Tidal Marsh Restoration Brief

Long Term Outcomes of Tidal Marsh Restoration Efforts on the U.S. West Coast

Addressing key questions about plant community development, carbon sequestration, and resilience to sea-level rise

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Introduction

Although significant investments in tidal wetland restoration have been made over the past 30+ years to reverse historical wetland losses in Washington, Oregon, and California estuaries, land managers, scientists, policy makers, and others frequently express the need for information about the long-term effectiveness of these restored sites to better inform current and future tidal wetland restoration planning and design.

Some important questions about restoration include:

- *Do mature restored tidal wetland plant communities resemble those of least-disturbed reference wetlands?*
- *How resilient are tidal wetland restoration projects to sea-level rise?*
- *Are restored tidal marshes sequestering as much carbon as least-disturbed sites?*

This Restoration Brief focuses on these three key questions for tidal marshes*, reporting the results of a 2.5 yr NERRS Science Collaborative-funded research project entitled, *A Long-Term Perspective on Tidal Wetland Restoration: Vegetation Development, Elevation Capital, and Carbon Sequestration in the Oldest Projects Along the U.S. West Coast*, also known as the MAREA Project (MAture REstoration Assessment).

Working with four West Coast National Estuarine Research Reserve System reserves, the PNW Blue Carbon Working Group, and other partners, the MAREA team compiled data on marsh elevation, vegetation communities, and carbon sequestration in multiple older restored and reference tidal marshes in Washington, Oregon, and California (Figure 1). Restored sites ranged from 22 to 62 years old at the time of sampling. The team used consistent methods to examine restored and reference marsh conditions for three major parameters of interest: vegetation, elevation, and carbon sequestration capacity.

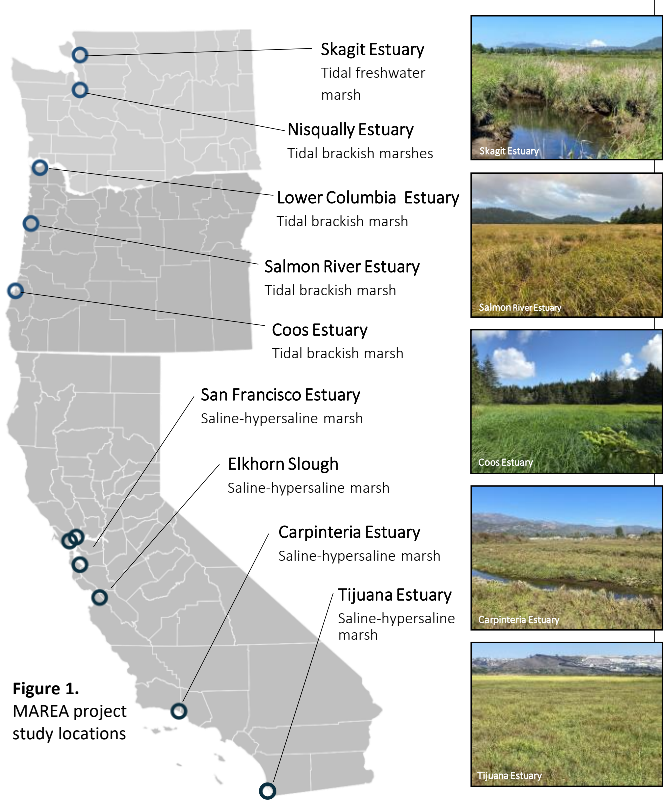


Figure 1. MAREA project study locations

* The project did not investigate restoration of forested or shrub tidal wetlands.

Background

The extensive global loss of tidal wetlands over the past several centuries has diminished vital coastal ecosystem services, contributed to local and regional fishery declines, and increased greenhouse gas emissions (Barbier et al. 2011, Pendleton et al. 2012, Whitfield 2017). Much of this loss is attributed to the conversion of tidal wetlands for agriculture and urban development, a trend also evident in the United States, where a recent study shows that loss along the West Coast is greater than along the Atlantic and Gulf coasts (Endris et al. 2024). In Washington, Oregon, and California, as much as 85% of historical tidal wetlands have been lost, with the majority of estuaries seeing at least a 50% reduction, illustrating the severe degradation of West Coast estuaries (Brophy et al. 2019; Figure 2).

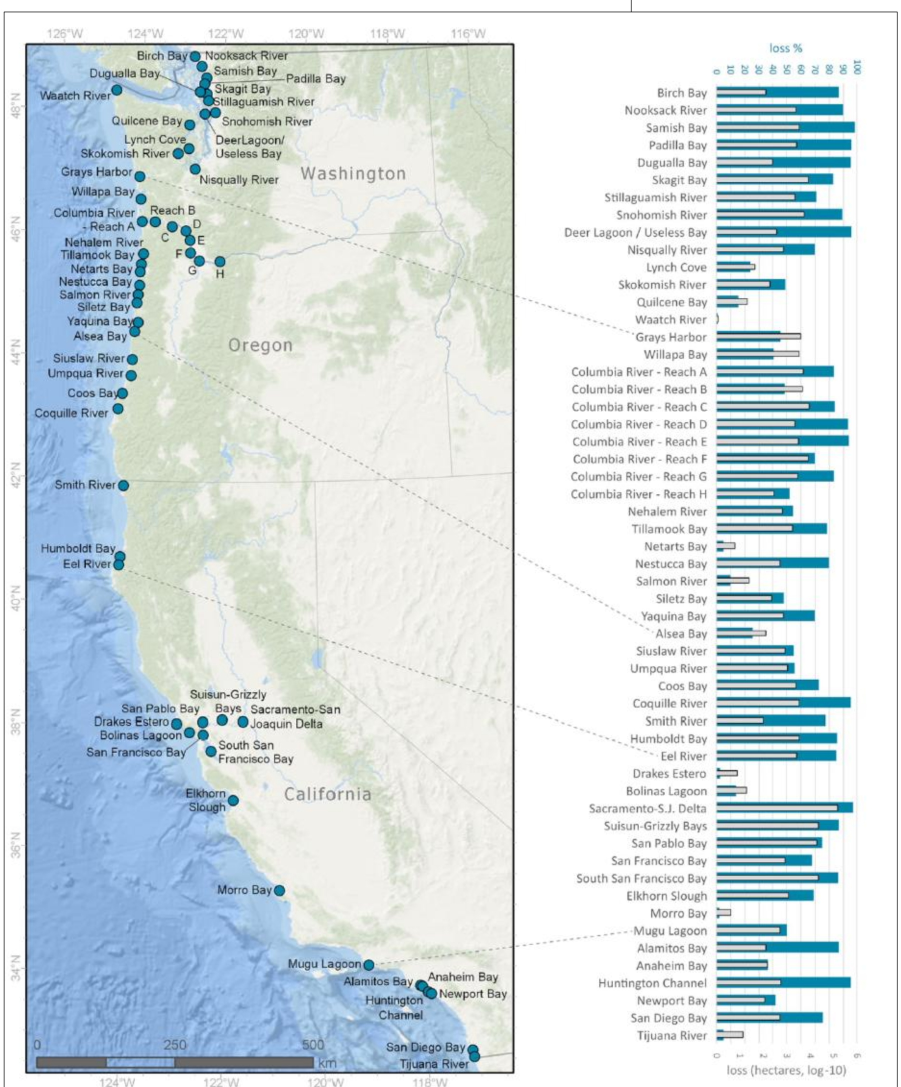


Figure 2. Wetland loss in 55 Pacific Coast estuaries (from Brophy et al. 2019).

In response to this widespread wetland loss, coastal restoration efforts have grown worldwide. These efforts aim to reduce biodiversity loss, restore ecosystem services, and provide protection from coastal flooding due to sea-level rise or storms (Liu et al. 2016). Common restoration strategies include breaching or removing dikes to restore tidal flows to areas previously converted for agriculture or urban development (Gerwing et al. 2020). Restoring tidal hydrology to a tidal wetland may often have multiple positive benefits for coastal communities including increasing habitat for estuarine-dependent fish and wildlife species, boosting carbon sequestration, and strengthening resilience against climate change impacts (Schulz et al. 2020, Poppe & Rybczyk 2021, Martin et al. 2021, Janousek et al. 2025).

Dike breach and removal projects have been implemented for decades along the U.S. West Coast, with projects varying in setting, scale, and design. As more (and increasingly expensive) projects are being implemented, land managers and restoration practitioners are looking for "lessons learned" from completed restoration projects, especially older projects which help shed light on longer-term restoration outcomes.

In addition, insights from investigating older projects can help regional planners with site prioritization and planning for new projects, help restoration practitioners better evaluate design options, and help establish realistic quantitative benchmarks to use in monitoring projects over time.

In the next three sections we address the three major tidal wetland restoration questions which were the focus of the MAREA project.

Question 1: *To what extent do mature restored tidal marsh plant communities resemble those of least-disturbed reference wetlands?*

Summary of Findings

- *Like reference sites, mature restored marshes were mostly dominated by native plant species and characterized by high total plant cover.*
- *However, restored sites often had different species composition and lower species diversity than reference marshes. Restored sites may also lack rare species important to local biodiversity like salt marsh bird's beak (right).*
- *Non-native species were more common in tidal fresh to brackish marshes in the Pacific Northwest than those in the saline to hypersaline marshes in California.*

Vegetation, including both plants and benthic algae, is key to the functioning of tidal wetlands including their productivity, sediment capture, and soil conditions (e.g., Zedler 1980, Cherry et al. 2009, Foster-Martinez et al. 2018). Vegetation may undergo major changes when a diked site is restored to a tidal marsh. For example, in PNW estuaries, early change typically includes rapid dieback of plant communities characteristic of disturbed sites followed by growth of low marsh vegetation because diked former tidal wetlands are often subsided (Thom et al. 2002, Janousek et al. 2021). After several years, restored marshes gradually develop more complex plant communities, but less is known about the long-term development of those communities (Simenstad & Thom 1996, Callaway 2005).

The MAREA project assessed vegetation community structure (plant cover, composition, diversity, and macroalgal cover) in 16 tidal marsh restoration projects on the U.S. West Coast. Each site was paired with a reference marsh usually located adjacent to the restoration site. Overall, our data suggested that vegetation structure in decades-old restored sites was similar to least-disturbed reference wetlands in some ways but not in others. Total plant cover and non-native cover was often similar between older restored and reference sites (Table 1) and both types of sites were usually dominated by native species. But at many restored sites, species diversity was often lower, and species composition was somewhat different than reference marshes. We also found that non-native species cover was often higher in PNW low salinity sites.

These findings suggest that plant community structure and function have not fully recovered at many restored sites.

Differences in species composition were in some cases caused by differences in the relative abundance of dominant or sub-dominant species since pairs of sites often shared the same list of species present. Because plant species tend to serve unique functions in ecosystems, differences in species composition may lead to functional differences between older restored sites and reference marshes.

Additional research will be needed to help explain the persisting differences in species composition and diversity between restored and reference marshes after decades of development. Explanations could include limitations on dispersal and establishment for some species, differences in soil conditions, or lack of microtopographic features that promote diversity in restoring wetlands.

Table 1. Summary of vegetation differences between pairs of older restored and reference marshes in the study. Red downward arrows indicate the restored site parameter was lower than the reference site. Blue upward arrows indicate the opposite. Sideways arrows indicate lack of statistical differences. Under species composition, 6 letter codes indicate dominant or subdominant species differing in cover between restored and reference marshes.

		Vegetation metric				
Restored site	Estuary	Macro-algal cover	Plant cover	Non-native plant cover	Species composition	Plot-level diversity
Deepwater	SKA	↔	↔	↔	↔	↔
Pilot	NIS	↑	↓	↔	↔	↓
Phase 1	NIS	↔	↓	↔	DisSpi ↓	↓
Netul River	COL	↔	↑	↔	PhaAru ↑	↔
Mitchell	SAL	↔	↔	↓	CarLyn ↑	↔
Kunz High	COO	↔	↔	↓	CarLyn ↑	↓
Kunz Middle	COO	↔	↔	↓	CarLyn ↑	↓
Kunz Low	COO	↔	↔	↓	CarLyn ↑	↓
Kunz Passive	COO	↑	↔	↓	AgrSto ↓	↓
Fredrickson	COO	↔	↓	↑	AgrSto ↑	↓
Sonoma Baylands	SFE	↔	↔	↔	SalPac ↓	↑
Muzzi	SFE	↔	↔	↔	JauCar ↓	↓
Faber	SFE	↔	↓	↔	↔	↔
Parsons	ELK	↑	↓	↔	NA	↓
Ash Avenue	CAR	↔	↑	↔	↔	↔
Model	TIJ	↔	↔	↔	SalPac ↑	↔

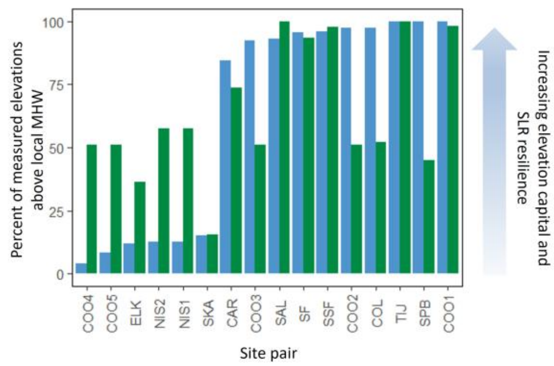
Estuary codes: CAR: Carpinteria (CA), COO: Coos (OR), COL: Columbia River (OR), ELK: Elkhorn Slough (CA), NIS: Nisqually (WA), SAL: Salmon River (OR), SF: San Francisco (CA), SKA: Skagit (WA), SPB: San Pablo (CA), SSF: South San Francisco (CA), TIJ: Tijuana (CA) **Species codes:** AgrSto: *Agrostis stolonifera*, CarLyn: *Carex lyngbyei*, DisSpi: *Distichlis spicata*, JauCar: *Jaumea carnosa*, PhaAru: *Phalaris arundinacea*, SalPac: *Salicornia pacifica*

Question 2: *How resilient are tidal wetland restoration projects to sea-level rise?*

Summary of Findings

- *Sites where marsh elevation was manipulated as a restoration design strategy tended to match reference site elevations more closely.*
- *How closely sites matched their paired reference site elevations was not necessarily a good indicator of elevation capital and resilience to sea-level rise.*
- *Both elevation and vertical accretion data are needed to accurately assess sites' resilience to sea-level rise.*

Figure 4. Elevation capital of restored (blue) and reference (green) marshes as determined by the percent of each site's elevation points occurring in mid- or high-marsh zones (i.e., above Mean High Water (MHW)). Restored sites are ordered from least to greatest elevation capital.



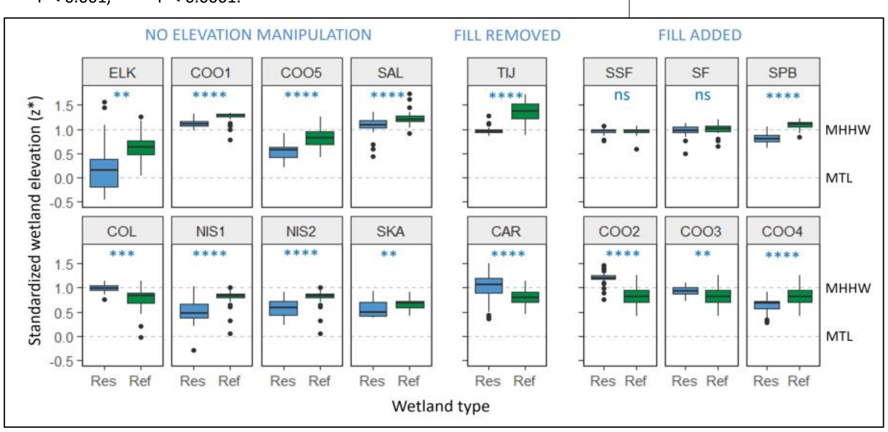
Site codes:
CAR: Carpinteria (CA), COO1: Fredrickson marsh, Coos Estuary (OR), COO2-5: Kunz marsh cells, Coos Estuary, COL: Columbia River (OR), ELK: Elkhorn Slough (CA), NIS1: Pilot marsh, Nisqually (WA), NIS2: Phase 2 marsh, Nisqually, SAL: Salmon River (OR), SF: San Francisco (CA), SKA: Skagit (WA), SPB: San Pablo (CA), SSF: South San Francisco (CA), TIJ: Tijuana (CA)

Historical conversions of tidal wetlands to agricultural lands through diking and draining activities, and their subsequent use for agricultural production have typically resulted in land subsidence and altered soil characteristics in restorable former tidal wetlands on the U.S. West Coast. Key factors involved in these changes include the elimination of sedimentation processes, physical compaction of sediments, and organic matter oxidation (Spencer et al. 2017). The resulting loss of "elevation capital" poses challenges to restoration practitioners and requires them to consider including possible sea-level rise (SLR) resilience strategies, such as wetland elevation manipulation, into project designs (Watson et al. 2017).

At MAREA sites, marsh surface elevations in seven of eight marshes restored without elevation manipulation were significantly lower than their paired reference wetlands (Figure 3). In contrast, manipulated sites (i.e., dredged sediment placement, fill removal) matched reference sites more closely. These results suggest the utility of elevation manipulation as a restoration approach for potentially improving site resilience to SLR. But how much elevation capital did the project sites have after so many years of post-restoration recovery? The MAREA team addressed this question by calculating for each site the percent of site elevations greater than mean high water (MHW), the threshold above which sites may be considered to have significant elevation capital (Cahoon et al. 2019).

This analysis suggests that 10 of the 16 mature restored sites studied could be considered potentially resilient to SLR, based on the high percentage (85-100%) of elevation measurements greater than MHW (Figure 4). For other sites, elevation capital appears to be low, indicating possible vulnerability to future SLR-driven wetland conversion to unvegetated tidal flat.

Figure 3. Marsh surface elevation in restored (Res/blue) versus reference (Ref/green) sites. Elevations are scaled to local tide range (z*). ns** P < 0.01, *** P < 0.001, **** P < 0.0001.



Present-day elevation results, however, tell only part of the story. Vertical accretion rate data—discussed in the next section—are also needed to determine which sites may be most resilient to future sea-level rise and which may require adaptive management (such as thin layer sediment placement) to improve their resilience.

Question 3: *Are restored tidal marshes sequestering as much carbon as least-disturbed sites?*

Summary of Findings

- *Sediment accretion and carbon accumulation rates recover quickly after restoration project implementation and stabilize at approximately 30 years post-restoration.*
- *After about 30 years, accretion and carbon accumulation rates in mature restored marshes become similar to those observed in reference marshes.*
- *Soil carbon density in mature restored marshes lags behind reference marshes, suggesting at least several decades may be required to rebuild soil carbon stocks.*
- *Most project sites, including both restored and reference marshes, have a positive accretionary balance, indicating resilience to sea-level rise over the last few decades.*

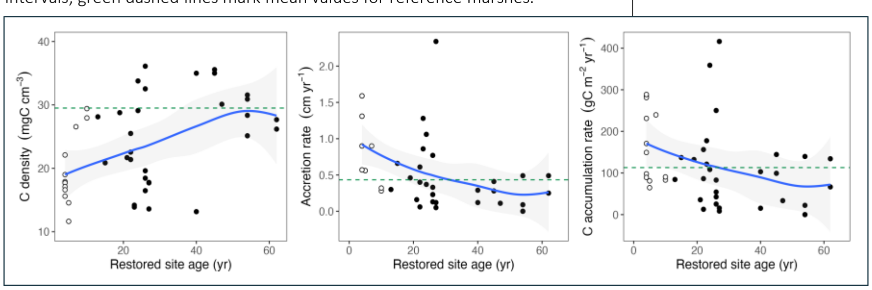
Tidal marsh soil core

Once converted to other land uses, former tidal wetlands may stop sequestering significant amounts of carbon, and their soils lose stored carbon through organic matter oxidation as they dry out either seasonally or permanently. For policy makers and agency managers charged with developing and implementing restoration and conservation-focused natural climate solution approaches to climate mitigation especially, key questions remain about the time required for restored tidal wetlands to achieve carbon sequestration rates and storage levels comparable to those in least-disturbed tidal wetlands.

Research at individual sites on the West Coast shows that younger restored marshes can attain high accretion and carbon accumulation rates relative to reference marshes as they recover from subsidence (Drexler et al. 2019, Poppe & Rybczyk 2021). But until now researchers could not extrapolate beyond the first 10-20 years to predict the longer-term trajectory of these rates.

By studying MAREA sites (and adding in some data from younger sites as well), we found that accretion and carbon accumulation rates tend to stabilize at reference marsh levels by approximately 30 years following restoration, while soil carbon density continues to gradually increase even at 60 years (Figure 5). Although soil carbon density is relatively slow to recover after restoration, this has little impact on carbon accumulation rates, which are primarily driven by accretion rates. As mentioned in the previous section, soil vertical accretion rates are important indicators of marsh SLR resilience (Raposa et al. 2016). The project compared accretion rates to local rates of relative SLR to evaluate accretionary balance (a site's relative resilience to SLR). Assuming no major current subsidence, the balance for most restored and reference marshes is positive, suggesting most project sites are SLR resilient for the near term. (Figure 6, see also Ensign et al. 2023). Only a few restored sites appear to be SLR vulnerable, including sites in the Nisqually and San Francisco estuaries with relatively low accretion rates near reference sites with only slightly better accretion rates. The implication is that these sites' SLR vulnerabilities may stem more from low sediment availability to the estuary and less from site-level limitations.

Figure 5. Soil carbon density, accretion, and carbon accumulation rates by restored marsh age. Solid points are MAREA sites; hollow points are younger restoration sites from other studies. Gray bands show 95% confidence intervals; green dashed lines mark mean values for reference marshes.



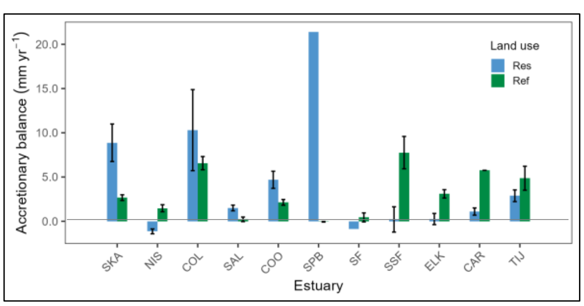


Figure 6. Accretionary balance for MAREA project sites. Positive values indicate SLR resilient sites; negative values indicate sites vulnerable to SLR. Data for 5 Coos Estuary sites and 2 Nisqually Estuary sites were combined.

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Restoration Recommendations

Tidal wetland restoration practitioners use both well-tested and innovative techniques to re-establish ecosystem services such as fish and wildlife habitat, shoreline stabilization, flood and storm surge protection, and carbon storage and sequestration. Yet, because many uncertainties remain in the practice of tidal wetland restoration, those designing and implementing new projects may benefit from the lessons learned from over 50 years of completed restoration efforts on the U.S. West Coast.

With the understanding that additional study of mature tidal wetland restoration projects is needed, we offer here a few restoration recommendations based on results from the MAREA project. Some recommendations will serve to confirm existing practices, while others may offer useful new insights based on newly collected and analyzed data. Although our study included only tidal marsh restoration sites, many of these recommendations are applicable to restoration of other tidal wetland types such as forested and scrub-shrub tidal wetlands.

Plant Communities

- Even at restored tidal wetland sites with robust natural recruitment, planting or seeding during restoration project implementation or early site development should be considered for establishing plant community diversity before early colonizing native perennials have a chance to form exclusive monocultures.
- Given the key role that wetland elevation and salinity play in determining plant community structure, project results confirm the need for the careful consideration of initial elevation distributions, salinity regime, and vertical accretion rate potential in tidal wetland restoration designs. As-built elevations relative to local tidal levels and salinity regime inform expectations about naturally recruited plant communities and determine appropriate native species for any added plantings or seeding. Vertical accretion rate informs practitioners about the long-term sustainability of site plant communities and their resilience to SLR.
- Continued attention needs to be focused on the development of native plant community restoration approaches in freshwater and low salinity tidal marsh and swamp projects to both eliminate existing non-native plant communities and to prevent their post-project colonization and future long-term persistence, especially in the Pacific Northwest.

Elevation Capital and Resilience to Sea-level Rise

Tidal wetland restoration is intended to re-establish ecosystem services, but the long-term viability of those services depends on project site resilience to SLR. Designing for site resilience includes first understanding the local rate of SLR and the accretionary balance of local least-disturbed tidal wetlands. Guided by those data, restoration designs and post-restoration adaptive measures that establish and maintain long-term site elevation capital can then be developed. Design options include the strategic manipulation of site elevations through grading, use of dike and other fill material to reverse site subsidence and enhance elevation capital, and the incorporation of topographic features (e.g., large woody debris) to enhance vegetation recruitment which helps facilitate natural sediment deposition processes.

Carbon Accumulation Rates and Vertical Accretion

Results from recent regional blue carbon projects now provide land managers with more regionally relevant data on carbon storage in U.S. West Coast tidal wetlands (Kauffman et al. 2020, Janousek et al. 2025), the influence of salinity and other drivers on methane emissions in PNW wetlands (Williams et al. 2025), and both short-term (Poppe & Rybczyk 2021) and long-term (this project) post-restoration carbon accumulation rates. Integrated into blue carbon tools under development (e.g., PNW Regional Blue Carbon Calculator), these findings will help policy makers and planners generate more accurate estimates of how restoration projects can contribute to natural climate solutions.

These advancements provide improved guidance for site selection and project design for restoration efforts that prioritize carbon sequestration among other co-benefits. For example, we can recommend with greater confidence that planners favor intermediate elevation sites in estuaries with ample sediment supply—site elevations high enough to sustain robust vegetation growth but low enough to allow frequent tidal flooding and rapid accumulation of sediment and organic matter early in site development.

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Recommended citation: Cornu C, Janousek C, Williams T, Schmitt J, Schroeder J, Kirkland J, Wasson K, Rybczyk J, Poppe K, Crooks J, Schooler S, Ferner M, Siegel S, Brophy L, Comet S. 2025. Tidal Marsh Restoration Brief: Long-term outcomes of tidal marsh restoration efforts on the U.S. West Coast. Corvallis, OR: Institute for Applied Ecology, Oregon State University, Western Washington University, South Slough National Estuarine Research Reserve, Elkhorn Slough National Estuarine Research Reserve, Tijuana River National Estuarine Research Reserve, San Francisco Bay National Estuarine Research Reserve.

This research was funded by the National Estuarine Research Reserve System's Science Collaborative program (grant NA19NOS4290058, SUBK00018014). The blue carbon component of this study is a contribution of the Pacific Northwest Blue Carbon Working Group.