



Sea Level Rise and Adaptation Strategies Assessment for the Morro Bay Estuary

Field and Modeling Summary Report



Prepared as part of the

Sea Level Rise and Adaptation Strategies Assessment for the Morro Bay Estuary

A study on the projected effects of sea level rise on the Morro Bay estuary and adaptation solutions for resilient tidal habitats.

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1.0 Executive Summary

Sea level rise (SLR) poses a significant threat to estuarine ecosystems, human communities, infrastructure, and economies. The Morro Bay estuary is vulnerable to SLR and will be faced with challenging decisions regarding where and how to improve habitat resilience. The MBNEP partnered with U.S. Geological Survey (USGS) to model the effects of SLR (0.18-1.9 m) in the estuary and surrounding transition zones through 2100 and to develop possible adaptation strategies. This information will be critical to inform management and engage stakeholders.

The goals of the project were: 1) to collate existing and collect new information on soil properties, including bulk density, organic matter content, and grain size, to inform modeling for estuarine ecosystems, 2) to model future ecological outcomes considering several scenarios including a range of sea levels and sediment availability, and 3) to identify and model possible management scenarios or actions that may be implemented with partners.

The MBNEP and USGS developed an innovative modeling framework, WARMER-Coast, that incorporates simplified hydrodynamics and mechanistic soil and plant dynamics to explore alternative SLR scenarios, sediment availability, and potential restoration and ecosystem enhancement strategies.

This report summarizes the field data collection, provides a high-level overview of the WARMER-Coast framework, describes model application and calibration for Morro Bay, and presents projections of intertidal habitat under baseline scenarios spanning five sea-level-rise (SLR) trajectories and three climate scenarios, as well as under two management interventions: thin-layer sediment placement and natural barriers. Model results indicate that tidal marsh habitat remains relatively resilient under SLR rates up to the intermediate scenario, with marsh persistence through 2100 generally associated with rates below approximately 12 mm yr^{-1} . Differences among wetter, historical, and drier climate scenarios further emphasize the importance of sediment delivery and deposition in maintaining marsh elevation relative to tidal inundation. Thin-layer sediment placement modeling indicate it can be an effective strategy for increasing marsh resilience to SLR, although outcomes depended on the timing, frequency, and volume of placement. A journal article is in preparation that can provide a more complete description of the model framework, along with formal sensitivity and uncertainty analyses.

2. Methods

2.1 Surface Elevation Table and Marker Horizon Plots

Surface elevation change and shallow sediment accretion were quantified using surface elevation table–marker horizon (SET-MH; Figs. 1-2) stations following established methods (Cahoon et al., 2002). SETs measure changes in wetland surface elevation relative to a subsurface benchmark, whereas feldspar marker horizons measure vertical sediment accretion above a known reference horizon. Differences between surface elevation change and vertical accretion reflect shallow subsurface processes such as compaction, expansion, and organic matter dynamics within the soil profile above the benchmark.

Monitoring data used to inform WARMER-Coast included three groups of stations distributed across Morro Bay (Fig. 3):

- Four long-term rod SET-MH stations installed by USGS in 2013 along the interior and edge of tidal marsh near the Chorro and Los Osos Creek outlets;
- Nine stations established by the University of San Francisco in 2004 across the Chorro Creek marsh, including three high-marsh SET-MH stations, three low-marsh SET-MH stations, and three mudflat marker-horizon sites; and
- Eight marker-horizon sites installed by USGS and the Morro Bay National Estuary Program (MBNEP) in 2023 within the Chorro Creek marsh and fringing marsh at Sweet Springs Nature Preserve.

Station locations, installation dates and measurement periods are summarized in Figure 3. Feldspar plots established in 2023 were remeasured twice during the study period, in September 2024 and May 2025.

SET measurements provide millimeter-scale estimates of relative surface elevation change, while marker horizons isolate the contribution of near-surface sediment and organic matter accumulation. Together, the measurements were used to characterize spatial variation in

contemporary elevation change and accretion and to evaluate WARMER-Coast simulations of marsh-surface adjustment. Additional details on SET-MH installation and measurement procedures are provided by Cahoon et al. (2002) and in the MBNEP Quality Assurance Project Plan (<https://www.mbnep.org/QAPP/>).

SET-MH measurements do not directly track changes in absolute surface elevation relative to North American Vertical Datum of 1988 (NAVD88) through time. Vertical land motion (VLM) occurring below the depth of the SET benchmark therefore is not captured by the measurements. Consequently, comparisons between observed elevation change and projected relative sea-level rise assume that deeper VLM is adequately represented by the sea-level-rise scenarios. Potential spatial variability in VLM represents an additional source of uncertainty in interpreting long-term wetland vulnerability. To support future assessments of VLM in Morro Bay tidal marshes, we occupied two USGS rod SETs, representing high- and low-elevation marsh settings, for approximately 24 hours using static GPS and conducted differential leveling surveys to establish vertical ties between the geodetic measurements and the associated SET benchmarks. Repeated static GPS occupations of these sites will allow VLM to be estimated independently and incorporated into future assessments of marsh elevation change and sea-level-rise vulnerability.

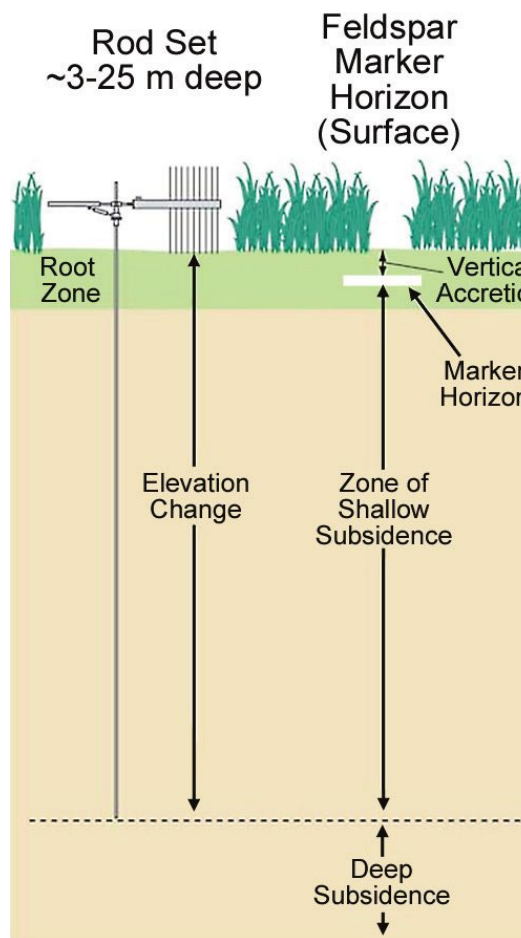


Figure 1. Layout of surface elevation table. Credit: Callaway et al. 2013



Figure 2. Surface elevation table monitoring near Chorro Creek by USGS. Photo credit: Carolyn Geraghty

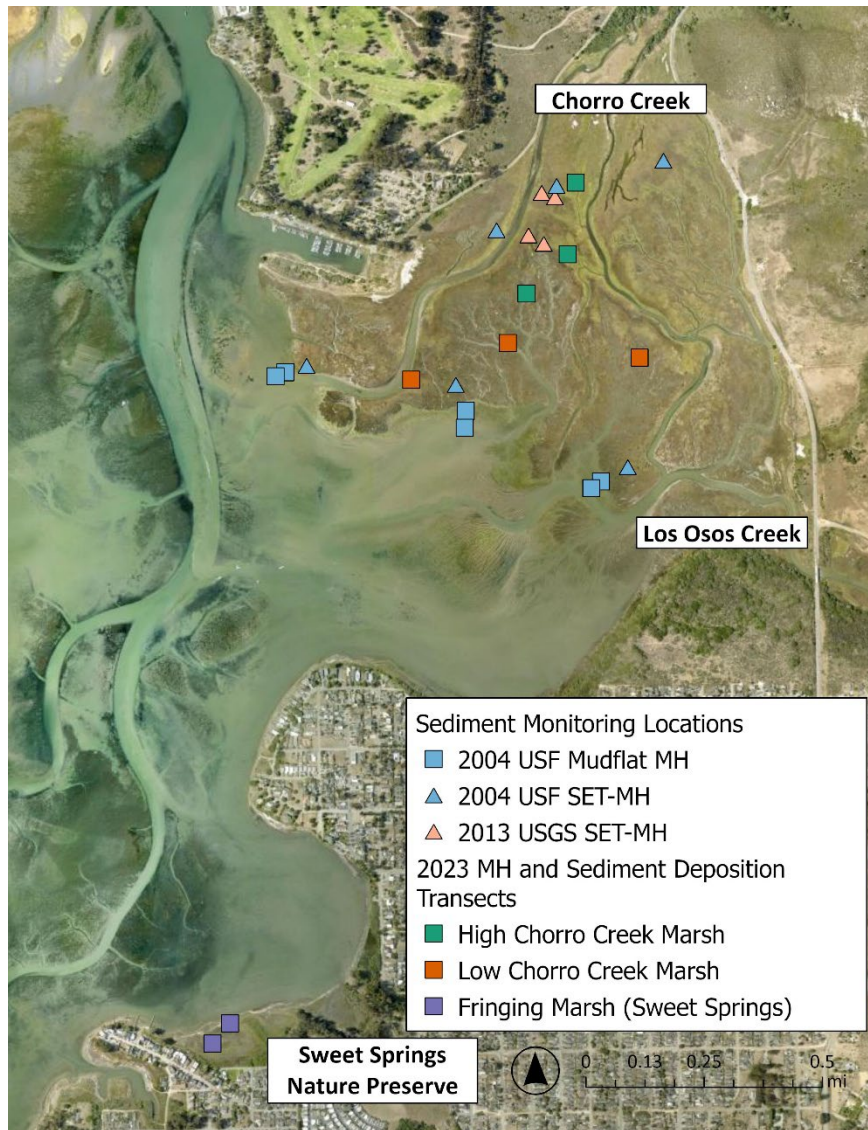


Figure 3. Map of surface elevation table (SET) and Marker Horizon (MH) plots. University of San Francisco (USF) professor John Callaway installed pipe SETs in 2004. Deep rod SETs were installed by the U.S. Geological Survey in 2013. Deep-rod SETs use coupled stainless-steel rods driven to a stable subsurface layer, often several to tens of meters deep, whereas the original pipe SETs use a 3-in-diameter aluminum pipe driven into the substrate until substantial resistance or refusal is reached. The Morro Bay pipe SETs established in 2004 used aluminum benchmarks driven by hand to refusal. Base map imagery is from Vantor

(Westminster, CO).

2.2 Soil cores

Soil cores were collected to understand spatial variation in depth profiles of organic matter and bulk density (Fig. 4). Long soil cores (core length 50-100 cm; 9 samples) were collected at low and high marsh elevations, adjacent to the USF SET-MHs, as well as in upland transition zones and were used to constrain emergent vegetation productivity and mineral deposition. Each long core was collected using a gouge auger and was sectioned into regular intervals. The samples were processed for bulk density with a drying oven and for percent organic matter (LOI) with a muffle furnace.

Short cores (core length 5 to 10 cm; 32 samples) were collected using a handheld soil core device from sites around the estuary and analyzed grain size to help evaluate spatial patterns in fluvial sediment deposition. Short cores, and a subset of the long core sections, were processed through 63 and 125- μ m sieves to determine a mass distribution of each grain size (coarse sand, fine sand or mud).



Figure 4. Long core collected at Sweet Springs Marsh. Photo credit: Jenn Fields.



Figure 5. Map of deep soil core collection locations. Basemap imagery is from the National Agricultural Inventory Program, 2020.

2.3 Water Level Loggers

To fill data gaps, pressure transducers (water level loggers; Solinst Levellogger 5 Model 3001, Georgetown, Ontario, Canada) were installed in two main channels of the Chorro Creek marsh and an interior channel of a Sweet Springs marsh to measure tidal dynamics and to better understand how the tidal marsh attenuates water levels (Fig. 6). A pressure transducer (barometer; Solinst Levellogger 5 Model 3001) was installed outside the MBNEP office to track barometric patterns throughout the study. Loggers were downloaded and

replaced with a new calibrated logger every six months. Water level logger elevation was determined using survey-grade global positioning system equipment (Leica GS 15, Leica Geosystems, Heerbrugg, Switzerland). We were unable to resolve a persistent bias in the real-time kinematic (RTK) GPS measurements of the water logger sensors. Instead, we leveraged data from monitoring efforts by Dr. Talke's lab at California Polytechnic University from Los Osos Creek and Chorro Creek (Maas 2025).



Figure 6. Map of level logger locations and timing of deployment. Basemap imagery is from the National Agricultural Inventory Program, 2020.

2.4 Sediment Deposition

This study was conducted prior to RAE grant funding, but marker horizon data was collected and used as part of model calibration, so it is summarized below. We deployed sediment traps (Fig. 7) across the marsh along transects that were aligned perpendicular to tidal creeks (Fig. 8). Each transect had five stations that were 0.5, 2, 6, 12, and 24 m from the channel, and each station had two replicate traps. The sediment traps consisted of a quantitative filter pad attached to a ceramic tile with rubber bands. Eight transects were located across the marsh, distributed in high and low relative elevation zones. At a subset of stations, we also deployed feldspar clay in 0.1 x 0.1m plots at 2, 12, and 24m to track cumulative surface accretion over time. These marker horizon plots were measured at least every six months from April 2023-May 2025.

The study focused on comparing winter and summer deposition patterns. Traps were deployed in late January 2023 and replaced every two weeks with a new, pre-weighed pad until April 12, 2023. Traps were then re-deployed June 21, 2023 in Chorro Creek marsh sites and July 2023 for the fringing marsh at Sweet Springs and replaced monthly until September 27, 2023. Once removed from the field, pads were dried in an 80°C oven until constant mass and weighed. We used loss-on-ignition (LOI) to determine the organic fraction of deposition. Pads were placed in a muffle furnace and burned at 500°C for at least 4 hours and reweighed for LOI.



Figure 7. Sediment deposition pad placed in marsh to track seasonal deposition patterns. Photo credit: Jenn Fields.

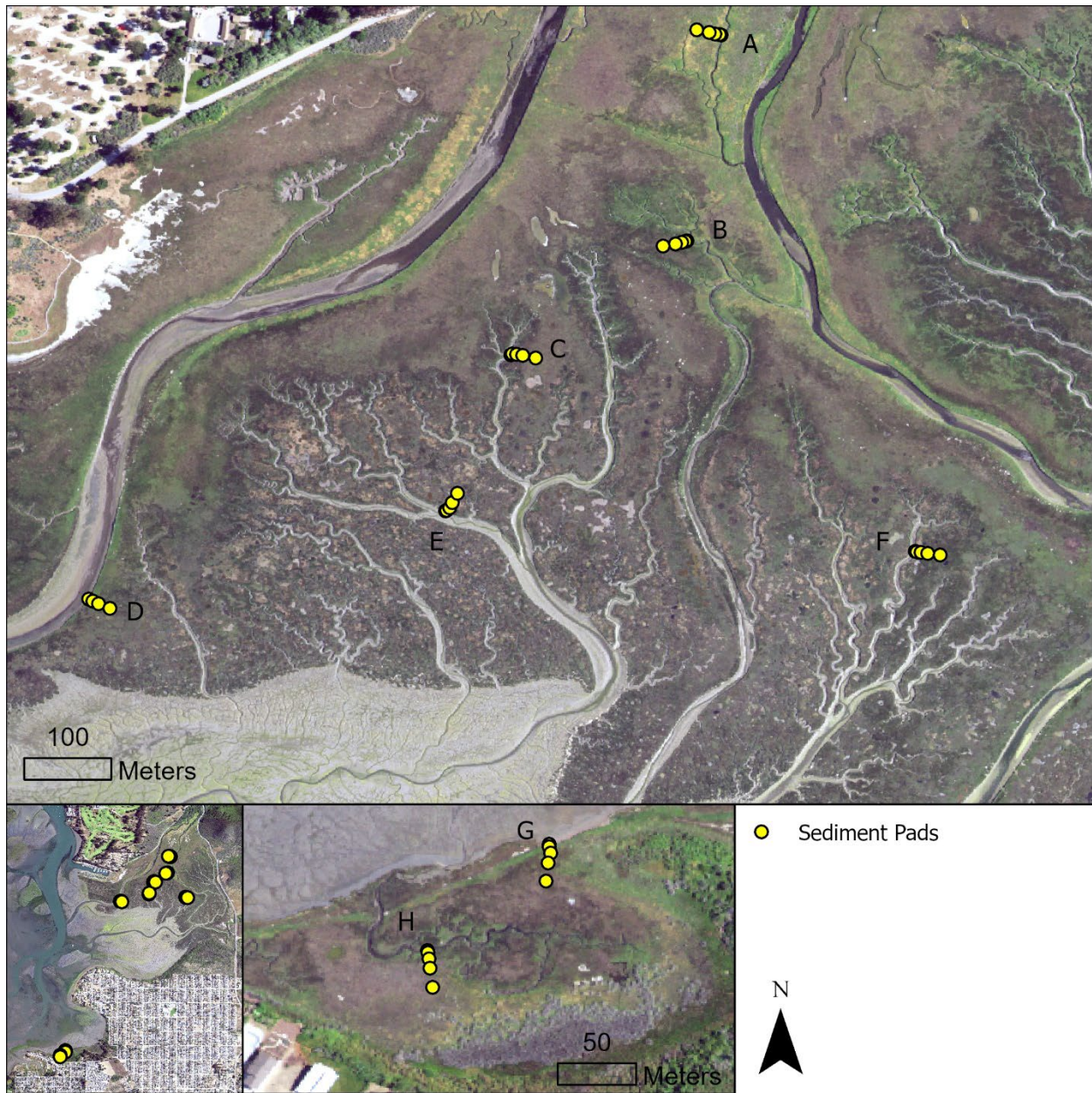


Figure 8. Map of 2023 sediment deposition transect locations with marker horizon plots. Basemap imagery is from the National Agricultural Inventory Program, 2020.

2.5 Model Description

We developed a new modeling framework (WARMER-Coast) that integrates tidal and riverine hydrodynamics, sediment transport, plant community dynamics, and belowground processes to simulate the effects of alternative environmental futures on bathymetry and vegetation across Morro Bay (Fig. 9). Typical models that are used to assess tidal wetland vulnerability to sea-level rise neglect the spatial interactions of key processes, such as edge

erosion and sediment transport (Fagherazzi et al., 2020; Breda et al., 2021). WARMER-Coast simulates them explicitly using a tidal-phase averaging approach that captures variation in tidal range and differences in tidal phase velocities. Our framework was inspired by CoastMorph2D (Mariotti and Murshid, 2018) and MarshMorpho2D (Mariotti et al., 2020) but simulates processes at a resolution and fidelity more suited for decadal-scale simulations relevant for decision makers.

To accommodate seasonal differences amongst major physical drivers (e.g. wind, tides, and riverine input) each modeled year was subdivided into seasons corresponding to different hydrological conditions. Within each of these seasons the model was further subdivided by freshwater flow conditions as outlined in the subsections below. This approach captures both typical flow conditions and short-duration, high-discharge events, which can contribute disproportionately to sediment erosion and transport. Because hydrodynamic conditions are solved as steady states, sediment transport associated with each representative flow condition is weighed by its duration and summed to estimate net seasonal transport.

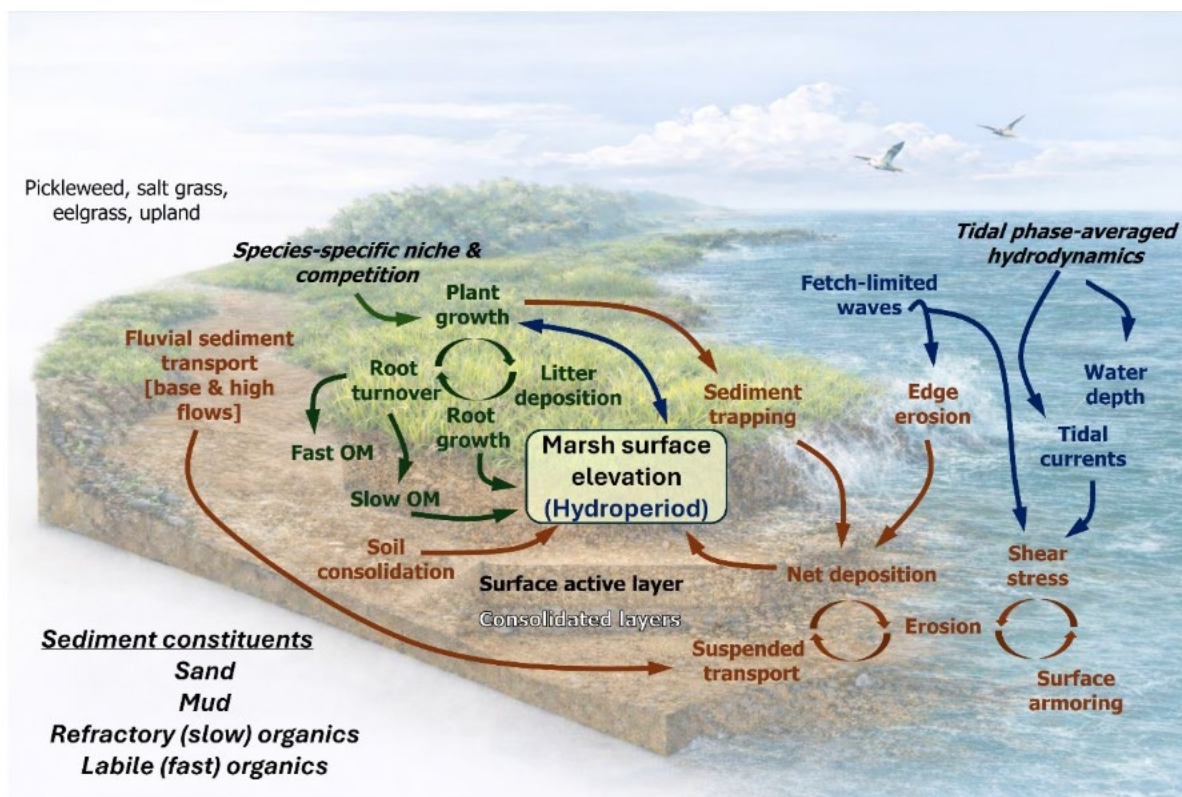


Figure 9. Conceptual diagram of WARMER-Coast model.

2.5.1 Hydrodynamics

To simulate tidal velocities, which are key for mobilizing sediment via bed erosion and controlling deposition patterns, we divided the water level time series into four representative tide ranges, spring high, spring low, neap high and neap low. For each of these representative tide ranges we generate baseline tidal velocities following the tidal dispersion methodology of DiSilvio et al. (2010) with a constant Manning's friction coefficient across the domain that represents bare substrate friction. Baseline fluvial flow estimates are simulated in a similar fashion for five separate flow bins to cover base flow conditions as well as high flow conditions summarized by stage percentile (p0-50, p50-90, p90-99.5, p99.5-100).

From these initial estimates, tidal flow is represented by characteristic ebb and flood phases. This two-phase representation provides a computationally efficient approximation of tidal asymmetry, which can produce differences in the duration and magnitude of flood and ebb currents and associated sediment transport (Dronkers, 1986; Friedrichs and Aubrey, 1994). In mixed semidiurnal–diurnal systems such as those along the U.S. West Coast, however, tidal asymmetry also varies with the relative amplitude and phasing of the principal tidal constituents and with estuarine distortion of the tidal wave (Nidzieko, 2010; Hudson et al., 2026). The dispersion solution is treated as the representative ebb-directed tidal flow field, while the corresponding flood field is generated by reversing the flow direction and scaling its magnitude by a user-defined flood-to-ebb ratio that can vary among representative tidal ranges. This simplified representation captures differences in characteristic flood and ebb transport while avoiding explicit simulation of individual tidal cycles.

River discharge is assumed to persist throughout both tidal phases and is combined with the phase-specific tidal transport in discharge space before being converted back to velocity. Each representative tidal range is paired with up to five fluvial-flow regimes, producing as many as 10 initial combined flow fields (5 fluvial-flow regimes $\times$ 2 tidal phases) for each tidal-range class. These fields provide the starting point for subsequent corrections that account for channel curvature and spatial variation in momentum and friction.

To improve the fidelity of these dispersion-based flow field estimates, a two-step correction is applied. First, a stream function-based curvature correction is used to account for the redistribution of momentum that occurs in curved channels due to secondary circulation and helical flow. In the absence of this correction, depth-averaged solutions tend to place maximum velocities along the inner bank of channel bends, whereas observations and higher-order hydrodynamic models show velocity maxima shifting toward the outer bank because of curvature-induced momentum transport and flow separation processes

(Kalkwijk and Booij, 1986; Blanckaert and Graf, 2004; Bo and Ralston, 2020). The correction is applied after tidal and fluvial velocity fields are combined, allowing the resulting flow field to reflect the phase-specific interaction between channel curvature, river discharge, and tidal forcing.

Second, a momentum correction is applied to account for spatially varying frictional resistance and momentum diffusion across the domain. Effective drag fields are calculated from substrate roughness in unvegetated areas and from species-specific vegetation characteristics, including frontal area density, canopy height, and drag coefficients, scaled by the fractional cover of each species. This approach follows established formulations for representing vegetation-flow interactions, where vegetation extracts momentum from the flow through form drag and modifies turbulent exchange within and above the canopy (Nepf, 1999; Baptist et al., 2007; Luhar and Nepf, 2013). Because tidal and river forcing are adjusted together through the momentum–continuity solution, the resulting flood and ebb currents are not simple linear superpositions of tidal and fluvial velocities.

The hydrodynamic simulations for each season therefore represent up to 40 unique flow conditions (4 tidal-range classes $\times$ 5 fluvial discharge classes $\times$ 2 tidal phases), allowing spatial patterns of flow velocity and sediment transport to respond to interactions among tidal forcing, river discharge, channel morphology, and vegetation structure.

2.5.2 Fluvial flows

To represent seasonal and event-scale variability in river discharge, fluvial flow is simulated for five representative flow bins spanning baseflow through extreme flood conditions. Under low and moderate river stages, flow is assumed to remain confined within the channel network. In these cases, water depths are calculated as the sum of tidal inundation depth and river depth, and velocities are solved over the connected channel system using the same dispersion-based framework described above.

When river stage exceeds a user-defined overbank threshold, floodplain inundation is explicitly simulated. River boundary conditions are expanded laterally from the channel network across hydraulically connected floodplain areas identified from the local topography. Floodwater propagation is constrained to connected low-lying terrain and limited by a maximum inundation distance from the channel. Water-surface elevations are initialized from river stage and allowed to decrease with downstream and lateral distance from the source channel, representing attenuation of flood energy across the floodplain. Where multiple river branches contribute to inundation, the maximum local water-surface elevation is retained. The resulting floodplain water-surface elevation field is then smoothed to remove numerical discontinuities while preserving channel-stage boundary conditions. Overbank flooding is represented using a stage-based floodplain connectivity approach in

which inundation extent is determined from local topography, hydraulic connectivity to the channel network, and river stage. Similar approaches have been widely used to efficiently represent river-floodplain exchange and inundation dynamics without requiring fully dynamic shallow-water solutions (Yamazaki et al., 2011; Czuba et al., 2019; Tull et al., 2024).

The floodplain inundation surface is combined with tidal water depths to define the active hydrodynamic domain for each flow condition. Flow velocities are subsequently solved over the expanded inundated area, allowing floodwaters to move through both channelized and overbank environments. This approach permits the modeled wetted area to dynamically expand during high-discharge events while maintaining computational efficiency during more common channel-confined flow conditions. Because extreme overbank events occupy only a small fraction of the simulation period, this threshold-based formulation efficiently captures the first-order effects of floodplain connectivity and inundation extent without requiring a fully dynamic shallow-water solution (Bates et al. 2010).

2.5.3 Edge Erosion

To simulate edge erosion, we use the finite-depth, fetch-limited wind-wave growth equations of Young and Verhagen (1996), which account for both fetch and water-depth constraints on wave development. Fetch is calculated from the elevation model in 24 directions and weighted based on locally observed hourly wind records. The directional fetch is then smoothed to generate continuous fields of fetch exposure. We assume that edge erosion is proportional to local wave power and hydrodynamic exposure, with vegetation reducing erodibility. Sub-grid retreat is tracked as fractional cell width, distributing eroded soil material via downslope diffusion.

2.5.4 Bed Erosion

Bed erosion is represented as a two-layer system consisting of a mobile surface layer and an underlying consolidated bed. Erosion is driven by exceedance of the applied bed shear stress above layer-specific critical shear stress thresholds using an excess-stress formulation (Partheniades, 1965; Ariathurai and Arulanandan, 1978). The surface layer is assumed to be relatively porous and weakly consolidated, while the underlying consolidated bed develops greater resistance to erosion through compaction, dewatering, and aging processes that increase bulk density and sediment strength (Parchure and Mehta, 1985; Sanford and Maa, 2001). Critical shear stress for erosion is therefore allowed to vary as a function of sediment properties and consolidation state, consistent with observations from estuarine and marsh sediments where erosion resistance increases strongly with bulk density and depositional history (Mitchener and Torfs, 1996; Grabowski et al., 2011).

Erosion occurs hierarchically, with sediment removed first from the mobile surface layer and subsequently from the consolidated layer once the surface layer is exhausted. This conceptualization is consistent with the distinction between recently deposited, readily erodible material and deeper consolidated deposits commonly employed in cohesive sediment transport models (Winterwerp and van Kesteren, 2004). To limit unrealistically persistent erosion of consolidated deposits, a simple armoring mechanism is implemented whereby the critical shear stress increases as cumulative erosion progresses. Similar approaches have been used to represent selective removal of fine material, exposure of more resistant sediments, and strengthening of the bed surface during prolonged erosion events (Harris and Wiberg, 2001; Sanford and Maa, 2001).

2.5.5 Sediment Transport

WARMER-Coast explicitly tracks the fate of four soil constituents: sand, mud, refractory organic matter (ROM), and labile organic matter (LOM). Each constituent is transported using a steady advection-diffusion-reaction formulation that balances erosion, transport, deposition, and settling within the water column (Fischer et al., 1979; Winterwerp and van Kesteren, 2004). Similar formulations have been widely applied in estuarine and wetland environments to represent the transport of suspended sediments under spatially varying flow conditions (Dyer, 1973; Sanford, 2008). Each constituent may have distinct transport properties, particularly settling velocity, although for simplicity we assume a settling velocity of 0.5 mm s^{-1} for sand and 0.1 mm s^{-1} for mud and organic particles. These values are within the range commonly reported for fine estuarine sediments and particulate organic matter (Krone, 1963; Mudd et al., 2010).

Direct capture of suspended material by vegetation is represented by scaling effective settling velocity as a function of plant cover. This approach reflects the ability of emergent vegetation to enhance deposition through flow attenuation, turbulence suppression, and particle interception within the canopy (Leonard and Luther, 1995; Nepf, 1999; Mudd et al., 2010). Sediment transport is solved independently for each hydrodynamic condition and subsequently aggregated according to the duration of each flow event, thereby capturing variability associated with tidal phase, tidal range, and fluvial discharge. Deposited material is initially incorporated into the surface sediment pool and subsequently transferred into underlying soil layers through constituent-specific consolidation and burial processes, consistent with conceptual models of marsh accretion and cohesive sediment dynamics (Allen, 2000; Temmerman et al., 2003; Winterwerp and van Kesteren, 2004).

2.5.6 Plant Dynamics

Plant dynamics were simulated on the model grid by tracking live and standing dead cover for each species. Species growth and mortality are based on a niche-based function (Figs.

16-17), here derived based on relative elevation. Stress modifiers to the niche include hydrodynamic forcing (water velocities), wave power and wave-induced shear stress, sediment conditions (suspended sediment concentrations [SSC] limitations in seagrass), and direct burial (when seasonal deposition is deeper than a species-specific threshold, which by default is half the canopy height). Local growth of each species is modified by biotic interactions, represented as a balance between competition from neighboring heterospecifics and facilitation from conspecifics. Recruitment occurs based on a general background seeding rate as well as neighbor-driven propagule supply/rhizome expansion. Growth is allocated proportionally across species in each cell, based on the available space. Losses from live biomass are transferred to the standing dead pool, which falls at specific-specific rates.

2.5.7 Belowground Processes

Belowground dynamics are represented using a vertically resolved cohort framework in which each grid cell contains stacks of soil layers with defined thickness (increasing thickness with depth; Buffington et al. 2024). At the soil surface, aboveground litter inputs are partitioned into LOM (fast decomposing) and ROM (slow decomposing) pools. Materials from the surface transport layer are moved into the top cohort based on their consolidation rate. Root biomass is distributed vertically using species-specific depth weighting functions. Live roots are split into three size classes (structural/rhizome, coarse, fine) and subject to size-and depth-dependent turnover. Dead roots are tracked and converted to particulate organic matter, which is then subject to decomposition.

Conceptually, organic matter decomposition depends on the availability of oxygen, which regulates microbial respiration and the relative importance of aerobic versus anaerobic decomposition pathways (Morris and Bowden, 1986; Megonigal, 2004). Higher soil saturation, estimated from constituent-specific hydraulic properties and hydroperiod, limits oxygen diffusion into the soil profile and therefore slows decomposition rates (Mitsch and Gosselink, 2015). In contrast, oxygenation associated with living roots can enhance decomposition through radial oxygen loss and localized oxidation of otherwise anaerobic sediments, increasing microbial activity within the rhizosphere (Armstrong, 1979; Howes et al., 1981; Morris and Bowden, 1986). Consequently, decomposition rates in WARMER-Coast vary as a function of both hydrologic controls on soil saturation and biological controls associated with live root abundance. A baseline decomposition rate is determined for LOM; that rate is divided by 1000 for ROM.

Vertical soil consolidation is represented as a rate-limited relaxation of the void ratio toward a stress-dependent equilibrium state. This approach follows the conceptual framework of one-dimensional consolidation theory, in which increases in effective stress led to

reductions in pore volume and sediment thickness over time (Terzaghi, 1943; Gibson et al., 1967). Total vertical stress is calculated from the cumulative mass of overlying material and augmented by depositional loading. Changes in cohort volume, and consequently soil elevation, depend on the rate of deposition, the composition of mineral and organic soil constituents, live and dead root volume, and available pore space.

WARMER-Coast was developed in R (R Core Team, 2026, version 4.5.3) and C++.

2.6 Model Application to Morro Bay

WARMER-Coast assumes elevation is relative to mean sea level (MSL). MSL is the offset from the North American Vertical Datum of 1988 (NAVD88) and was estimated to be 0.87 m from the Port San Luis station (2001-2020 epoch, NOAA tidal gauge 9412110, NOAA Tides and Currents, accessed 24 October 2024). Harmonic tidal constituents from NOAA were used to define the flooding duration functions for each season, and the four tidal ranges (Fig. 10).

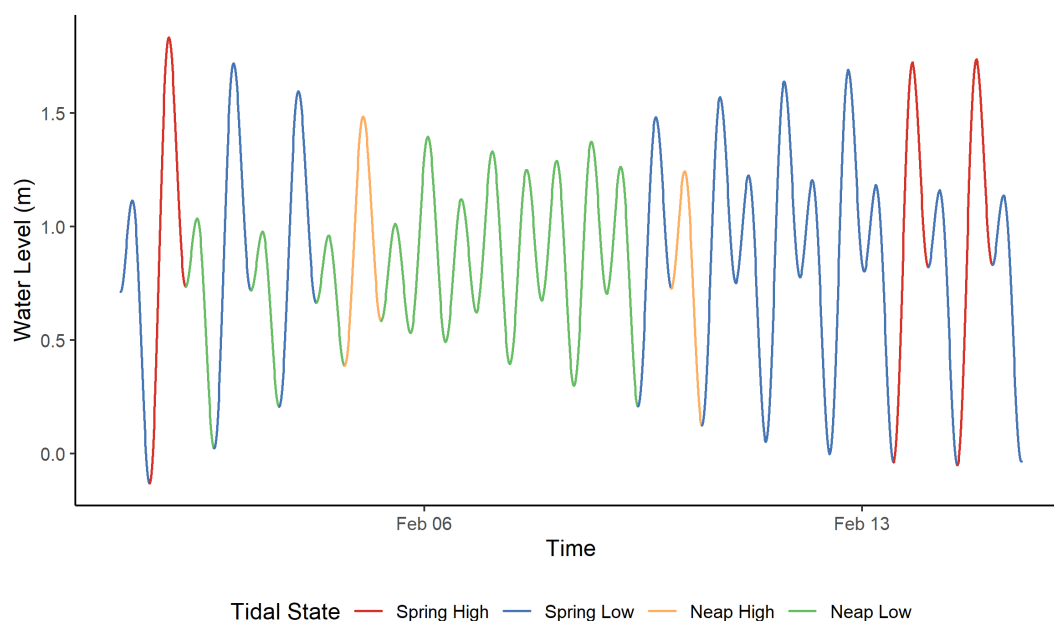


Figure 10. Mixed semi-diurnal tidal signal and the assigned tidal state for an example time period.

2.6.1 Topobathymetry

Elevation data for the 1 m digital elevation model (DEM) were compiled from two sources. The majority of the model domain was represented by a 2019 lidar dataset (Office for Coastal Management, 2023), while subtidal elevations were obtained from the 2013 California merged topobathymetry dataset (OCM Partners, 2023). Vegetation-related bias in

the lidar-derived DEM across tidal marsh areas was corrected using extensive RTK GPS elevation measurements collected in 2013 across the Chorro Creek marsh (Thorne et al., 2016). Vertical bias, defined as the difference between the lidar bare-earth DEM and RTK GPS elevations, was modeled as a function of DEM elevation and two vegetation indices derived from 2020 National Agriculture Imagery Program (NAIP) imagery: the Normalized Difference Vegetation Index (NDVI) and Green Normalized Difference Vegetation Index (GNDVI). NDVI was calculated using the near-infrared and red bands, whereas GNDVI substituted the green band for the red band. Bias was modeled using a random forest algorithm with default parameters implemented in the R package randomForest (Liaw and Wiener, 2002). Prior to correction, the root-mean-squared error (RMSE) between lidar and RTK GPS elevations was 0.206 m. Following correction, RMSE was reduced to 0.049 m and mean error was effectively zero. The vegetation-bias correction was applied only within tidal marsh areas.

WARMER-Coast is resolution agnostic. To balance computational efficiency with spatial fidelity, simulations were conducted at a 30-m spatial resolution (each pixel is 0.22 acres). To better preserve narrow channels during aggregation to the coarser grid, cell elevations were assigned using the 25th percentile of the underlying higher-resolution elevation data rather than the mean. Further evaluation of model performance at finer spatial and temporal resolutions would be beneficial to compare against the sediment pad deposition study, and our ongoing development is exploring approaches for incorporating subgrid-scale information into the hydrodynamic and sediment-transport calculations.

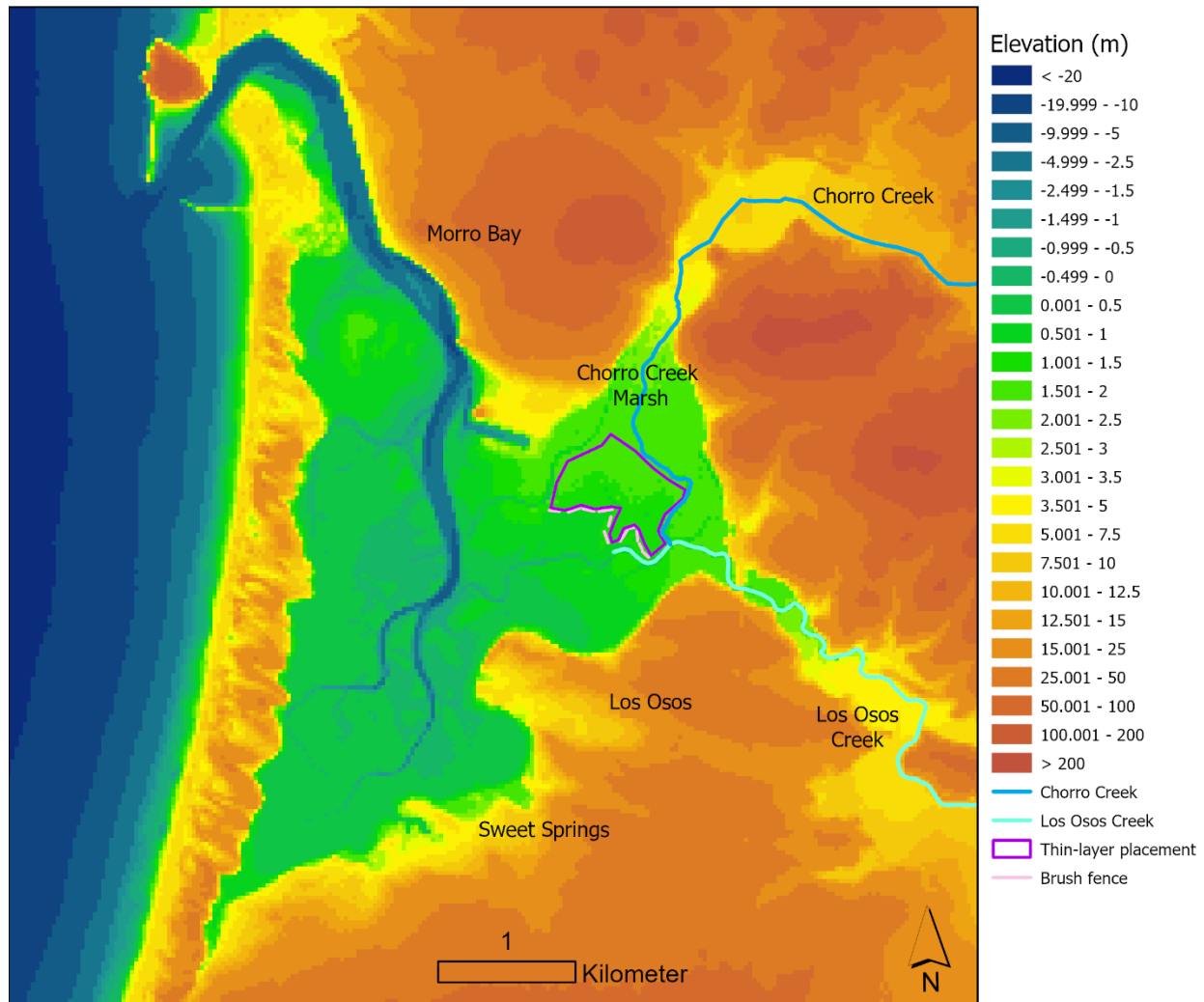


Figure 11. Model domain, elevation (30 m resolution), creek inputs and location of simulated management actions for the WARMER-Coast application to Morro Bay estuary. Elevation is in meters relative to the North American Vertical Datum of 1988.

2.6.2 Wind climatology

Hourly wind speed data and direction data from the CeNCOOS BS1 monitoring station (2016-2023; CeNCOOS, n.d.) were used to define the characteristics of wave generation across the domain. Wind observations were grouped into 24 directional sectors, and for each sector a spatially explicit fetch field was calculated by tracing an upwind path from each water cell to the nearest shoreline or other land boundary. The resulting distance represents the unobstructed over-water distance available for wind-wave development under winds from that direction. Wind direction records were used to identify the fetch field

applicable to each modeled wind condition, while wind speed was used separately in the wave-generation calculations to determine the magnitude of wave development over the available fetch. Thus, the fetch fields describe the geometry of wind exposure, whereas the observed wind climatology determines how frequently, and under what wind speeds, each directional fetch field contributes to wave conditions.

2.6.3 Fluvial input

River stage monitoring at the Canet Street bridge over Chorro Creek provided the baseline fluvial information (San Luis Obispo County Flood Control and Water Conservation District, n.d.), and a revised stage-discharge relationship developed by the Morro Bay National Estuary Program was used (Morro Bay National Estuary Program, 2024) to define boundary condition river velocities. Regular monitoring of suspended sediments at the Canet gauge by the MBNEP supported the development of a predictive spline model for SSC based on discharge; we leveraged this relationship in our projections of fluvial sediment loading. Los Osos creek does not have a robust monitoring program. Instead, we assumed a constant proportion (0.162) of the Chorro Creek sediment load was being delivered by Los Osos to the estuary, following prior sediment loading analysis that showed Chorro creek provides ~86% of the sediment each year (Tetra Tech, 1998).

2.6.4 Grain size distributions

Soil samples collected throughout the estuary were used to develop a multiple regression model predicting sediment grain-size composition, specifically the relative fractions of sand and mud. Spatial predictors included spring high-tide water velocity, the annual proportion of time flooded, and Euclidean distance from the mouth of Chorro and Los Osos creeks. The resulting model explained a substantial proportion of the observed spatial variability in grain size ($R^2 = 0.61$; Fig. 12).

The sand-proportion model was used to initialize the spatial distribution of sand and mud soil constituents in WARMER-Coast. Initial soil organic matter was assumed to consist entirely of refractory organic material and was parameterized as an inverse function of annual flooding duration, consistent with patterns observed in soil cores. The organic fraction decreased linearly from a maximum of 0.20 in areas that were rarely flooded to a minimum of 0.018 in frequently flooded areas, with the lower bound imposed to maintain realistic organic matter concentrations across the estuary.

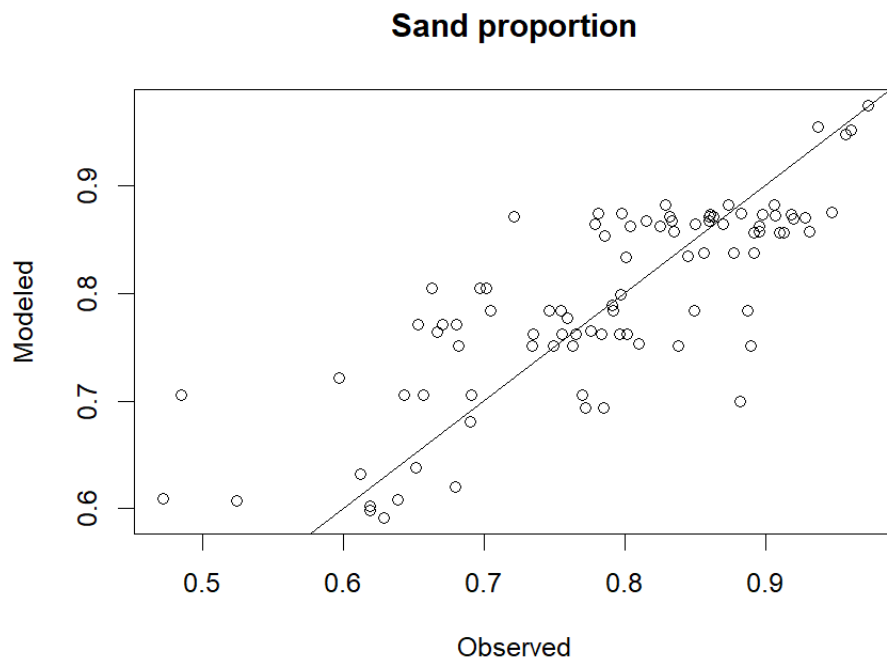


Figure 12. The relationship between observed and modeled proportion sand grain size across Morro Bay. The model was used to inform initial conditions for all WARMER-Coast simulations.

2.6.5 Belowground processes

Maximum rooting depth varied among species and was parameterized from available literature (Moffett and Gorelick, 2016; Cooke et al., 1993; Hughes et al., 2009). Root size-specific turnover rates were assigned so that turnover decreased with increasing root size. Bulk-density profiles from long soil cores were used to calibrate the void-ratio parameters governing mud, sand, and organic-matter contributions to soil porosity. A one-dimensional version of the model was then run across the elevations represented by the soil cores to calibrate parameters controlling organic matter accumulation and overall accretion. Calibrated parameters included species-specific maximum biomass and rates of refractory and labile organic matter decomposition, dead-root decomposition, litter deposition, and mud consolidation. Parameter optimization was performed using the differential evolution algorithm implemented in the DEoptim R package (Mullen et al., 2011).

2.6.6 Plant community niches

Four plant communities were selected for simulation across Morro Bay: eelgrass (*Zostera marina*), pickleweed (*Salicornia pacifica*), saltgrass (*Distichlis spicata*), and a generalized upland community. Pickleweed is the dominant tidal-marsh species in Morro Bay and was

expected to exert the strongest influence on belowground processes. Saltgrass was included to represent additional spatial heterogeneity within the marsh, while the upland community was included primarily to constrain pickleweed expansion and identify areas where tidal-marsh vegetation may migrate under sea-level rise. Species-specific niche suitability functions were developed from observed relationships between elevation and species presence or cover and were subsequently refined using expert judgment (Fig.13). Pickleweed and saltgrass distributions were derived from 2013 USGS vegetation surveys (Thorne et al., 2016). Eelgrass polygons mapped in 2021 (MBNEP, 2022) were converted to a 0.1-m presence/absence raster and aggregated to 1-m resolution to produce a continuous cover surface. Eelgrass cover was then related to elevation relative to mean sea level, and the resulting relationship was used, together with expert judgment, to define the eelgrass niche suitability function (Fig. 14). Eelgrass seeding and growth rates were calibrated against a time-series of mapping products produced by the MBNEP (MBNEP 2013, 2017, 2018, 2019, 2020, 2021, 2023, 2024).

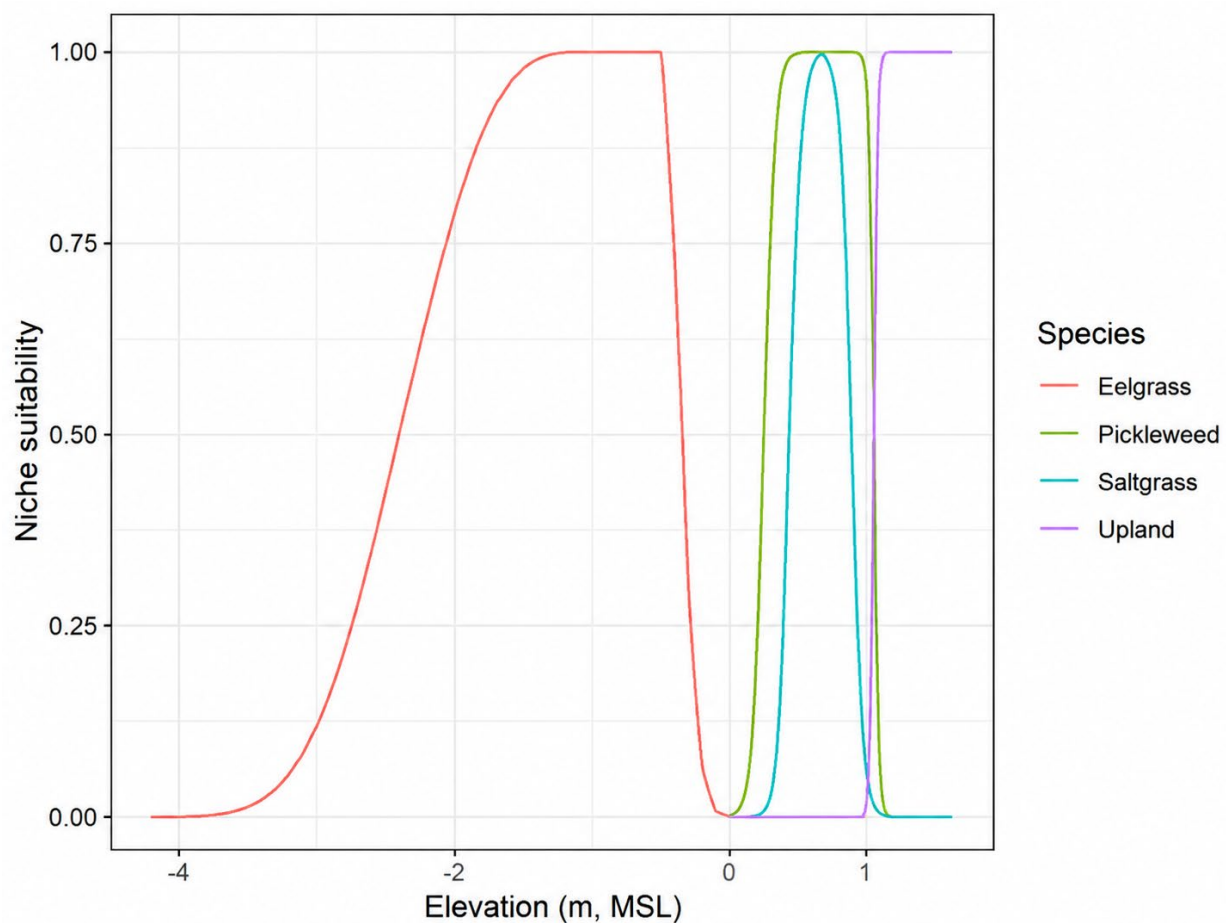


Figure 13. Simulated niche across the four species/communities.

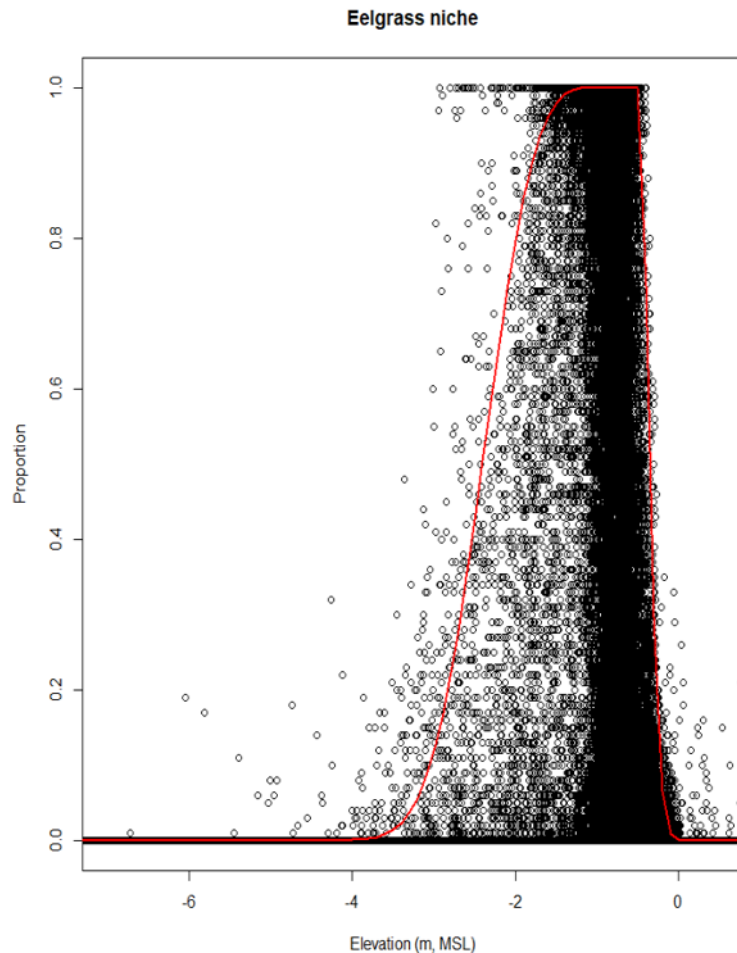


Figure 14. Eelgrass cover relative to elevation (points) and the simulated niche (red line).

2.6.7 Model calibration

Multiple phases of calibration were conducted to ensure reasonable parameterization. Modeled bulk density was calibrated against average down core bulk density from the marsh and mudflat soil cores. Decomposition rates, and the parameters that control sensitivity to flooding and root oxygenation, were calibrated against soil core-derived organic accumulation rates. Both calibrations were conducted using an 800-timestep spin-up simulation where elevation was held constant and organic and mineral deposition, as well as belowground processes, occurred as normal. A separate calibration of seagrass growth and seeding parameters was conducted using a time-series of seagrass monitoring data (2019, 2020, 2021, 2023), which corresponded to a period of rapid growth from historically low coverage (MBNEP, 2024). Rates of soil consolidation were calibrated to monitoring data of a thin-layer placement project in Chesapeake Bay (J. Carr, unpublished data). Tidal water velocities were compared to Delft3D model output (Taherkhani et al., 2023) at

representative channel locations across the estuary (Fig. 15). Calibration of key sediment transport parameters was conducted by running WARMER-Coast for 21 years, which corresponded with available stream monitoring and SET-MH data (2004-2024).

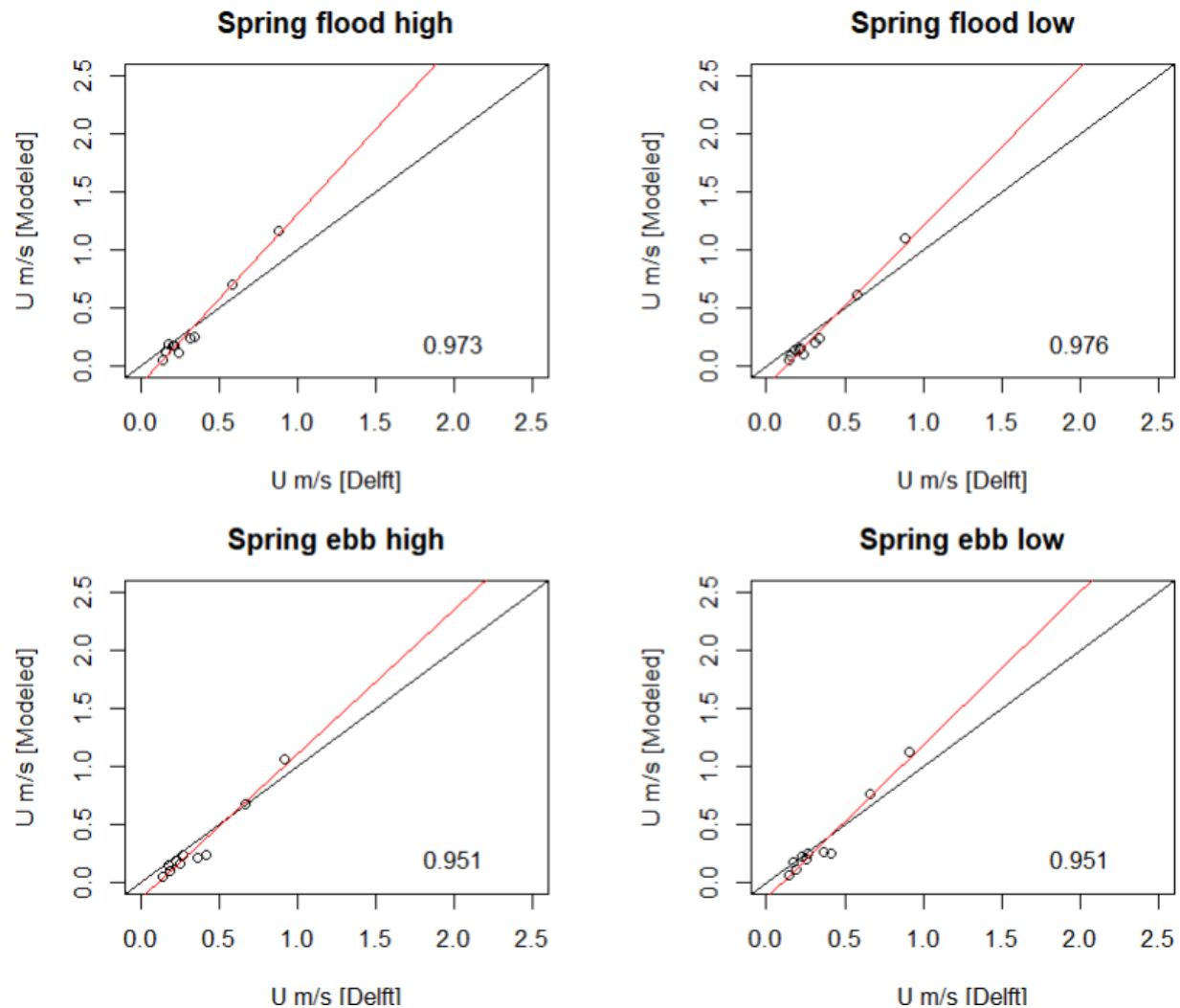


Figure 15. Comparison of tidal velocities (U) between Delft3D (x-axis) and WARMER-Coast (y-axis) at select channel locations across the model domain. Values are the correlation between the two models. Black line is the 1:1 and the red line is the linear regression.

Tidal velocity by tide range

Flood

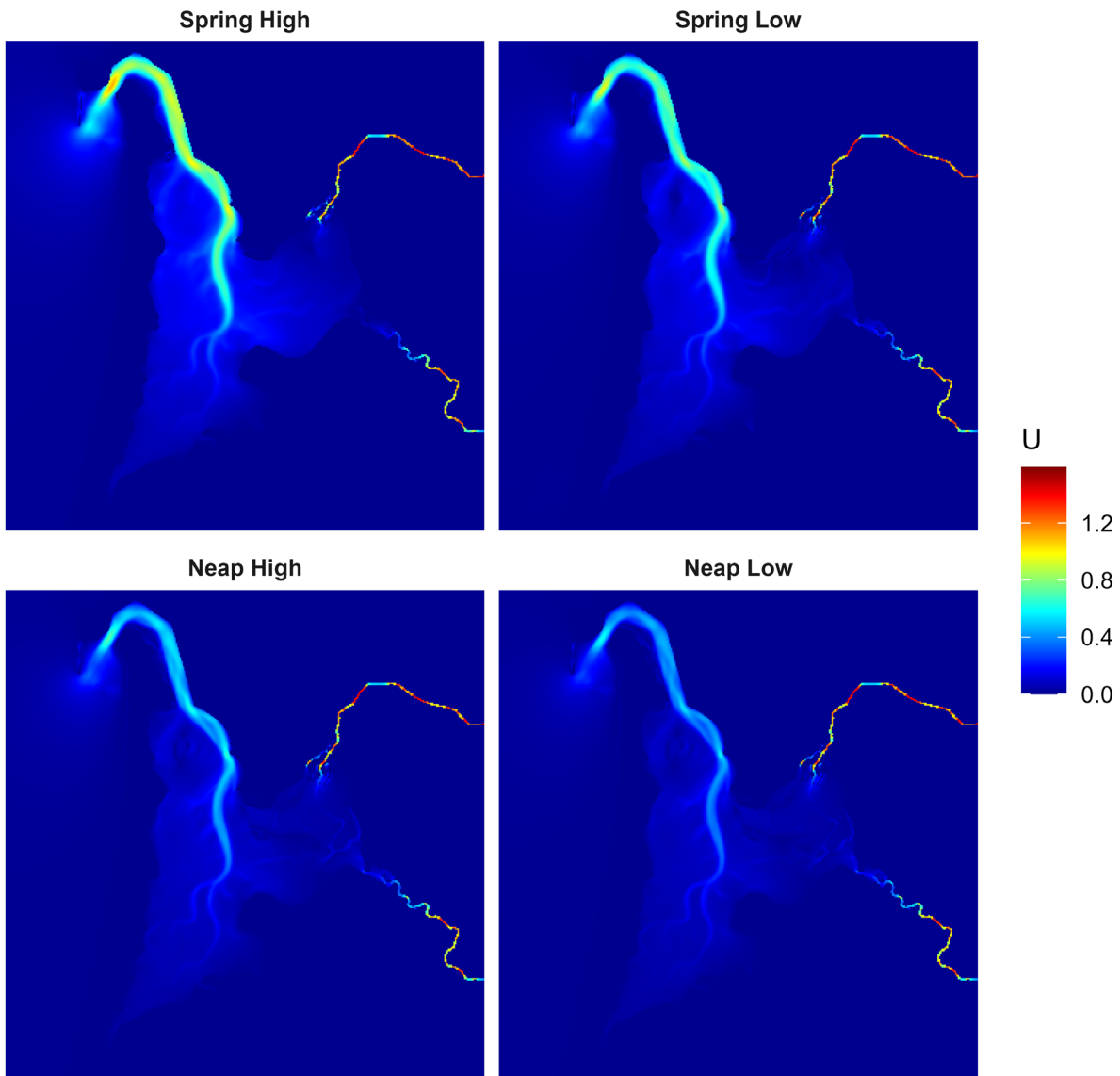


Figure 16. Spatial distribution of flood tidal velocity (U , m/s) across the model domain for each tidal state.

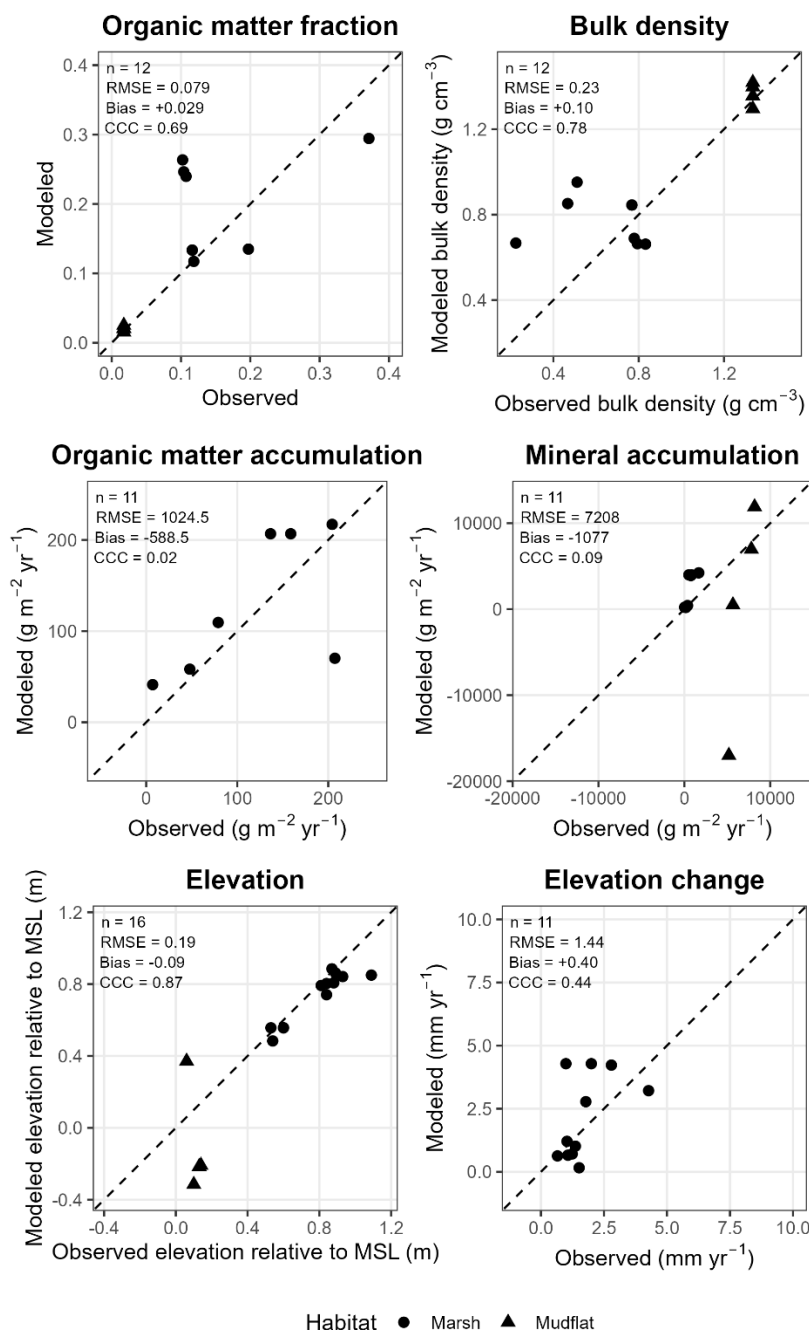


Figure 17. Comparison of observed and modeled calibration targets for marsh and mudflat sites in Morro Bay. Calibration targets include organic matter fraction, bulk density, organic matter accumulation, mineral accumulation, elevation relative to mean sea level (MSL), and elevation change rate. Circles indicate marsh sites and triangles indicate mudflat sites. Dashed lines represent 1:1 agreement between observed and modeled values. Statistics reported within each panel include the number of paired observations (n), root mean square error (RMSE), mean bias calculated as modeled minus observed, and Lin's concordance correlation coefficient (CCC). Positive bias indicates model overprediction and negative bias indicates underprediction.

2.6.8 Sea-level rise and Sediment Scenarios

We explored a range of future scenarios for Morro Bay that covered uncertainties in key drivers (Table 1). First, a combination of SLR and sediment availability scenarios were run to 2100 to understand the overall vulnerability of Morro Bay. Five SLR scenarios were run: low, intermediate low, intermediate, intermediate high, and high, which correspond to 0.18, 0.38, 0.86, 1.37, and 1.93 m of SLR in 2100 relative to 2020, respectively (Sweet et al., 2022). These are projections of relative sea-level rise and include regional effects like deep subsidence and tectonic plate movement.

Sediment delivery from the watershed is likely the most critical, yet uncertain, model input determining future evolution of Morro Bay. To explore the sensitivity of the estuary, we ran a baseline scenario using historic sediment loading, informed from stream monitoring data, and scenarios that simulated wetter and drier conditions. Sediment scenarios were imposed using class-specific scaling factors applied to sediment load (metric tons per year), discharge, event duration, and stage. In the wet scenario, the characteristics across the five modeled fluvial bins were all increased with sediment load scaled from 1.10 to 1.90, discharge from 1.05 to 1.50, duration from 1.00 to 1.50, and stage from 1.00 to 1.15. In the dry scenario, the same variables were reduced across the flow bins, with sediment load scaled from 0.90 to 0.35, discharge from 0.95 to 0.50, duration from 1.00 to 0.35, and stage from 1.00 to 0.85. This approach assumed that future changes in sediment supply would be concentrated in the upper tail of the hydrograph rather than distributed uniformly across all flow conditions, consistent with projections of disproportionate increases in peak discharge and sediment loads under climate change (Stern et al., 2020) and the dominant contribution of infrequent, high-magnitude events to coastal sediment delivery (Warrick et al., 2023).

Table 1. Future scenarios explored with WARMER-Coast across Morro Bay.

Scenarios	Description
<i>Sea-level rise</i>	
Low	0.185 m increase in sea level in 2100, relative to 2020
Intermediate Low	0.375 m increase in sea level in 2100, relative to 2020
Intermediate	0.859 m increase in sea level in 2100, relative to 2020
Intermediate High	1.350 m increase in sea level in 2100, relative to 2020
High	1.892 m increase in sea level in 2100, relative to 2020
<i>Climate</i>	
Drier	Fluvial discharge during high flow events is reduced
Historic	Fluvial discharge based on 21-year record
Wetter	Fluvial discharge during high flow events is increased
<i>Management</i>	
Thin layer placement	Sediment is added to a specific elevation across a 100-acre parcel in Chorro Creek marsh

2.6.9 Management Scenarios

Two sediment management techniques were then explored based on the results of the future scenarios: 1) thin layer placement of sediment directly on the marsh and 2) deployment of natural sediment trapping structures, conceptualized as brush fencing and installed as a fence-like structure (brush fence, hereafter). Thin layer placement of sediment was simulated by adding sediment mass within a predetermined polygon (100 acres across the lower elevations of the main tidal marsh). Three target elevations for the placement were tested, 0.4, 0.8, and 1.2 m above mean sea level. Three time periods of the initiation of placement were considered, 2040, 2060, and 2080, informed by future projections without management actions, and three placement cadence strategies were tested, a single placement and placement every 10 or 20 years. Based on grain size analysis conducted for the State Park Marina (CA Coastal Commission, 2011), we assumed that 55% of the sediment mass was mud, 40% was sand, and 5% was organic, split equally between refractory and labile organic matter. The brush fence, which in the model encouraged sedimentation by slowing water velocities and blocked wave action, was placed at the bay-fronting marsh boundary, totaling 800 m in length.

3.0 Results

3.1 Surface elevation table and marker horizon plots

Overall, all SETs had positive elevation change (Fig. 18; Bristow et al. 2026). These rates were greater near the bay where tides provide a primary source of sediment deposition. When compared with the local rate of SLR, calculated over 1973-2023 as 1.33 mm yr^{-1} from the NOAA Port San Luis tide gauge (NOAA Tides & Currents, accessed 25 October 2024), most SET sites are keeping pace with current sea level rise, especially near the bay edge. Marker horizon (MH) plot trends were similar to SET trends (Fig. 19). Positive change and greater rates near the bay (especially in the mudflats – the darkest blue lines). When compared to SLR rates, nearly all MH sites were currently outpacing SLR.

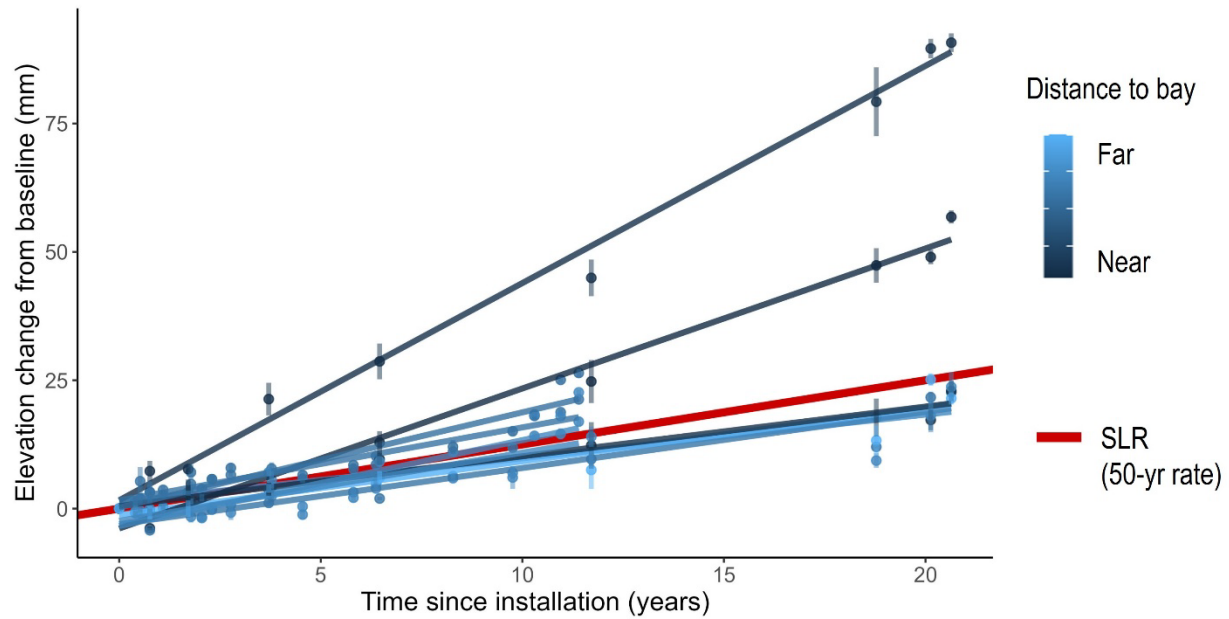


Figure 18. Elevation change from baseline (mm) over time from all SET stations in Morro Bay.

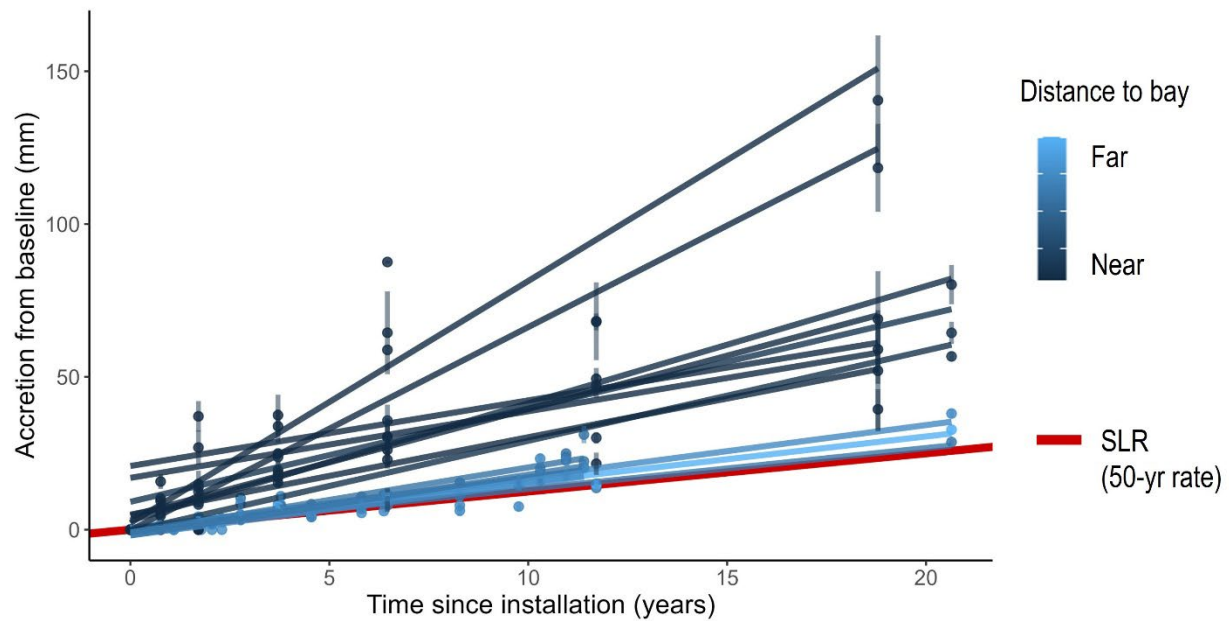


Figure 19. Accretion from baseline (mm) over time from all marker horizon locations in Morro Bay.

3.2 Soil Cores

In the Chorro Creek marsh, bulk density is lowest in low marsh soil cores (Fig. 19). High marsh and upland cores are more variable along the depth profile and mudflat cores have higher bulk density than low marsh sites. Cores decreased in organic matter as the depth increased besides the mudflat and upland cores that stayed consistently low. The highest percent organic matter occurred within high and low cores, with high marsh cores decreasing more quickly along the soil profile. The fringing marsh at Sweet Springs has low bulk density but high percent organic matter, suggesting the soil is peat dominant.

In general, low marsh sites had a higher proportion of organic matter and lower bulk density through time (Fig. 20). These samples were used to calculate mass-based accumulation rates using long-term SET monitoring and for calibrating the marsh evolution model. Data are available in Buffington et al. (2026).

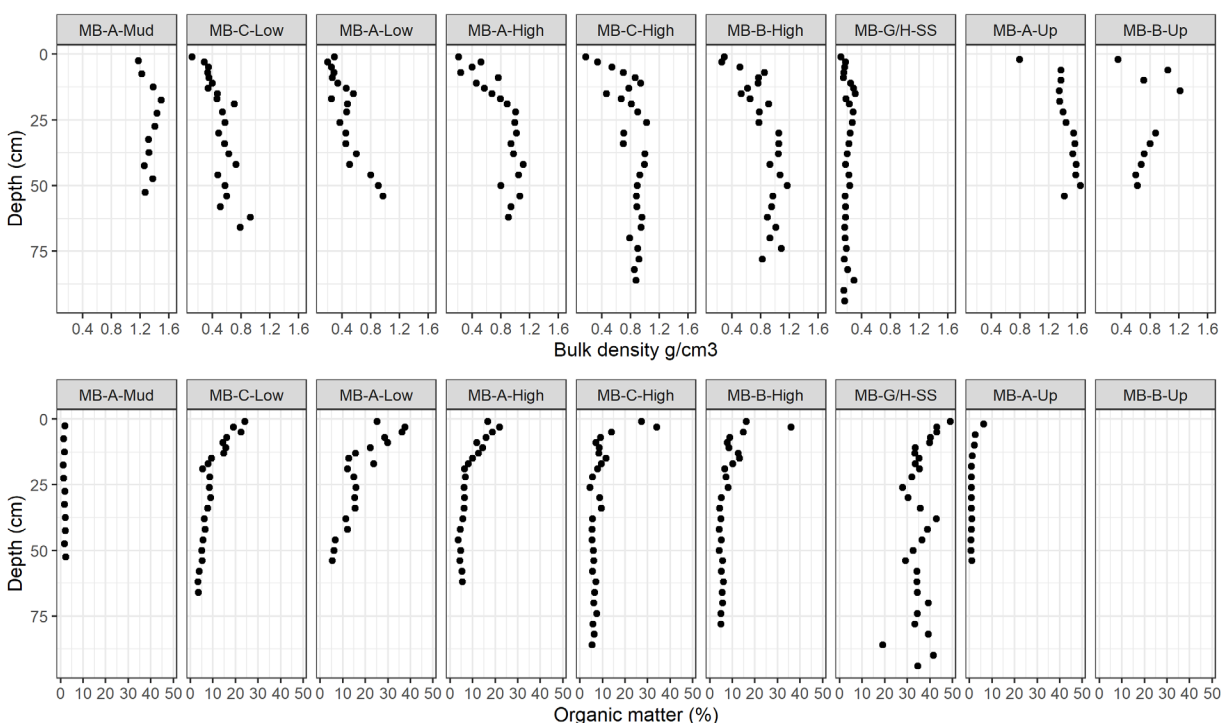


Figure 19. Bulk density (top) and percent organic matter (bottom) sampled with long soil cores along the soil core depth. Percent organic matter was not processed for the MB-B-Up core. Cores sorted by elevation [low-high, left--right], except for G/H-SS which is a fringing peat marsh in a geographically distinct region of the bay.

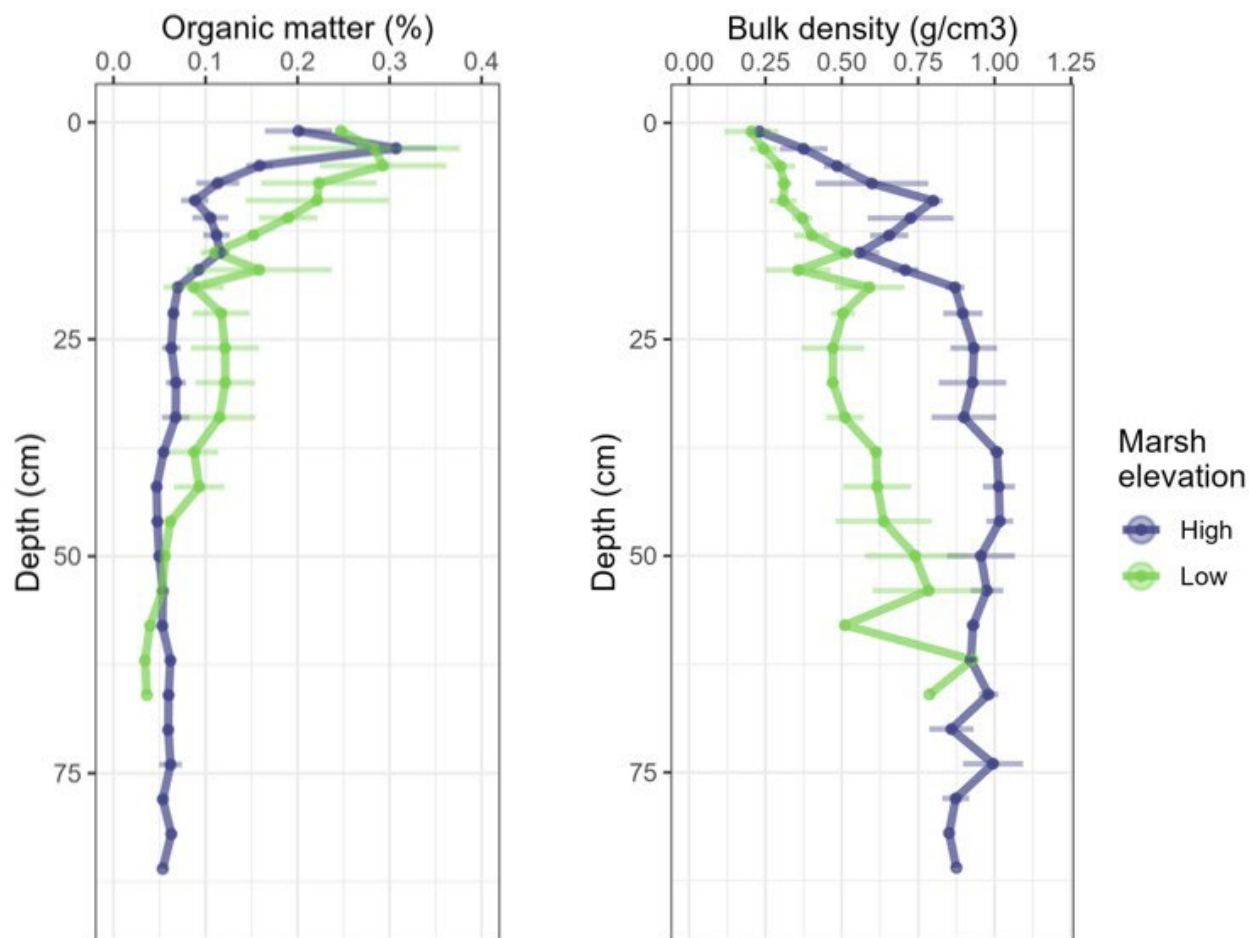


Figure 20. Mean ($\pm$ SE) percent organic matter (left) and bulk density in g/cm^3 (right) of low (green) and high (purple) long soil cores along soil core depth.

Grain size varied throughout the bay based on elevation, water velocity, and distance from creek channels (Fig. 21). The sandier concentrations were located near ocean inlet channels and downwind and current of the sandspit. The mudflat closest to the tidal marsh and creek outlets had the highest concentration of fine particles. Grain size near the mouth of the bay was collected and shared by Hannah Lyford (personal communication).

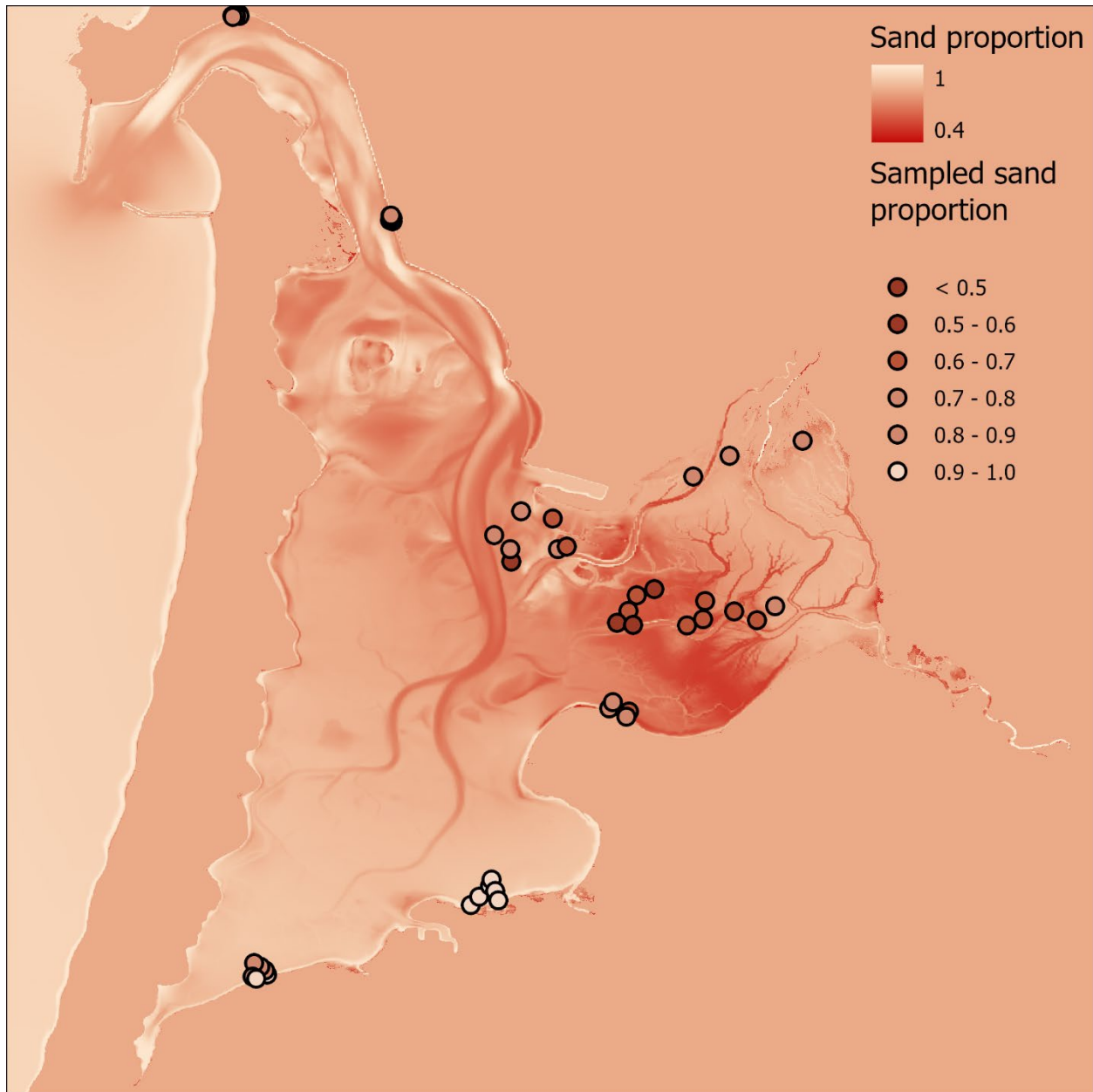


Figure 21. Grain size across Morro Bay. Sand proportion was modeled as a function of elevation, water velocity, and distance from river mouth. Data points are from this study and Lydford et al. (*in prep*).

3.3 Sediment deposition

We found distinct seasonal and spatial patterns in deposition rates in grams of dried sediment/meter sq/day (Fig. 22). Higher deposition occurred in the upper tidal marsh during the winter likely due to large run-off events (Fig. 23). In the summer, low marsh sites had

higher deposition. Further analysis is needed to understand the relative importance of creek discharge, wind, and tidal inundation on the spatial deposition patterns that were observed.

The 2023 MH plots showed a clear seasonal pattern in sediment accretion. Low-marsh sites along Chorro Creek accumulated the most sediment overall, with accretion appearing to peak following the summer high-tide period (Fig. 24). Compared with the current local rate of sea-level rise, most sites accumulated sediment rapidly enough to keep pace, consistent with patterns observed at long-term MH sites. Seasonal differences in accretion suggest that particular periods of the year may contribute disproportionately to annual elevation gain.

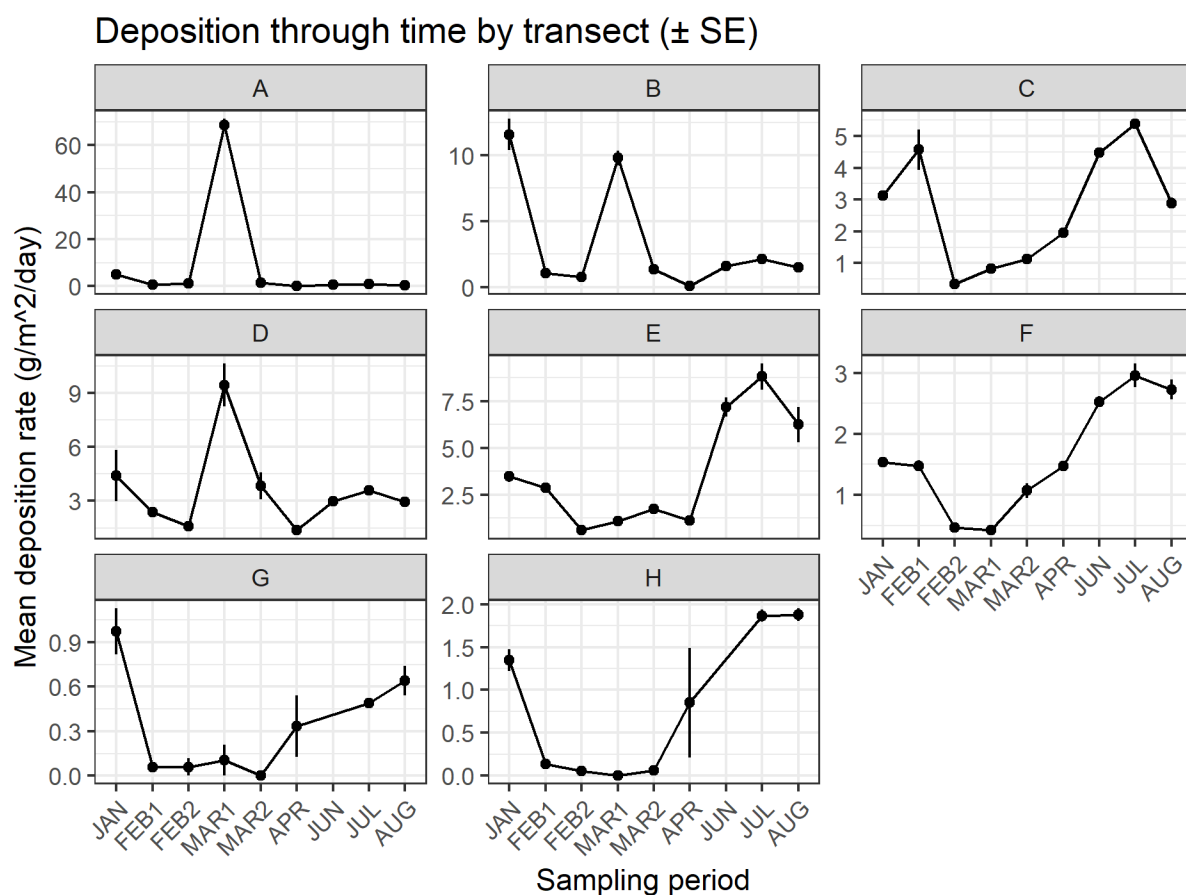


Figure 22. Mean ($\pm$ SE) sediment deposition through time by sampling transect (transect averages; five stations per transect and two traps per station). The deposition study was conducted in 2023. Transect locations are defined in Figure 8.

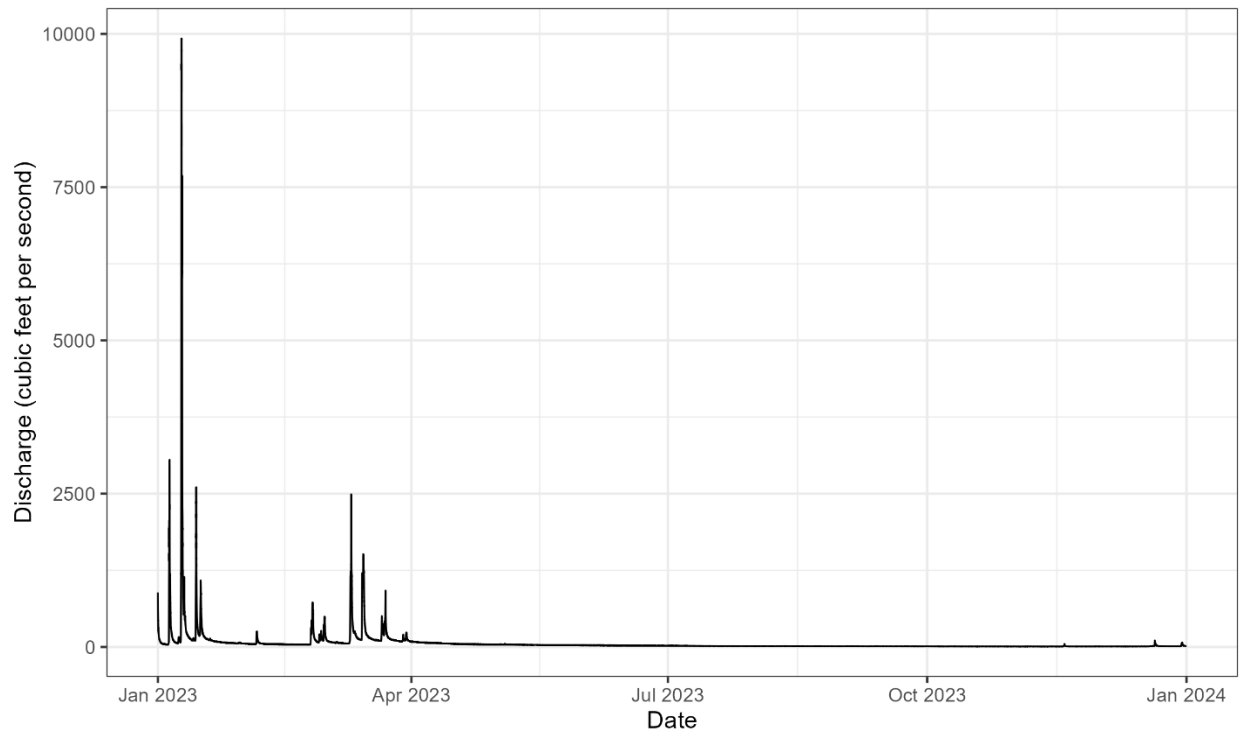


Figure 23. Creek discharge (cubic feet per second) at the Canet Bridge gauge on Chorro Creek for 2023.

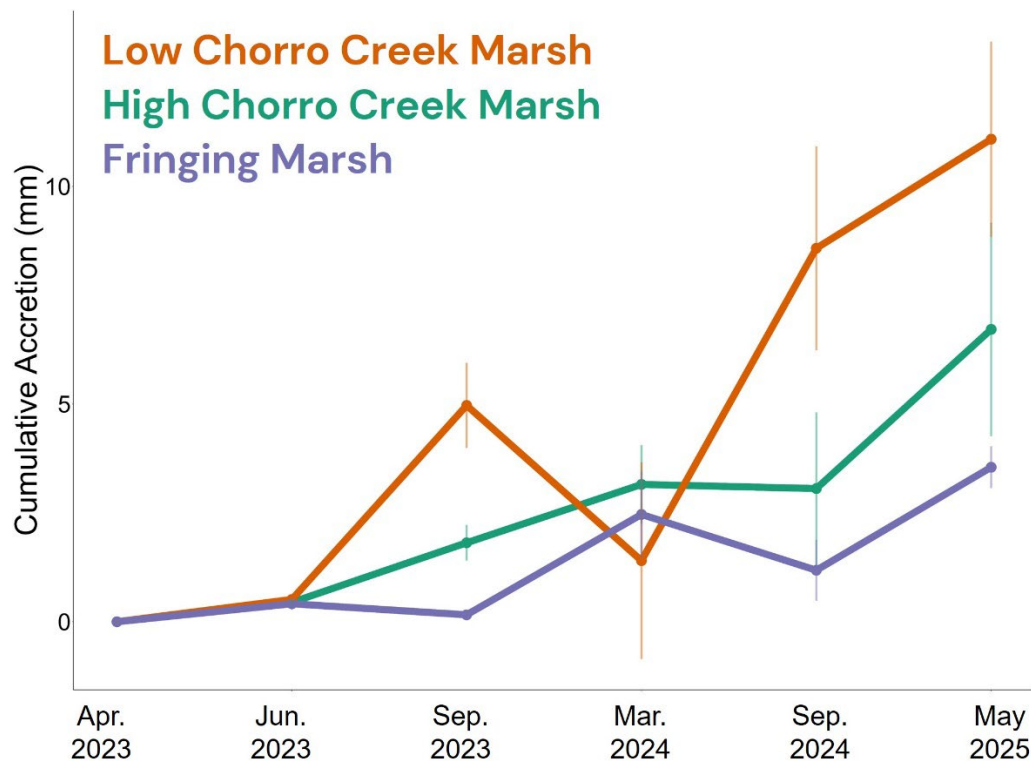


Figure 24. Accretion from baseline (mm $\pm$ SE) over time at sediment deposition study MH locations in low (orange), high (green), and fringing/Sweet Springs marsh (purple) locations.

3.4 Sea-level rise vulnerability

Projections of estuary evolution varied widely across the SLR and climate scenarios we explored. Across all SLR scenarios, the model projected greater marsh area under the wetter climate scenario and less marsh area under the drier climate scenario (Fig. 25, Table 2; Buffington and Carr 2026). Increases in marsh area under wetter conditions exceeded the corresponding losses under drier conditions. The asymmetrical response arose in part because wetter conditions more frequently pushed river stage above the bankfull-height threshold, allowing sheet flow across the marsh and increasing sediment delivery to the marsh platform.

Projected marsh persistence depended strongly on the interaction between SLR rate and sediment availability, with greater sediment loading delaying or reducing marsh loss along a given SLR trajectory (Fig. 25). Under low and intermediate low SLR, tidal marsh area persisted or expanded through 2100. Under intermediate SLR, marsh area began a sustained decline around 2070 and decreased by 37.2% by 2100 under the drier climate scenario, whereas the wetter climate scenario maintained nearly all the initial marsh area. Intermediate high and high SLR produced substantially greater losses, with marsh area declining by 66.8% and 77.6%, respectively, by 2100 under the reference climate trajectory,

and losses beginning around 2050–2060 before accelerating later in the century. Modeled climate-driven differences in sediment delivery strongly affected both the timing and magnitude of marsh loss. The intermediate SLR scenario produced the widest range in end-of-century outcomes, from a 37.2% decline under the dry scenario to less than 0.01% decline under the wet scenario. Increased sediment delivery therefore delayed the onset of marsh loss and, under intermediate SLR, could offset projected losses through the end of the century. Under intermediate high and high SLR, however, increased sediment delivery reduced but did not prevent substantial marsh loss.

Patterns of habitat gain and loss reflected the same divergence among modeled SLR trajectories (Fig. 26). Marsh gains exceeded losses throughout the century under low and intermediate low SLR, whereas losses increasingly outpaced gains as SLR accelerated. Under intermediate SLR, cumulative gains and losses remained similar through approximately 2080 before losses increased rapidly. Intermediate high and high SLR shifted toward net marsh loss earlier, with cumulative losses increasing sharply after approximately 2060 and greatly exceeding gains by 2100. Spatial projections showed relatively little divergence among scenarios by 2040, but differences became increasingly pronounced after 2060 (Figs. 27–30). The higher SLR scenarios progressively converted lower-elevation and interior marsh to mudflat and subtidal habitat, while emergent marsh persisted more extensively along channel margins and higher-elevation portions of the estuary. Wetter conditions maintained larger and more connected areas of emergent marsh, particularly under intermediate to high SLR, whereas drier conditions accelerated fragmentation and conversion to unvegetated intertidal and subtidal habitat. By 2100, projected marsh area ranged from approximately 95 acres under high SLR and dry conditions to 510 acres under low SLR and wet conditions, illustrating how sediment availability increasingly modified habitat outcomes as SLR accelerated.

Transitions of tidal marsh, both losses and gains in marsh area, were distributed across the estuary, with projections under higher SLR scenarios demonstrating classic ‘coastal-squeeze’ behavior due to the steep topography of the watershed. The largest area of projected marsh loss was in the current low marsh areas of the Chorro Creek tidal marsh. Marsh expansion upslope was limited to relatively small areas along Chorro and Los Osos creeks, with higher rates of SLR associated with greater marsh expansion (Fig. 31). Under lower SLR, marsh expansion into the mudflats were projected, with increases in area scaling with sediment loading across the climate scenarios.

Projections of marsh area from all SLR and climate scenarios were used to determine the threshold SLR rate for Morro Bay beyond which tidal marsh is unlikely to persist (Fig. 32). At SLR rates of about 12 mm/yr and above, reductions in marsh area were projected under the historic climate conditions. The onset of marsh loss varied substantially across climate

scenarios. Wetter, higher-sedimentation conditions allowed marsh area to be maintained at substantially higher SLR rates, approaching 20 mm/yr, while drier, lower-sedimentation conditions resulted in marsh loss at lower rates.

This rate-based threshold provides a means of comparing vulnerability across SLR scenarios that is less dependent on the timing of each projection. Importantly, the cumulative amount of SLR at which marsh loss occurs is not fixed; the same cumulative rise could produce different marsh areas depending on how rapidly that rise occurred and on contemporaneous sedimentation. Consequently, this threshold is most appropriately interpreted as a model-based vulnerability indicator rather than an instantaneous monitoring trigger. In practice, continued long-term monitoring could evaluate sustained multi-year rates of local relative SLR together with sediment accretion or sediment-supply indicators to determine whether conditions are approaching the modeled vulnerability range.

Table 2. Projected marsh area across Morro Bay under sea-level rise (SLR) and climate scenarios. Currently there are about 400 acres of tidal marsh in Morro Bay (MBNEP 2021); areal differences can arise from the elevation-based approach used in the model. Initial (2020) variation in area is from stochastic vegetation processes during the spin-up period.

		Tidal marsh area (acres)								
SLR	Climate	2020	2030	2040	2050	2060	2070	2080	2090	2100
Low	Dry	407.6	409.2	409.4	415.2	417.4	419.2	419.4	420.3	420.8
Low	Historic	408.3	409.2	410.1	415.9	421.7	425.7	434.8	439.2	441.7
Low	Wet	407.2	408.8	414.5	435.2	445.7	463.2	483.0	499.7	510.4
Intermediate Low	Dry	408.1	409.0	409.4	414.5	414.3	410.5	406.3	396.8	385.2
Intermediate Low	Historic	408.1	409.0	409.4	417.0	417.7	419.7	420.8	420.5	413.4
Intermediate Low	Wet	407.2	408.8	413.2	431.4	436.8	454.4	468.4	478.4	482.8
Intermediate	Dry	409.9	409.2	408.8	411.0	403.2	391.6	365.4	290.0	222.2
Intermediate	Historic	408.3	408.3	408.5	413.7	411.2	405.9	387.2	332.9	256.4
Intermediate	Wet	407.2	408.3	413.0	432.1	434.1	445.9	449.0	436.6	408.3
Intermediate High	Dry	408.3	407.6	406.1	396.8	371.4	295.8	213.5	150.6	116.3
Intermediate High	Historic	408.3	407.6	407.2	402.5	383.9	326.7	236.9	173.0	135.4
Intermediate High	Wet	407.2	408.8	410.1	422.6	408.3	401.6	354.3	279.1	216.2
High	Dry	408.1	408.5	404.5	389.9	324.0	209.9	142.1	99.2	79.8
High	Historic	408.3	408.1	405.0	395.0	342.0	230.8	160.1	116.8	91.4
High	Wet	407.2	408.8	408.1	418.5	387.4	350.3	238.2	185.5	138.8

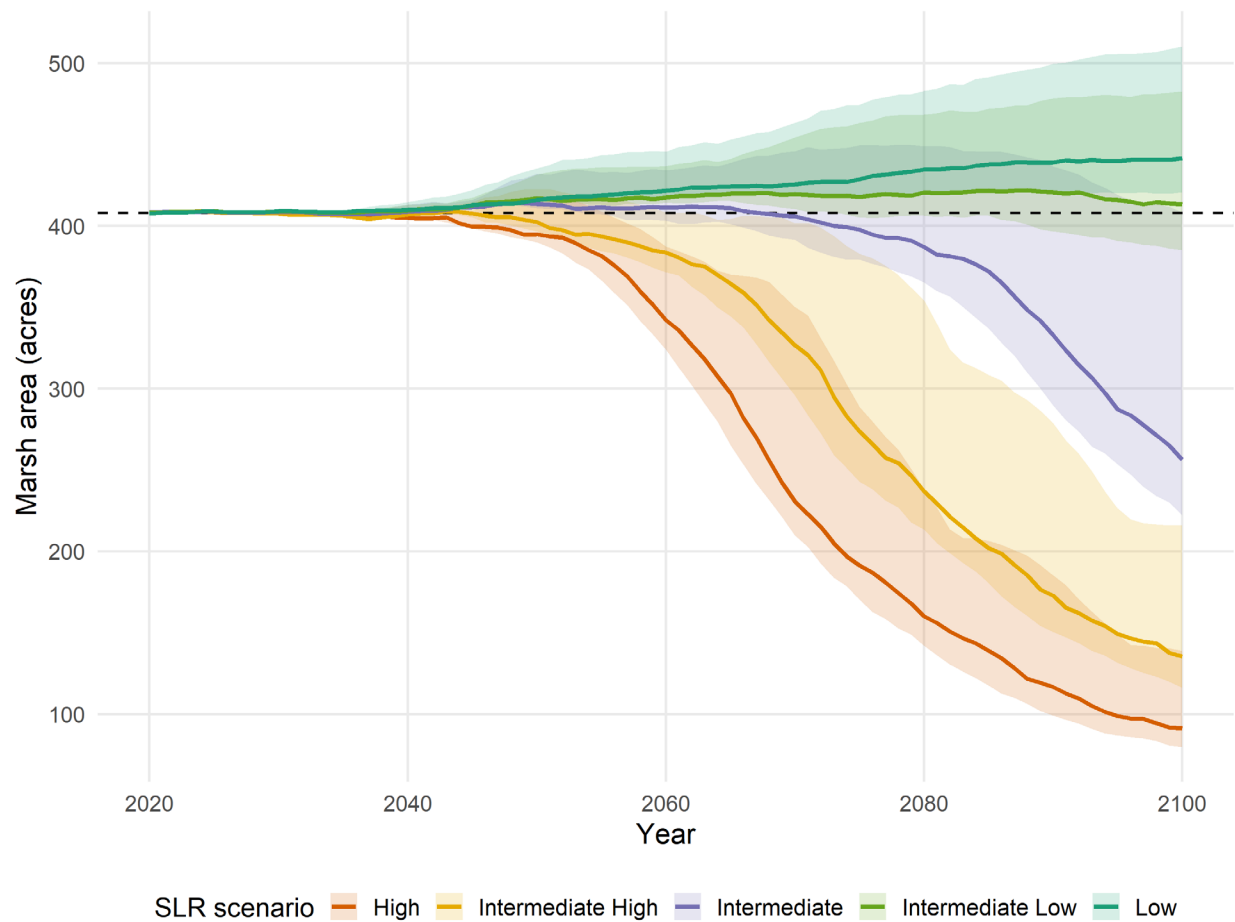


Figure 25. Total marsh area projected for Morro Bay estuary across sea-level rise and climate scenarios. The solid line represents the projection under the historic climate scenario, where river discharge from the last ~20 years was used to drive sediment loading. The upper range of the ribbon represents the wetter climate scenario, while the lower range represents the drier climate scenario. Horizontal line denotes current marsh area. Dashed line represents the initial marsh area.

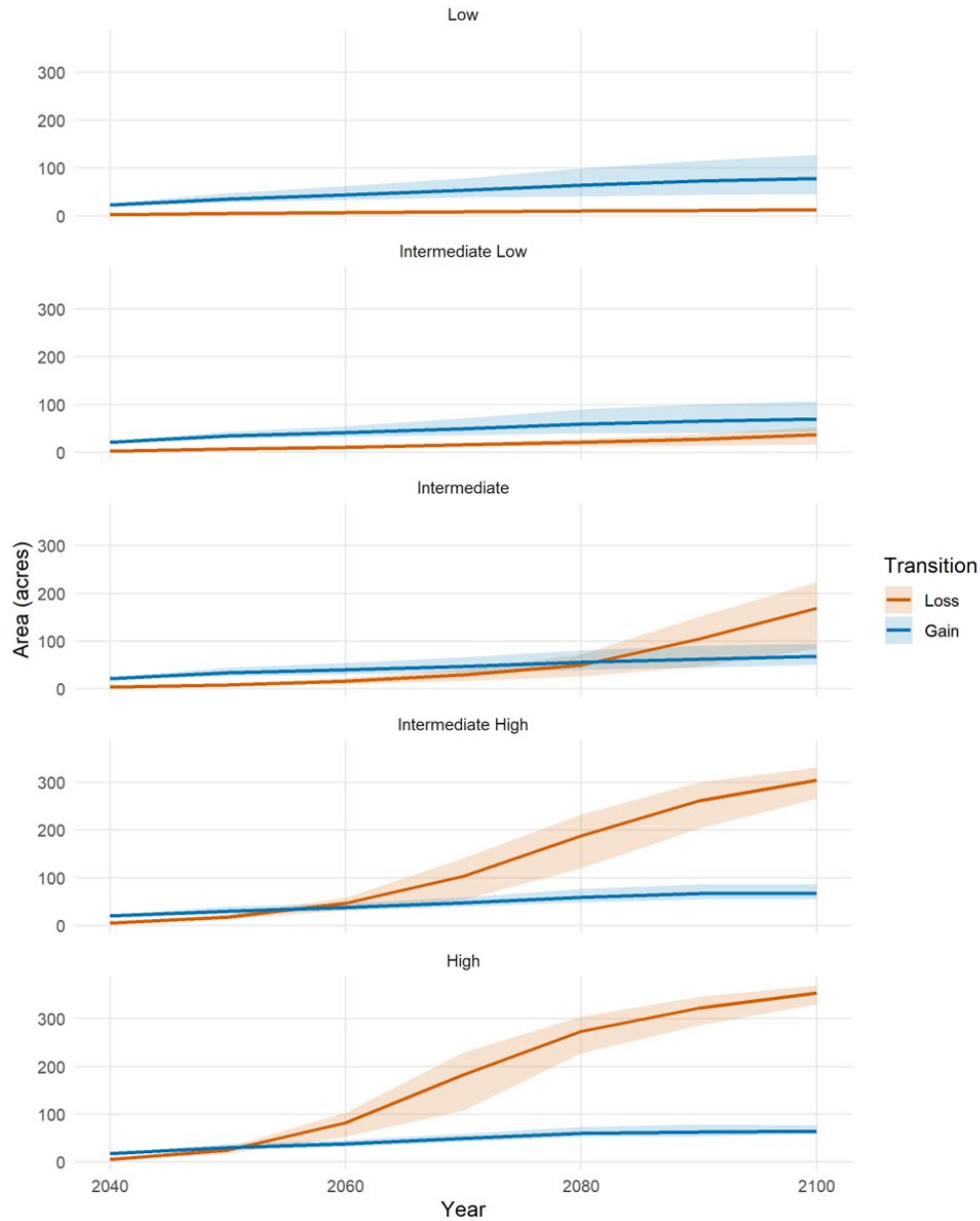


Figure 26. Relative changes in marsh area (acres) compared to 2020 across sea-level rise scenarios. The upper range of the ribbon represents the wetter climate scenario, while the lower range represents the drier climate scenario. Net marsh loss occurs when loss exceeds gains.

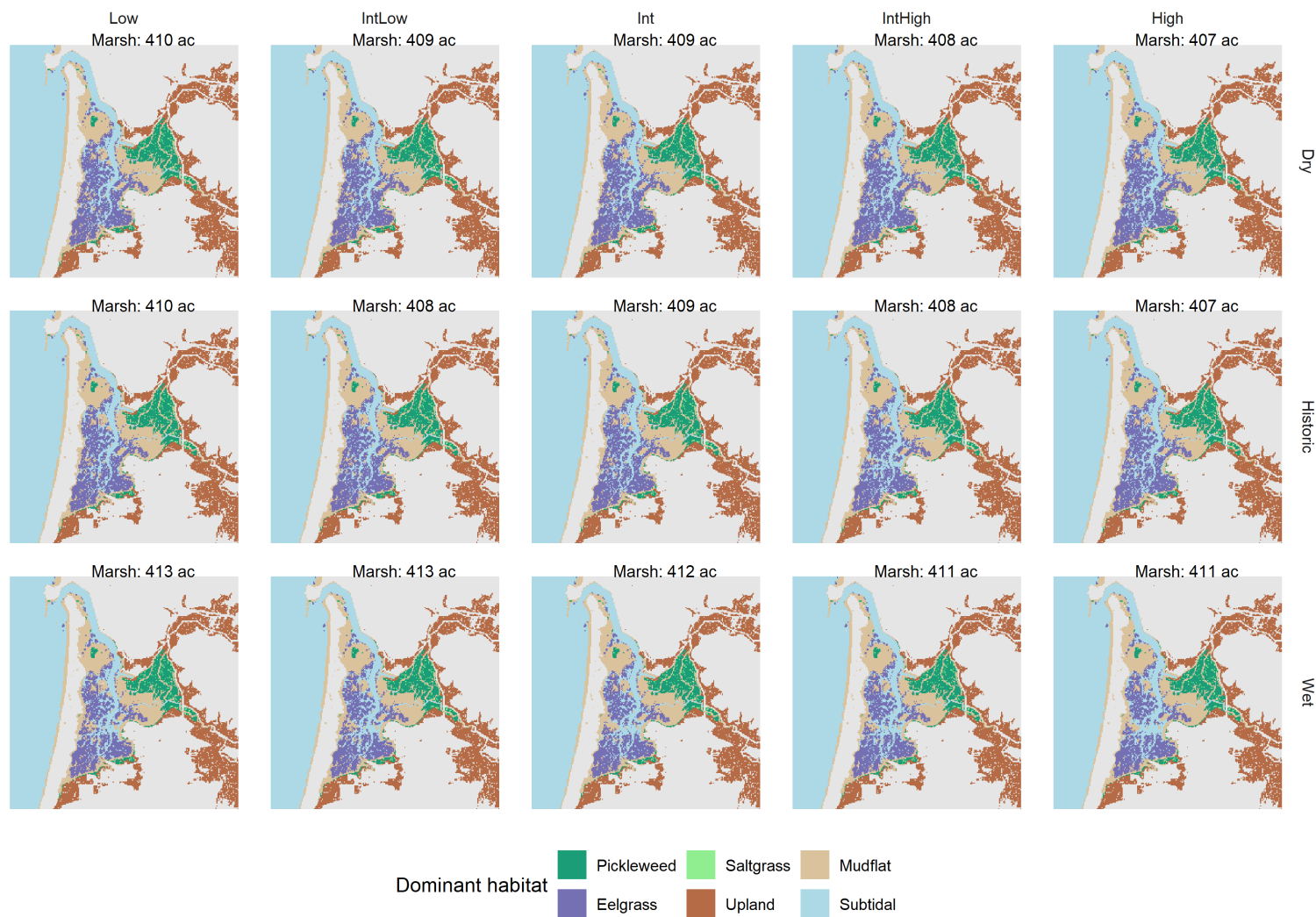


Figure 27. Projections for 2040 of habitats for Morro Bay across sea-level rise and sediment scenarios.

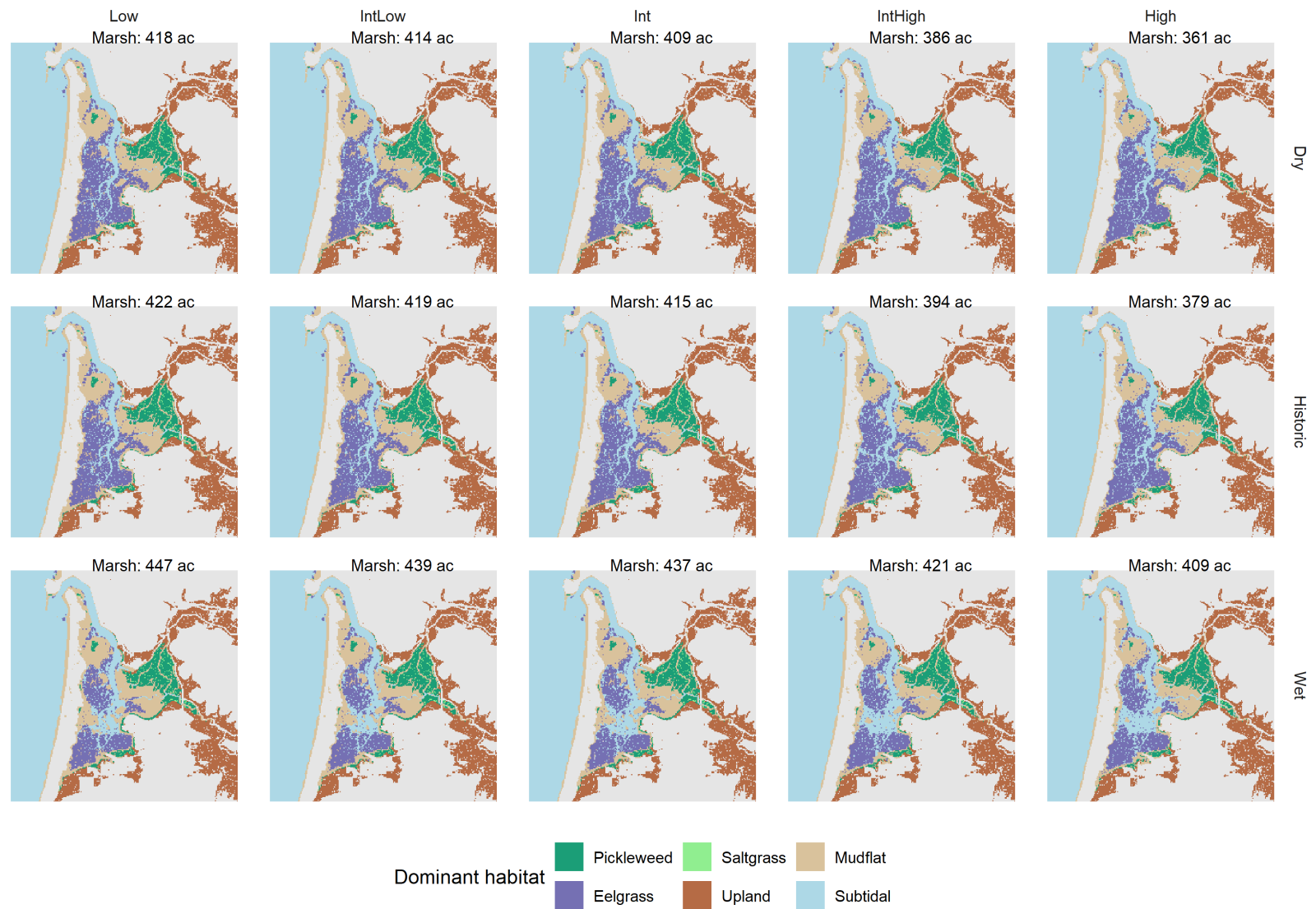


Figure 28. Projections for 2060 of habitats for Morro Bay across sea-level rise and sediment scenarios.

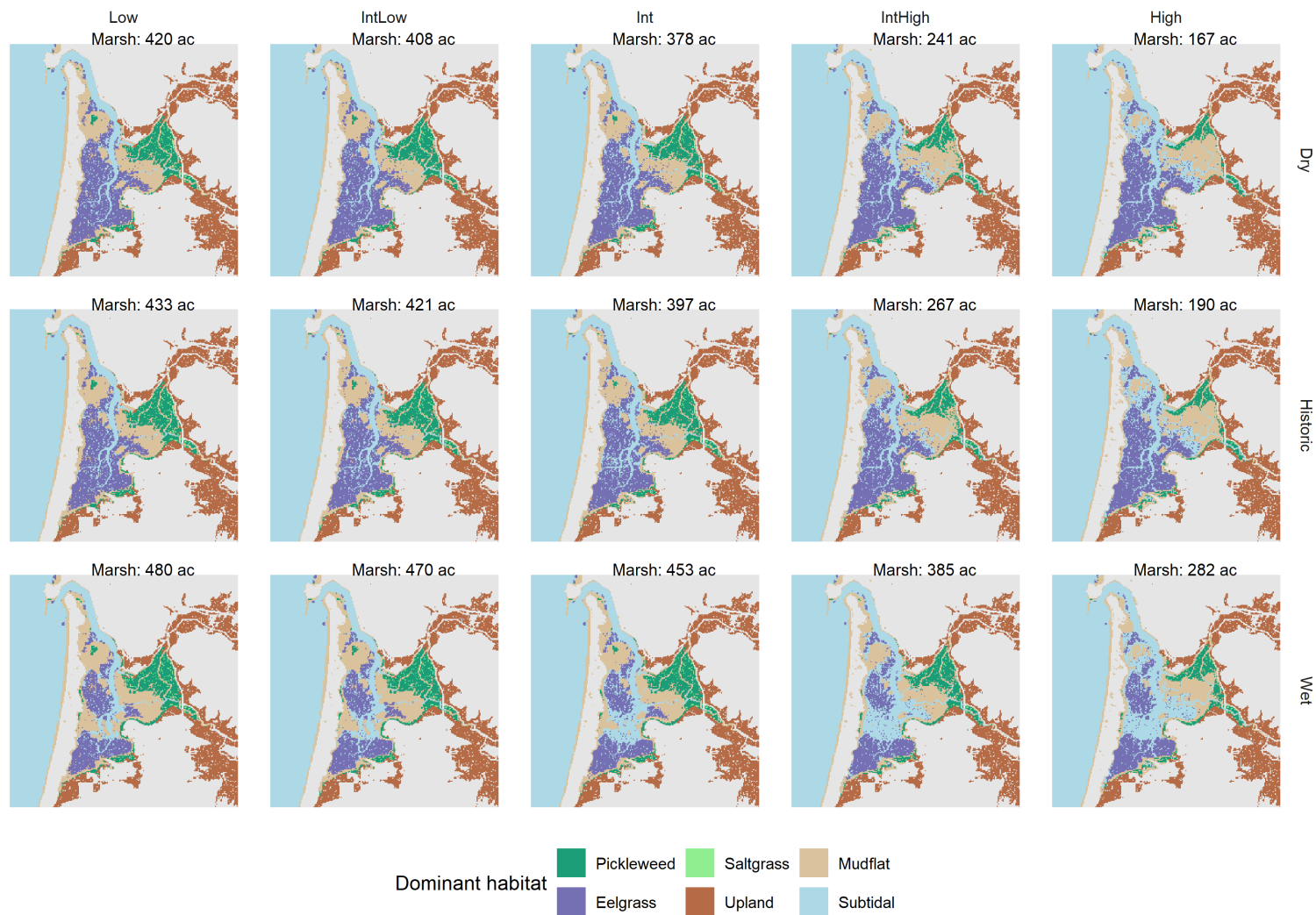


Figure 29. Projections of 2080 of habitats for Morro Bay across sea-level rise and sediment scenarios.

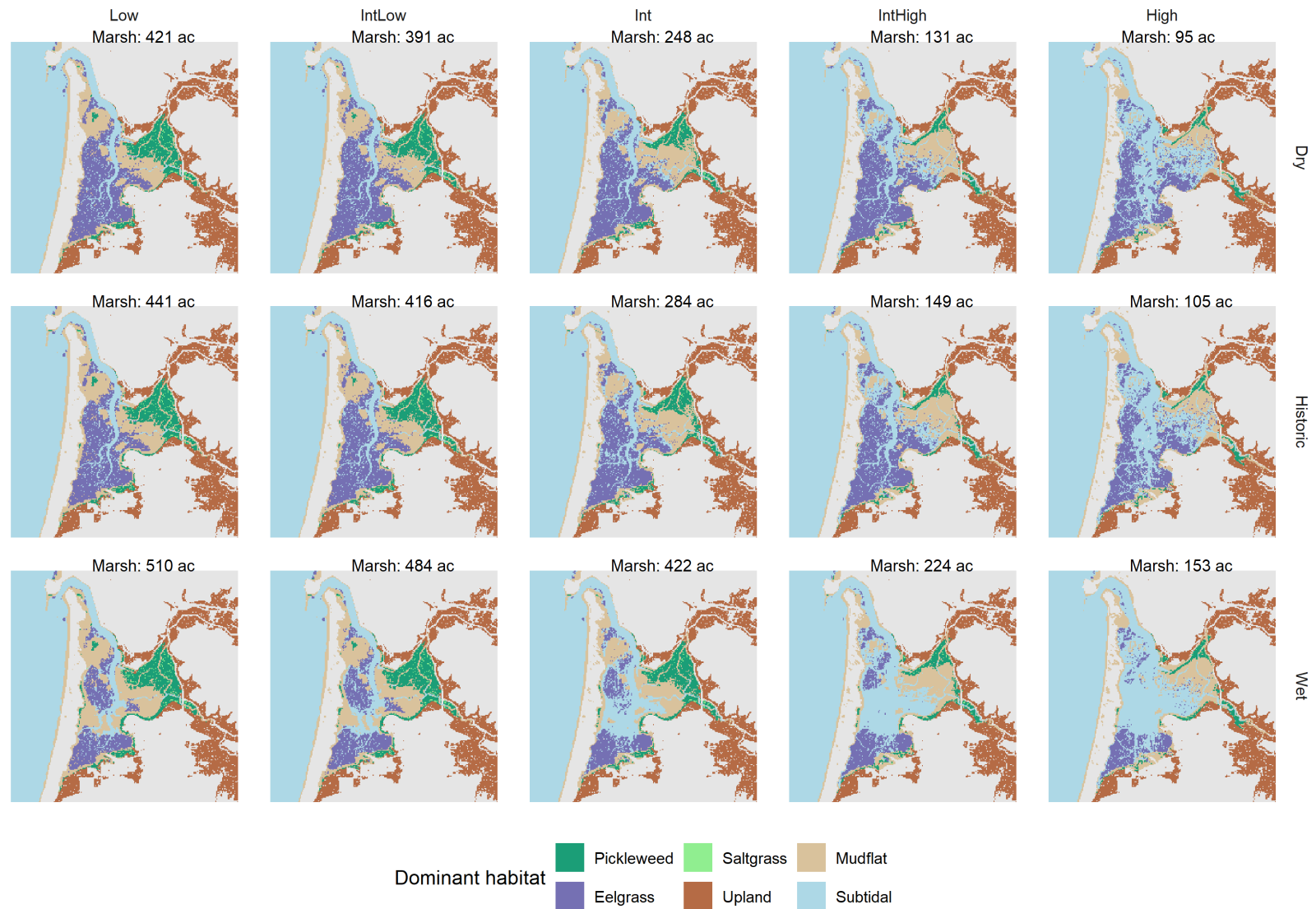


Figure 30. Projections of 2100 of habitats for Morro Bay across sea-level rise and sediment scenarios.

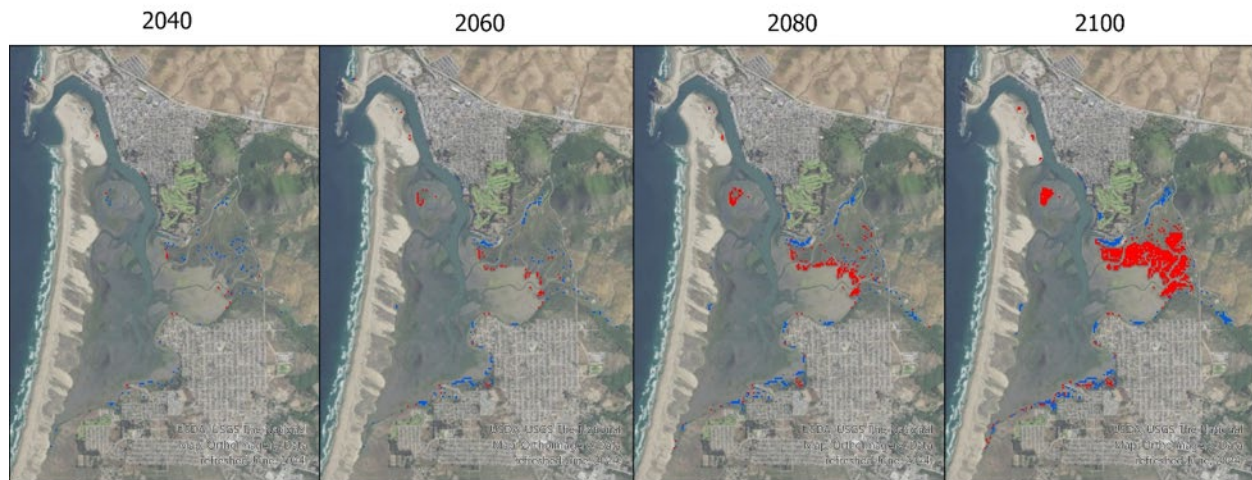


Figure 31. Changes in marsh area across Morro Bay for the intermediate sea-level rise and historic climate scenario. Blue represents area of marsh gain, relative to 2020, while red represents areas of marsh loss. Basemap imagery is from Vantor.

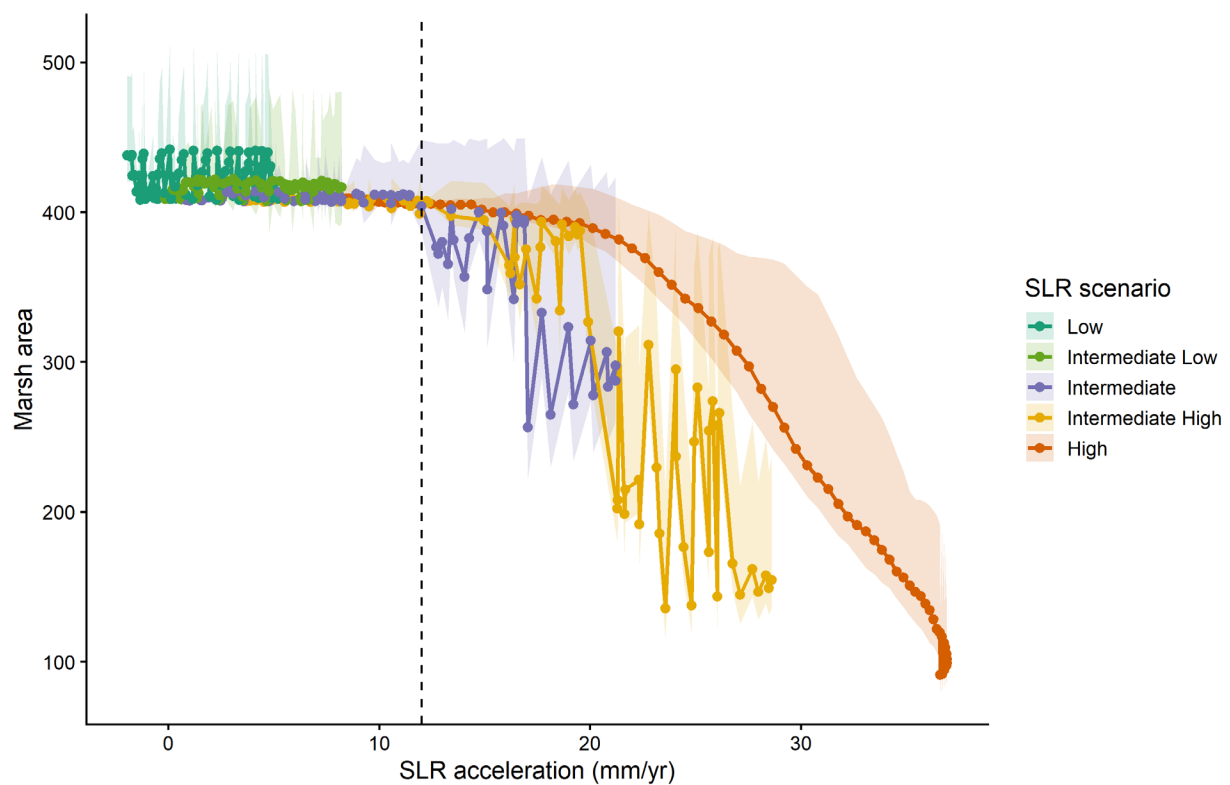


Figure 32. Acceleration in sea-level rise (SLR) relative to projected marsh area. Solid line represents historic climate conditions, the upper and lower bounds of the ribbons represent the wetter and drier climate scenarios, respectively. The dotted line at 12 mm/yr indicates the threshold SLR beyond which declines in marsh area are likely. The variation observed in the intermediate and intermediate high scenarios are from the nodal tidal cycle that causes changes in the rate of SLR; under the high SLR scenario, the annual rate of change is far greater than the amplitude of the nodal cycle.

3.5 Management Scenarios

3.5.1 Thin layer placement

Thin-layer placement (TLP) generally increased marsh area relative to the no-action baseline under both intermediate and intermediate high SLR scenarios, although the magnitude and persistence of benefits depended strongly on placement thickness, repeat interval, timing, and SLR trajectory (Figs. 33-35).

Under the intermediate SLR scenario, marsh gains increased with placement thickness and were generally maintained through the end of the century. For the smallest placement depth (0.40 m), marsh area gains remained modest (<20 acres) regardless of implementation timing. In contrast, the 0.80 m placement produced substantially larger benefits, particularly when repeated every 10 or 20 years, although repeat placement did not provide substantial additional benefit in marsh area until after 2080. With implementation beginning in 2040, a single 1.20 m treatment increased marsh area by approximately 80 acres by 2100, and repeated placements diverged in area increase only after 2080. Delaying implementation to 2060 reduced overall gains slightly, while delaying until 2080 compressed benefits into the final decades of the century and limited relative marsh expansion to roughly 75 acres.

Responses under the intermediate high SLR scenario were more complex. Although larger placement depths initially generated substantial marsh gains, benefits declined through time as sea-level rise accelerated. Single-placement treatments provided temporary increases in marsh area (e.g., <40 years with 0.8 m target elevation in 2040, and ~25 years with placement in 2060), with gains peaking after implementation before declining toward baseline conditions. For example, a single 1.20 m placement initiated in 2040 increased marsh area by approximately 80 acres around 2080, but this benefit was lost by 2100. These transient responses reflect the finite elevation capital provided by a single placement: natural sediment accumulation continues after placement, but under the intermediate high SLR scenario it is insufficient to maintain the added elevation advantage indefinitely as the rate of SLR increases. Repeated placements substantially improved persistence. A 10-year

repeat interval consistently produced the largest and longest-lasting benefits, maintaining gains of approximately 90–110 acres through much of the late century under the 0.8 m treatment. Twenty-year repeat intervals generated intermediate outcomes, prolonging marsh persistence relative to a single placement but generally producing lower end-of-century gains than 10-year repeats.

The timing of implementation strongly influenced project effectiveness. Earlier implementation (2040) produced the greatest cumulative marsh-area gains under both SLR scenarios, particularly for larger placement depths. However, early implementation also exhibited periods of temporary marsh loss immediately following placement in the deepest (1.20 m) treatments, reflecting short-term conversion of marsh habitat to supratidal elevations before vegetation recovery. These transient losses were most evident under repeated-placement scenarios and diminished within one to two decades after implementation. Intermediate implementation (2060) generally balanced short-term disturbance and long-term benefits, while late implementation (2080) produced the smallest overall gains because less time remained for marsh expansion and persistence before 2100.

Across all implementation years, placement depth exerted the strongest control on marsh response. Increasing placement thickness from 0.40 m to 0.80 m substantially increased marsh gains, while increasing thickness to 1.20 m produced the largest benefits under intermediate SLR. Under intermediate high SLR, however, the 0.8 and 1.2 m placement depths required repeated applications to maintain gains through the end of the century, indicating that repeated sediment additions would likely be necessary to maintain marsh habitat in Morro Bay within this scenario. Overall, the results suggest that marsh resilience is maximized through a combination of larger placement depths (0.80–1.20 m), frequent reapplication (10-year intervals), and earlier implementation, particularly under higher rates of sea-level rise. In contrast, single-placement strategies provided temporary benefits under intermediate high SLR and were unable to sustain marsh gains through 2100.

Sediment requirements increased with both target placement elevation and implementation delay (Fig. 36). Under intermediate SLR, placement volumes ranged from approximately 25,000–55,000 yd³ at 0.4 m to 430,000–520,000 yd³ at 1.2 m. Under intermediate high SLR, sediment demands were consistently higher, reaching nearly 750,000 yd³ for the 1.2 m treatment when implementation was delayed until 2080. Overall, delaying restoration increased the sediment volume needed to achieve a given target elevation, particularly under higher rates of modeled sea-level rise.

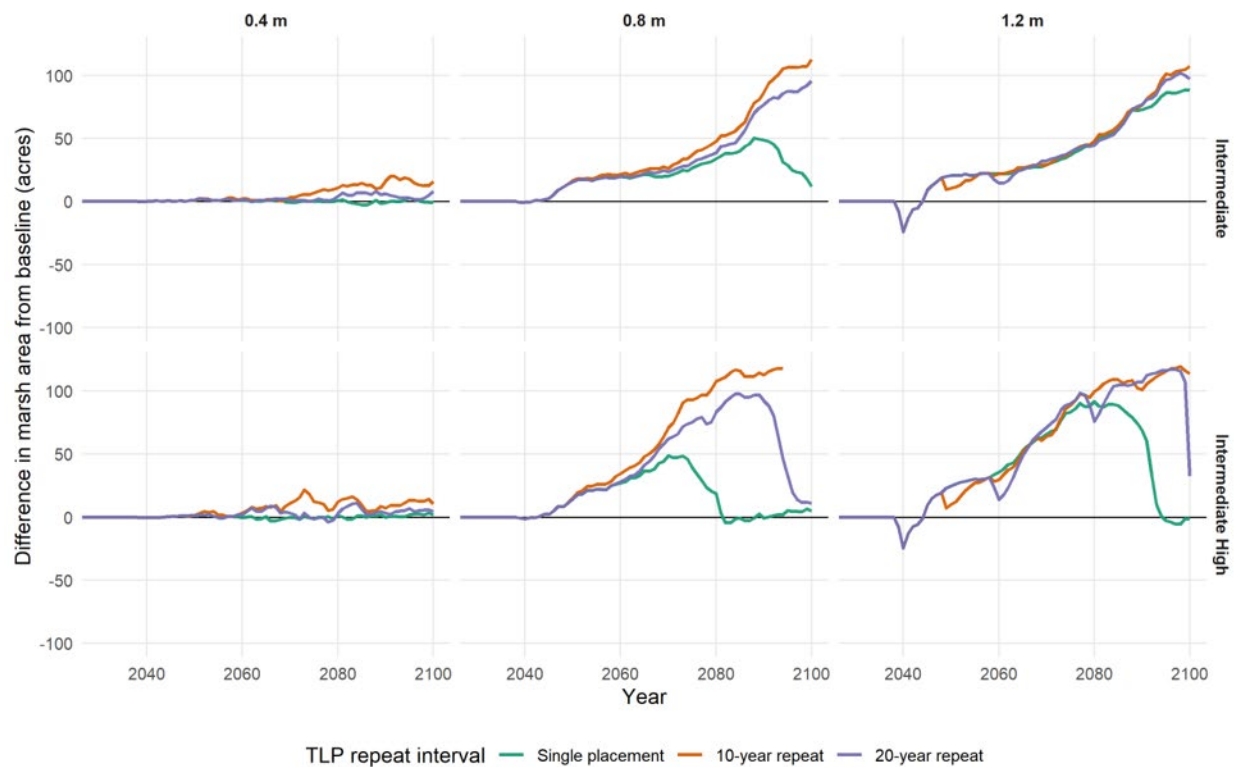


Figure 33. Difference in marsh area between thin-layer placement management actions in 2040 compared to a baseline, no-management action and historic climate scenario. Three target elevations (0.4, 0.8, and 1.2 m MSL) were compared, along with three placement cadences for intermediate [top] and intermediate high [bottom] sea-level rise.

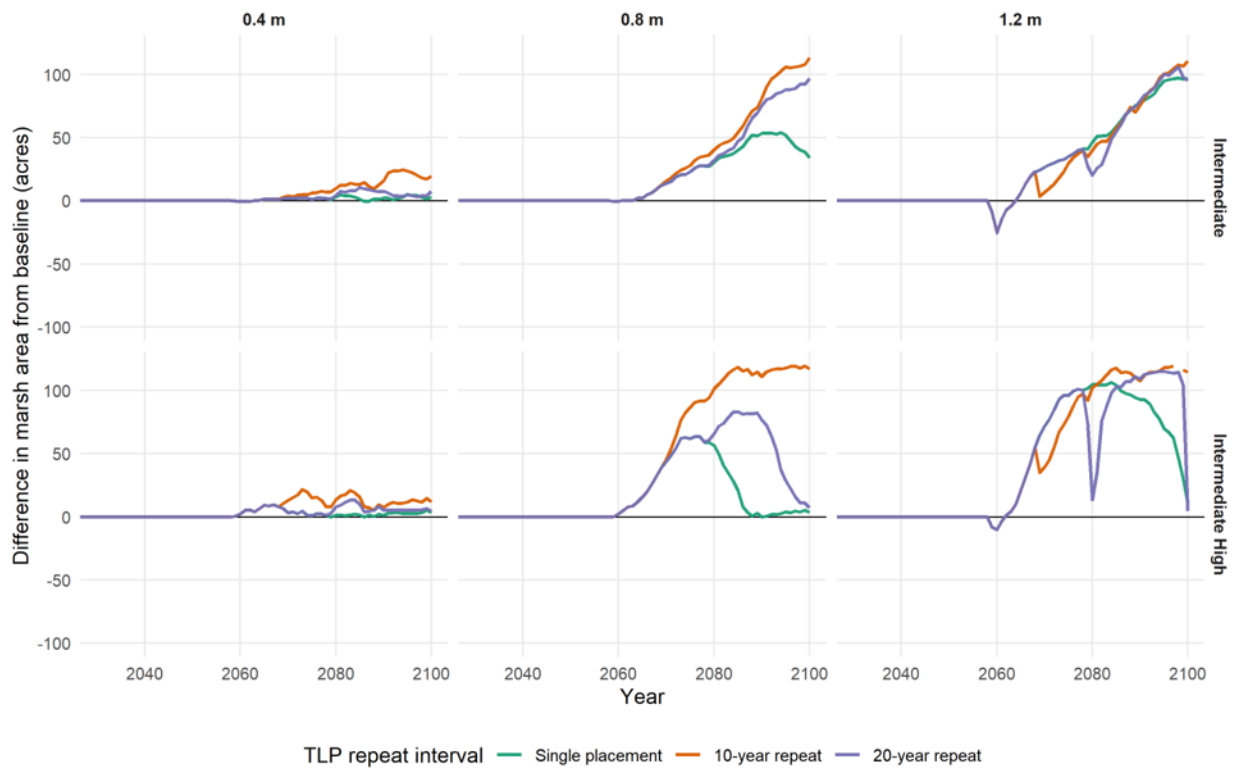


Figure 34. Difference in marsh area between thin-layer placement management actions in 2060 compared to a baseline, no-management action and historic climate scenario. Three target elevations (0.4, 0.8, and 1.2 m MSL) were compared, along with three placement intervals for intermediate [top] and intermediate high [bottom] sea-level rise.

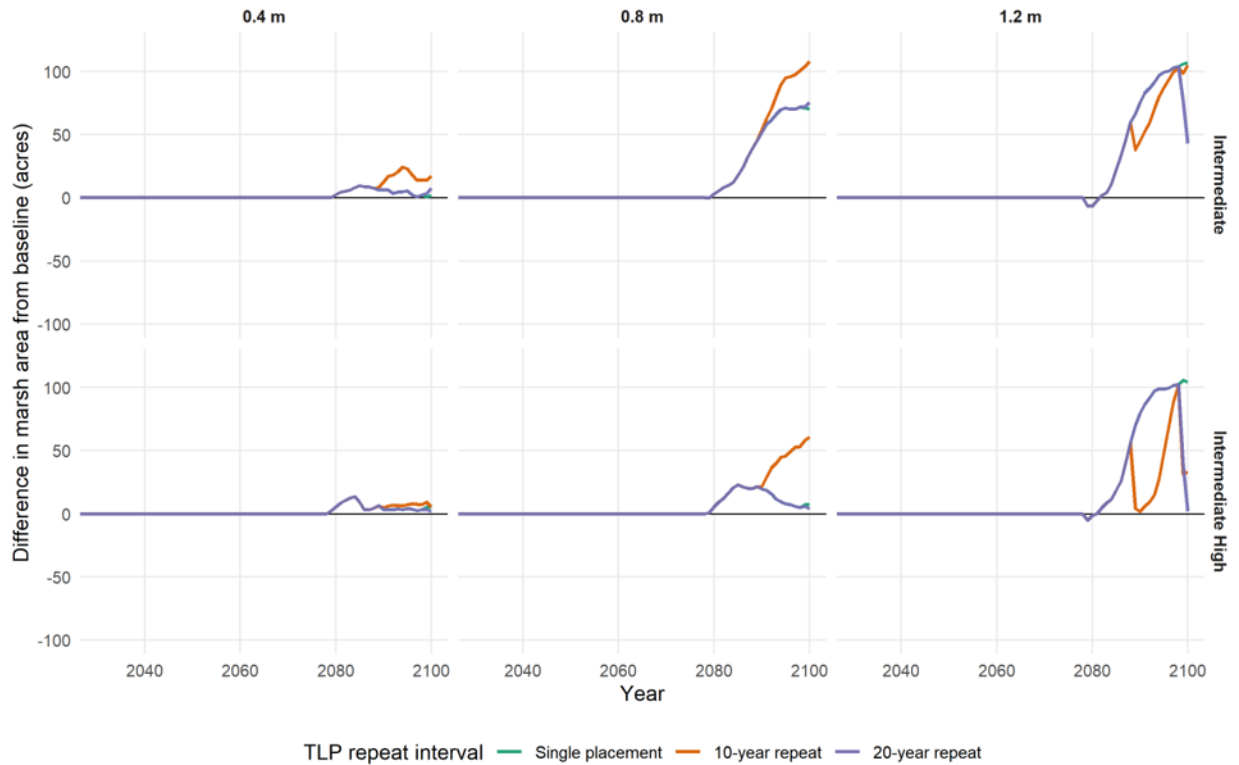


Figure 35. Difference in marsh area between thin-layer placement management actions in 2080 compared to a baseline, no-management action and historic climate scenario. Three target elevations (0.4, 0.8, and 1.2 m MSL) were compared, along with three placement intervals for intermediate [top] and intermediate high [bottom] sea-level rise.

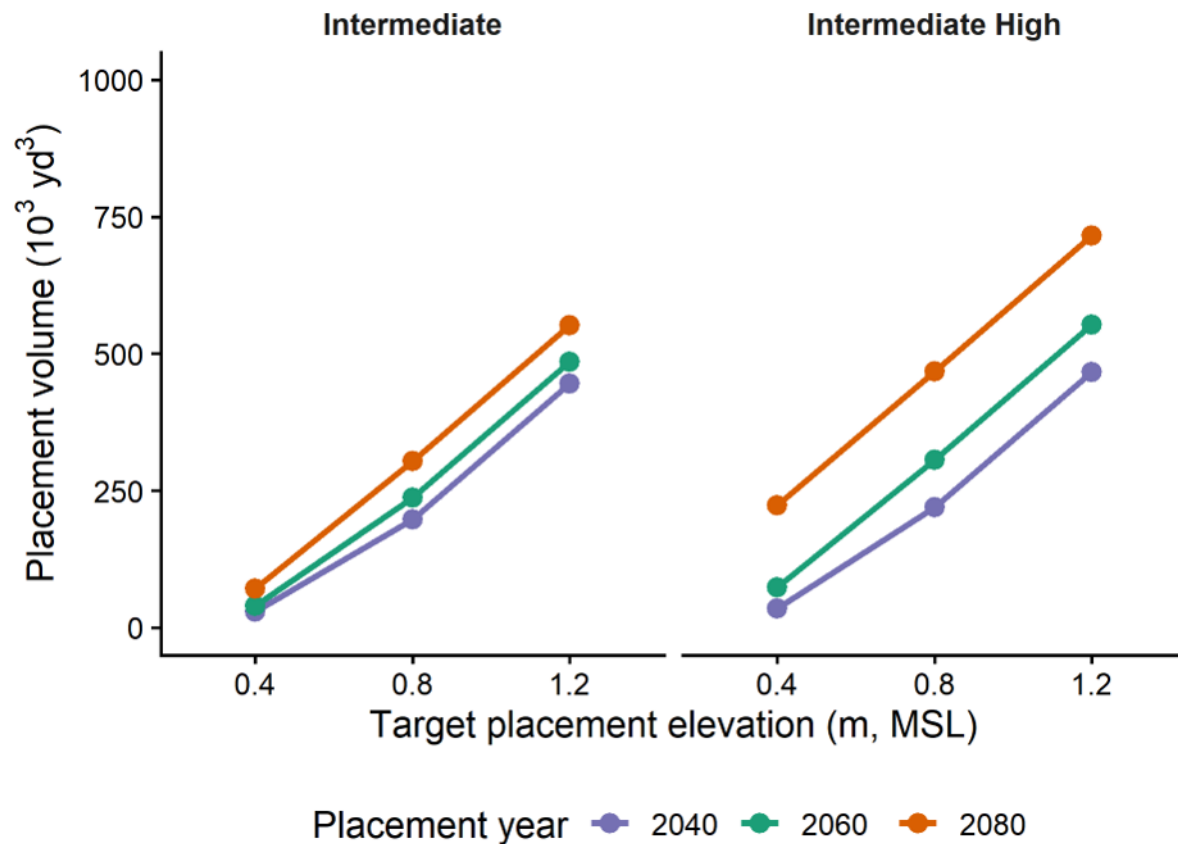


Figure 36. Sediment volume within the 100-acre placement area across target placement elevations (relative to mean sea level), placement year, and sea-level rise scenarios. Sediment volume is from the single placement scenario. Information provided as context for assessments of effort and cost.

3.5.2 Natural barriers

We explored the effect of installing a natural brush fence along the bay-fronting edge of the marsh to promote sediment deposition and reduce wave erosion. After placement in 2060, projections indicated that the brush fence facilitated a relative increase in marsh area compared to baseline of about 20 acres under intermediate SLR by 2100 (Fig. 33). Under intermediate high SLR, there was a net increase in marsh area of about 10 acres (10% of the placement area), 20 years after placement, although by 2100 the relative difference dropped to about 4 acres. Installation of the brush fence in 2080 resulted in a 10-acre net increase in marsh area under intermediate SLR and a minimal difference from baseline under intermediate high SLR (Fig. 34).

3.5.3 Complementary management actions

The simulations indicate that the effectiveness of complementary TLP + brush fencing depends strongly on implementation timing, placement elevation, and SLR scenario (Figs. 37-38). Across most scenarios, the combined treatment produced larger marsh-area gains than either action alone, but the magnitude and persistence of those gains varied substantially. TLP was the dominant driver of large marsh-area increases, especially at higher placement elevations, while brush fencing alone produced smaller benefits. In many cases, the combined response closely followed the additive expectation, suggesting that the benefits of combining TLP and fencing primarily reflected the sum of their independent effects rather than strong synergy.

For treatments initiated in 2060, marsh-area gains began earlier and were generally larger but were less persistent under intermediate high SLR. Under intermediate SLR, the combined treatment increased marsh area across all placement elevations. The 0.4 m treatment produced modest gains, peaking near 25 acres in the 2080s before declining to roughly 10–15 acres by 2100. The 0.8 m treatment generated larger gains, reaching approximately 80–85 acres in the 2090s before declining to about 70–75 acres by 2100. The 1.2 m treatment produced the largest and most persistent response, increasing through the end of the century to roughly 115–120 acres. Under intermediate high SLR, benefits were more transient. The 0.4 m treatment produced only small gains, generally less than 15 acres. The 0.8 m treatment peaked near 80–85 acres in the 2070s to early 2080s but declined rapidly toward baseline conditions by the 2090s. The 1.2 m treatment produced the strongest response under intermediate high SLR, peaking near 115–120 acres in the 2080s before declining to roughly 45–50 acres by 2100.

When implementation was delayed until 2080, responses were concentrated in the final two decades of the simulation. Under intermediate SLR, treatment effects increased strongly with placement elevation. The 0.4 m treatment produced only small gains, generally less than 10–12 acres and declining by 2100. The 0.8 m treatment increased marsh area rapidly after implementation, reaching approximately 80–85 acres by 2100. The 1.2 m treatment produced the largest gain, increasing to roughly 115–120 acres by 2100. Under intermediate high SLR, delayed implementation produced a strong target elevation-dependent response. The 0.4 m and 0.8 m treatments generated limited or transient benefits, with the 0.8 m treatment peaking around 20–25 acres before declining to less than 10 acres by 2100. In contrast, the 1.2 m treatment produced a large and persistent gain, reaching roughly 100–110 acres by 2100.

Overall, higher placement elevations produced larger and more persistent marsh-area gains, especially under intermediate high SLR. The 1.2 m placement elevation was consistently the

most effective treatment, while lower placements often produced only modest or temporary benefits. Combining TLP with brush fencing generally improved outcomes relative to TLP alone, but the combined response was often close to the additive expectation.

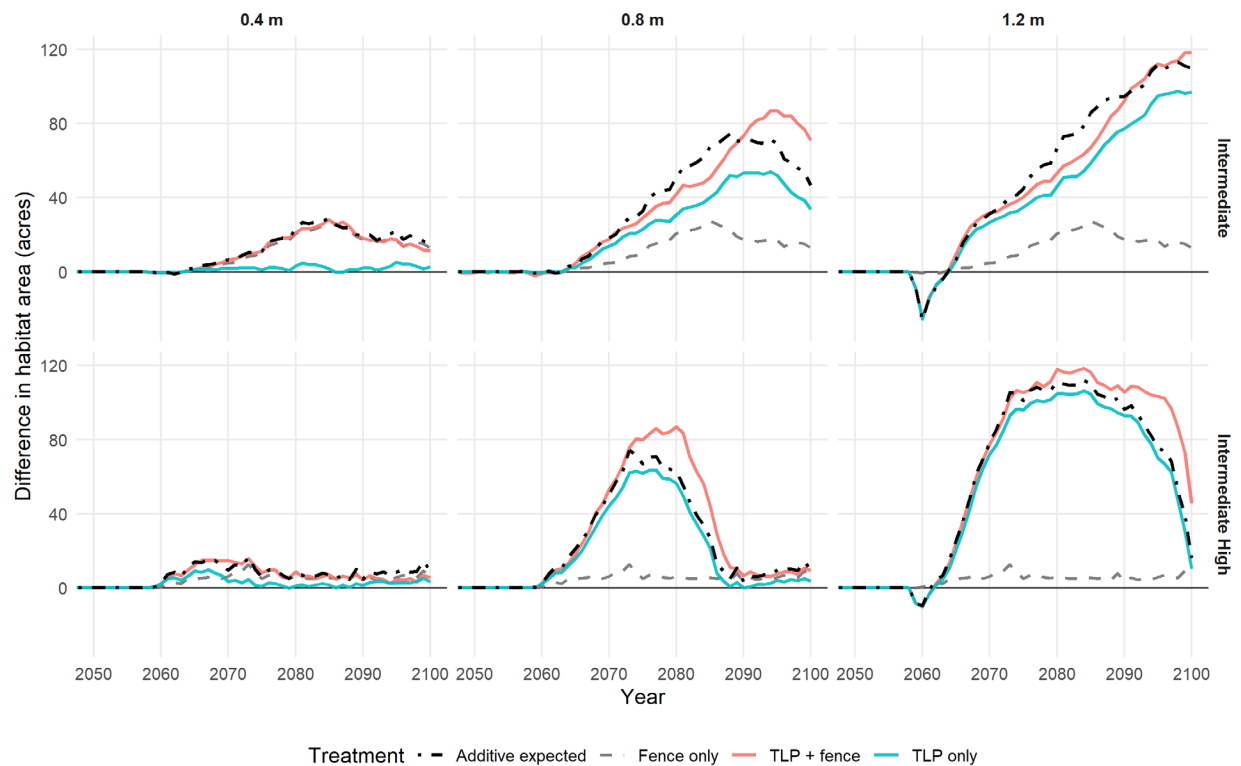


Figure 37. Difference in marsh area from baseline compared across a natural barrier action [brush fencing], thin-layer placement [TLP] management action, and a combined TLP action with brush fencing, across three target elevations for placement and two sea-level rise scenarios with installation in 2060. Results are from the historic climate scenario. Also shown is the expected additive effect of the two actions; values of TLP+brush fencing above the additive line indicate synergistic effects.

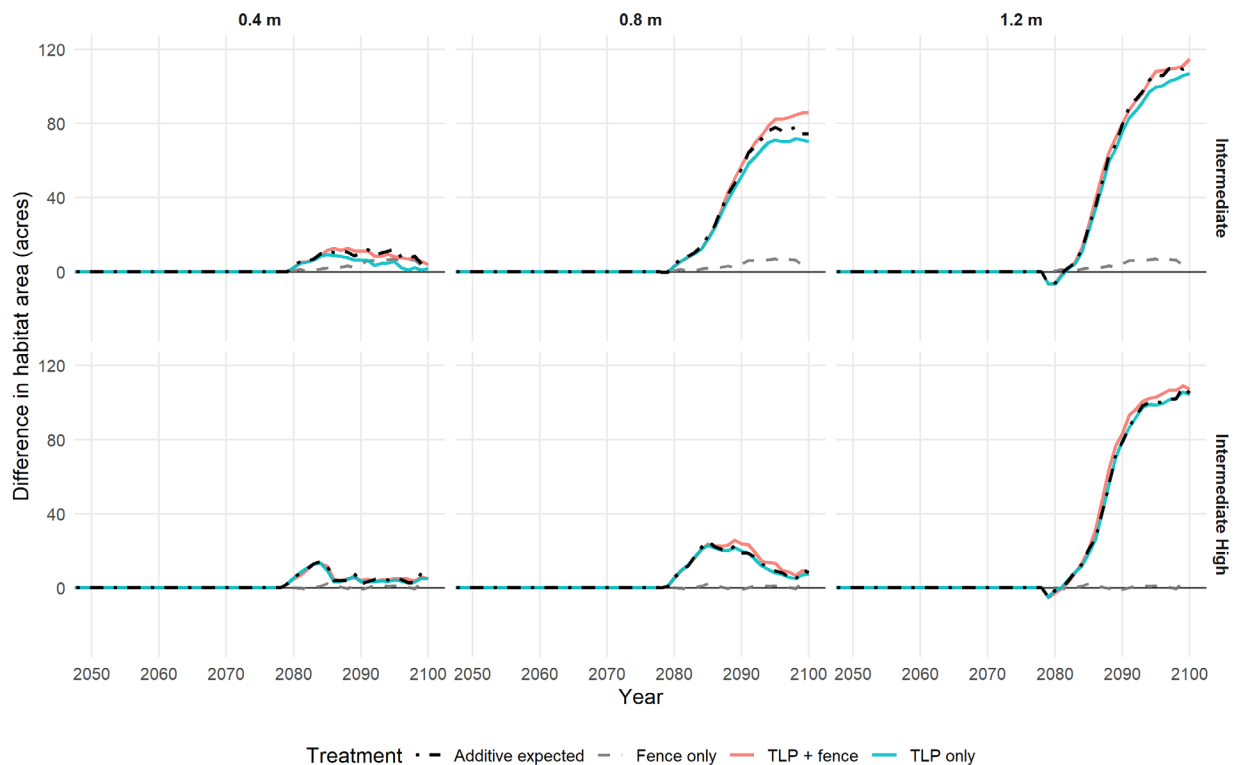


Figure 38. Difference in marsh area from baseline compared across a natural barrier action [brush fencing], thin-layer placement [TLP] management action, and a combined TLP action with brush fencing, across three target elevations for placement and two sea-level rise scenarios with installation in 2080. Results are from the historic climate scenario. Also shown is the expected additive effect of the two actions; values of TLP+brush fencing above the additive line indicate synergistic effects.

4.0 Discussion

Projections of Morro Bay evolution with WARMER-Coast suggest a relatively resilient tidal marsh system, with sufficient sediment loading from the watershed to offset at least moderate sea-level rise levels by 2100. If faster trajectories of SLR are realized or the climate tends toward the drier scenario, the marsh may begin to lose area by the middle of this century. Alternatively, if SLR is slower or the future is wetter, the model suggests that the marsh will likely continue its historic trajectory of expansion into the tidal flats (Figs. 27-30).

WARMER-Coast represents a novel collection of process-based functions to simulate estuarine evolution. By incorporating spatial dynamics, including wind-wave resuspension,

edge erosion and downslope diffusion, explicit sediment transport from intermittently flooded creeks, and neighborhood plant interactions, the model accounts for important feedbacks that are typically overlooked in multi-decadal projections of tidal marsh responses to SLR. These feedbacks can be critical for accurate simulations of estuarine dynamics, especially in systems where sediment plays an important role in driving changes in elevation.

The TLP scenarios indicated that placement beginning around 2060 and targeting an elevation of approximately 0.8 m above MSL produced a favorable balance between sediment requirements and impacts to existing marsh within the modeled scenarios. This timing is best interpreted as a model-derived benchmark rather than a prescribed implementation date. Because planning, permitting, design, sediment sourcing, and regulatory coordination for large-scale sediment placement can require substantial lead time, it would be advantageous to evaluate potential actions well in advance of the modeled period of greatest benefit. Monitoring of sea-level rise, marsh condition, and sediment availability could help determine whether observed conditions are tracking the scenarios in which placement around 2060 was most effective.

The 200,000–250,000 yd³ of sediment required for the 100-acre TLP scenario is relatively modest compared with the ~500,000–800,000 yd³ currently dredged from the main navigation channel every 5–10 years (City of Morro Bay, n.d.). The comparison is intended to place the scale of potential future management actions within the context of ongoing sediment-handling activities in the estuary, rather than to imply that material dredged from the main channel would be suitable for marsh placement. For comparison, Phase 1 of the Hester Marsh restoration in Elkhorn Slough placed ~250,000 yd³ of sediment across 61 acres (Haskins et al., 2021) at a reported cost of \$4.8 million (CA SCC, 2018). Sediment placement raised the marsh surface by an average of 0.7 m to a target elevation of approximately 1 m MSL (Haskins et al., 2021). Costs are not directly transferable to Morro Bay because some material used at Hester Marsh came from adjacent uplands and project-specific conditions differ, but the project provides a useful regional example of sediment placement at a scale comparable to the modeled TLP scenarios.

The management scenarios in this study were designed to explore the sensitivity of the estuary to specific interventions; however, project planning would benefit from addressing several specific issues prior to implementation. Potential sediment sources, whether dredged material or material from other sources, would require evaluation for contaminants of concern and environmental suitability prior to placement (Yozzo et al., 2004). Placement design would also need to minimize impacts to sensitive adjacent habitats, particularly eelgrass beds, which can be affected by increased turbidity, sediment deposition, and

burial associated with dredging and sediment placement activities (Erftemeijer and Lewis, 2006; Zabarte-Maeztu et al., 2021). To minimize sediment exports from the placement area, temporary sediment barriers can be installed around the placement area and channels plugged to restrict tidal exchange (e.g., Davis et al., 2024). Grain size distribution can also be evaluated to confirm that the source sediments are generally compatible with existing marsh sediments.

Although WARMER-Coast is well suited for evaluating long-term estuarine trajectories and comparing management strategies across many climate and sediment scenarios, it is not intended to replace higher-resolution numerical modeling for the design of individual sediment placement projects. The hydrodynamic and sediment-transport formulations are necessarily simplified to permit simulations over multi-decadal time scales and large scenario ensembles, and therefore do not resolve short-term circulation, event-scale sediment plumes, or site-specific depositional patterns with the fidelity needed for engineering design. Project-scale design and evaluation would therefore benefit from a calibrated and validated, high-temporal-resolution hydrodynamic and sediment-transport model capable of resolving tides, currents, waves, and sediment dispersal at the scale of the proposed action (Ganju, 2019). WARMER-Coast can instead serve as a screening and planning tool to identify where and when sediment addition may provide the greatest long-term ecological benefit and to define the range of future conditions that more detailed project-scale modeling should evaluate.

Other models have been applied at Morro Bay to assess SLR effects. For example, the NOAA Sea Level Rise Viewer provides nationally consistent estimates of potential inundation using elevation data, spatially varying tidal surfaces and hydrologic connectivity (NOAA Office for Coastal Management, 2026). However, the inundation analysis assumes that present-day coastal morphology persists as sea level rises. Such static or bathtub-type approaches cannot represent important feedbacks among inundation, sediment deposition, vegetation, erosion, and land-surface elevation that can influence tidal wetland resilience to SLR (Passeri et al., 2015; Wiberg et al., 2020; Fagherazzri et al., 2020).

This initial application of WARMER-Coast contains detailed simulation of many important estuarine processes; however, several omitted processes could be considered in future applications. For instance, the dune system was not represented. Migration or reconfiguration of the sandspit with SLR could alter the morphology and hydrodynamic setting of adjacent tidal flats and eelgrass habitat. Aeolian transport of sand from the dune system onto the adjacent intertidal areas was also not simulated, contributing to the more mud-dominated grain-size distributions projected by the model. Longshore sediment transport is an important component of the sediment budget near the Morro Bay entrance and contributes to entrance-channel shoaling and associated maintenance dredging

(Kaihatu et al., 1989). Because that mechanism of sand delivery was not represented, regular dredging near the estuary mouth was also excluded from the simulations.

Water temperature can play an important role in influencing eelgrass growth, productivity, and survival (Jiang et al., 2022) but was not accounted for in this application. Salinity influences estuarine plant productivity and species distributions (Janousek et al., 2020; Xin et al., 2022). A process-based soil salinity submodel would add substantially to the complexity but represents a potential direction for future development. Salinity can also influence hydrodynamics and sediment transport by modifying sediment erosion thresholds (San Juan et al., 2024), altering flocculation and settling behavior of fine particles (Abolfazli and Strom, 2023) and generating baroclinic pressure gradients and stratification that influence gravitational circulation and interact with tidal currents (Geyer and MacCready, 2014; Burchard and Schuttelaars, 2012). Given our depth-averaged hydrodynamic approach and absence of salinity dynamics in this application, these feedbacks were not represented.

Model uncertainty arises from both future forcing and uncertainty in the representation and parameterization of estuarine processes. This study explicitly evaluated uncertainty associated with SLR and sediment-loading trajectories, which produced substantial variation in projected marsh response. However, a comprehensive sensitivity analysis of all hydrodynamic, sediment-transport, erosion, and ecological parameters was beyond the scope of this study. Previous applications of the underlying WARMER framework have reproduced observed contemporary accretion rates and demonstrated strong sensitivity to sediment availability and vegetation processes (Buffington et al., 2021), while comparisons with other marsh-response models have shown broad agreement in projected trajectories but meaningful differences in the timing and magnitude of change (Martinez et al., 2025). Accordingly, WARMER-Coast projections are best interpreted as estimates of potential trajectories and relative responses among scenarios rather than precise forecasts of future marsh area or timing. Confidence is greatest in broad patterns that persist across scenario combinations, whereas exact transition dates, local sedimentation patterns, and projected acreages are more uncertain. Continued comparison of modeled elevation change, vegetation distribution, sediment accumulation, shoreline change, and hydrodynamic conditions with field observations would provide opportunities to evaluate model skill and identify processes or parameters requiring refinement.

In discussions with the project's Technical Advisory Committee, a couple of topics were raised that were beyond the scope of our project. First, there was interest in simulating the downstream impacts of a large fire in the watershed. In 1994, the Highway 41 fire burned 50,000 acres, and subsequent erosion brought large amounts of sediment into Morro Bay, burying the eelgrass beds. While WARMER-Coast can simulate such a stochastic and

potentially catastrophic event, the team opted to focus on the management intervention and climate scenarios. A targeted study with a more detailed eelgrass module and improved constraint on the sediment loading from such an event could be warranted to understand potential impacts across the estuary.

There was also interest in understanding the future extent of California seablite (*Suaeda californica*), a species found near the upper edge of the tidal extent. Given our 30 m resolution, we were unable to resolve the narrow habitat zone this species currently occupies. However, if it is assumed that seablite can migrate with higher tides, the modeled tidal extent provides a reasonable estimate of its future distribution.

This study provides a scientific basis for evaluating potential future changes in estuarine habitats in Morro Bay and for identifying observations that could help distinguish the modeled trajectories. Key information for evaluating future conditions includes long-term trends in local relative sea-level rise, marsh area and elevation change, sediment accumulation, creek discharge and sediment loads, and vertical land motion. For example, the approximately 12 mm yr⁻¹ SLR threshold rate associated with declining marsh area under historic sedimentation conditions may provide a useful benchmark for interpreting future observations, but is not meant to be considered a fixed management trigger because the onset of marsh loss varied substantially with sedimentation and other environmental conditions. Continued observations of these variables would allow assessment of which modeled climate and sediment trajectories are most consistent with realized conditions and provide opportunities to evaluate model skill as environmental change progresses. Additional investigation of key process uncertainties, including tidal velocities, wave-driven resuspension, sediment transport, and flocculation, could further refine projections. Any future adaptation actions would also depend on regulatory, engineering, policy, funding, and other considerations beyond the scope of this study.

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for accuracy. The authors validated AI-generated code through extensive testing, manual review, consistency checks, and visual and analytical inspection of model outputs. Code was modified as necessary to ensure scientific rigor, integrity, accuracy, and compliance with USGS standards. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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