REVISITING HISTORIC DREDGED MATERIAL HABITAT IMPROVEMENT SITES INFORMS THE FUTURE OF BENEFICIAL USE INITIATIVES

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ABSTRACT

The beneficial use (BU) of dredged materials improves environmental outcomes while maximizing navigation benefits and minimizing costs. As a result, numerous BU projects have been implemented since the 1970s and BU efforts continue to expand within the navigation dredging portfolio. Yet, few studies document mid- to long-term project benefits due to a combination of 1) short monitoring timeframes and 2) the paucity of BU sites that have reached maturity since most BU projects were recently constructed. In response we conducted a survey of six historic (>40 years old) BU locations designed to improve habitat, where initial post-construction data was collected. Conditions at natural reference locations were also documented for comparison. This approach allows for an analysis of the long-term success of BU initiatives and the development of BU trajectory curves. Study sites were geographically diverse (TX, FL, GA, CT, MI, OR) and incorporated data from coastal marshes, freshwater wetlands, and upland habitats. The current analysis reports on habitat diversity and vegetation communities and compares those results with historic data. Results indicate that the BU projects provide valuable habitat for a variety of species in addition to yielding a number of engineering (e.g., shoreline protection) and other (e.g., water quality) benefits. In general, BU locations evolved into the habitat types targeted during construction. However, the specific habitat assemblages at BU locations often diverged from reference conditions. Most BU sites exhibited more diverse habitat distributions than natural reference areas, largely due to construction activities and the establishment of elevation gradients absent from unaltered locations. Experimental plantings conducted post-construction apparently had limited influence on community composition after >40 years of succession, as environmental conditions (elevation, salinity) dictate long term vegetation community dynamics. However, plantings likely play a key role in maintaining the physical stability of recently constructed BU projects and decrease the potential for invasive species establishment. Our findings suggest that establishment of BU success criteria should not over-emphasize replicating reference conditions but should focus on achieving specific ecosystem functions (i.e., energy dissipation) and engineering outcomes (i.e., storm surge reduction). The analysis also highlights the need for additional research into long-term BU project trajectories, especially as new initiatives including Engineering With Nature® continue to expand. The abundance of completed BU projects provides opportunities to conduct chronosequence analysis to document project successes, predict conditions for milestone establishment, and inform the design of future projects to maximize environmental, navigation, and engineering benefits.

Keywords: Engineering With Nature®, Ecosystem functions, Engineering benefits, Restoration trajectory, Chronosequence analysis

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INTRODUCTION

Recent initiatives have focused on the capacity of natural processes to improve ecological endpoints while accomplishing engineering objectives and reducing project costs within a dredged materials management context (Yozzo et al. 2004). The concept of integrating ecosystem and dredged material management is encapsulated by the Engineering with Nature® (EWN) initiative, an intentional alignment of natural and engineering processes to deliver economic, environmental, and social benefits efficiently and sustainably through collaborative processes (Bridges et al., 2014). The beneficial use of dredged material is consistent with EWN.

The incorporation of dredged material beneficial use into navigation channel maintenance portfolios and long-term management plans has increased since the first studied were conducted in the 1960s and 1970s, and additional interest in identifying opportunities to expand beneficial use applications are increasing in the United States and abroad (Sheehan et al., 2012). For example, a recent analysis of shallow draft dredged material projects within the U.S. Army Corps of Engineers Baltimore District area of responsibility demonstrates the increase in beneficial use features over the past four decades (Berkowitz and Szimanski 2020) (Figure 1a). These projects ranged from beach nourishment and restoration efforts to the creation of oyster bays, islands, and wetlands, highlighting the diversity of beneficial use projects (Figure 1b).

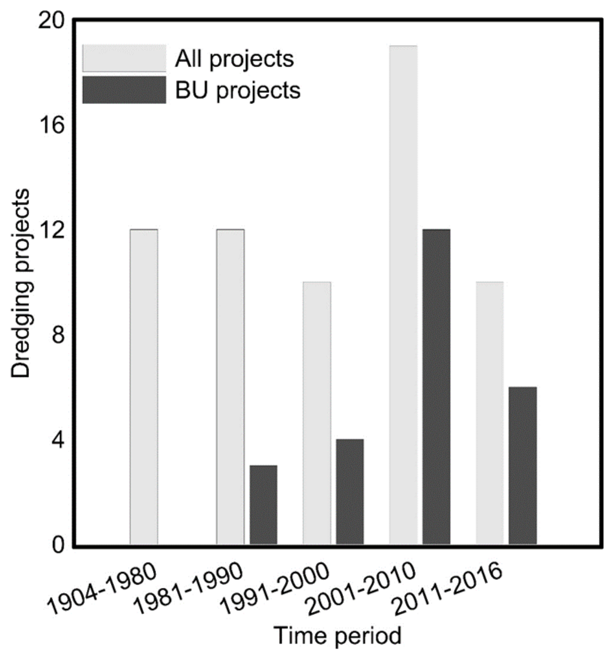

Figure 1a. Temporal distribution of shallow draft dredging projects and associated beneficial use (BU) activities executed by the U.S. Army Corps of Engineers Baltimore District. Note that the abundance and relative proportion of BU projects increased each decade since the 1980s, with BU incorporated into >60% of projects implemented after 2010 (Berkowitz and Szimanski 2020).

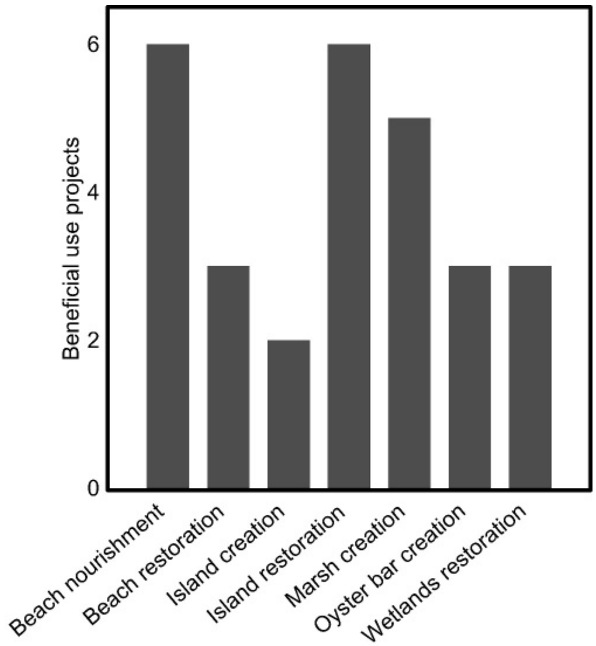

Figure 1b. Distribution of shallow draft dredging beneficial use (BU) project types executed in the U.S. Army Corps of Engineers Baltimore District 1980-2016 (Berkowitz and Szimanski 2020).

Not unexpectedly, the availability of data documenting the outcomes of beneficial use projects has increased as the number of beneficial projects being implemented has expanded. These studies now provide a rich body of literature informing the design, construction, and operation of a variety of beneficial use activities. In particular, the environmental benefits of these projects have been evaluated across multiple disciplines and geographic areas (Edwards and Proffitt 2003). For example, Faulkner and Poach (1996) assessed the functional capacity of created and natural wetlands and identified similarities and differences between natural and built environments; and Mallach and Leberg (1999) evaluated avian community use at natural islands and those created using dredged material composed of varying substrates identifying variables that effected faunal community composition and abundance. Importantly, Streever (2000) highlighted the finding that project designs that incorporate engineering elements that mimic natural processes display ecosystem characteristics similar to natural systems to a greater extent than landscape features created using traditional dredged material management techniques.

Despite the increasing number of beneficial use projects and the associated studies researching project outcomes, the long-term trajectory of beneficial use projects remains unclear. These uncertainties result from the limited period that dredged material management designed for ecosystem improvements have been implemented. In other words, most beneficial use projects are relatively ‘young’ landscape features compared with their unaltered counterparts which evolved over periods ranging from centuries to millennia (Coleman et al. 1998). This limitation precludes the collection and analysis of data from fully “mature” beneficial use study locations.

Additionally, few studies track the trajectory of habitat restoration/creation sites for extended periods, with most monitoring efforts occurring over short durations (often 2-5 years) which D'Avanzo (1989) and others recognize is not sufficient for documenting the long-term benefits and outcomes of restoration/creation projects. The paucity of information reflecting the mid- to long-term ecological conditions at historic beneficial use sites represents a significant knowledge gap, limiting our ability to account for project benefits over decadal (or longer) timescales and develop data driven trajectory curves used to develop ecological success criteria and project milestones.

The absence of long-term datasets also represents an ecological trajectory gap that persists between documenting conditions at recently constructed beneficial use projects and projecting those conditions across project lifespans (Figure 2). Without that information our capacity to develop accurate project lifecycle analysis, including long-term benefit-cost determinations remains constrained. In response, a research effort was initiated to evaluate conditions at six of the oldest dredged material beneficial use projects for which historic data is available in order to evaluate the long-term ecological trajectory of engineered systems and compare them with their natural counterparts.

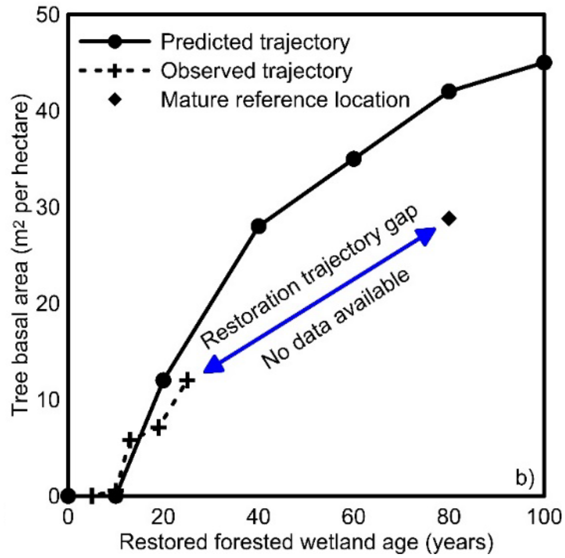

Figure 2. Example of a restoration trajectory curve evaluating tree growth following implementation of habitat restoration projects. This highlights the knowledge and ecological trajectory gaps between conditions documented at mature natural reference areas (◆), observations at established habitat improvement projects (✚), and estimated conditions under post construction scenarios (●). Adapted from Berkowitz (2019).

STUDY LOCATIONS AND APPROACH

During 2019, researchers conducted natural resource assessments at six historic dredged material beneficial use projects constructed between 1974 and 1977, where earlier studies were completed as described in Landin et al., (1989) and others. These project locations represent some of the earliest beneficial use sites with available post construction monitoring data in the United States. As a result, the projects sites provide a unique opportunity to investigate the mid- to long-term outcomes of early dredged material beneficial use initiatives. Additionally, the projects occurred across a range of geographic locations and target habitat types (e.g., marsh, upland meadow), allowing for the evaluation of outcomes across the nation and in a variety of ecological settings (Figure 3).

Figure 3. Location (●) of the six historic beneficial use projects evaluated.

The U.S. Army Corps of Engineers Dredged Material Research Program funded construction or the six project sites. A monitoring program was initiated under the U.S. Army Corps of Engineers Dredging Operation Technical Support (DOTS) Program to document the stability and successional changes of the projects, and relate the observed conditions at the project sites to natural, reference systems (Newling and Landin 1985). The monitoring program concluded in 1987. Notably, the projects focused on improving habitat at each location and the historic monitoring efforts did not consider engineering benefits or other factors that are now recognized within broader contexts such as the EWN initiative.

The following section provides a general overview of each beneficial use project and outlines the construction and initial monitoring results for each study location. Subsequent sections describe the results of the 2019 data collection effort and compare results to both 1) the early (1974-1987) study data and 2) conditions observed at reference systems. To the extent possible, researchers applied the same monitoring techniques utilized during the historical monitoring efforts to support these comparisons.

Accordingly, the 2019 assessment effort established triplicate vegetation sample points within representative locations of each plant community observed within the beneficial use sites and at corresponding reference locations (Figure 4). Meter square quadrats were used to estimate percent cover by species and 0.25 m2 quadrats were used to calculate stem densities at each vegetation sampling location. The results of three triplicate measurements were averaged for reporting purposes. In some cases, transects were established to stratify sampling across elevation gradients and associated plant community types (e.g., low marsh, high marsh, transitional zones, herbaceous upland, forested upland).

Plant communities were classified based on dominant and/or diagnostic species assemblages. Values for community composition and species abundance that were reported in historic monitoring studies were compared to current data to assess contemporary conditions and development and maintenance of target ecological outcomes (Allen et al. 1978; Landin et al. 1989; Newling & Landin 1985; Webb et al. 1978).

Additionally, data on avian species assemblages and soil properties were collected, but those results are not presented herein and will available following publication of a comprehensive technical report (Berkowitz et al., In Review) and journal paper. The following provides a brief description of each beneficial use project, focusing on the objectives of construction, target habitat types, and other supporting information.

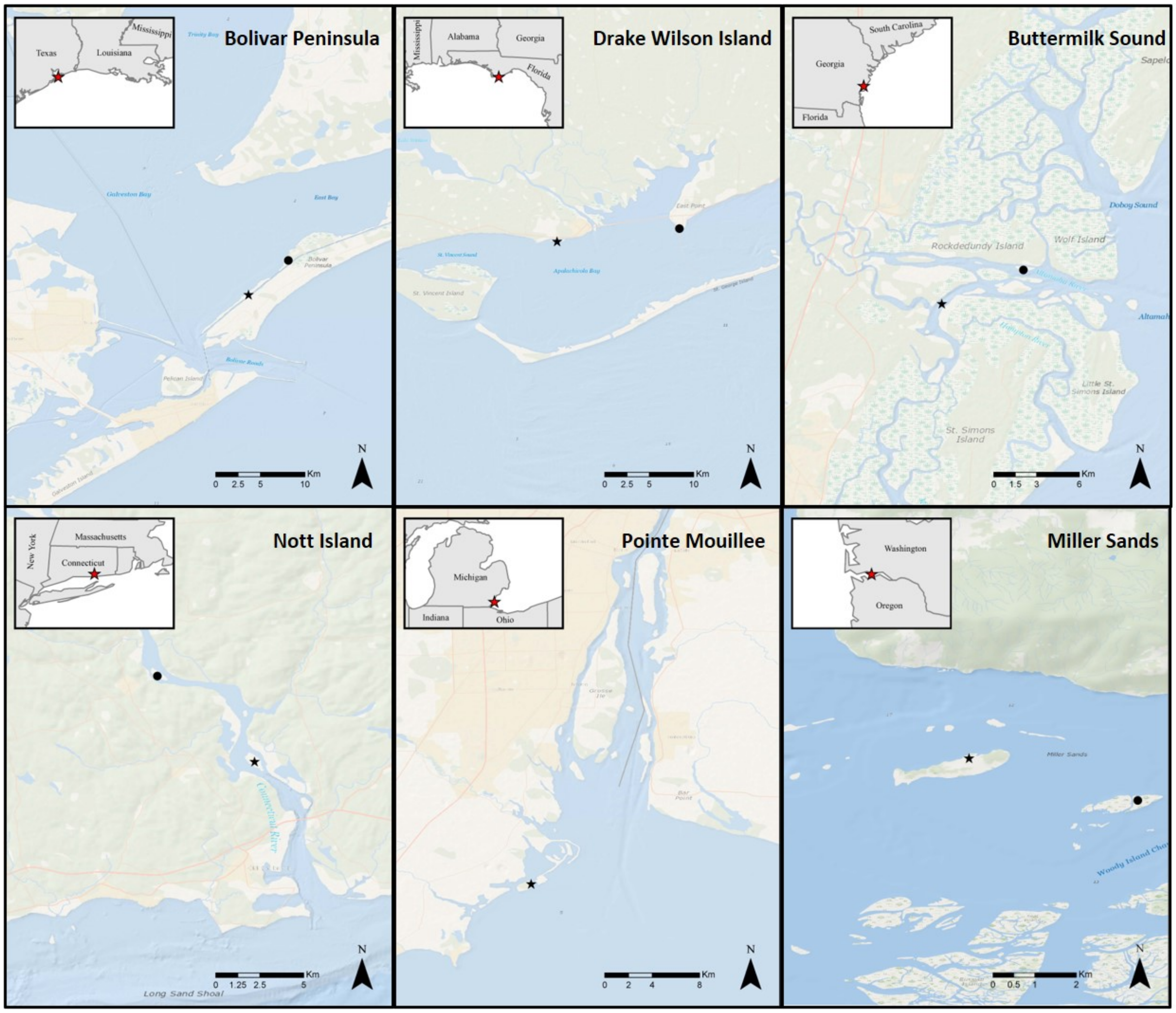

Figure 4. Beneficial use study locations (★) and reference sites (●) evaluated during the study.

Bolivar Peninsula, TX

The Bolivar Peninsula beneficial use project is located adjacent to the Gulf Intercoastal Waterway near the Houston Ship Channel. The location was selected because it exhibited representative conditions observed at many of the dredge material placement sites in coastal Texas and the Gulf of Mexico (Allen et al. 1978). In 1976, a 11.1 ha area of dredged materials previously deposited on the peninsula were contoured using construction equipment to create an elevation gradient capable of supporting the establishment of upland, high marsh and low marsh/intertidal habitats oriented perpendicular to Galveston Bay. A temporary sandbag dike was constructed to protect the dredged material placed into a lower intertidal marsh environment from the erosive forces of waves and encourage stabilization/consolidation of the dredged materials. Vegetation plantings were established in 1976 and 1977 in both wetland and upland areas using different fertilizer treatment and plantings. A reference marsh, Pepper Grove, was identified east that had similar wind and wave characteristics as 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. These early reports indicated that plant growth equaled or exceeded values at the Pepper Grove reference area; however, root biomass remained lower than observed in the unaltered natural marsh. General findings of the early monitoring efforts indicated that smooth cordgrass and saltmeadow cordgrass can be established on dredged materials, but that elevation gradients strongly influenced species survival and vigor and should be incorporated into project design and implementation.

This project adheres to the principles and objectives of EWN because it mimicked natural elevation gradients to establish a variety of habitats and target vegetation community types based upon observations made at natural, unaltered locations in the region. Additionally, the project avoided the inclusion of hardened engineering features (e.g., riprap) and, following initial construction, allowed for natural tidal processes and natural patterns of succession and landform change to drive the projects evolution.

Drake Wilson Island, FL

Drake Wilson Island was developed in 1976 using sandy dredged material derived from the adjacent Two-Mile Channel, a navigation route used to access the city of Apalachicola Florida, the Gulf Intercostal Waterway, Apalachicola Bay, and the Gulf of Mexico. The navigation channel is utilized by the local commercial fishery fleet, recreational boaters, and those transporting materials through northeast Florida waterways. In early 1976, the 5-ha project sought to develop an emergent marsh by placing hydraulically pumped dredged material into an intertidal environment. The location was selected because it typifies the northeast Gulf Coast intertidal islands in the region. Prior to dredged material placement, a temporary dike and weir was installed adjacent navigation channel to prevent erosion until consolidation occurred. This allowed intertidal exchange and protected the newly established marsh vegetation. During construction, fine-grained silty dredged material was pumped into the site, covering older course-grained sandy dredged material deposited during previous dredging operations. Planting was conducted and the site was fully vegetated by 1978. Later monitoring efforts reported that the site was heavily utilized by wildlife in 1986 (Landin et al. 1989). A reference marsh, Cat Point, was located east of the study site.

This project adheres to the principles and objectives of EWN because it utilized fine grained sediments that occur in the natural marshes within the region to cap the older sandy dredges materials, encouraged natural patterns of marsh inundation using the weir during the initial post construction phase, and allowed natural processes to degrade the weir and dike needed for initial stabilization ensuring tidal exchange would continue. Plantings utilized locally sourced materials selected based upon appropriate landscape positions and salinity/inundation tolerances. Additionally, the project avoided the inclusion of hardened engineering features and, following initial construction allowed natural processes (e.g., tides, species succession) to drive the evolution of the project area.

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 area is used by the local fishing community, those transporting goods along the intercostal waterway, and those accessing the barrier islands and open ocean from the nearby cities of Brunswick and Darien, GA. The beneficial use project site was selected because it was representative of a South Atlantic sandy dredged material disposal sites in the region that buried natural salt marshes. The objectives of the project were to: 1) convert the ~5m high dredged material sand mound to a 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 material. The area was graded to a 3.7% slope and planted with vegetation. A nearby reference marsh location, Hardhead Island, was selected to assess vegetation and site characteristics of a naturally evolved wetland ecosystem in close proximity to the project. Within five years of construction, the project is reported to be visually indistinguishable from unaltered marshes (Landin et al., 1989).

This project adheres to the principles and objectives of EWN because it re-established the environmental gradient of elevation, inundation, and salinity observed in unaltered areas in the region. Also, the project allowed for natural processes (e.g., tidal creek evolution and migration) to occur while avoiding the use of hardened engineering features.

Nott Island, CT

The Nott Island beneficial use site is located on the Connecticut River, one of the state's most vital waterways servicing recreational harbors and commercial waterfronts in Essex, Lyme, Hartford, Haddam, and other communities. The 3.2-ha project was developed in 1974. Nott island had been used a dredged material placement area during periodic channel unvegetated mound of sand, substantially raising the elevation of the island. The location was selected because it reflected conditions at many islands in the northeastern United States where navigation channel maintenance dredging deposited materials on top of natural landforms. The sandy dredge material deposits were low quality habitat and poor vegetation established on the sites due to nutrient limitations, course soil textures, and steep grades. The beneficial use project incorporated fine grained dredged materials into the sandy substrate. Temporary dikes were built to contain the fine-grained materials during dewatering and homogenization using construction equipment and farming implements (e.g., disking). Follow substate mixing, the site was treated with lime and fertilizer. Vegetation was planted to create a nesting and feeding meadow for mallards, Canada geese, and other species. In general, the grasses were successfully established, with approximately 80% of the planted area vegetated within the first growing season. Eustasia Island was selected as a reference monitoring site due to its similar geomorphology, substrate, and proximal location to Nott Island.

This project adheres to the principles and objectives of EWN because it incorporated finer grained sediments into the sandy dredged material deposits to mimic soil textures found in unaltered habitats in the region, encouraged the establishment of plant communities of high habitat value, and allowed natural patterns of plant species succession to occur following initial construction and planting efforts. Additionally, the project avoided the inclusion of hardened engineering features and attempted to diversify the variety of habitat types found within the project area.

Pointe Mouillee, MI

The Pointe Mouillee beneficial use project is located adjacent to the western shore of Lake Erie, Michigan. Historically, the area included a barrier beach, which protected an extensive marsh from wind and wave driven erosion. However, the barrier beach was destroyed in the 1960's by a series of high energy storm events coinciding with a period of high lake levels. Following degradation of the barrier beach extensive erosion decreased the spatial extent of the marsh. Concurrently, sediments from the Huron River that historically supported and nourished the Pointe Mouillee marshes and barrier beach were reduced by the construction of dams and reservoirs that prevented sediment transport and deposition. This resulted in the degradation and inundation of >1618 ha of marshes and an expansion of open water. In response, 148-ha were diked in 1963 to protect and maintain the remaining marsh habitats. In 1967, a Confined Disposal Facility (CDF) was constructed at Pointe Mouillee to hold dredged materials removed from the Lake Erie Ship Channel and protect provide additional protection for the degraded adjacent marsh. The CDF was strategically situated and designed to match the configuration of the historic barrier island to support revitalization of the degraded marsh. Dikes facing the open expanse of Lake Erie were armored with riprap to protect the feature from erosion, and a system of culverts and water control structures were used to manage water levels within the project area.

The objectives of the project were to: 1) protect and stabilize the wetlands and shoreline and an adjacent wildlife management area; 2) reestablish the degraded marsh through sedimentation and plant colonization; 3) establish a multiuse site on both the CDF and the wildlife management area that includes a visitors' center and supports multiple recreational activities; and 4) provide opportunities for the deposition of dredged material from western Lake Erie harbors and channels as part of re-occurring maintenance dredging operations. Vegetation communities inside the CDF included emergent cattail and bulrush wetlands, and a high marsh component dominated by common reed. Vegetation data indicated that plant colonization took place within three growing seasons after construction (Landin et al. 1989). No reference monitoring location was selected near the Pointe Mouillee beneficial use site.

The Pointe Mouillee project adheres to the principles and objectives of EWN because it protected the existing marshes to the west, while providing habitat and recreational opportunities and maintaining the capacity to manage dredged materials and navigation channels within the western Lake Erie basin. Unlike the other projects examined in the study, the Pointe Mouillee project did utilize hard infrastructure including protected dikes to stabilize project features and prevent wind and wave erosion from occurring. However, the development of infrastructure was needed to replace the ecological functions (i.e, wave energy attenuation) and engineering benefits (i.e., shoreline stabilization; storm surge reduction) provided by the eroded barrier beach that previously protected the surrounding marshes.

Miller Sands, OR

The Miller Sands beneficial use project is located in close proximity to the Columbia River navigation channel near Astoria, OR. The site is a large, horseshoe-shaped dredged material island within the freshwater intertidal reach of the river. The original island was constructed with dredged materials in 1932 and continued to receive additional dredged materials during maintenance operations at approximate 4-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 on the sand spit designed to protect the adjacent wetlands and other features from wind and wave driven erosion. In 1974, the upland portion was disked using farming implements and heavy machinery to prepare a seed bed, followed by planting; portions of the islands were graded to an intertidal elevation and planted to support development of the wetland habitats; and the sand spit was planted with beachgrass interspersed with sand fencing, rapidly inducing the formation of dunes. A nearby marsh, Snag Island, was select as reference location for comparison with the wetland portions of the beneficial use project.

This project adheres to the principles and objectives of EWN because it was designed to provide a variety of habitat types (uplands, wetland, dune) common in the region based on the 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 naturally contour and shape the island after construction, while providing for the management of dredged materials in the Columbia River navigation channel. Plantings materials were selected based upon appropriate landscape positions and inundation tolerances to establish a variety of habitats and target vegetation community types using observations made at natural, unaltered locations in the region. Additionally, the project avoided the inclusion of hardened engineering features and, following initial construction, let natural processes drive the ecological evolution of the project area.

RESULTS AND DISCUSSION

The beneficial use projects successfully developed the target habitat types described in the project objectives and historic monitoring reports, and 13 of the 15 target habitats continue to persist more than four decades after project construction (Table 1; Figures 5a and 5b). The vegetation community data collected during the 2019 survey demonstrates that the beneficial use projects continue to provide a variety of habitat, physical/hydrology, and biogeochemical cycling functions important to ecological processes that can be linked with associated engineering benefits.

Table 1. Summary of target vegetation community types, success of sustained development over >40-years, challenges, and management opportunities to improve conditions at the study locations.

Location	Habitat type	Present after >40 years	Sustainable without intervention	Challenges	Management opportunities
Bolivar Peninsula	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	Species planted outside of native range, poor survival	Selective species control
Drake Wilson Island, FL	Low marsh	Yes	Yes	Land surface decrease	Sediment placement
	High marsh	Yes	Yes	Land surface decrease	Sediment placement
	Woody upland	Yes	Yes	None	None
Buttermilk Sound, GA	Low marsh	Yes	Yes	None	None
	High marsh	Yes	Yes	None	None
	Un-vegetated upland	Yes	No	Woody species	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, ongoing management	Selective species control
Miller Sands, OR	Upland meadow	Yes	No	Poor soil quality, woody vegetation	Selective species control, soil amendments
	Tidal marsh	Yes	Yes	Erosion, Invasive species	Selective species control
	Dune	Yes	No	Lack of sediment	Sediment placement

Notably, the spatial distribution of habitat components and/or the suite of vegetation 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 vegetation 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 (Zedler 2000).

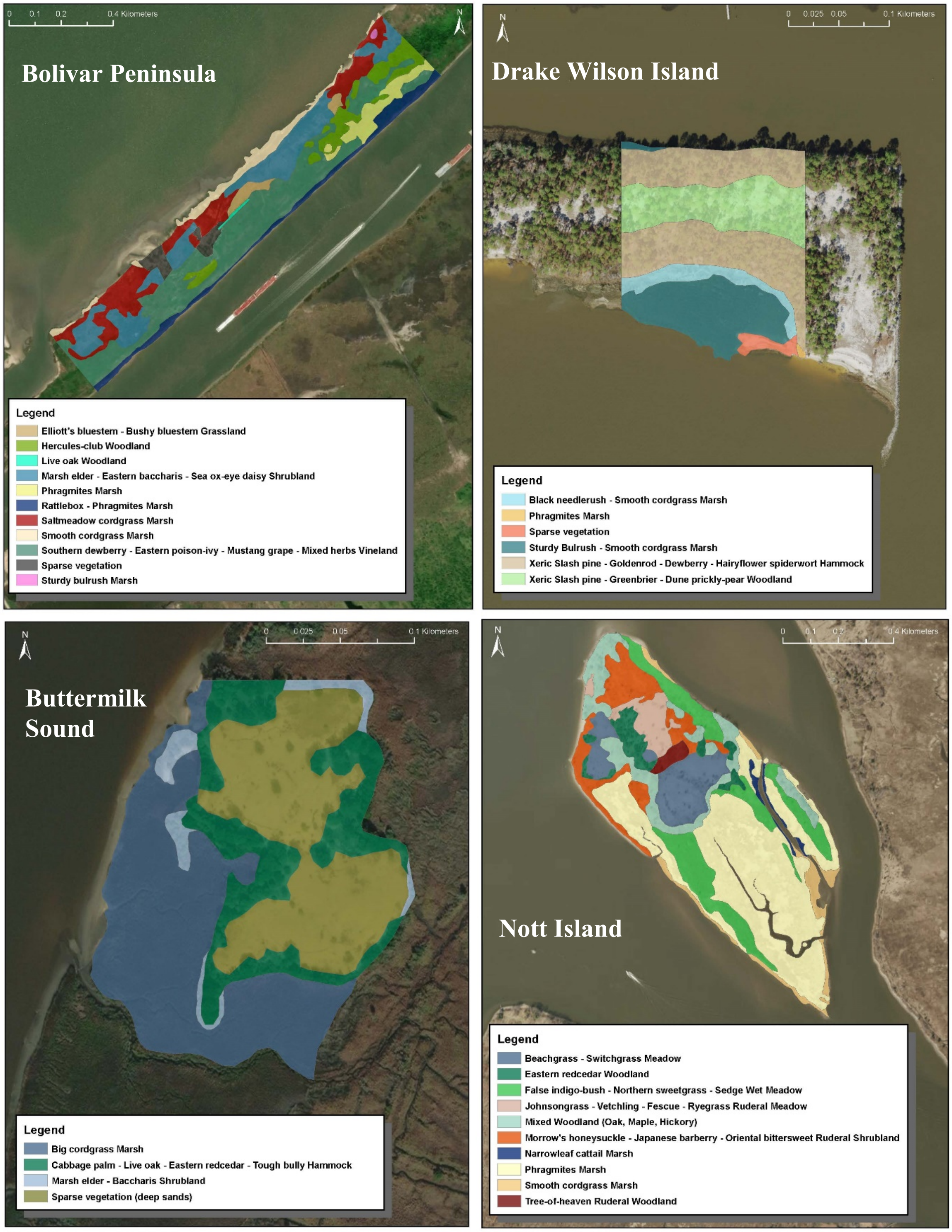

Figure 5a. Vegetation community composition at beneficial use projects after >40 years.

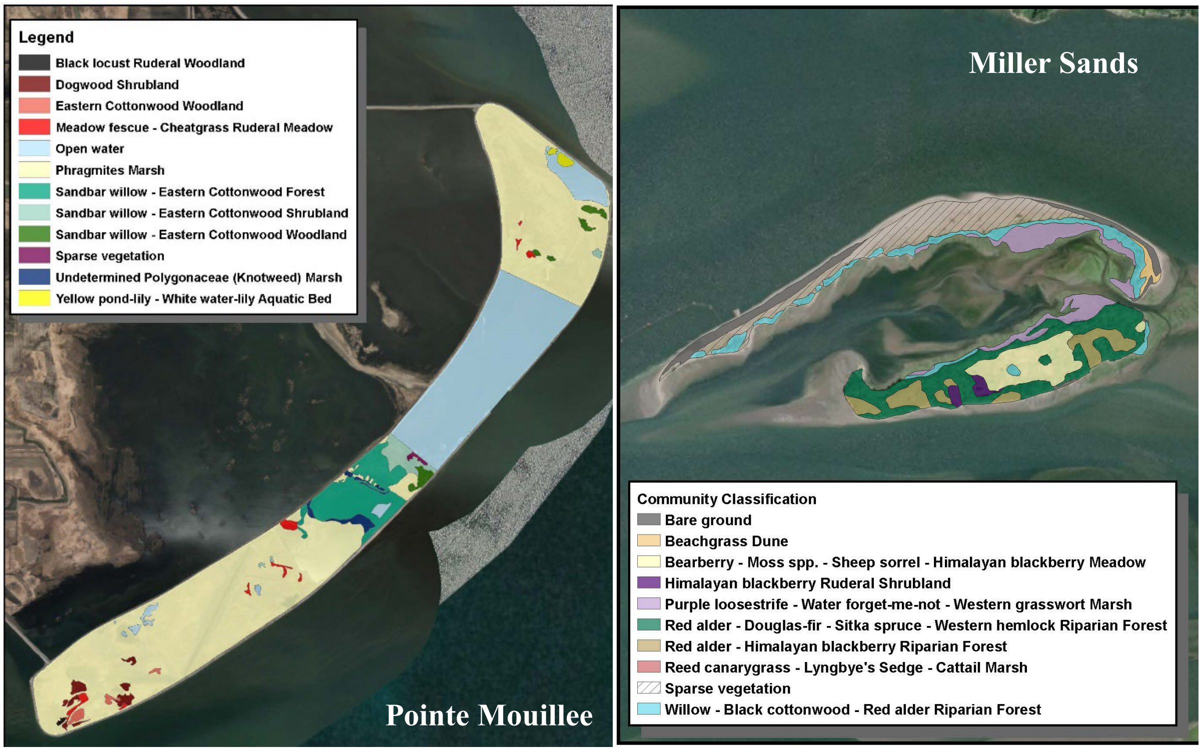

Figure 5b. Vegetation community composition at beneficial use projects after >40 years.

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, 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 non-native species pose a significant challenge to achieving ecological goals across many of the study sites, as well as a number of the reference locations evaluated. In general, the number of undesirable species and their abundance has increased during the post construction period in both beneficial use and reference monitoring areas.

The available data suggests that initial planting efforts had limited effects on the persistence and distribution of plant species after 40 years of ecological succession, and some studies have inferred that in areas with rapid natural recruitment post restoration plantings may not be necessary (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 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 undergo alteration over decadal timescales. Initiating vegetative growth after disturbance has been shown to stabilize soils and sediments, accelerate dewatering, provide habitat, retain sediment and build elevation, improve soil health, and promote ecological functions and engineering benefits (Bailey et al. 2019). Additionally, establishing plant communities can influence the trajectory of restoration areas, even if the initial species introduced fail to persist, migrates in response to environmental conditions, or becomes integrated into a more diverse plant assemblage (Simonstad et al. 2006). The establishment of desirable species has also been shown to preclude the invasion of non-desirable species and may provide other ecosystem functions and engineering benefits as site maturation and succession takes place.

The major trends and findings of this study that can help inform the development of future beneficial use projects are highlighted below.

1) The habitat complexity of study locations generally increased over time, as observed at Bolivar Peninsula, TX which exhibited six distinct vegetation communities during the 1988 assessment, increasing to 10 vegetation communities in 2019 (Table 2). 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 over time. Baldwin (2004) provides a model outlining patterns of plant distribution following restoration, planting, colonization, and expansion of clonal perennials in restored/created marsh habitats. As outlined in the model, observed increases in species richness are not expected to continue indefinitely as the project sites reach equilibrium, however species composition will continue to respond to disturbances (e.g., floods, fire) and changes in ecological conditions (e.g., climate; invasive species introduction) in the future. These changes reflect natural and anthropogenic drivers occurring in both beneficial use locations and reference communities.

Table 2. Summary of vegetation community characteristics. NA = no data available.

	Vegetation community assemblages (count)		Dominant species richness in target community types (count)			
Location	Beneficial use (BU) site	Reference location	Habitat type	BU (2019)	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	3	4	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

2) 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 reference area which exhibited barrier beach features absent at the Drake Wilson Island study location (Table 2). The 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 (e.g., microtopography) as a limitation on many restoration projects (Bruland and Richardson 2005). However, within the locations examined, one of the driving factors behind the restoration design was to create appropriate ecological gradients that would support a variety of habitats. This included the intentional establishment of upland, transitional, high marsh, and low marsh target habitats with ecologically based landforms and hydropatterns.

3) The number of species in target communities has generally remained stable or increased over time and display higher species richness than the reference locations examined. This finding suggest that the beneficial use projects have reached a moderate level of maturity yet 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 projects have trended towards conditions observed in reference areas, differences continue to persist after more than four decades of plant succession.

4) Both beneficial use locations and reference areas appear to be responding to environmental conditions in similar ways despite the observed differences in species composition and structural complexity. More invasive species were observed at the study locations and reference areas during 2019 than during previous investigations and those species appear to be increasing in abundance. This trend has been reported in other areas and at larger spatial scales, where anthropogenic landscape alterations coupled with natural patterns of disturbance and plant dispersal are leading to increased alien invasions (Richardson et al 2007). Additionally, 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 6). 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.

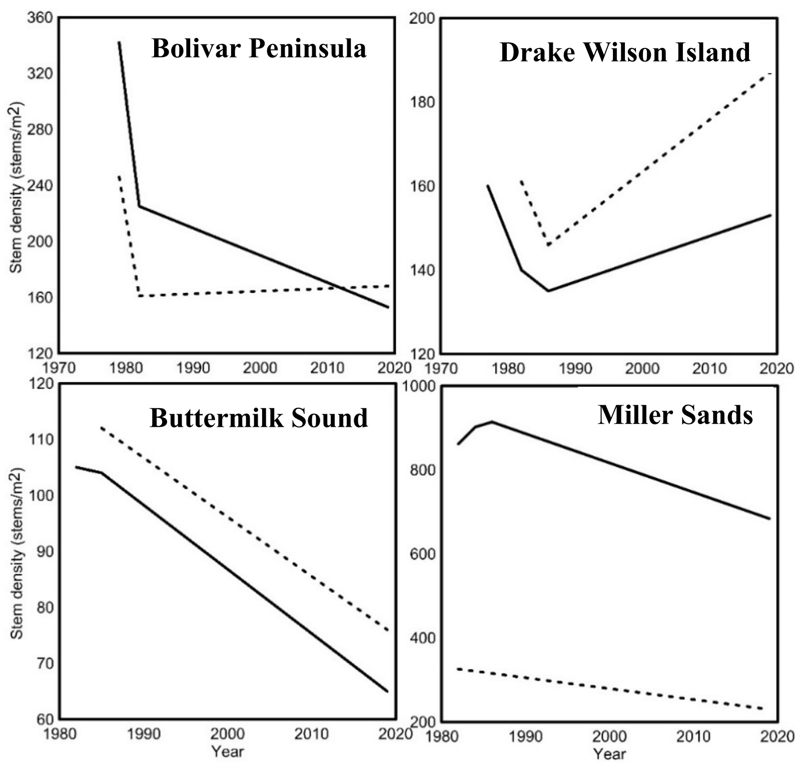

Figure 6. Comparison of stem density data from beneficial use locations (solid lines) and reference areas (dashed lines) over time. Note that while the magnitude of stem densities varies, the constructed and reference locations display similar patterns and responses to environmental conditions over time.

In summary, these findings suggest that the vegetation communities established at the beneficial use sites undoubtedly improved habitat. The project areas generally reflect the conditions at reference locations and have become more similar to reference conditions with age, but do not replicate the conditions observed in un-engineered systems. The study locations are effectively providing habitat for a number of species and represent stable features that will persist into the future, yielding a variety of ecological functions and engineering benefits. Notably, these study locations have persisted over more than 4 decades without the need for intervention, highlighting the sustainability of beneficial use projects that incorporate ecological drivers (i.e., hydroperiod, salinity tolerance, and topography) into project design and execution. Results also indicate that additional 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 sediment deposition) may improve the sustainability of some landscape features including low marshes and coastal fringe wetlands.

RECOMMENDATIONS AND CONCLUSIONS

Our findings indicate that beneficial use projects improve habitat, while providing ecological functions and engineering benefits, for multiple decades when designs consider ecosystem factors such as topography and hydrology. However, these projects highlight the fact that environmental factors, not initial planting activities, determine long-term vegetation community composition; and that while the projects trended toward reference location conditions over time, they continue to maintain distinct differences in both habitat type and species composition. The beneficial use projects are more structurally complex than reference areas due to increased topographic heterogeneity and other factors, resulting in additional habitat diversity and a wider range of ecological functions and engineering benefits. This suggests that mimicking reference conditions should not be over-emphasized when evaluating project success and establishing monitoring milestones. Instead practitioners should focus on maximizing the ecological benefits and engineering functions that can be achieved through beneficial use activities.

Management opportunities exist to improve a subset of the beneficial use projects examined projects with periodic interventions, including additional sediment placement and selective species control. Additionally, the historic beneficial use projects examined herein can be placed within the context of the Engineering With Nature® initiative, providing a mechanism to conduct chronosequence analysis through incorporation of newer projects to support life-cycle analysis to promote further integration of beneficial use projects into the navigation management portfolio. Ongoing research will place these results in a framework to better evaluate ecological functions and associated engineering benefits resulting from beneficial use project implementation.

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DATA AVAILABILITY

Additional data supporting the results and conclusions presented herein will be available in a forthcoming technical report and may be obtained from the corresponding author by request.

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