS, (601) 619-5155, Brian.D.Harris@usace.army.mil
[2] Research Civil Engineer, ERDC-CHL, Vicksburg, MS, (601) 634-7638, Kathleen.E.Harris@usace.army.mil
[3] Associate Professor, Louisiana State University CEE, Baton Rouge, LA, (225) 578-8475, njafari@lsu.edu
[4] Graduate Research Assistant, Louisiana State University CEE, jbekka1@lsu.edu
[5] Research Biologist, ERDC-EL, Vicksburg, MS, (925) 212-1359, Elizabeth.O.Murray@usace.army.mil
[6] Research Ecologist, ERDC-EL, Vicksburg, MS, (601) 634-3435, Safra.Altman@usace.army.mil

Over nearly the past four decades, the Sabine National Wildlife Refuge (SNWF) has been the site of numerous BU placements across various Calcasieu Ship Channel (CSC) maintenance events (CPRA 2017), which has been a combined effort between the USACE, Louisiana's Coastal Protection and Restoration Authority (CPRA), and the SNWF. The USACE has maintained the CSC since 1874, when an 80 ft-wide, 5 ft-deep navigation channel was constructed through the outer bar of Calcasieu Pass, between Calcasieu Lake and the Gulf of Mexico (Waldon 1996). The channel has since been enlarged to its current width and depth of 400 ft and 40 ft, respectively (Waldon 1996). This channel is a vital component of southwest Louisiana's economy by providing $5.7 billion in gross domestic product (GDP) and generating $118.8 million in local sales and property taxes (CSRS 2017).

The development of regional Composite Time Series Trajectories (CTST) of marsh restoration projects is key to improved design, management, and implementation of adaptive management principles (Runion et al. 2022). The overall objective of this research effort, of which this TN is a part, is to develop regional recovery trajectories of created or nourished wetlands to determine what defines restoration success. Specifically, this document focuses on identifying Gulf Coast sites created using the same borrow source and have similar ecosystem characteristics (e.g., elevation, vegetation, salinity, hydrology) of multiple ages (i.e., time since created). The construction methods of the sites were summarized in addition to the current elevation and vegetation status using a combination of field data, multispectral images, and lidar surveys.

METHODOLOGY: The site selection for the Gulf Coast primarily focused on Louisiana due to the extensive number of marshes created or nourished by CPRA. The site requirements included having a consistent source of dredged borrow material and comparable elevation, hydrology, salinity, and vegetation types within the placement area. Constructed marshes in the Slidell, Hope Dale, Jean Lafitte, Lake De Cade/Jug Lake, and Sabine-Calcasieu areas were considered. Ultimately, through visual assessment and discussions with district planners and engineers, it was decided to proceed with the Sabine-Calcasieu since it was the only site to fit these criteria.

The Sabine-Calcasieu sites lie within the eastern edge of the SNWF in coastal Louisiana, west of Highway 27 and 20 miles south of Lake Charles, LA. Since 2001, there have been nine BU placements in the area with a total of ~2,100 acres nourished to varying degrees. All were constructed within similar hydrology due to the sites being largely confined by dikes and adjacent marshlands. The 2020 hurricane season was incredibly destructive to this region of the state with two named hurricanes making landfall within a month of each other: Hurricane Laura (Category 4) on 27 August 2020 and Hurricane Delta (Category 2) on 9 October 2020. In addition to COVID-19 impacts, these events hindered planned field expeditions; thus, this study was focused heavily on remote sensing. However, a team was able to perform visual site assessments in May 2021 successfully. Figure 1 shows the location of the nourishment sites within the SNWF.

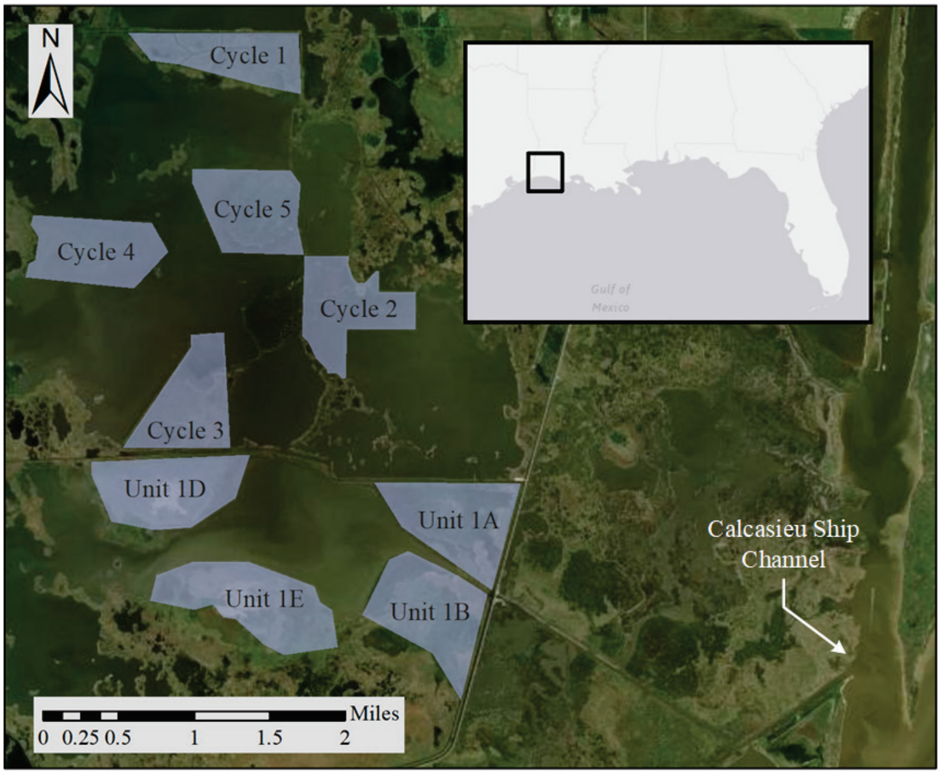

Figure 1. Overview of beneficial use marsh creation sites constructed since 2001 in the Sabine National Wildlife Refuge, Louisiana.

To approximate vegetation establishment throughout the created sites, the following vegetation indices were calculated: normalized difference vegetation index (NDVI), modified soil adjusted vegetation index 2 ($MSAVI_2$), and visible difference vegetation index (VDVI). The NDVI and $MSAVI_2$ determine plant greenness using visible and near-infrared wavelengths, with $MSAVI_2$ considering the influence of soil visibility, while VDVI uses exclusively visible components of the spectrum (Rouse et al. 1974; Qi et al. 1994; Xu and Su 2017; Miller et al. 2019). These indices are calculated using the following equations:

$$NDVI = \frac{NIR - red}{NIR + red} \tag{1}$$

$$MSAVI_2 = \frac{2NIR + 1 - \sqrt{(2NIR + 1)^2 - 8(NIR - red)}}{2} \tag{2}$$

$$VDVI = \frac{2 \times green - red - blue}{2 \times green + red + blue} \tag{3}$$

where NIR is near-infrared, and the colors correspond to the respective wavelengths. These indices were calculated using the raster calculator within ArcMap Version 10.8 from Landsat 8 satellite imagery at a 30 m resolution. Although this resolution is relatively coarse to identify marsh vegetation, Landsat data is more readily available and widely used than the preferred higher resolution, commercial products used in some studies.

MARSH CREATION SITES: The SBWF placement sites were constructed using sediment from maintenance events between 2001 and 2019 and divided into "cycles" and then later "units." Before construction, the impacted sites consisted of a mixture of shallow open water and eroded marsh. The following summarizes the construction details and overall outcomes from each nourishment cycle.

Cycle 1. Sediment placement for Cycle 1 was performed during the 2001 CSC maintenance event. The site was bounded to the north and east by the North Starks Canal Levee that sat at 4.4 ft North American Vertical Datum of 1988 (NAVD88). Dikes were constructed from in situ material along the southern border to between 2.9 ft and 3.4 ft NAVD88. The site was divided into an east (125 acres) and west (78 acres) cell by an interior dike running north to south. Approximately 835,000 cubic yards (yd^3) of dredged sediment was placed into the cells between 01 January 2002 and 20 January 2002 (USACE 2008). Sections of the interior and southern dikes were breached to enhance sediment flow from the eastern cell into the western cell and along the southern perimeter to create mudflats. In total, 450,000 yd^3 was placed into the eastern cell to 2.3 ft NAVD88, 235,000 yd^3 was placed into the western cell to 1.9 ft NAVD88, and 150,000 yd^3 of sediment flowed out from the southern dike to create the mudflats, which ultimately created 186 acres of marsh. *Spartina alterniflora* was planted along the interior perimeter after project completion, while *Spartina patens* naturally colonized the interior portions. By 2004, the cells were dominated by *S. alterniflora*.

Cycle 2. Construction of Cycle 2 containment began in 2007, but dredging did not commence until the 2010 CSC maintenance event. Levees, previously constructed in 2007 from *in-situ* material, had experienced erosion, and therefore certain portions required maintenance to achieve a maximum height of 4.4 ft NAVD88. A low-level weir was constructed along the western boundary to a maximum elevation of 1.4 ft to 1.9 ft NAVD88 to facilitate the overflow of material to create mudflats and emergent marsh in the adjacent shallow water, in total creating a 220-acre cell (USACE 2019). Approximately 1,080,686 yd^3 of dredged sediment was placed into the cell between 01 April 2010 and 14 May 2010. In total, 282 acres of marsh and mudflat were created and, at the time of this study, was predominately vegetated by *Bolboschoenus robustus* and *S. alterniflora*.

Cycle 3. Sediment placement for Cycle 3 was performed during the 2007 CSC maintenance event. Levees were constructed along the southern and eastern boundaries to a maximum height of 4.4 ft NAVD88. At the same time, low-level earthen weirs were placed along the western and northern boundaries to a maximum height of 1.4 ft NAVD88 to facilitate overflow, in total creating a 230-acre cell (USACE 2008). Approximately 828,767 yd^3 of dredged sediment was placed within the cell between 12 February 2007 and 21 March 2007 to a maximum height of 2.1 ft NAVD88. After dredging, the southern and eastern dikes were breached every 500 ft to an elevation of 0.9 ft NAVD88 to facilitate tidal flushing. In total, approximately 180 acres of marsh and mudflats were created. In 2010, the dikes were degraded to an elevation of -0.1 ft NAVD88, and six 50 ft breaches were constructed down to -0.6 ft NAVD88 to facilitate tidal flushing and fisheries access. As of that time, the dominant vegetation was comprised of *S. alterniflora* and *Salicornia depressa*. At the time of this study, the site was predominately vegetated by *B. robustus and S. alterniflora*.

Cycle 4. Sediment placement for Cycle 4 was performed during the 2015 CSC maintenance event. Levees were constructed from *in-situ* material along the western and northern boundaries to a maximum height of 4.4 ft NAVD88. Along the southern and eastern boundaries, low-level earthen weirs were constructed to 1.9 ft NAVD88 to facilitate the overflow of dredged sediment onto adjacent shallow open water areas, in total creating a 217-acre cell (USACE 2019). Approximately 1,002,519 yd^3 of dredged sediment was placed within the cell between 27 November 2014 and 15 January 2015 to a maximum height of 2.4 ft NAVD88. In total, approximately 116 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *B. robustus*.

Cycle 5. Sediment placement for Cycle 5 was performed during the 2015 CSC maintenance event. Levees were constructed from *in-situ* material along the northern, southern, and eastern boundaries to an elevation of 4.4 ft NAVD88. A low-level earthen weir was constructed to 1.9 ft NAVD88 along the western boundary to facilitate the overflow of dredged sediment onto adjacent shallow open water areas, in total creating a 223-acre cell (USACE 2019). Approximately 813,097 $yd^3$of dredged sediment was placed within the cell between 15 January 2015 and 01 March 2015. In total, approximately 149 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *B. robustus*.

Unit 1A. Sediment placement for Unit 1A was performed during the 2015 CSC maintenance event. Levees were constructed from *in-situ* material along the northern and eastern boundaries to an elevation of 4.4 ft NAVD88. Low-level earthen weirs were constructed to 1.9 ft NAVD88 along the southern and western boundaries to facilitate the overflow of dredged sediment onto adjacent shallow open water areas, in total creating a 250-acre cell (USACE 2019). Approximately 1,060,996 yd^3 of dredged sediment was placed within the cell between 22 September 2014 and 21 November 2014. In total, approximately 359 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *S. alterniflora*.

Unit 1B. Sediment placement for Unit 1B was performed during the 2015 CSC maintenance event. Site containment consisted of previously constructed earthen levees along the eastern boundary, a low-level weir constructed to 1.9 ft NAVD88 along the northwestern boundary to facilitate the overflow of dredged sediment onto adjacent shallow open water areas. Rich vegetation encompassed the remaining boundaries, and in total, a 194-acre cell was created (USACE 2019). Approximately 1,091,431 yd^3 of dredged sediment was placed within the cell between 02 April 2015 and 29 May 2015. In total, approximately 238 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *S. alterniflora*.

Unit 1D. Sediment placement for Unit 1D was performed during the 2019 CSC maintenance event. Site containment consisted of The Back Ridge Canal Dike, a pre-existing dike running along the northern boundary, while a combination of discontinuous low-level weirs (constructed to 1.9 ft NAVD88) and existing marshes were utilized along the western, eastern, and southern boundaries to create a 229-acre cell (USACE 2019). Approximately 729,441 yd^3 of dredged sediment was placed within the cell between 13 August 2019 to 30 September 2019. In total, approximately 277 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *S. alterniflora*.

Unit 1E. Sediment placement for Unit 1E was performed during the 2019 CSC maintenance event. Site containment consisted of a combination of low-level dikes constructed of *in-situ* material to 1.9 ft NAVD88 along the northern boundary to facilitate the overflow of dredged sediment onto adjacent shallow open water areas and existing marsh, in total creating a 300-acre cell (USACE 2019). Approximately 1,043,646 yd^3 of dredged sediment was placed within the cell between 19 June 2019 and 12 August 2019 to a maximum height of 2.4 ft NAVD88. In total, approximately 318 acres of marsh and mudflats were created and, at the time of this study, was predominately vegetated by *S. alterniflora*.

Table 1. Marsh creation sites, extent, date completed, dredging duration, volume of material placed, and the extent of marsh/mudflat created.

Site	Containment Size (Acres)	Month Completed	Dredge Duration (days)	Dredged Material (yd^3)	Habitat Created (Acres)
Cycle 1	203	Jan. 2002	19	835,000	186
Cycle 2	220	May 2010	43	1,080,686	282
Cycle 3	230	Mar. 2007	37	828,767	180
Cycle 4	217	Jan. 2015	49	1,002,519	116
Cycle 5	223	Mar. 2015	47	813,097	149
Unit 1A	250	Nov. 2014	60	1,060,996	359
Unit 1B	194	May 2015	57	1,091,431	238
Unit 1D	229	Sept. 2019	48	729,441	277
Unit 1E	300	Aug. 2019	54	1,043,646	318

RESULTS AND DISCUSSION: A Coastwide Reference Monitoring System (CRMS) station was installed within Cycle 1 in June 2008. Funded by the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) of 1990 and now managed by the US Geological Survey (USGS) and CPRA, CRMS utilizes 390 sites to monitor the effectiveness of restoration actions across Louisiana coastal management zones (CPRA 2017). The CRMS stations 0685, 0687, 6301, and 6302 records an average salinity range between 8 to 14 ppt from June 2008 through May 2021, while Abbot et al. (2019) recorded an average salinity of 15 psu (comparable measure with ppt) from April 2016 to July 2016. Despite the relatively low salinity levels, the CRMS data has primarily categorized Cycle as saline but occasionally as brackish. In addition, Cycle 1 is impounded mainly by levees and natural marsh, so conditions are assumed to be relatively consistent for the other created sites.

The DEM of the marsh creation sites from 2018, shown in Figure 2(*a*), displays several vital features within the created marsh, such as the drainage ditches (constructed tidal creeks) in Cycle 1 and the breaches on the northern end of the Cycle 3 earthen containment dikes. The created marsh platforms ranged in elevations from -0.6 ft to 1.6 ft NAVD88. Cycles 1, 2, and 3, along with Units 1A and 1B, exhibited consistent elevations at around 1.4 ft NAVD88 while Cycles 4 and 5 sat at 0.7 ft NAVD88, Figure 2(*b*). This difference is attributed to Cycles 4 and 5 not receiving sufficient sediment volume to achieve the desired marsh platform elevation during the 2015 maintenance event.[7] Despite the volumes displayed in Table 1 showing similar amounts placed

[7] Personal communication, James Lafleur, construction representative-MVN, May 5, 2021.

here as in the other placements, these sites likely exhibited lower initial elevations, thus requiring more volume to reach the design height. Cycles 4 and 5 would likely have exhibited even lower average elevations; however, the lidar data did not provide elevations for the sections underwater (e.g., the western half of Cycle 4). On a similar note, Units 1D and 1E are not depicted in Figure 2 because the most recent elevation data was from 2018, a year before site construction. Overall, the selected nourishment sites are relatively consistent, especially compared to East and West coast sites that exhibit much larger elevation gradients due to their respective tidal ranges.

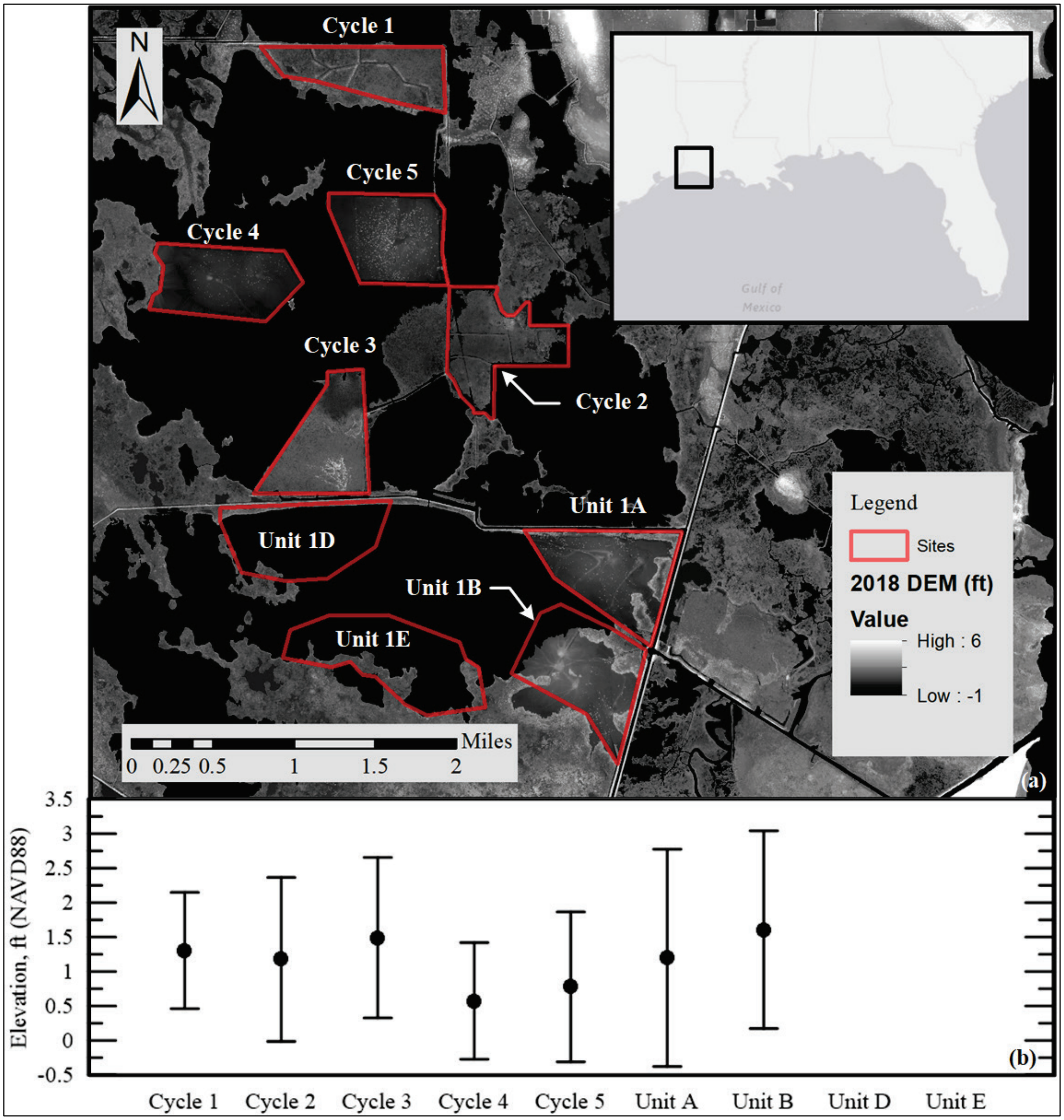

Figure 2. (*a*) Digital elevation map of a 2018 DEM downloaded from USGS's National Map and (*b*) average elevation ±1 standard deviation for each marsh creation site.

The vegetation indices calculated from Landsat 8 satellite imagery downloaded from USGS's Earth Explorer, updated for September 2021, are shown in Figure 3. The created marshes exhibited NDVI values between 0 and 0.33 (possible range of 0 to 1), VDVI values between 0 and 0.04 (possible range of -1 to 1), and $MSAVI_2$ values between 0 and 0.5 (possible range of -1 to 1); these values correspond with a combination of bare earth and shrubs/grassland. NDVI and $MSAVI_2$ showed similar trends, with Cycle 4 lagging behind the other created sites while VDVI presented low values across all sites, not lending much additional insight. As stated previously, VDVI is the only index to include only visible spectrums. While VDVI is determined to be a successful index to decipher between vegetative and non-vegetated areas, the lack of variety makes drawing conclusions between sites difficult. Based on the May 2021 site visit and results presented in Abbot et al. (2019), the NDVI and $MSAVI_2$ measurements appear reasonable, with *S. alterniflora, Spartina patens, Distichlis spicata*, and *Bolboscoenus robustus* found throughout. Various publications have developed regressions and subsequent formulas to infer an amount of biomass from vegetation indices. While this is a useful comparative tool, field verification is needed to calibrate the equation to the specific site (Yunxiang et al. 2014; Miller et al. 2019). Future field data collection will verify suspected relationships between remote sensing vegetation indices and biomass. Overall, the vegetation found throughout the sites was consistent with a brackish to saline marsh.

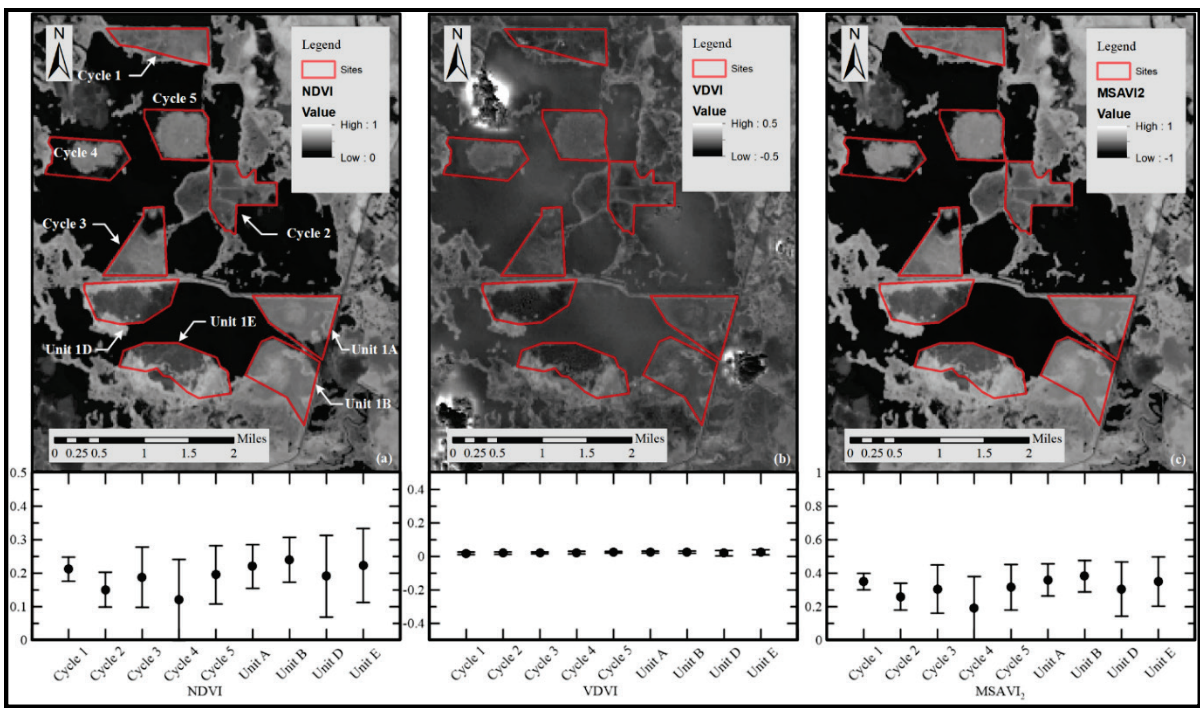

Figure 3. (a) NDVI, (b), VDVI and (c) MSAVI2 for the created marshes.

CONCLUSION: Developing CTST of nourished or created marshes is key to improving the planning and management of future restoration projects involving BU. For the Gulf Coast region, the marsh creation projects within the Sabine National Wildlife Refuge were selected due to the presence of several sites constructed over multiple decades that utilized the same source material and possessed similar ecosystem characteristics (e.g., hydrology, salinity, and elevation) within the placement area. They represent a range of ages from 2 to nearly 20 years post-construction and provide an appropriate time series to establish restoration trajectories. In addition, the SNWF has ample nearby native marsh not impacted by the nourishments to serve as reference sites.

In addition to these sites and native marshes, several older restorations dating back to the 1980s may be added to the trajectory time series if the sediment and other characteristics can be shown through field verification to be like this core set of sites. Furthermore, new sites will likely be developed as the CSC maintenance dredging continues to be important to the local economy (CSRS 2017). Additionally, the SNWF will continue to benefit from additional marsh creation. Future restorations might allow for a “Year 0” site to be added later to provide a baseline.

Going forward, sampling these sites for soil, geochemical, and vegetative characteristics will occur over the next year, allowing the development and assessment of multiple trajectories and functions. Developing these trajectories by documenting vegetation establishment and other ecological functions within these constructed marshes will be vital in optimizing future restoration efforts that incorporate dredged sediment.

ADDITIONAL INFORMATION: Research presented in this TN was developed under the Environmental Management and Restoration Research Program (EMRPP). The USACE proponent for EMRPP is Ms. Mindy Simmons, the Program Manager is Dr. Brook Herman, and the Technical Director is Dr. Jennifer Seiter-Moser. Technical reviews provided by Ms. Abigail Eilar and Ms. Krystyna Powell (ERDC Environmental Laboratory) are gratefully acknowledged.

For additional information, contact the authors (information provided on first page), or contact the EMRRP program manager, Dr. Brook Herman (601-634-3248, Brook.D.Herman@erdc.dren.mil).

This technical note should be cited as follows:

> Harris, B. D., K. E. Harris, N. H. Jafari, J. H. Bekkaye, E. O. Murray, and S. Altman. 2023. *Selection of a time series of beneficial use wetland creation sites in the Sabine National Wildlife Refuge for use in restoration trajectory development*. ERDC/TN EMRRP-ER-25. Vicksburg, MS: US Army Engineer Research and Development Center.

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