A MULTI-DECADAL ASSESSMENT OF DREDGED SEDIMENT BENEFICIAL USE PROJECTS PART 1: ECOLOGICAL OUTCOMES

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ABSTRACT

Dredged sediment has been used to create and restore wetlands and other landforms for decades as part of beneficial use initiatives. Previous studies demonstrate that beneficial use projects yield ecological functions such as habitat maintenance, floodwater detention, and biogeochemical cycling. However, questions persist about the long term ecological trajectory of beneficial use projects due to 1) short monitoring timeframes and 2) the paucity of beneficial use sites that have reached maturity since most beneficial use projects were recently constructed. In response, ecological functions were assessed at six >40 year old dredged sediment beneficial use projects and adjacent reference areas with available historic post construction monitoring data. Results indicate that after four decades the beneficial use projects 1) generally achieved and maintained their target habitats, 2) became more similar to reference areas over time while remaining on unique trajectories, 3) display similar responses to environmental conditions as reference areas despite some persistent differences, and 4) continue to provide a wide array of ecological functions. Findings suggest that establishment of beneficial use success criteria should not over emphasize replicating reference conditions but should focus on achieving specific ecosystem functions (i.e., energy dissipation) and desirable outcomes (i.e., storm surge reduction). The analysis also highlights the need for additional research into long term beneficial use project trajectories, especially as new initiatives including Working with Nature and Engineering With Nature® continue to expand. A companion paper links these findings with an established ecosystem goods and services framework to holistically evaluate the long term outcomes of dredged sediment beneficial use projects.

Keywords: Natural and nature-based features, habitat, soil, vegetation communities, avian communities

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) and cooperating agencies constructed multiple habitat improvement projects using dredged sediment from 1974 to 1978 (Landin et al. 1989). The projects sought to establish high quality target habitats including coastal marshes, upland meadows, and other desirable landscape features. These sites were monitored intermittently until 1987, documenting the capability of dredged sediment beneficial use activities to improve habitat. The projects document some of the first research into dredged sediment beneficial use applications in the United States. Early monitoring results suggested the projects improved habitat and demonstrated the utility of incorporating the beneficial use of dredged sediment into federal navigation, sediment management, and ecosystem restoration programs. Notably, this early research focused on habitat creation and enhancement and did not directly consider the full suite of functions and desirable outcomes (e.g., energy dissipation; storm surge reduction) frequently discussed today.

Subsequent research completed at dozens of dredged sediment placement locations over the last four decades highlights the interplay between habitat restoration and creation, engineering design, and environmental outcomes (Edwards and Proffitt 2003). For example, Faulkner and Poach (1996) assessed the functional capacity of created and natural wetlands, detecting similarities and differences between natural and built environments; Mallach and Leberg (1999) evaluated faunal community use of natural islands and islands created using dredged sediment, identifying variables that affected faunal community composition and abundance; and Yozzo et al. (2004) reported that dredged sediment is valuable for achieving a variety of habitat creation and restoration objectives including constructing artificial reefs, oyster reef restoration, intertidal wetland and mudflat creation, and the development of bird and wildlife islands as part of a regional sediment management strategy. These studies demonstrate that use of dredged sediment for habitat restoration and creation supports some of the ecological functions observed in natural systems, although the magnitude and trajectory of functions may differ (Faulkner and Poach 1996). Additionally, Streever (2000) reported that project designs incorporating elements that mimic natural processes begin to display ecosystem characteristics similar to natural systems faster and to a greater extent than landscape features constructed using traditional techniques.

The implementation of dredged sediment beneficial use projects has continued to expand over time, and the evaluation of beneficial use alternatives is now commonly incorporated into navigation programs, regional sediment management plans, and agency operational guidelines (Berkowitz and Szimanski 2020). However, while the number of dredging projects that incorporate beneficial use features continues to increase, the absolute volume of dredged sediment being used beneficially has not increased concurrently (ranging from 20 to 50% of the annual dredging volume in the United States; 1997-2017 average = 38%; Bell et al. 2021). To further promote beneficial use projects, ongoing research is focused on the capacity of natural processes to improve ecological endpoints while accomplishing engineering objectives including the maintenance of navigation channels (Daigneault et al. 2016). Additionally, efforts are underway to more fully capture the full suite of benefits provided by projects, which can improve the benefit-cost ratios used in evaluating dredged material management options (Foran et al. 2018; Ahadi et al. 2018). In the United States, the newest phase of ecosystem and dredged sediment management is encapsulated by the Engineering with Nature® (EWN) initiative, an intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits (Table 1; Bridges et al. 2014). The beneficial use of dredged sediment is consistent with EWN within emerging water resources infrastructure paradigms (King et al. 2021).

Table 1. Key elements associated with the Engineering With Nature® initiative

1. Use science and engineering to produce operational efficiencies supporting sustainable delivery of project benefits.
2. Use natural processes to maximum benefit, reducing demands on limited resources, minimizing the environmental footprint of projects, and enhancing the quality of project benefits.
3. Broaden and extend the base of benefits provided by projects to include substantiated economic, social, and environmental benefits.
4. Use science-based collaboration to organize and focus interests, stakeholders, and partners to reduce social friction, resistance, and delays while producing more broadly acceptable projects.

The absence of long term studies evaluating dredged sediment beneficial use project outcomes remains one of the challenges precluding further expansion of beneficial use initiatives. These uncertainties result from the limited period (several decades) that dredged material management projects have incorporated opportunities for ecosystem improvement, representing much shorter time frames than reflected in natural system evolution (Coleman et al. 1998). The lack of constructed projects >50 years old precludes the collection and analysis of data from fully ‘mature’ beneficial use study locations. Also, few studies track the trajectory of beneficial use sites for extended periods, with most monitoring efforts occurring over short durations (often <2–5 years), which while generating valuable information D'Avanzo (1989) and others suggest is insufficient for documenting the long term benefits and outcomes of ecological restoration and creation projects. The paucity of long-term ecological monitoring data represents a significant ecological trajectory gap, limiting practitioner’s ability to conduct project life cycle analysis and develop data driven success criteria and project milestones (Berkowitz et al. 2021a).

Another challenge to expanding beneficial use activities is cost, since beneficial use project implementation can be more expensive than traditional dredged sediment disposal options (PIANC 2009). However, to date few projects capture the true economic value delivered by beneficial use projects. Failure to account for all project benefits, in conjunction with the Federal Standard that has required implementation of the least cost alternative limits practitioners’ ability to implement innovative dredged sediment management strategies (Brandon and Price 2007; Bell et al. 2021). As a result, there is a need to develop frameworks that document the full suite of positive outcomes associated with dredged sediment beneficial use projects, including ecological functions, goods, and services (Kolman 2014).

In response to these challenges, six historic dredged sediment beneficial use projects were assessed to document long term ecological outcomes and compare them with natural reference areas. The following provides descriptions of each study site and subsequent sections highlight the findings of vegetation community surveys, avian habitats assessments, and an evaluation of soil conditions at each location.

STUDY LOCATIONS

Natural resource assessments were conducted in 2019 at six historic dredged sediment beneficial use project locations. These projects were initially developed between 1974 and 1977, and post construction monitoring data was collected for up to 10 years (Landin et al.1989). The project locations represent some of the earliest beneficial use sites with monitoring data in the United States. As a result, the project sites provided a unique opportunity to investigate mid to long term outcomes of dredged sediment beneficial use initiatives. Additionally, the projects represented a range of geographic locations and target habitat types (e.g., marsh, meadow, dune), allowing for the evaluation of beneficial use outcomes in a variety of ecological settings (Figure 1).

The historic (1974 to 1987) monitoring documented vegetation, avian communities, and soil characteristics at each project location and compared their results with observations made at natural, unaltered reference areas (Newling and Landin 1985). Notably, the projects’ design and early monitoring focused on improving habitat and did not consider economic parameters, social implications, or other factors that are now recognized within broader contexts such as the EWN initiative. However, the historic studies did attempt to utilize natural processes to improve habitat through the creation of target ecosystems (e.g., marshes, upland meadows). The following sections provide a brief description of each study site. They also indicate how each project reflects aspects of the EWN initiative to place the projects within a modern perspective and utilize them as proxies to evaluate how other projects will likely evolve at decadal timescales. While limited historical data were available regarding the sources, quantity, and pre-construction characteristics of the dredged sediments used at the project sites, Berkowitz et al. (2021) describes available data related to the study locations and provides a full accounting of all methods along with the complete 2019 assessment dataset.

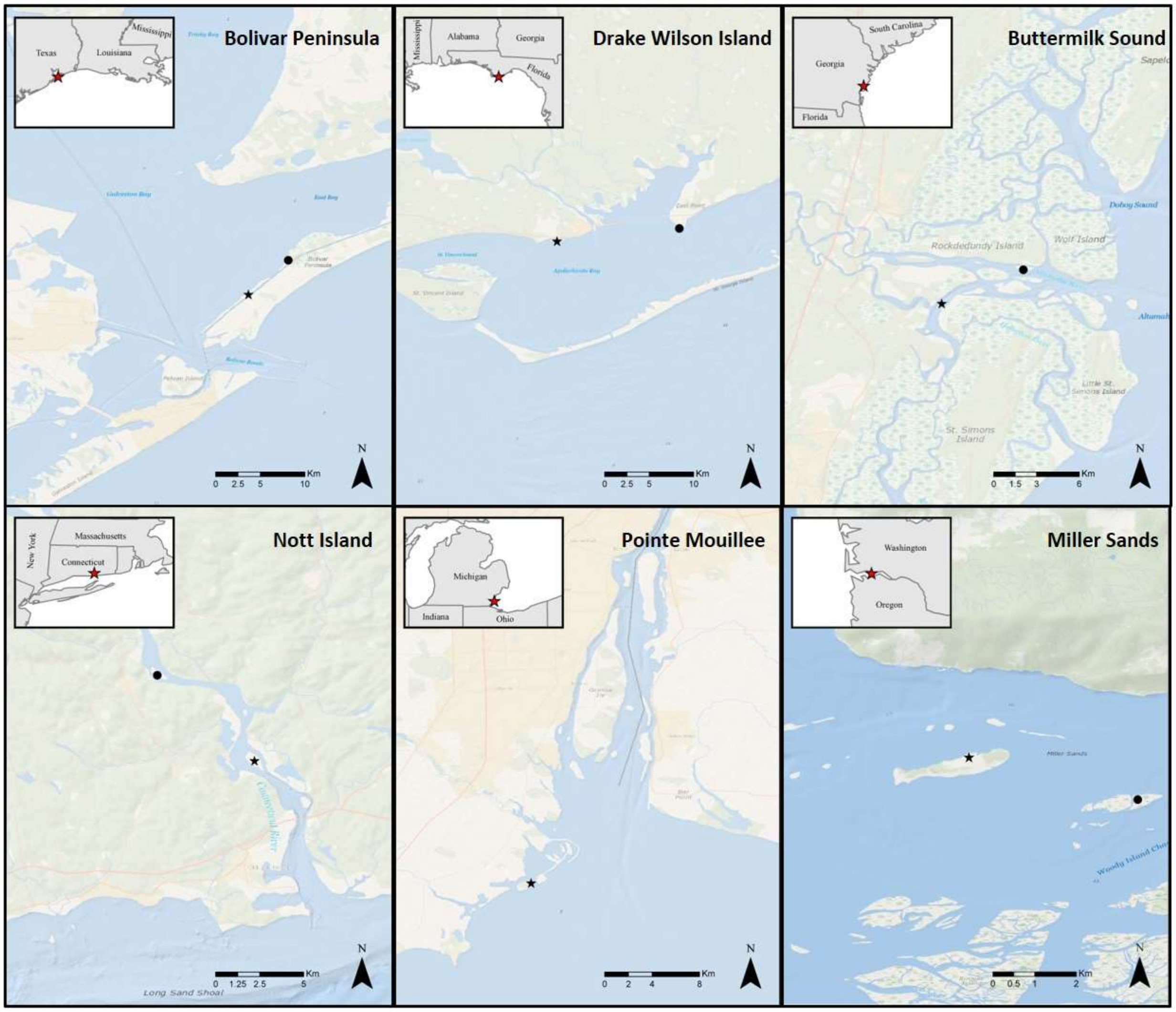

Figure 1. Location of the beneficial use projects (★) and reference areas (●) assessed.

Bolivar Peninsula, TX

The Bolivar Peninsula beneficial use project is located adjacent to the Gulf Intercoastal Waterway near the Houston Ship Channel. An 11.1 ha area of dredged sediment previously deposited on the peninsula was contoured using construction equipment in 1976 to create an elevation gradient capable of supporting the establishment of upland, high marsh, and low marsh/intertidal habitats. Vegetation was established using fertilizer and plantings. A reference area composed of saltmarsh habitat, Pepper Grove, was selected near the beneficial use project location. Differences in elevation between the beneficial use site and the reference marsh were identified as important during the historic studies and indicated that plant growth at the project site equaled or exceeded growth at the reference area. However, root biomass remained lower at the project site than in the unaltered natural marsh. The early monitoring efforts indicated that elevation gradients strongly influenced species survival and vigor. This project included features that align with aspects of the EWN initiative because it mimicked natural elevation gradients to establish a variety of habitats and target vegetation community types. Additionally, after the initial construction phase natural tidal processes and ecological succession were allowed to drive landscape evolution within the project area. The project also avoided the inclusion of hardened engineering features, which are used in a variety of shoreline stabilization and other restoration contexts but have been shown to alter a number of ecological functions and processes to varying degrees (Fischenich 2003; Peters et al. 2015).

Drake Wilson Island, FL

Drake Wilson Island was constructed in 1976 using sediment derived from the adjacent Two-Mile Channel, a navigation route linking the Gulf Intercostal Waterway, Apalachicola Bay, and the Gulf of Mexico. The 5 ha project sought to develop an emergent marsh and woody upland habitats by placing hydraulically pumped fine-grained silty dredged sediment onto older coarse-grained sandy dredged sediment deposited during previous dredging operations. Transplants of smooth cordgrass and salt meadow cordgrass were installed in wetland areas. Landin et al. (1989) reported that by 1982 the site was almost totally covered with vegetation with only one small open water pond located at the dredged material dispersal outlet pipe. Researchers noted that the entire complex was vegetated and heavily used by wildlife in 1986, 10 years after project construction. A reference marsh, Cat Point, was located east of the study site. This project included features that align with aspects of the EWN initiative because it utilized fine-grained dredged sediment that mimicked substrates found in the natural marshes of the region, and a weir was installed to ensure tidal inundation patterns were established during the initial post construction phase. Natural tidal exchange occurred following dredged material consolidation and the weir was allowed to degrade. Plantings utilizing locally sourced vegetation avoided the inclusion of hardened engineering features, and following initial construction natural processes (e.g., tides, species succession) were allowed to drive environmental evolution at the project site.

Buttermilk Sound, GA

The 2.1 ha beneficial use project at Buttermilk Sound was developed in 1975, adjacent to the Atlantic Intracoastal Waterway near the mouth of the Altamaha River, GA. The objectives of the project were to: 1) convert a ~5 m high dredged sediment sand mound to intertidal marsh habitat; 2) document changes in the field site over time; and 3) demonstrate that a stable marsh could be created using sandy dredged sediment. The area was graded and planted with vegetation. A nearby reference marsh, Hardhead Island, was selected to assess characteristics of a naturally evolved wetland ecosystem. Within five years of construction, the project was reported to be visually indistinguishable from unaltered marshes (Landin et al.1989). This project included features that align with aspects of the EWN initiative because it established an environmental gradient of elevation with tidal inundation similar to unaltered areas in the region, and allowed for natural processes (e.g., tidal creek migration) to occur while avoiding the use of hardened features.

Nott Island, CT

The Nott Island beneficial use site is located on the Connecticut River, one of the state's most vital waterways. The 3.2 ha project was developed in 1974 in an area where historic dredged sediment deposits raised the elevation of the island by several meters. The unvegetated sand mound was considered low quality habitat due to nutrient limitations associated with coarse soil textures and steep slopes that precluded the establishment of vegetative communities and the utilization of the site by faunal communities of interest. The beneficial use project included grading the site to create an upland meadow, incorporating fine-grained dredged sediment into the sandy substrate to improve conditions for plant growth, and amending the soils with lime and fertilizer. Vegetation was successfully established to create habitat for birds and other species, with approximately 80% of the planted area vegetated within the first growing season (Landin et al.1989). Eustasia Island was selected as a reference monitoring site due to its similar geomorphology, substrate, and proximal location. This project included features that align with aspects of the EWN initiative because it incorporated finer grained sediment into the sandy dredged sediment deposits to mimic soil textures found in unaltered habitats in the region, encouraged the establishment of plant communities of high habitat value, allowed natural patterns of plant species succession to occur following construction, and avoided the inclusion of hardened engineering features.

Pointe Mouillee, MI

The Pointe Mouillee beneficial use project is adjacent to the western shore of Lake Erie. Historically, the area included a barrier beach that protected an extensive marsh complex from wind and wave driven erosion. However, the barrier beach was destroyed by high energy storm events coinciding with a period of high lake levels in the 1960's, which induced extensive erosion and degradation of >1,618 ha of marsh. In response, a 148 ha area was diked to provide protection for the degraded adjacent marsh from wind and wave erosion and a Confined Disposal Facility (CDF) was constructed to hold dredged sediment removed from the Lake Erie Ship Channel. The CDF was strategically situated and designed to match the configuration of the historic barrier island to support revitalization of the degraded marsh. The project objectives included: 1) protect and stabilize the wetlands and adjacent wildlife management area; 2) reestablish marsh habitat through sedimentation and plant colonization; 3) establish a multi-use site that includes a visitors' center and recreational opportunities; and 4) provide for the deposition of dredged sediment from Lake Erie harbors and channels. Historic monitoring data indicated that plant colonization took place within three growing seasons after construction (Landin et al. 1989). No suitable reference monitoring location was identified near the Pointe Mouillee beneficial use site. The Pointe Mouillee project included features that align with aspects of the EWN initiative because it protected the remaining adjacent marshes, provided habitat and recreational opportunities while maintaining the capacity to manage dredged sediment from the nearby navigation channel. Unlike the other projects examined, the Pointe Mouillee project utilized hard infrastructure including dikes and riprap to stabilize project features and prevent erosion as well as to contain contaminated sediment. This infrastructure was needed for wave energy attenuation which served to replace the ecological functions (e.g., energy dissipation) provided by the eroded barrier beach that previously protected the surrounding marshes and to prevent the contaminated sediment release identified in a subset of the dredged sediment in the project area.

Miller Sands, OR

The Miller Sands beneficial use project is located in the Columbia River adjacent to a navigation channel serving Astoria, OR. The original island was constructed with dredged sediment in 1932, and it received additional dredged sediment during maintenance operations at approximately four year intervals (Landin et al. 1989). The beneficial use project resulted in development of three distinct habitats including 1) upland meadows, 2) wetland marshes, and 3) dunes. In 1974, the upland portion was disked using farming implements to prepare a seed bed, which was subsequently planted. Other parts of the island were graded to an intertidal elevation and planted to establish wetland habitats; and the sand spit was planted with beachgrass interspersed with sand fencing. A nearby marsh, Snag Island, was selected as a reference location. This project includes features that align with aspects of the principles and objectives of EWN because it was designed to provide a variety of habitat types common in the region based on a gradient of elevations and associated inundation patterns. Additionally, the project utilized natural processes (e.g., erosion of the sand berm and dunes, sediment accretion in wetlands) to contour and shape the island after construction, while providing for the management of dredged sediment in the Columbia River navigation channel. Specific plantings were selected for each target habitat based on inundation tolerances and the project avoided the inclusion of hardened engineering features.

METHODS

The 2019 assessment utilized the same metrics and sampling techniques applied in the original monitoring program conducted in the 1970s and 1980s, including assessments of vegetation community composition and distribution, avian habitat utilization, and soil characteristics at each beneficial use site and at unaltered reference locations. This approach allowed for time series comparisons between the unaltered reference locations and the historic monitoring data to evaluate how the project sites matured and evolved over the past four decades (Newling & Landin 1985).

Vegetation sampling utilized triplicate sample points within representative locations of each plant community observed at the beneficial use sites and corresponding reference locations (Figure 1). Plant communities were classified based on dominant and/or diagnostic species assemblages. Triplicate 1 m^2 quadrats were used to estimate percent cover of all species and triplicate 0.25 m^2 quadrats were used to calculate the stem density (i.e., the number of vegetative stems occurring within a defined area) of all species present.

Avian community surveys utilized fixed point count locations at an intensity of one sample point per 10 ha, resulting in a total of 117 unique point count locations. At each sample point an unlimited distance, five minute point count was conducted, during which all individual birds seen or heard were recorded. Birds that were flying over the survey area were tallied separately, as the observer could not determine whether these birds were using the survey area. The survey then calculated total and average bird abundance and species richness at each study site.

For the soils assessment, triplicate 5 cm soil cores were collected from the surface horizons within each vegetation community at the beneficial use project locations and at the associated reference areas. Soils data were not available from the Pointe Mouillee, MI, beneficial use site or the Cat Point, FL, reference area. Soils were homogenized and analyzed for moisture content (MC); bulk density (BD); loss on ignition (LOI), which provides a measure of soil organic matter content; pH; salinity; extractable ammonium (NH_4^+), nitrate (NO_3^-), and soluble reactive phosphorus (SRP); and total carbon (TC), nitrogen (TN), and phosphorus (TP). Triplicate 10 cm soil cores were also collected for below ground biomass (BGB) determinations. Soil samples were processed following the same methods used during the 1970s assessment period. Berkowitz et al. (2021) provides comprehensive description of all analytical methodologies.

RESULTS AND DISCUSSION

The 2019 assessment indicates that the historic beneficial use projects successfully developed the target habitat types described in the project objectives and early monitoring reports, and 13 of the 15 target habitats remain functional more than four decades after project construction (Table 2; Figures 2a and 2b). The finding that most of the target habitats were achieved and remain functional after multiple decades is significant because few studies evaluate beneficial use outcomes over long periods. Further, sustainability is one of the goals of the EWN initiative and the fact that, in general, the target habitats remain functional while continuing to respond to natural processes suggests that beneficial use projects can yield long term benefits across a variety of landforms, regions, and ecological contexts.

The beneficial use projects have evolved both ecologically and geomorphologically over time, with most study areas displaying increases in total landcover and vegetation abundance, coupled with decreases in the spatial extent of open water and barren areas (Berkowitz et al. 2021). In total, the projects have resulted in the creation of >70 ha of new land since construction and have expanded at an average rate of 0.33 ha/yr (range = -0.16 to 1.6 ha/yr). These findings, in conjunction with the vegetation, avian, and soil condition

Table 2. Summary of target habitats, success of sustained development over >40 years, challenges, and management opportunities to improve conditions at beneficial use sites.

Location	Target habitat type	Present after >40 years	Functional without intervention	Challenges	Management opportunities
Bolivar Peninsula, TX	Low marsh	No	No	Erosion	Sediment placement
	High marsh	Yes	Yes	None	None
	Herbaceous upland	Yes	Yes	Undesirable species	Selective species control
	Woody upland	Yes	Yes	Planted species outside of native range	Selective species control
Drake Wilson Island, FL	Low marsh	Yes	Yes	Erosion	Sediment placement
	High marsh	Yes	Yes	Erosion	Sediment placement
	Woody upland	Yes	Yes	None	None
Buttermilk Sound, GA	Low marsh	Yes	Yes	None	None
	High marsh	Yes	Yes	None	None
	Unvegetated upland	Yes	No	Woody species encroachment	Selective species control
Nott Island, CT	Upland meadow	Yes	Yes	Undesirable species, poor soil quality	Selective species control, soil amendments
Pointe Mouillee, MI	Freshwater marsh	Yes	No	Woody species encroachment, Invasive species	Selective species control
Miller Sands, OR	Upland meadow	Yes	No	Poor soil quality, woody species encroachment	Selective species control, soil amendments
	Tidal marsh	Yes	Yes	Erosion, Invasive species	Selective species control
	Dune	Yes	No	Erosion	Sediment placement

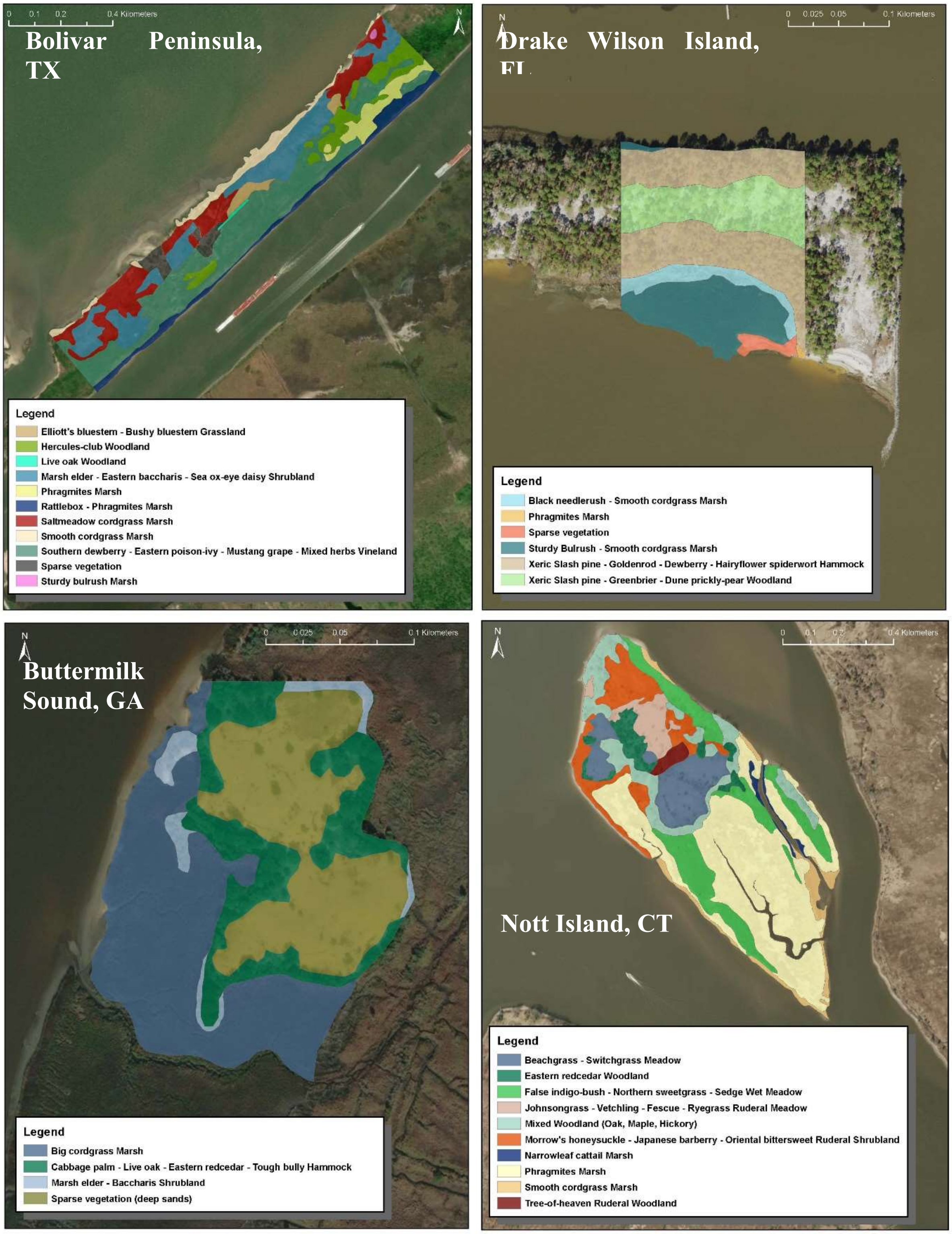

Figure 2a. Vegetation community composition at beneficial use projects after >40 years.

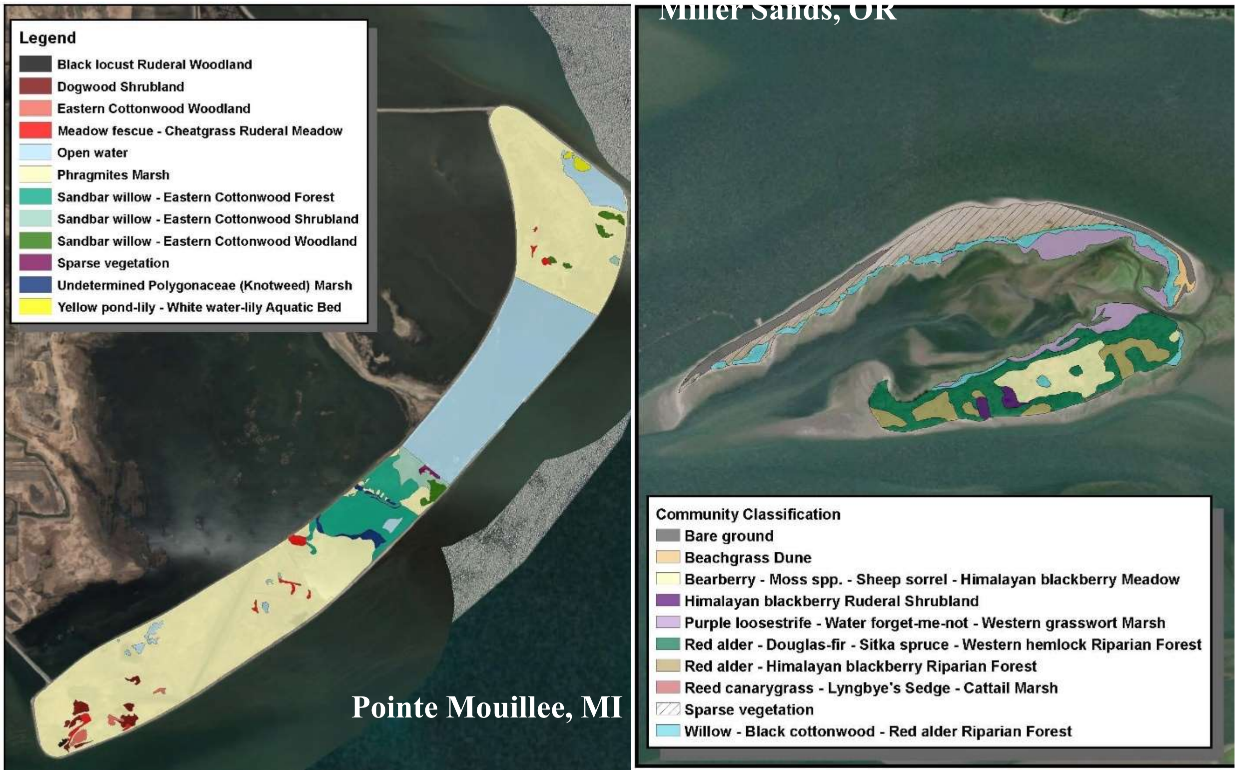

Figure 2b. Vegetation community composition at beneficial use projects after >40 years.

data described below demonstrate that the beneficial use projects provide a variety of habitat, physical, and biogeochemical cycling functions.

Vegetation community assessment

Diverse vegetation community assemblages were identified at the six beneficial use project sites, ranging from densely vegetated marshes to forested areas and sparsely vegetated dunes. Notably, the spatial distribution of habitat components and/or the suite of species present today differs from the conditions observed during post construction and early monitoring surveys at some study locations. For example, a number of the species planted and/or initially established at the Bolivar Peninsula are either absent or occur as minor components of the plant community.

The shift in species composition following construction is not unanticipated as ecological succession occurs in response to biotic and abiotic factors that drive the success of individual species and plant communities over time, and natural processes were allowed to drive the evolution of the project areas after establishment (Zedler 2000). In some cases, the disconnect between project designs and steady state conditions can be attributed to inappropriate species selection, including the planting of some species (e.g., sand pine in coastal TX) outside of their native ranges.

At other project locations, target habitat communities may not be sustainable without further interventions to maintain favorable conditions. For example, additional periodic sediment placement may be required to maintain low marsh communities (Bolivar Peninsula, TX), woody plant removal would help sustain open sandy habitats (Buttermilk Sound, GA), and soil amendments would help improve the conditions for vegetative growth and habitat development in areas subject to nutrient limitations (Miller Sands, OR). Additionally, nuisance, invasive, and nonnative species pose a significant challenge to achieving ecological goals across many of the project sites, as well as the reference locations evaluated. In general, the number and abundance of undesirable species has increased during the post construction period at both beneficial use and reference areas (Berkowitz et al. 2021).

The available data indicates that initial planting efforts had limited effects on the distribution of plant species after 40 years of ecological succession, and others have suggested that post restoration plantings may not be necessary in areas with rapid natural recruitment (Mitsch et al. 1998). In the current study, plantings of saltmeadow cordgrass and smooth cordgrass at Drake Wilson Island, FL have become components of more complex communities, as other species that were not planted have been naturally recruited. In other cases, planted species (e.g., black needlerush at Buttermilk Sound, GA) are no longer observed within the project area, or occur to a much lower extent. Despite the absence of some planted species at beneficial use locations >40 years after construction, establishing appropriate species following project construction likely has advantages even if those plant communities do not persist or decline in abundance over decadal timescales. Initiating vegetative growth after disturbance has been shown to stabilize soils and sediment, accelerate dewatering, provide habitat, retain sediment and build elevation, improve soil health, and promote ecological functions (Bailey et al. 2019). Additionally, establishing plant communities can influence the ecological trajectory of project areas, even if the planted species fail to persist, migrate in response to environmental conditions, or become integrated into a more diverse plant assemblage. The establishment of desirable species has also been shown to delay or preclude the invasion of undesirable species and planted species can deliver ecological functions and other benefits more quickly and to a greater magnitude while site maturation and natural patterns of vegetation succession occur (Simonstad et al. 2006).

The habitat complexity of study locations generally increased over time. At Bolivar Peninsula, TX, distinct plant communities increased from 6 to 10 between 1988 and 2019 (Table 3). The increase in complexity over time is not unexpected given natural patterns of vegetation recruitment, response to disturbance, and the adjustment of plant communities to local conditions following four decades of ecological succession. Increases in species complexity following restoration have been reported in other studies, especially as seed banks become enriched. Baldwin (2004) provides a model outlining plant distribution patterns following marsh habitat restoration, indicating that increases in species richness are not expected to continue indefinitely as the project sites reach equilibrium. However, species composition will naturally respond to disturbances (e.g., floods, fire) and changes in ecological conditions (e.g., climate; invasive species), at both beneficial use and reference locations.

Table 3. Summary of vegetation community characteristics at dredged sediment beneficial use (BU) and reference locations. NA = no data available.

	Vegetation community assemblages (count)		**Dominant species richness in target community types (count)**			
Location	**BU location**	**Reference location**	**Habitat type**	**BU (2019)**	**BU (historic)**	**Reference (2019)**
Bolivar Peninsula, TX	10	1	Low marsh	4	2	2
Drake Wilson Island, FL	6	8	Low marsh	2	2	2
Buttermilk Sound, GA	4	2	Marsh	4	3	3
Nott Island, CT	10	4	Meadow	16	5	NA
Pointe Mouillee, MI	7	NA	Marsh	7	4	NA
Miller Sands, OR	7	1	Marsh	18	17	15

The vegetation community assemblages observed in the beneficial use sites were more ecologically complex than the reference areas, with the exception of the Cat Point, FL, reference area which exhibited barrier beach features absent at the Drake Wilson Island beneficial use project (Table 3). This increased complexity results from a combination of factors including the wider degree of topographic relief within the constructed project areas relative to the reference areas. This finding may seem counterintuitive, as other studies have identified the lack of topographic heterogeneity, especially with regards to surface microtopography as a limitation in many restoration projects (Bruland and Richardson 2005). However, within the locations examined, the habitat improvement project designs deliberately created ecological gradients that would support a variety of habitat types. This included the intentional establishment of upland, transitional, high marsh, low marsh, and other target habitats with appropriate elevations and hydropatterns.

The number of species in target communities has remained stable or increased over time at the beneficial use project sites, which display higher species richness than the reference locations. This suggests that while the beneficial use projects have reached a moderate to high level of maturity, based on the high stem densities and percentage of ground cover, they do not directly mimic the plant community assemblages of reference areas. The differences in species richness aligns with other studies that report engineered or restored areas often exhibit more species than their natural counterparts (Ehrenfeld 2000). The differences in species composition and richness may include intentionally or unintentionally introduced plants, the response of plant communities to varying substrate conditions, or reflect disturbance patterns associated with restoration design and implementation (Baldwin and Derico 1999). While the beneficial use project plant communities have trended towards conditions observed in reference areas, differences continue to persist after more than four decades of ecological succession.

Notably, both beneficial use locations and reference areas appear to be responding to environmental conditions in similar ways. For example, stem densities in both restored and reference areas follow similar patterns over the multi-decadal assessment period despite the observed differences in species composition and habitat complexity (Figure 3). Additionally, more invasive species were observed at both beneficial use and reference areas during 2019 than during previous investigations and those species appear to be increasing in abundance (Berkowitz et al. 2021). This trend has been reported in other areas, where anthropogenic alterations coupled with natural patterns of disturbance and plant dispersal are leading to increased alien invasions (Richardson et al. 2007). This further suggests that the vegetation communities at beneficial use locations are exhibiting similar responses to changing environmental conditions that impact plant distribution and growth at reference areas.

In summary, the vegetation communities established at the beneficial use sites undoubtedly improved habitat compared with preconstruction conditions. The project areas generally reflect the species assemblages at reference locations and have become more similar to reference locations with age, but do not replicate the reference systems. Notably, these plant communities have persisted for more than four decades without the need for major intervention. The findings of the current study align with previous research suggesting that beneficial use projects that incorporate ecological drivers (i.e., hydroperiod, salinity tolerance, and topography) into project design are sustainable and may have advantages over projects constructed with conventional techniques (Streever 2000). Additional studies directly comparing the long-term outcomes of beneficial use projects constructed using a variety of techniques is recommended to further investigate the relationship between ecological outcomes and construction techniques.

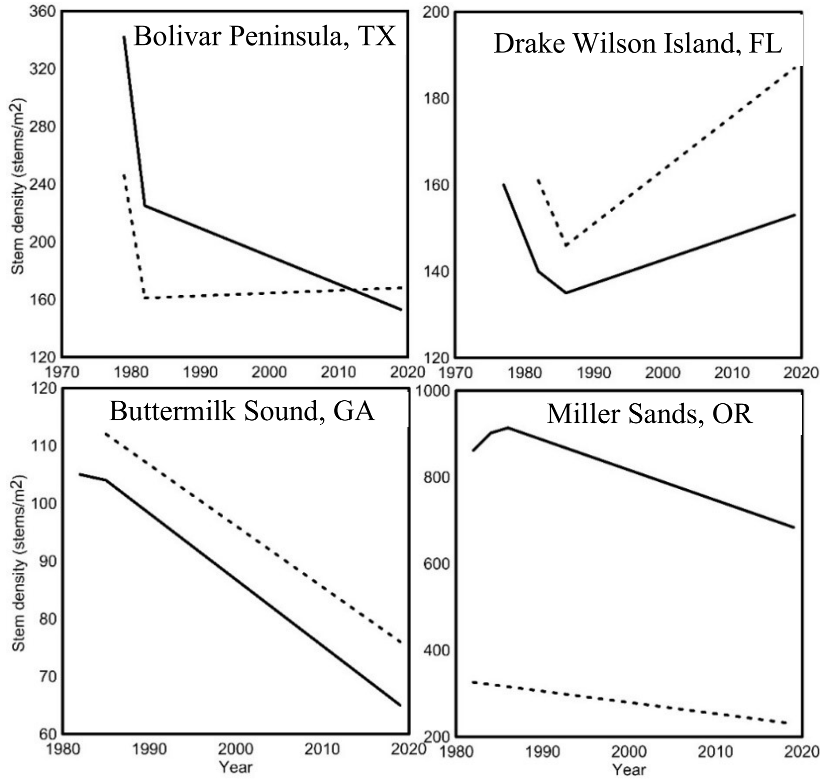

Figure 3. Comparison of vegetation stem density data from marsh habitats at beneficial use locations (solid lines) and reference areas (dashed lines) over time. Note that while the magnitude of stem densities varies, the constructed and reference locations display similar patterns and responses to environmental conditions over time.

Results also suggest that management activities could further improve site conditions especially with regard to selective species management, and in some cases the implementation of periodic disturbance regimes (e.g., additional dredged sediment deposition) may improve the functionality and sustainability of some landscape features including low marshes and coastal fringe wetlands (Table 2). For example, using thin layers of sediment to increase the elevation of areas threatened by subsidence and high rates of relative sea level rise has been shown to improve habitat conditions for plant growth, biogeochemical cycling, and other ecological functions (Puchkoff and Lawrence 2022).

Avian community assessment

The evaluation of avian communities provides additional data to document the habitat functions delivered by beneficial use projects (Neckles et al. 2002). The targeted, intentional placement of dredged sediment has been shown to effectively develop new habitats or improve existing habitat for birds (Erwin et al. 2003), and habitats supported with dredged sediment have proven as productive as natural marshes in some circumstances (Streever 2000). A total of 3,790 individual birds were encountered during the 2019 assessment, including wetland dependent birds which were present at each of the beneficial use project sites (Table 4). Marsh wren, red-winged blackbird, and yellow warbler were the most commonly detected species. Other common wetland breeding species frequently observed included boat-tailed grackle, clapper rail, common yellowthroat, and willow flycatcher (Berkowitz et al. 2021).

Table 4. Summary of avian species detected at beneficial use (BU) and reference area (RA) locations during 2019. †Indicates locations surveyed outside of the breeding season and colored text identifies paired beneficial use and reference sites.

Location	Number of point counts surveyed	Total abundance including flyovers	Total abundance excluding flyovers	Average abundance per point including flyovers	Average abundance per point excluding flyovers
Bolivar Peninsula, TX (BU)†	21	406	256	19	12.2
Pepper Grove, TX (RA)†	6	746	586	124	97.7
Drake Wilson Island, FL (BU)	8	129	78	16	9.8
Cat Point, FL (RA)	6	100	60	17	10
Buttermilk Sound, GA (BU)	6	118	93	20	15.5
Hardhead Island, GA (RA)	8	115	59	14	7.4
Nott Island, CT (BU)	11	202	179	18	16.3
Eustasia Island, CT (RA)	9	132	127	15	14.1
Pointe Mouillee (BU)	16	871	558	54	34.9
Miller Sands, OR (BU)	22	776	715	35	32.1
Snag Island, OR (RA)	3	155	147	52	49

Data from locations surveyed during the breeding season indicated that the beneficial use sites support higher total species richness and average species richness than unaltered reference areas (Table 5). Habitats were generally more diverse within beneficial use areas, which likely contributed to the higher levels of species abundance and richness compared to reference sites. However, the highest total and average species richness was observed at the Pepper Grove reference site, but this area was surveyed outside of the breeding season during the spring migration period when high numbers of waterbirds use the area as stopover habitat.

Ospreys and bald eagles are raptor species indicative of high habitat quality that utilize coastal and inland freshwater areas. Ospreys were observed at 50% of beneficial use sites conducted by Landin et al. (1989) but were observed at all sites during 2019, including nesting activities at the Nott Island, CT, and Pointe Mouillee, MI, beneficial use sites (Table 6). Bald eagles were also observed nesting successfully at the Miller Sands, OR, beneficial use project site. While osprey and bald eagle populations have recovered following legislative protection and the ban of the chemical dichlorodiphenyltrichloroethane (DDT). The 2019 avian community assessment demonstrates that these species are using the dredged sediment beneficial use sites for foraging and nesting, and that their habitat utilization has increased over the past >40 years.

The beneficial use projects examined herein continue to serve as important habitat for a diversity of avian communities since their creation over 40 years ago. The establishment of vegetation communities ranging from coastal salt marshes to upland habitats support a wide range of bird species, including numerous Species of Conservation Concern (USFWS 2021). While the habitat improvement sites continue to support abundant populations of birds, the 2019 survey observed differences in species assemblages and abundances when comparing the assessment data with both previous survey efforts and results collected at reference areas.

Table 5. Avian species richness detected at the beneficial use (BU) and reference area (RA) locations during 2019. †Indicates locations surveyed outside of the breeding season and colored text identifies paired beneficial use and reference sites.

Location	Number of point counts surveyed	Total species richness including flyovers	Total species richness excluding flyovers	Average species richness per point including flyovers	Average species richness per point excluding flyovers
Bolivar Peninsula, TX (BU)†	21	61	49	7.5	4.52
Pepper Grove, TX (RA)†	6	60	57	18.33	14.17
Drake Wilson Island, FL (BU)	8	32	24	10.88	7.5
Cat Point, FL (RA)	6	28	20	8.83	5.5
Buttermilk Sound, GA (BU)	8	16	12	8.0	6.17
Hardhead Island, GA (RA)	6	14	5	6.0	3.5
Nott Island, CT (BU)	11	43	36	9.75	9.45
Eustasia Island, CT (RA)	9	30	26	8.77	8.22
Pointe Mouillee (BU)	16	52	45	10.81	8.06
Miller Sands, OR (BU)	22	39	37	8.77	8.09
Snag Island, OR (RA)	3	16	11	7.0	5.0

Table 6. Comparison of observations of osprey and bald eagles at projects during the historic monitoring (Landin et al.1989) and the 2019 assessment.

Beneficial use location	Osprey		Bald Eagle	
	1989	2019	1989	2019
Bolivar Peninsula, TX	X	X		
Drake Wilson Island, FL		X		X
Buttermilk Sound, GA	X	X		
Nott Island, CT	X	X		X
Pointe Mouillee, MI		X		
Miller Sands, OR		X	X	X

In general, restoration sites had higher species richness compared to reference sites due to a greater diversity of habitats. Other studies have reported successful establishment of avian populations at beneficial use project sites, including rates of bird usage that exceed undisturbed reference areas (Warren et al. 2002). The intentional placement and manipulation of dredged sediment to yield gradients of elevation, soil conditions, and hydrologic regime resulted in the development of a wider range of target habitat types compared to reference sites, and a diversity of habitats is more attractive to nesting and foraging birds than homogenous expanses of a single habitat type (Rafe et al. 1985). The observed differences in species composition between constructed and natural areas result from broad habitat type effects (e.g., marsh, scrub-shrub, forest) and the presence of more complex habitats at the beneficial use locations; not differences in microhabitats within a particular habitat type (e.g., lack of tidal creeks in salt marshes). This suggests that future projects seeking to maximize avian community diversity should focus on creating a variety of target habitats as opposed to mimicking the less complex landforms observed at reference areas. Berkowitz et al. (2021) reports the full dataset generated during the 2019 avian community assessment.

Differences in species assemblages were also observed between the 2019 surveys and previous surveys described in Landin et al. (1989). In the years immediately following construction of the beneficial use projects numerous shorebirds, terns, and skimmers were documented on unvegetated dredged sediment deposits. However, with the exception of American white pelicans on the dune habitat at Miller Sands, beach nesting habitat is no longer available to support this community of waterbirds after more than four decades of ecological succession. This is not unexpected considering the duration of time since construction activities occurred. Areas that receive dredged sediment undergo a series of plant successional changes that eventually result in the development of dense herbaceous, shrub-scrub, or forested communities in the absence of frequent inundation or intermittent disturbance (Soots and Parnell 1975). Since the construction of the beneficial use projects, the vegetation communities have reached the later stages of succession and extensive shorebird habitat is no longer available at the study locations.

In summary, the 2019 surveys documented the persistence of moderate to high levels of avian community diversity and abundance at the beneficial use project locations. The results confirm the findings of previous studies that report islands constructed off the mainland are often more successful for bird reproduction because they lack mammalian predators in comparison to landscape features connected to the mainland. Over the past 40 years, plant succession and soil development occurred, and bird communities responded as anticipated with declines in habitat for beach-nesting birds and the expansion of habitat for species that forage and nest in densely vegetated areas. As a result, the periodic placement of additional dredged sediment at the project sites or the intentional removal of woody vegetation represent potential management activities that would increase habitat for beach-nesting species while providing opportunities to maintain the adjacent navigation channels (Guilfoyle et al. 2019).

Soils assessment

Soils and sediment characteristics play a key role in determining ecological outcomes (Muñoz Rojas 2018). Soils provide the physical substrate supporting habitats and also supply seed sources, nutrients, and organic matter to initiate plant establishment and succession (Abella et al. 2020). However, soils can limit or postpone the success of projects when their characteristics are not adequately considered (Eviner and Hawkes 2008). Common soil parameters limiting positive beneficial use outcomes include high salinity, low nutrient or organic matter content, bulk densities too low to support plant establishment or too high (compaction) to promote root penetration, and the alteration of soil structure during project construction (Mendes et al. 2019). Additionally, soils in dredged sediment beneficial use project areas may exhibit textures, microbial and fungal communities, and other characteristics that differ from reference conditions. These factors influence soil-plant interactions, and, although soils generally become more similar to natural substrates over time, the differences in soil characteristics can persist for several decades or even centuries after the implementation of management activities (Craft et al. 2002). The following reports changes in soil conditions >40 years after beneficial use project implementation and discusses soil characteristics in comparison to natural reference areas.

Each of the beneficial use projects displayed improvements in soil physiochemical properties with age, including increasing nutrient content and improved physical structure (Table 7). For example, loss on ignition (LOI), which reflects soil organic matter content and serves as a proxy measure of soil organic carbon storage, increased over time and in most cases approached the values observed in reference locations. This demonstrates that carbon is accumulating in the beneficial use sites, increasing soil water holding capacity and decreasing bulk density to improve conditions for flora and fauna. Extractable NO_3^- and NH_4^+ also increased over time, indicating that enhanced nutrient and biogeochemical cycling is occurring in beneficial use sites.

Table 7. Summary of soil characteristics in marsh communities at beneficial use (BU) and reference areas (RA) observed during the 2019 assessment and available historic monitoring data. Colored text identifies paired beneficial use and reference sites. The full soil assessment results are provided in Berkowitz et al. (2021).

Parameter[†]	Bolivar Peninsula (BU; 2019)	Pepper Grove (RA; 2019)	Bolivar Peninsula (BU; 1970s)	Drake Wilson Island (BU; 2019)	Drake Wilson Island (BU; 1979)
BD (g/cm^3)	1.26±0.12	0.60±0.19	N/A	0.37±0.04	N/A
pH	7.72±0.27	7.12±0.09	8.0-8.9	6.47±0.1	7.88–8.21
Salinity (ppt)	1.43±0.15	1.70±0.30	5.9	1.05±0.09	10–18
BGB (g/m^2)	54±13	292±62	N/A	446±64	N/A
NO_3^- (mg/kg)	1.78±0.07	7.64±2.23	<0.60	1.37±0.26	N/A
NH_4^+ (mg/kg)	7.29±2.98	11.71±8.6	<0.02	6±0.65	N/A
SRP (mg/kg)	0.63±0.32	0.27±0.27	<0.2	0.18±0.1	N/A
LOI (%)	3.82±0.59	10.4±3.6	>0.56	19.8±2.14	4.53–6.10
TC (%)	1.3±0.3	3.87±1.62	N/A	8.32±0.97	N/A
TN (%)	0.09±0.02	0.3±0.11	N/A	0.49±0.054	N/A
TP (mg/g)	286±54	397±24	N/A	421±46.5	N/A

Parameter	Buttermilk Sound (BU; 2019)	Hardhead Island (RA; 2019)	Buttermilk Sound (BU; 1979)	Miller Sands (BU; 2019)	Snag Island (RA; 2019)	Miller Sands (BU; 1979)
BD (g/cm^3)	0.49±0.40	0.37±0.04	N/A	0.98±0.04	0.73±0.1	N/A
pH	6.5±0.08	6.26±0.25	6.9–7.2	5.55±0.13	6.76±0.23	7.0
Salinity (ppt)	0.23±0.04	1.4±0.12	N/A	0.01±0.01	0.03±0.03	N/A
BGB (g/m^2)	188±96	191±86	N/A	104±20	106±28	128
NO_3^- (mg/kg)	1.86±1.75	3.3±0.74	0.1–0.75	4.92±1.01	7.3±3.23	<1.1
NH_4^+ (mg/kg)	24.4±14.5	4.92±0.98	8.7–12.2	2.71±0.67	20.4±15.3	5–12
SRP (mg/kg)	0.33±0.12	0.35±0.12	N/A	0.88±0.09	0.43±0.26	N/A
LOI (%)	13.7±4.5	18.4±2.7	<5.5	4.87±0.61	5.57±1.36	0.32
TC (%)	5.76±1.9	6.72±1.37	N/A	2.77±0.49	2.55±0.62	N/A
TN (%)	0.45±0.14	0.54±0.06	0.1–0.97	0.21±0.034	0.22±0.041	N/A
TP (mg/g)	543±102	938±73	<10.4	551±15.2	667±129	N/A

[†]Bulk density (BD); below ground biomass (BGB); nitrate-nitrogen (NO_3^-); ammonium-nitrogen (NH_4^+); soluble reactive phosphorus (SRP); loss on ignition (LOI); total carbon (TC); total nitrogen (TN); total phosphorus (TP);

Beneficial use sites not only displayed improvements in soil characteristics relative to initial post-construction conditions, but also currently exhibit a number of similarities with their natural reference counterparts. Only one site, Bolivar Peninsula, TX, displayed more than three of the soil properties that substantially differed from conditions at reference locations. Where variations were observed, most can be attributed to the heterogeneity of habitat types present at beneficial use projects compared with unaltered reference locations (Berkowitz et al. 2021).

Despite the similarities observed in most soil parameters at beneficial use and reference areas, the belowground biomass at the beneficial use sites remains significantly lower than reference conditions. However, increases in this parameter over time were proportional and correlated to increases in soil organic matter, total carbon, and total nitrogen measurements. The lower belowground biomass content in beneficial use sites is not unexpected, as restoration projects often contain less carbon following construction and store carbon differently than natural areas (Mitsch and Hernandez 2013). This finding aligns with results of other studies, including Abbott et al. (2019), who report lower carbon concentrations in marshes created using dredged sediment across a 32-year chronosequence than in natural marshes. However, the observed trends in soil carbon and biomass accumulation suggest that soil carbon assimilation and nutrient concentrations will continue to improve over time. In other words, the soils at the beneficial use sites have yet to reach the same level of ecological equilibria observed in the assessment of vegetation and faunal communities described above. These findings further support the conclusion that the beneficial use projects share characteristics with reference areas yet remain on unique ecological trajectories and emphasizes the utility of incorporating soil parameters into post construction monitoring programs.

Notably, the study locations display the ability to sustain the soil physical substrate needed to support the growth of robust rooted vegetation communities. Additionally, observations of stratified layers of sediment in the wetland habitats indicate that the beneficial use sites are detaining sediments during flooding, which provides a proxy measure of the energy dissipation and other physical/hydrologic functions (Berkowitz et al. 2021). Further, each of the wetland areas exhibited field indicators of hydric soils which document biogeochemical cycling functions including the retention and transformation of elements and compounds, carbon sequestration, and nutrient cycling functions are occurring at the study locations (USDA-NRCS 2018). These findings, in conjunction with the vegetation and avian community survey results highlight the fact that the dredged sediment beneficial use projects are performing the full suite of ecological functions associated with each targeted habitat type.

CONCLUSIONS

The assessment of six historic dredged sediment beneficial use sites demonstrates that positive project outcomes can be sustained over multiple decades, and that these outcomes can be achieved with limited use of hard structures or intervention (e.g., extensive management). The fact that the target habitats remain functional after more than four decades and have evolved through natural processes to provide moderate to high habitat values represents a significant finding that can be used to promote expansion of beneficial use initiatives. Results indicate that beneficial use projects incorporating a variety of landforms and environmental conditions (e.g., elevation and inundation gradients) delivered a wide array of ecological functions derived from habitat, biogeochemical cycling, and physical processes. The inclusion of these project features yielded a diversity of vegetation and avian community assemblages that exceeded observations made at some of the unaltered reference areas evaluated.

The study results improve our understanding of how projects will evolve ecologically over long periods and inform future project design, implementation, and management. For example, while vegetation communities, bird utilization, and soil properties became more similar to unaltered reference areas over time, they remain on distinct trajectories that do not directly reflect reference conditions (Moreno-Mateos et al. 2012). This does not suggest that the projects failed to achieve their objectives but instead highlights the need to develop realistic project milestones based on the time needed for delivery of ecosystem functions and other benefits. Further, the use of habitat quality or value as the major determinant of project success has likely been over-emphasized and practitioners should work toward basing success criteria on the full suite of habitat, biogeochemical, and physical/hydrologic ecological functions delivered by beneficial use projects as well as associated positive societal outcomes. To promote this approach, a companion paper further explores this concept within a dredged sediment beneficial use context utilizing an established ecosystem functions, goods, and services framework.

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