ERDC/TN DOER-E44
January 2020

Thin Layer Placement of Sediments for Restoring Ecological Function to Submerging Salt Marshes: A Quantitative Review of Scientific Literature

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PURPOSE: The inundation of salt marshes, due in part to sea level rise, can result in elevation loss and a corresponding reduction in marsh ecological function. Several small-scale marsh restoration pilot projects have involved the addition of a thin layer of sediment to offset excessive inundation caused by loss of salt marsh elevation and resulting submergence. However, a comprehensive review, as well as a synthesis of project designs and the effects of sediment additions on ecological function, is lacking. This technical note reviews the impacts of thin layer placement of sediment on salt marsh ecological function and will serve as a resource for salt marsh restoration projects utilizing thin layer placement of sediments.

INTRODUCTION: Salt marshes are some of the most productive ecosystems in the world, providing critical ecological functions and services (Mitsch and Gosselink 2007). Marsh hydrology, specifically hydroperiod, is one of the primary drivers of marsh vegetation species distribution (Silvestri et al. 2005; Kirwan et al. 2012). Tidal cycles influence sediment deposition, soil anaerobiosis, inundation period, nutrient availability, and salinity in coastal systems (Mitsch and Gosselink 2007). These abiotic physical processes exert feedbacks that regulate ecological functions such as primary productivity, organic matter accumulation, and nutrient cycling (Graham and Mendelssohn 2013). In emergent salt marshes, the coupling of these abiotic and biotic factors result in marsh elevation gains (French 2006; Redfield 1972). Excessive inundation and soil waterlogging, caused by sea level rise or decreasing sediment inputs, can increase soil anaerobiosis and accumulation of hydrogen sulfide that results in marsh elevation loss (Mendelssohn and McKee 1988).

BACKGROUND: The relative elevation of coastal salt marshes within the intertidal zone is a function of sea level, subsidence, and accretion (Reddy and DeLaune 2008). The rate of marsh surface accretion must, therefore, keep pace with sea level rise and subsidence or the marsh will be inundated, negatively impacting marsh stability and long-term sustainability (Kirwan and Megonigal 2013). The addition of mineral sediment during hydrologic events (i.e., tidal exchanges or storm events) contributes to an increase in elevation directly through mass accumulation, and indirectly through stimulating biological processes and reducing physiological stress on vegetation (Mendelssohn and Kuhn 2003).

Vegetation plays an extensive role in biotic and abiotic feedbacks that increase marsh elevation (Kirwan and Megonigal 2013). Vegetation aboveground biomass growth enhances mineral and organic matter deposition to the soil surface (French 2006), and belowground biomass accretes organic matter through decomposition and carbon mineralization, further raising the marsh elevation (Stagg and Mendelssohn 2011). Sediment deposition is enhanced as water velocity is slowed by aboveground biomass during tidal flooding. Nutrients associated with the deposited sediment stimulate vegetation growth (Schrift et al. 2008). This biophysical coupling creates a feedback that stabilizes the relative elevation of the marsh within the intertidal zone (Mudd et al. 2009).

Decoupling of these ecological and physical processes often results in marsh subsidence. Regions where the stabilizing feedback processes have been lost are typically characterized by low marsh elevations and increased inundation, frequency, or duration of flooding (Kirwan and Megonigal 2013). Marsh subsidence results in excessive inundation, a reduction in soil aeration, and production of phytotoxic hydrogen sulfide (Slocum et al. 2005). Ultimately, death of the vegetation occurs and the ecological functions associated with marsh vegetation are lost (Stagg and Mendelssohn 2011). Reestablishing the relative elevation of the marsh within the intertidal zone may reinstitute biophysical feedbacks necessary for long term marsh sustainability.

Thin layer placement, also known as thin layer deposition or sediment-slurry addition, has been utilized since the 1970s both intentionally and accidentally. Wilbur (1992) defined thin layer placement as sediment application to a thickness that does not change the ecological function of the receiving habitat. Thickness of a few centimeters to 0.5 m have been described as thin layer placement (VanZomeren et al. 2018). Studies documenting the ecological effects of mineral sediment placement in marsh environments are summarized within Ray (2007). Thin layer placement, as it is defined by the U.S. Army Corps of Engineers, refers to the purposeful placement of thin layers of sediment to achieve a target elevation or thickness (Berkowitz et al. 2019). The net elevation gained by thin layer sediment application is a function of depth of sediment application, compression of the underlying substrate caused by the additional weight of the sediment application, and the consolidation of the applied sediment itself (Graham and Mendelssohn 2013). Inorganic sediments are relatively incompressible as opposed to organic sediments (Mudd et al. 2009).

The increase in elevation reduces the inundation period, improves soil drainage, increases bulk density, and decreases soil phytotoxins (Stagg and Mendelssohn 2011). In addition, thin layer placement supplies minerals such as iron and manganese which precipitate hydrogen sulfide (Graham and Mendelssohn 2013; Mendelssohn and McKee 1988). These combined effects are expected to increase primary productivity and produce additional elevation gains by organic matter production (Slocum et al. 2005); thus, increasing ecological function to marshes receiving sediment additions (Stagg and Mendelssohn 2010).

Few previous studies document the effects of thin layer placement beyond two to five years after sediment addition, and often focus on the depth of the applied sediment layer as a factor explaining the observed differences in marsh response. Given the role hydroperiod plays in determining marsh function, it follows that sediment depth alone is insufficient to explain ecological changes. This technical note reexamines the available thin layer placement literature using marsh elevation as a surrogate for inundation. The focus of this technical note is on salt marshes; freshwater and brackish marshes tend to be more sensitive to sediment additions, less vulnerable to sea level rise, and overlay more compressible organic substrates, making elevation changes more difficult to quantify (Graham and Mendelssohn 2013; La Peyre et al. 2009; Ray 2007).

SUMMARY OF FINDINGS: Three studies relating to thin layer placement of sediment are reviewed herein, two in southern Louisiana, one near Venice (Mendelssohn and Kuhn 2003; Slocum et al. 2005; Stagg and Mendelssohn 2011), and one near Port Fourchon (Schrift et al. 2008; Stagg and Mendelssohn 2010; Stagg and Mendelssohn 2011; Tong et al. 2013), and one in North Carolina (Croft et al. 2006). This selection is based upon availability of geodetic elevation and tidal prism data. Topics derived from studies using thin layer placement of sediment were (1) elevation change following thin layer placement, (2) soil physicochemical modifications, and (3) vegetation response. Major conclusions observed within each theme are presented below and summarized in Table 1.

Table 1. Summary table of literature data utilized in the analysis.

	Soil Physicochemical Characterization											Vegetation Characterization												
Reference	**Flood duration**	**Bulk density**	**Organic content**	**Moisture content**	**Particle size**	**Redox potential**	**Conductivity (salinity)**	**pH**	**Extractable nutrients[1]**	**Other elements[2]**	**Benthic infauna**	**Percent cover**	**Stem density**	**Stem height**	**Number of species**	**Frequency of occurrence**	**Dominance of species**	**Vegetation recruitment**	**Net primary productivity**	**Root + rhizome:shoot ratio**	**Resilience and stability**	**Aboveground biomass**	**Belowground biomass**	**Other[3]**
Croft et al., 2006	x	x[4]	x		x	x					x		x	x										x
Mendelssohn & Kuhn, 2003	x	x	x		x	x	x		x	x		x			x							x		
Schrift et al., 2008	x	x	x	x	x	x	x	x	x	x		x	x			x	x	x						
Slocum et al., 2005		x				x	x		x	x		x		x	x							x		
Stagg & Mendelssohn, 2010		x	x	x		x	x	x	x	x									x	x		x	x	
Stagg & Mendelssohn, 2011		x	x	x		x	x	x	x	x		x									x			
Tong et al., 2013		x		x		x					x		x	x		x	x					x	x	

[1]NH_4-N, NO_3-N, P, and S; [2]Ca, Mg, K, Na, Fe, Mn, Cu, or Zn; [3]Vegetation survivorship (live vs. dead shoots) and benthic microalgae; [4] measured but not reported.

Elevation comparison methodology. Although marsh elevation is not a perfect analog for inundation (Kirwan et al. 2012), it serves as a useful surrogate in the absence of spatially-distributed inundation data (NOAA 2014). Comparing geodetic and relative elevation changes among different marsh sites can be difficult due to differences in tidal datums and local mean sea level (LMSL). To facilitate comparison, the reported elevations were normalized by setting mean low water (MLW) to -1, LMSL to 0, and mean high water (MHW) to 1 (Figure 1). The dimensionless normalized scale allows direct comparisons among salt marshes with varying LMSL and tide ranges, facilitating investigation of elevation changes between sites on the same scale. Normalized elevations greater than 1 indicate the marsh elevation is greater than MHW, positive elevations between 0 and 1 indicate the marsh elevation is within the upper intertidal zone, negative elevations between -1 and 0 indicate the marsh is within the lower intertidal zone, and elevations less than -1 indicate the elevation is subtidal. Generally, most low marsh exists in the upper intertidal range, between 0 and 1 on the normalized scale (Couvillion and Beck 2013).

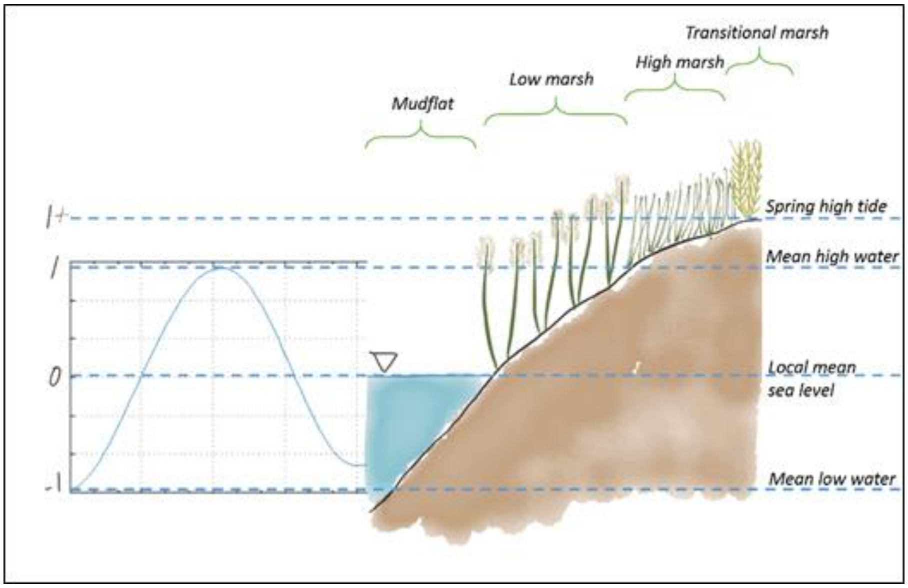

Figure 1. Salt marsh zonation in relation to normalized elevation and tidal datums.

Low marsh can also exist above 1 or below 0 under certain conditions (Snedden and Steyer 2013; Couvillion and Beck 2013).

All reported geodetic elevations were transformed to the most current National Geodetic Survey GEOID model, 12B. For most of the U.S., the transformation to GEOID model 12B did not dramatically change the estimated geodetic elevation (as is the case for the elevation data from Croft et al. 2006). However, former GEOID models did not represent southern Louisiana well, necessitating a transformation to the newest GEOID model.

Stagg and Mendelssohn (2011) utilized water level data from Coastwide Reference Monitoring System (CRMS) stations 0163 and 0292 to estimate LMSL and tide range at the marsh sites in Venice and Port Fourchon, LA. The Stagg and Mendelssohn (2011) estimates of tide range and LMSL were recalculated utilizing a longer period of record (2006–2015) using the Modified Range Ratio Method (Gill et al. 2014; NOAA 2003), using the primary water level gaging sites at Grand Isle (Venice, CRSMS 0163), and Port Fourchon (Port Fourchon, CRMS 0292). Additionally, older studies at the Venice and Port Fourchon sites (Schrift et al 2008; Slocum et al 2005; Mendelssohn and Kuhn 2003) reported relative elevations rather than geodetic elevations. The geodetic elevations for these older studies were hindcast from reported accretion rates at the local CRMS stations, and the normalized elevations were calculated using tidal datums for the prior tidal epoch. Normalized marsh elevations from these older studies presented here are approximate due to the uncertainty associated with the assumptions and data transformations.

1. Elevation change following thin layer placement

Healthy reference (untreated) sites at both Louisiana sites were located just above LMSL (normalized elevation ~0–0.4) around the time of thin layer sediment placement. The Fourchon site also utilized a degraded reference site within the same normalized elevation range. Four sediment thickness treatments at the Venice site ranged from a trace of sediment to between 30 and 60 cm, resulting in normalized elevations ranging from -0.13–2.4 (Figure 2). Four sediment treatment thicknesses at the Fourchon site ranged from 13–36 cm, resulting in normalized elevations ranging from 1.0–1.8 (Figure 2). After five years, elevation at both sites decreased due to a combination of sea level rise, subsidence, and compaction of the underlying marsh substrate and the applied sediment layer. Elevation decrease was greatest at higher placement thicknesses since compaction is proportional to the layer depth and the greater overburden weight of the mineral sediment, causing greater compression of the original marsh substrate.

After six to eight years, most sediment treatment levels at Venice and Fourchon resulted in normalized elevations similar to each other. At Venice, elevation continued to decrease at the untreated reference site and the treatment site that received only a trace amount of sediment. At Fourchon, both the degraded and healthy reference sites continued to lose elevation, though the degraded reference lost elevation very rapidly after five years, resulting in an elevation near MLW (normalized elevation ~-1). The tide range at the Masonboro Island, NC site was much greater (1.2 m vs. ~40 cm in Louisiana), so the elevation range over which low marsh occurred was much greater. The largest placement thickness Croft et al. (2006) utilized (10 cm) remained less than the highest thickness treatments at the Louisiana sites (>30 cm). Combined with the higher tide range, none of the resulting relative elevations at Masonboro Island exceeded 1, even on the non-degraded sites. While Croft et al. (2006) only monitored sediment thickness for two years following placement, the sand used in the treatments likely underwent little to no compaction. The high sand

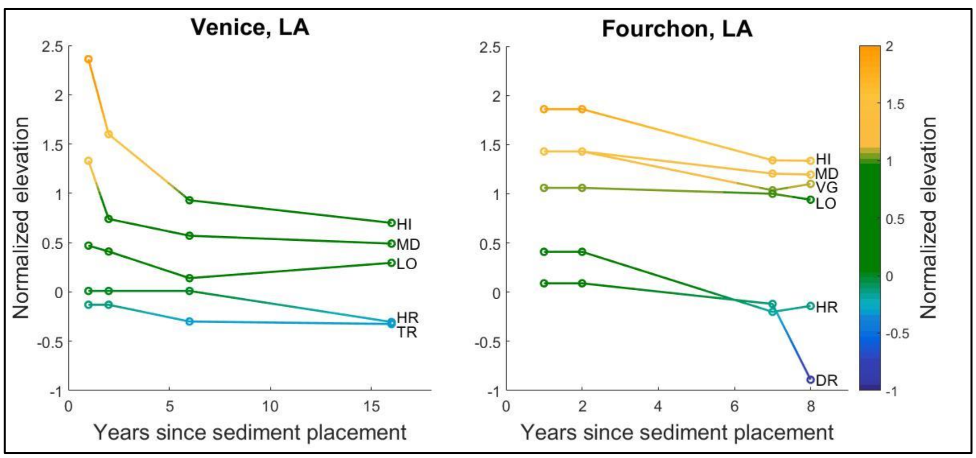

Figure 2. Changes in relative elevation since sediment placement. Lines represent different sediment thicknesses (HI: 30–60 cm; MD: 15–30 cm; LO: 5–18 cm; VG: 20–25 cm, vegetated; TR: trace; HR: healthy reference, DR: degraded reference). Adapted from Mendelssohn and Kuhn 2003; Schrift et al. 2008; Slocum et al. 2005; Stagg and Mendelssohn 2010; Stagg and Mendelssohn 2011; Tong et al. 2013.

content of the marsh soil (~50%) also decreases the likelihood for compression to occur. Given the limited normalized elevation range and short monitoring period, no data from Masonboro Island, NC are visualized in this report.

2. Soil physicochemical modifications

Application of sediment to the marsh surface occurred by sediment-water slurry containing ~70–85% liquid and ~15–30% solids by volume, typical of most hydraulic dredging operations (Mendelssohn and Kuhn 2003; Shrift et al. 2008). The thickness of sediment application ranged between a trace and up to 60 cm, with an average of 45 cm, typically measured a few months to a year after placement. The depths during, and at the cessation of construction, were not measured, and are assumed to be higher as settling and consolidation is most dramatic during the first days and weeks following sediment application (USACE 2015). The addition of a thin sediment layer to the marsh surface decreased the frequency and duration of marsh inundation (Mendelssohn and Kuhn 2003; Schrift et al. 2008) in the years immediately after placement. In general, sediment layer thickness was positively correlated with sand content and bulk density, and inversely correlated with percent organic matter in the top 10 cm of soil. This pattern is due to the sand settling in close proximity to the sediment pipe outlet leading to greater sediment thicknesses (Croft et al. 2006; Stagg and Mendelssohn 2011). Thinner applications of sediment did not increase the percent sand and bulk density or lower the percent organic matter as dramatically. The Venice and Port Fourchon, LA sites were revisited periodically over 15 and 8 years, respectively. Soil bulk density increased, likely due to continued compaction of the applied sediment, reaching a maximum four to six years after placement, then decreased as percent organic matter increased over time (Figure 3). Sites that received more than a trace of sediment had higher bulk densities than reference sites after 15 and 8 years. None of the soil bulk densities observed were high enough to limit root growth (Stagg and Mendelssohn 2011). The increase in elevation and mineral content reduced the hydroperiod, improved soil aeration, had more positive oxidation-reduction potentials, and decreased phytotoxic sulfide concentrations, all of which likely contributed to a more favorable environment for vegetation growth (Stagg and Mendelssohn 2010). Compared to the reference sites, organic matter and organic carbon remained lower on sites receiving sediment; although, in all but the highest treatment elevations, organic matter and carbon increased over time. Changes in the sediment texture over time indicated the placed sediment was worked into the underlying marsh soil by benthic infauna (Croft et al. 2006; Tong et al. 2013).

Croft et al. (2006) also reported thin layer sediment applications resulted in more positive oxidation-reduction potentials, with the most positive oxidation-reduction potential occurring with the thickest sediment additions (Croft et al. 2006). Redox potentials were not compared among

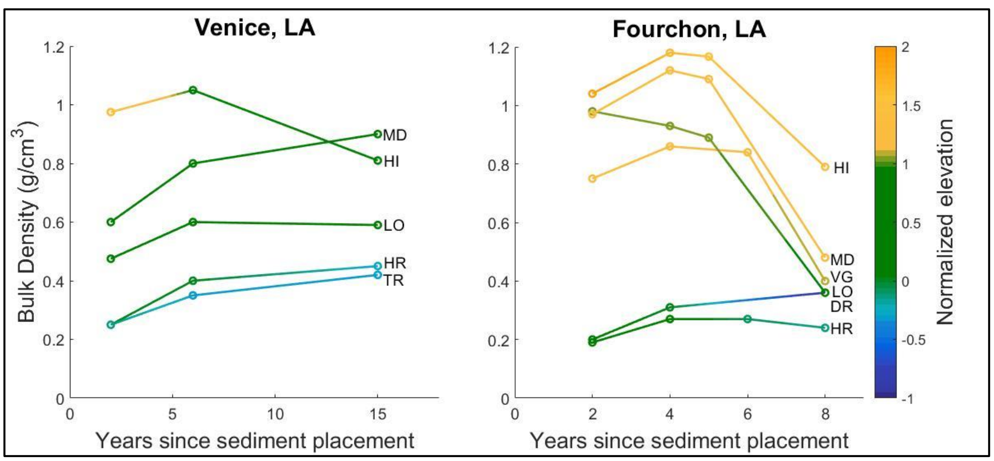

Figure 3. Changes in marsh substrate bulk density since sediment placement. Lines represent different sediment thicknesses (HI: 30–60 cm; MD: 15–30 cm; LO: 5–18 cm; VG: 20–25 cm, vegetated; TR: trace; HR: healthy reference, DR: degraded). Adapted from Mendelssohn and Kuhn 2003; Schrift et al. 2008; Slocum et al. 2005; Stagg and Mendelssohn 2010; Stagg and Mendelssohn 2011; Tong et al. 2013.

sites and between sampling events, as redox potentials in tidal salt marshes vary with tide levels (Catallo 1999). Sulfide concentrations in all sediment-treated sites were lower or similar to reference site concentrations (Stagg and Mendelssohn 2011). Sulfide concentrations on amended sites were lower than healthy and degraded reference sites, indicating a lasting reduction in potential sulfide stress even as the marsh relative elevation decreased over time.

Soil extractable ammonium in sites receiving sediment increased over time, but was generally lower than at the reference sites (Mendelssohn and Kuhn 2003; Schrift et al. 2008; Slocum et al. 2005; Stagg and Mendelssohn 2010; Stagg and Mendelssohn 2011). Soil extractable phosphorus and iron were highest in marshes with intermediate sediment additions ranging from around 10–30 cm of sediment with relative elevations in the upper intertidal range (~0–1) (Stagg and Mendelssohn 2011). High extractable ammonium concentrations at the end of the growing season in the low elevation reference sites suggests decreased ammonium uptake (Mendelssohn and Kuhn 2003; Schrift et al. 2008; Stagg and Mendelssohn 2010). High sulfide concentrations seen in the low elevation reference sites are known to inhibit the uptake of ammonium (Koch et al. 1990). Increased plant-available nitrogen has the potential to decrease belowground biomass; however, studies found that primary productivity was not limited by extractable ammonium (Mendelssohn and Kuhn 2003; Schrift et al. 2008; Stagg and Mendelssohn 2010). Rather, extractable phosphorus and iron supplemented by mineral sediment additions resulted in positive vegetation benefits (Schrift et al. 2008). Overall, marshes with the most favorable physicochemical properties received moderate applications of sediment ranging between 5 and 20 cm. Such additions resulted in normalized elevations between 0, and slightly greater than 1, five years after placement (Croft et al. 2006; Stagg and Mendelssohn 2011).

3. Vegetation response

In the years immediately following sediment placement, marshes that received moderate applications of sediment generally had equal or greater plant cover, stem density, and aboveground biomass compared to degraded marshes with no sediment additions. A lower percent plant cover was observed in marshes receiving the highest sediment applications (~ ≥30 cm) (Croft et al. 2006; Mendelssohn and Kuhn 2003; Schrift et al. 2008; Slocum et al. 2005; Stagg and Mendelssohn 2010; Stagg and Mendelssohn 2011). Sites that had minimal standing aboveground biomass prior to placement experienced the greatest increase in vegetation cover during the second growing season after placement (Figure 4). Stem densities increased during the first year following sediment addition and remained stable after the second year (Croft et al. 2006; Schrift et al. 2008; Tong et al. 2013). Decreases in vegetation cover over subsequent years was observed at both Venice and Fourchon sites, and was similar to the observed decreases in reference site vegetation cover indicating the reduction in cover was possibly due to other regional factors such as relative sea level rise or climactic conditions. Marshes receiving moderate sediment additions where relative elevations remained in the upper intertidal range (relative elevation between 0 and 1) experienced less dramatic reductions in vegetation cover and had similar or greater plant cover after 8–15 years. Intermediate levels of sediment additions restored above- and below- ground biomass production to healthy reference marsh production levels after five years (Stagg and Mendelssohn 2010). The root and rhizome to shoot ratio of live biomass receiving intermediate sediment additions was similar to healthy reference marshes (Stagg and Mendelssohn 2010).

Lower flood duration and frequency alleviated anaerobic soil conditions and reduced hydrogen sulfide production which contributed to a favorable environment for vegetation growth (Stagg and Mendelssohn 2010). In addition, sediment application provided plant available micronutrients, such as metals and cations, as well as phosphorus (Mendelssohn and Kuhn 2003; Schrift et al. 2008; Stagg

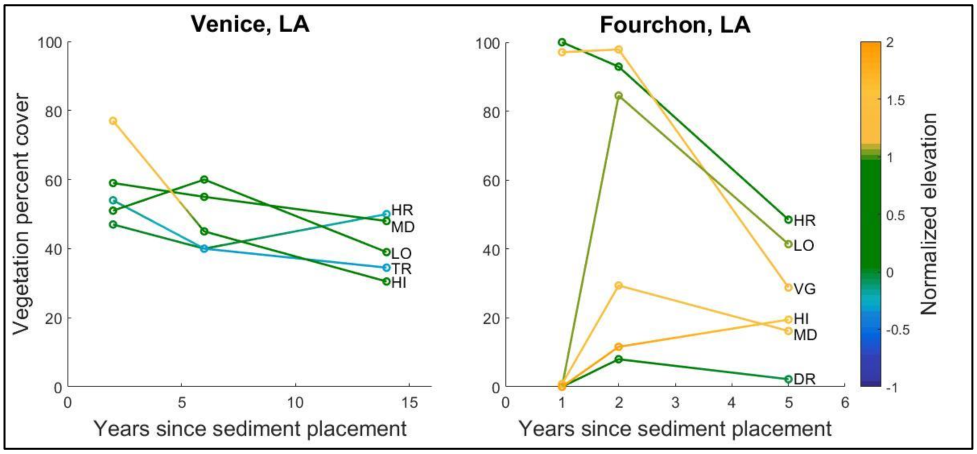

Figure 4. Changes in marsh vegetation cover since sediment placement. Lines represent different sediment thicknesses (HI: 30–60 cm; MD: 15-30 cm; LO: 5–18 cm; VG: 20–25 cm, vegetated; TR: trace; HR: healthy reference, DR: degraded reference). Adapted from Mendelssohn and Kuhn 2003; Schrift et al. 2008; Slocum et al. 2005; Stagg and Mendelssohn 2011.

and Mendelssohn 2010). Alleviation of flooding stress, hydrogen sulfide toxicity, and increased phosphorus availability resulted in improved marsh resilience and stability for marshes that received intermediate sediment applications (Stagg and Mendelssohn 2011). Marshes that received little or no sediment addition experienced prolonged anaerobic conditions, where marshes that received the thickest sediment applications experienced drought conditions and invasion of high marsh species (Slocum et al. 2005; Stagg and Mendelssohn 2010). Decreased marsh resilience and stability were observed both in marshes that received little or no sediment and in marshes that received very thick sediment applications (Stagg and Mendelssohn 2011).

The thickness of the sediment application to the marsh surface determines the vegetation response directly after application in areas that were previously vegetated (Venice and Masonboro Island). Re-vegetation of the marsh via rhizomes occurred at sediment thicknesses additions less than 30 cm (Ford et al. 1999; Schrift et al. 2008); whereas, sediment thicknesses in excess of 30 cm smothered existing vegetation and resulted in re-vegetation by seeds (Mendelssohn and Kuhn 2003), similarly to Cahoon and Cowan (1988) and Reimold et al. (1978). The application of sediment to previously vegetated marsh resulted in a greater percent cover after one year demonstrating the benefit of sediment addition to vegetated marshes (Schrift et al. 2008). In addition, vegetated healthy marshes positively benefited from sediment additions, although this positive result is likely a function of the sediment thickness applied, resulting in small changes in relative elevation (Croft et al. 2006). Overall, marshes had the best vegetation response, particularly when resilience and stability was considered, from applications of sediment resulting in elevations in the upper intertidal range after the first five years.

CONCLUSIONS: Generally, marshes receiving sufficient sediment to raise the elevation into the upper intertidal range exhibited increased vegetation resilience or displayed vegetation metrics similar to healthy reference sites. Even robust sites did not display long term negative impacts from sediment placement provided the final marsh elevation did not exceed the upper intertidal range. At sites in Venice and Port Fourchon, LA with significant post-placement compaction, sediment placement resulted in an increase in overall vigor and resilience despite not resulting in a long term increase in marsh elevation. The addition of mineral sediment likely influenced other marsh properties such as bulk density and sulfide concentrations that improved the condition of the marsh in the years subsequent to sediment placement. Without long term monitoring of thin layer placement sites, the sustainability of these beneficial effect of sediment additions is unclear.

These results are limited due to the availability of quantitative elevation and sediment thickness data in reference to the tidal prism. While all studies referenced in this technical note measured multiple soil and vegetation parameters, comparisons among sites and studies were limited, since only a few parameters were common among all studies and were measured with comparable methods. Future studies at these sites and others, should ensure high quality hydrologic and elevation data are collected. Additionally, the same soil and vegetation parameters should be collected in a consistent fashion to facilitate long-term monitoring and establishment of restoration trajectories. Future thin layer placement sites in other geographic areas should focus on collecting common physical, soil, and ecological parameters so scientists and engineers can develop common guidance for future marsh thin layer placement projects.

ADDITIONAL INFORMATION: This technical note was written under the Dredging Operations and Environmental Research (DOER) program by Dr. Christine VanZomeren (*Christine.M.VanZomeren@usace.army.mil*, Tel: 601-634-3702) and Dr. Candice Piercy (*Candice.D.Piercy@usace.army.mil*, Tel: 601-634-7253), of the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL).

This DOER Technical Note should be referenced as follows:

> VanZomeren, C. M., and C. D. Piercy. 2019. *Thin Layer Placement of Sediments for Restoring Ecological Function to Salt Marshes: A Quantitative Review of Scientific Literature*. DOER Technical Notes Collection. ERDC/TN DOER-E44. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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