DOES GRAIN SIZE MATTER? - A SURVEY OF NATURAL AND RESTORED MARSH SOIL CHARACTERISTICS

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ABSTRACT

Coastal marshes are a natural defense that develop on a variety of geomorphic landforms and occur across a wide range of tidal regimes. Marshes evolve over time in response to changing sea level, sediment supply, vegetation community succession, anthropogenic perturbations, and other factors. These ecosystems provide an important natural defense for coastal communities because marshes reduce wave energy which lowers flood risk and increases resilience. However, many marshes display degradation associated with erosion, decreased sediment availability, and storm damage. In response, coastal resource managers seek to restore and expand marshes to improve environmental outcomes while delivering other benefits to coastal communities. In particular, the beneficial use (BU) of dredged sediments provides a source of materials for marsh creation and restoration, while supporting the maintenance of economically essential navigation channels. The U.S. Army Corps of Engineers (USACE) recently introduced an initiative to increase dredged sediment BU from the current rate of 30-40% of the total dredged volume to >70% by 2030, further promoting marsh creation and restoration. Using dredged sediment that would otherwise be removed from the coastal zone protects critical infrastructure, military installations, and other assets from natural threats (e.g., storm surge and flooding). Yet questions persist regarding what types of BU sediments are appropriate for marsh creation and restoration. In response, we review marsh soil characteristics based on a survey of existing literature. While this review is not exhaustive, our findings show no statistically significant difference between BU and natural marsh soil grain sizes, organic matter, and bulk density, and a large range of values across all marshes. These results promote the application of both fine and coarse textured dredged sediment to create and restore marshes. Our findings also suggest the need to match dredged sediments with naturally occurring marsh soils be deemphasized to further expand beneficial use projects and provide critical support for coastal communities.

INTRODUCTION

Coastal wetland creation and restoration projects protect communities from natural threats, mitigate pollution, increase carbon storage, enhance habitat, and provide other ecosystem functions, goods, and services that benefit society (Shepard et al. 2011; Van Coppenolle and Temmerman 2019). The beneficial use (BU) of dredged sediment can rehabilitate degraded marshes, build elevation capital to improve conditions for plant growth, combat sea-level rise, and provide habitat for species that inhabit the coastal zone (Yozzo et al. 2004; Staver et al. 2024). Recent efforts to increase the number and scale of BU projects (including in marshes) focus on delivering sustainable outcomes by integrating economic, social, and environmental objectives via the use of natural and nature-based features, including the Engineering With Nature® and Working With Nature initiatives (Berkowitz and Hurst 2022; Bridges et al. 2018; Bridges et al. 2021; Runion et al. 2021).

Improving habitat is a common driver of marsh restoration and creation efforts. Plant community successional stage and elevation within the tidal prism represent two factors reported to affect the delivery of marsh habitat functions (e.g., maintenance of avian and nekton species assemblages). Available research suggests that BU marshes can provide more biodiverse habitat for a wide variety of both plant and animal species when compared to nearby natural marshes due to exaggerated elevation gradients within the tidal prism that results in more heterogeneous habitat types (Edwards and Proffitt 2003; Faulkner and Poach 1996). Further, older BU marshes more closely resemble natural marshes than newly restored or created areas in terms of habitat structures and functions but remain on unique habitat functional trajectories several decades after project implementation (Berkowitz, Bean, et al. 2022).

BU marshes can also restore and build elevation capital where natural marshes are losing relative elevation due to degradation or sea level rise and create new marshes in open water areas. These activities improve the delivery of the full suite of marsh ecosystem

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functions, delivering an array of hydrologic and biogeochemical cycling functions in addition to habitat maintenance (Berkowitz, Bean, et al. 2022; Berkowitz, Hurst, et al. 2022). Natural marshes build elevation through overwash events and sediment capture, which can lead to sandy soil horizons on seaward marshes and the dominance of fine textured silts and clays in many back-barrier marshes (Callaway et al. 1997; De Groot et al. 2011; Lenz et al. 2023). The restoration or creation of BU marshes mimics these natural sediment delivery processes by depositing mineral sediments onto the marsh soil surface, sediment particle size class sorting, and the establishment of plant communities that accrete organic matter and capture additional suspended sediments. Previous studies demonstrate that BU marshes can yield higher rates of accretion and/or lower rates of erosion than natural marshes, however these processes are nuanced in both BU marshes and their natural counterparts (Davis et al. 2022; DeLaune et al. 1990; Graham and Mendelssohn 2013; Poppe and Rybczyk 2021; Widdows et al. 2006). Davis et al. (2022) suggested that higher sand contents observed in many BU marsh soils relative to natural marshes promotes accretion and decreases erosion, but elevation gains and erosion decreases have also been associated with fine texture soils and combinations of fine and sandy substrates (DeLaune et al. 1990; Graham and Mendelssohn 2013; Poppe and Rybczyk 2021; Widdows et al. 2006). Well documented linkages exist between plant productivity in BU marshes constructed using fine sediment contents, contributing to BU marsh accretion (DeLaune et al. 1990; Graham and Mendelssohn 2013; Poppe and Rybczyk 2021), and between soil biotic productivity and observed decreases in marsh erosion (Widdows et al. 2006).

Interest in providing additional carbon storage using BU marshes continues to increase, further promoting wetland restoration and creation efforts. Natural marshes generally contain more carbon than BU sites, because many marshes have been vegetated and accumulating carbon for thousands of years. However, carbon storage rates can be higher in BU marshes due to their rapid accretion rates and the rapid development of marsh vegetation in previously unvegetated areas (Poppe and Rybczyk 2021). Additionally, BU marsh creation provides opportunities to build carbon stocks in open water areas where primary productivity and organic matter accumulation rates are lower than in wetlands (Maglio et al. 2020).

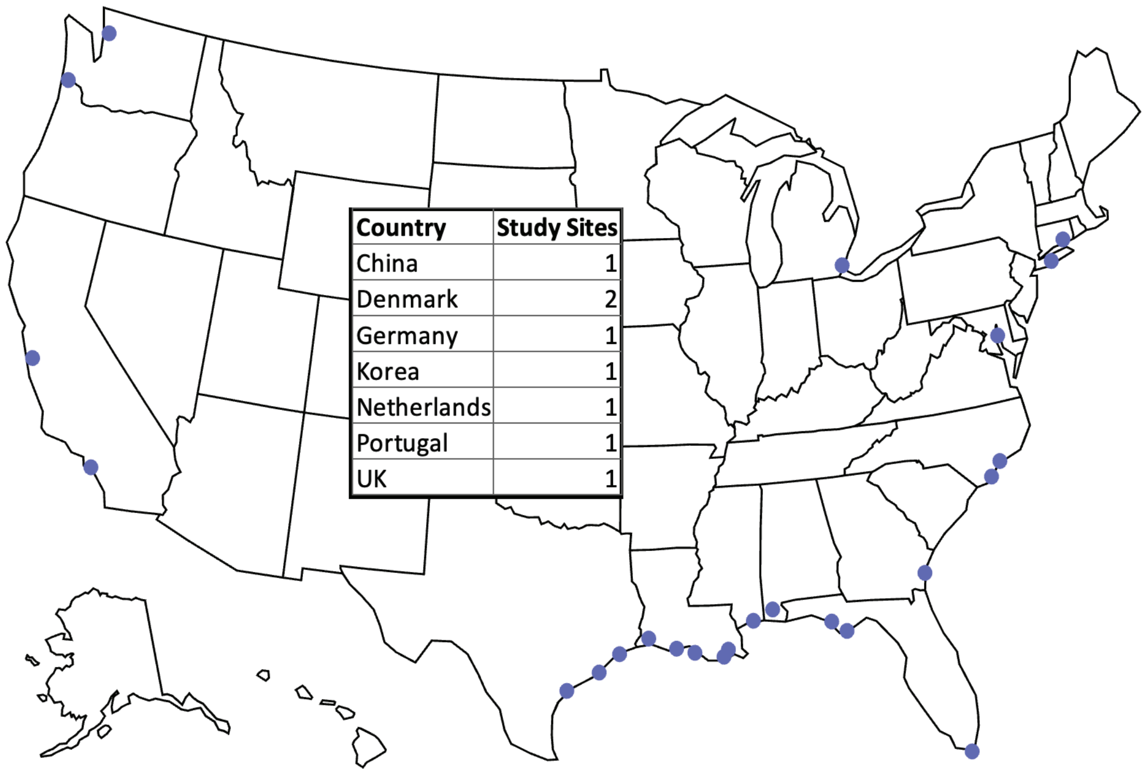
Despite the availability of case-studies investigating marsh creation and restoration utilizing BU, design questions persist regarding the deliberate application of dredged sediments into marshes. In particular, the use of different sediment grain sizes across coastal landforms has been debated, limiting practitioner capacity to successfully execute BU projects (Maglio et al. 2020). It can be difficult to accurately assess dredged sediment grain size prior to project implementation, and guidelines generally recommend matching dredged sediment characteristics with target placement locations to optimize positive outcomes (Piercy et al. 2023). Since previously published studies provide many examples of successful marsh creation and restoration projects that utilized sediments with characteristics that were substantially different from placement locations or nearby natural reference areas, existing literature was surveyed to investigate commonly reported marsh sediment characteristics in natural marshes and in marshes created or restored using dredged sediment BU.

LITERATURE SURVEY

The following presents a targeted literature survey of sediment characteristics in BU and natural marshes to evaluate the observed range of particle sizes, soil organic matter, and bulk density across geographically and ecologically diverse marshes. The survey was based on a Google Scholar keyword search that included the phrases "sediment grain size marsh restoration," "marsh sediment partitioning," "created and natural marshes," "marsh sediment grain size," "marsh particle sorting," and "case-studies beneficial use dredged sediment." These keywords yielded a dataset of 27 peer-reviewed journal papers, with 35 case studies and 32 study sites reporting sediment characteristics for BU and/or natural marshes. All particle size data presented herein are reported as the distribution of sand (particle sizes ≥50 um) and fine substrates (all grain sizes <50 um). When particle size, bulk density, or soil organic matter data was not directly reported in tables or text, data was derived from figures or underwent unit conversions as needed.

FINDINGS

The data were derived from marshes predominantly in the United States, but also included international case-studies in Denmark, Germany, Portugal, the United Kingdom, the Netherlands, Korea, and China



Country	Study Sites
China	1
Denmark	2
Germany	1
Korea	1
Netherlands	1
Portugal	1
UK	1

Figure 1. Study locations in the survey dataset included a wide variety of marshes from different regions. This figure focuses on the United States study sites to demonstrate the geographic distribution along the nation's coastlines and includes the other countries and study sites in the central table.

(Figure 1). The dataset includes a wide variety of tidal regimes, soil parent materials, geomorphic landscape positions, dissolved sediment concentrations, and other marsh physiological features.

As expected, results indicate marshes typically contain more fine textured soils (i.e., silt and clay) than sand in both natural and BU marshes (median fine sediment content = 70%; range = 0.3%-99.7%, Figure 2a) (Stumpf 1983). This finding aligns with the capacity of coastal wetlands to trap fine sediments present within the water column during tidal inundation when: coarse particles are less likely to be mobilized, the deposition of flocculated fine sediments occurs on the marsh surface, and highly transportable individual fine soil particles moves across the marsh surface (Christiansen et al. 2000). However, the extent of fine textured soils varies, with the data exhibiting a large fine textured soil content inner-quartile range of 30% to 85% (Figure 2a). The values are generally within the broad range of particle sizes reported in estuarine environments, where mean particle diameters often occur between 4 um and 250 um (Mudd et al. 2010). The BU marshes in this review tended to contain a higher proportion of coarse soils than natural marshes with a fine textured soil inner-quartile range of 15% to 82%, but both BU and natural marshes most frequently exhibited median fine sediment contents near 85%. Additionally, some natural marshes were dominated by sandy soils, with as few as 20% fine sediments (Figure 2b). Bradley and Morris (1990) found similar results with marsh sand contents as high as 92% in South Carolina. Additionally, a Kruskal-Wallis non-parametric test of the fine grain sizes between natural and BU marshes yielded no statistical significance, with a p-value of 0.38. The survey data suggest that marshes form and persist on a wide range of soil textures under natural conditions, and that marsh creation and restoration can be accomplished using a wide variety of sediment particle sizes.

Marsh soil organic matter (OM) contents displayed wide variability, with a median value of 15%, and a range that extended from near zero to over 60% (Figure 2c). Wang et al. (2017) reported a similar range of OM contents in a survey of >330 soils collected from multiple marsh types in Louisiana with the lowest OM contents <10%, and some exceeding 60%, although their study did not discuss whether marshes were natural or BU. The OM contents for both natural and restored BU marshes evaluated in our survey displayed median values close to 15% (Figure 2d). However, higher OM contents were observed in some natural marshes (interquartile maximum = 30%; maximum value = 60%) than in BU marshes (interquartile

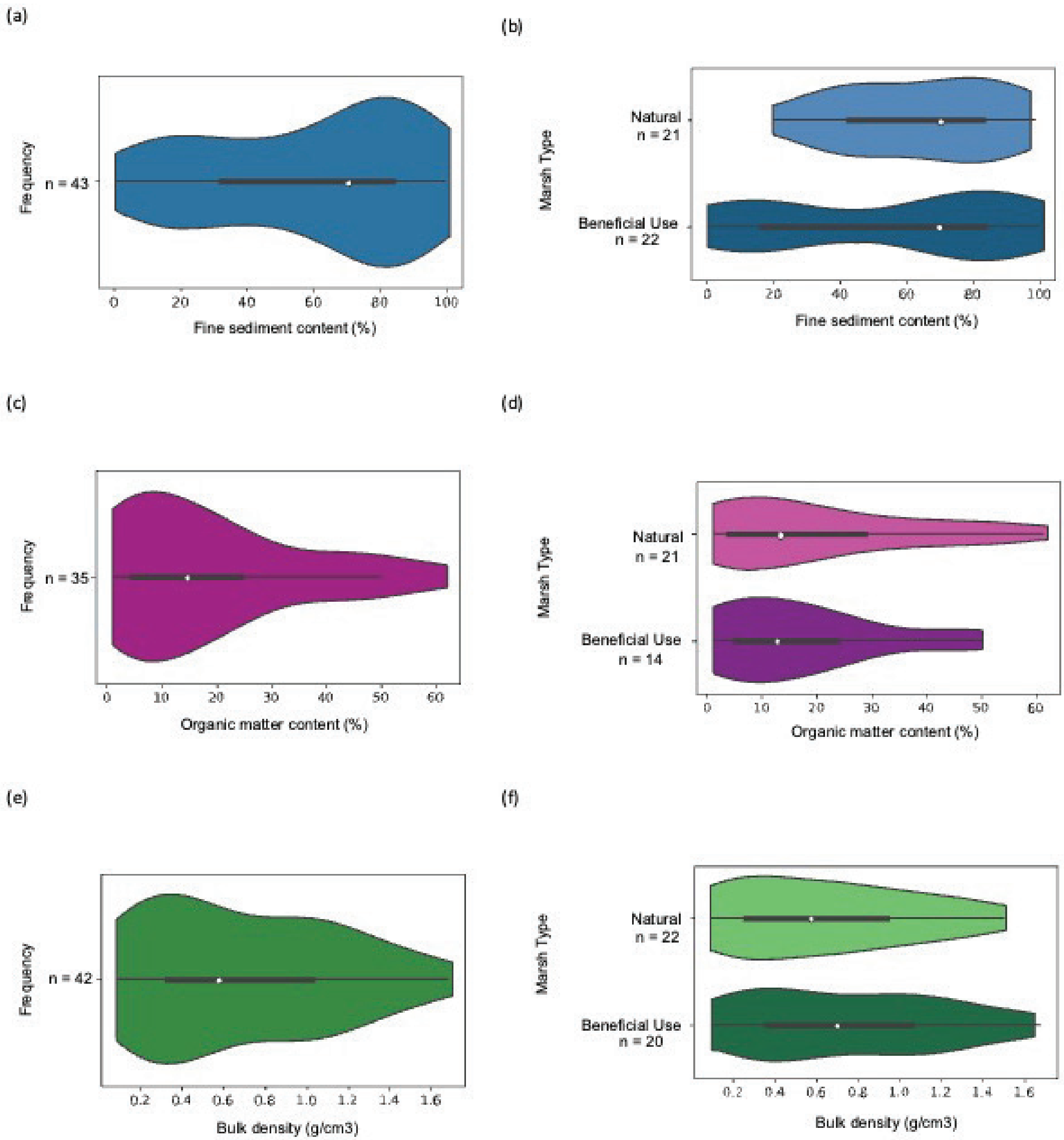


Figure 2. Soil characteristics observed in the survey data set, pooled (left panels) and separated into BU marshes and natural marsh groups (right panels). The thickness of the violin plots indicates the frequency of occurrence and n values report the sample size for each parameter. The white circle identifies the median value, and the thick and thin grey bars represent the interquartile and 1.5x interquartile ranges, respectively.

maximum = 23%; maximum value = 50%), although not statistically significant based on a Kruskal-Wallis non-parametric test p-value of 0.85. Higher soil organic matter contents in natural marshes relative to created and restored marshes is well documented in the literature, with many BU marshes continuing to display lower carbon contents than natural systems several decades after construction (Abbott et al. 2019; Berkowitz, Beane, et al. 2022). The lower soil OM content observed in managed systems is not surprising, as many natural marshes have accumulated soil OM over hundreds or thousands of years (e.g., ~4000 years on the United States eastern coast; Braswell et al. 2020). In contrast, the oldest BU created and restored marshes were constructed in the 1970s and most BU projects have been implemented after 1990 (Landin et al. 1989). Interestingly, in an evaluation of BU marshes created within the last 32 years in Louisiana, Abbott et al. (2019) demonstrated that some constructed marshes display faster soil carbon accumulation rates that natural marshes, despite lower overall carbon content. This finding emphasizes the complex relationship between marsh age and carbon accumulation, which results from the interplay of elevation, tidal regime, primary productivity, decomposition, and other factors that determine long term soil OM contents. Notably, Berkowitz and others have reported the delivery of many wetland functions by BU marshes, despite the persistence of lower soil OM relative to natural marshes.

Soil bulk density represents the amount of pore space within the soil matrix, provides a proxy to measure soil compaction, and influences water infiltration, rooting, and other factors related to organic matter production and decomposition. In marshes, high bulk densities (e.g., >1.8 g/cm^3) can restrict root penetration and hydraulic conductivity, and very low bulk densities (<0.20 g/cm^3) can lead to marsh platform collapse and precludes the establishment or productivity of common marsh plants due to poor structural stability (DeLaune et al. 1979). Bulk densities are related to particle size distributions because fine sediments have much higher internal pore space (as micropores) imparting lower bulk densities than macropore dominated sands. While few studies in the literature survey reported both particle size and bulk density, the inverse relationship between the presence of fine particles and bulk densities corroborates the general trends that more fine texture soil particles and fewer sands were present in the marsh soils evaluated (Figure 2e). The large inner-quartile ranges of 0.25 to 0.95 g/cm^3, with a median of 0.6 g/cm^3, in natural marshes and 0.3 to 1.05 g/cm^3, with a median of 0.7 g/cm^3, in BU marshes further indicates that marshes naturally develop on a variety of substrates and suggests a wide range of sediment particle sizes can be used during construction and restoration activities (Figure 2f). A one-way ANOVA test was performed as well, with a p-value of 0.35, demonstrating the similarity between bulk densities for natural and BU marshes. Also, bulk densities in constructed and restored marshes tend to decrease over time as the result of 1) organic matter accumulation and 2) rooting and bioturbation improve soil structure while increasing soil porosity. For example, Craft et al. (2002) reported a bulk density decline of >10% ten years after a marsh creation project was constructed in North Carolina.

A study spanning the Unites States highlighted soil property differences between BU and natural marshes (Berkowitz, Beane, et al. 2022; Berkowitz, Hurst, et al. 2022). The BU marsh soils were generally sandier than adjacent natural marshes, displayed higher bulk density, and contained less organic matter as indicated by the darker soil colors observed in natural marshes, even >40 years after construction (Figure 3). Despite the persistent differences in soil characteristics, the BU marshes provided similar ecosystem functions as their natural counterparts but remained on unique ecological trajectories despite becoming more similar to their natural counterparts over time (Berkowitz, Beane, et al. 2022; Berkowitz, Hurst, et al. 2022). Importantly, the

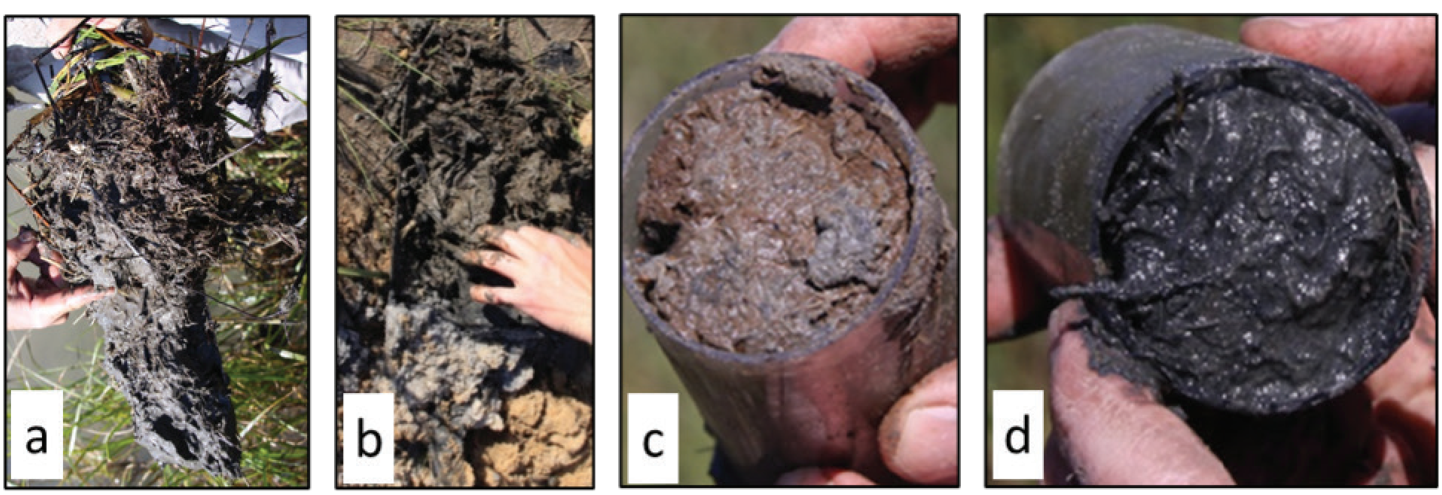


Figure 3. Soil profiles from Florida BU marshes display increases in soil organic matter over decadal timescales, denoted by dark surface layers in both (a) fine and (b) sandy sediments. Soil cores from a Texas BU marsh (c) exhibits less organic matter and higher bulk density than an adjacent natural marsh (d). The BU marshes were all constructed in 1976 (adapted from Berkowitz, Beane, et al. 2022).

completed studies and the data presented in this survey of available literature indicate that marshes naturally form, and can be successfully constructed and restored, using a wide variety of sediment types to achieve both environmental and societal objectives (e.g., improve habitat while reducing flood risk).

CONCLUSIONS

The restoration and construction of marshes using dredged sediments provides an important asset to help defend our coasts from natural threats, improve marsh longevity, and provide habitats using sediment that would otherwise be discharged off-shore. There are certain functions that some BU marshes perform even better than natural marshes, including providing diverse habitats and building elevation capital through accretion. As the U.S. Army Corps of Engineers (USACE) seeks to beneficially use 70% of the ~150 million cubic meters of dredged sediment they manage each year by 2030, the construction of BU marshes will continue to expand in the United States. Similar international efforts are underway to utilize dredged sediments to benefit communities and the environment (PIANC 2009).

Current operating principles for the USACE (Piercy et al. 2023) generally recommend matching grain size and other soil characteristics present within local marshes with the dredged sediments used to conduct BU marsh restoration and creation. However, this approach is often difficult to accomplish in practice because sediment dredged from channels may have different grain sizes than adjacent marshes. Our research found that both natural and BU marshes contain a wide range of soil textures, bulk densities, and organic matter contents that broadly overlap and allow them to provide similar ecosystem functions. Practitioners should deemphasize the need for BU marshes to exhibit soil characteristics that 'match' unrealistic concepts of natural reference marshes and focus on the need to beneficially use as much dredged sediment as possible to achieve diverse economic, environmental, and societal benefits. The fact that a range of soil particle sizes supports the applicability of most dredged sediments for marsh restoration and creation empowers stakeholders to broadly expand BU initiatives.

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Paper Citation	Location (state/country)	Marsh Focus	Data Extracted
Abbott et al., 2019	Louisiana	Natural and BU	% fines
Arriola & Cable, 2017	Florida	Natural	% organic matter
Bartholdy et al., 2004	Denmark	Natural	% fines, bulk density
Bartholdy, 2011	Denmark	Natural	% fines, bulk density
Berkowitz et al., 2022	Connecticut, Florida, Georgia, Michigan, Washington, Texas	Natural and BU	bulk density
Byrd & Kelly, 2006	California	Natural and BU	% fines
Callaway et al., 1997	Florida, Mississippi, Texas	Natural	bulk density, % organic matter
Cornwell et al., 2020	Maryland	Natural and BU	% fines
Croft et al., 2006	North Carolina	Natural and BU	
Davis et al., 2022	North Carolina	Natural and BU	% fines, % organic matter
DeLaune et al., 1990	Louisiana	BU	bulk density, % organic matter
Edwards & Profitt, 2003	Louisiana	Natural and BU	bulk density, % organic matter
Fard et al., 2023	California	Natural and BU	% fines, bulk density, % organic matter
Faulkner and Poach, 1996	Louisiana	Natural and BU	% fines, bulk density
Graham and Mendelsssohn, 2013	Louisiana	Natural and BU	% fines, bulk density, % organic matter
Groot et al., 2011	Denmark, Netherlands	Natural	
Koo et al., 2011	Korea	BU	
Lenz et al., 2022	Germany	Natural and BU	% fines
McAtee et al., 2020	California	Natural and BU	% fines
McKown et al., 2023	New Hampshire	BU	bulk density
Poppe & Rybczyk, 2021	Washington	Natural and BU	% fines, bulk density, % organic matter
Renner et al., 2020	New York	Natural and BU	
Runion et al., 2021	Alabama	Natural	% organic matter
Santos et al., 2019	Portugal	Natural	% organic matter
Schrift et al., 2008	Louisiana	Natural and BU	% fines, bulk density, % organic matter
Widdows et al., 2006	UK	Natural and BU	
Yang et al., 2008	China	Natural	% fines

Supplemental Table 1. Study locations and supporting information