



Establishing Targets for Regional Coastal Wetland Restoration Planning Using Historical Ecology and Future Scenario Analysis: The Past, Present, Future Approach

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Abstract

Regional approaches to coastal wetland restoration are one of the best ways to ensure that these threatened habitats persist in the face of sea level rise. Regional approaches provide a mechanism for prioritizing restoration actions in areas where future conditions will promote maximum resiliency while still providing for an appropriate composition of plant and animal habitats across the region as a whole. Developing a regional restoration strategy requires understanding historical losses relative to contemporary habitat distributions, predicting future changes due to sea level rise (and other stressors), and evaluating management actions with the potential to offset expected future losses. In this study, we present an approach to assess historical losses and future management options for more than 100 individual wetlands along the Southern California (USA) coast ranging in size from a few tenths of a hectare to over 250 ha. This analysis was conducted to support development of a regional wetland strategy that will guide restoration in Southern California for the next several decades. The approach consisted of reconstructing historical wetland distribution using US Coast and Geodetic Survey T-sheets, mapping current wetlands and classifying them into archetypes that represent different settings and processes, and predicting future distributions based on a hypsometric model of elevation changes under various sea level rise and management scenarios. Historical analysis revealed that two-thirds of the 331 wetlands present in ca. 1850 and 75% of vegetated estuarine habitat area has been lost, with most losses occurring in small to medium size wetlands. Up to 69% of the remaining marshes and flats could be lost with 1.7 m of sea level rise, with an associated increase in subtidal habitat. However, potential future losses could be largely offset, and total area could increase under scenarios of facilitated wetland migration and sediment augmentation. Although the future distribution of wetlands would likely be different from current conditions, sufficient habitat would be provided region-wide. This analysis demonstrates how regional analysis of historic, present, and likely future conditions can support a strategy that could lead to net wetland gain under future sea level rise conditions. However, immediate and decisive action is necessary.

Keywords Regional wetland planning · Sea level rise · Restoration · Historical ecology · Archetypes

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Introduction

Restoring and managing individual coastal wetlands in the face of complex landscape-level stressors are daunting propositions. Restoration challenges are exacerbated by the uncertainty of climate change which introduces additional pressures associated with rising sea levels, changing fluvial inputs, and changing water chemistry (e.g., acidification; Kirwan et al. 2010, Cazenave and Cozannet 2013, Mueller et al. 2016).

Successful restoration and management must be process-based and account for the inherent dynamism necessary to support species, habitats, and functions (Boesch 2006). Simenstad et al. (2006) argue that process-based coastal wetland restoration should be done in the context of large regional plans, as opposed to individual projects. These regional plans should focus on restoring landscape processes versus structure, should account for ecosystem dynamics and landscape context, must accommodate larger landscape-scale constraints, and must be adaptive to account for unpredictable long-term changes.

For regional wetland restoration planning to succeed, it must prioritize allocation of limited resources in ways that provide optimal function over the entirety of the coastal ecosystem and promote long-term resiliency to account for future uncertainties. This may involve making choices about prioritization of individual wetlands and how best to focus restoration of specific habitats at key locations to promote critical ecological connections, support metapopulation dynamics, and increase resiliency of wetlands in the entire region. These choices should be made in consideration of the uncertainty associated with global climate models and how they manifest at the local scale.

Such ambitious efforts require tools and analyses for establishing reasonable goals that can guide restoration and management actions and inform decisions about prioritization and allocation of resources. Analytical approaches must acknowledge past conditions when processes were more intact as well as future scenarios when key process drivers may change. Understanding historical conditions provides valuable context for the relationship between landscape-scale process and wetland composition and can inform decisions about appropriate restoration targets at different landscape positions. While not meant to provide a blueprint for the future, reconstructing historical patterns can inform decisions regarding restoration and management by improving understanding of both cultural and natural (i.e., geomorphic) processes that led to current conditions (Jacobs et al. 2011). Similarly, understanding how coastal wetlands will be impacted by changes in future conditions associated with sea level rise and changing runoff patterns is critical to making informed decisions regarding regional restoration planning. This is particularly true for coastlines characterized by a diversity of wetlands of different sizes and physical settings, such as the California coast.

Planning for sea level rise effects is particularly challenging along the Pacific coast because wetland migration is constrained in many places by steep topography or dense coastal development (Thorne et al. 2018). In such settings, inclusion of all wetlands and wetlands types can provide a more holistic regional perspective on sea level rise response and can help maintain ecological function and increase the resiliency of coastal ecosystem networks to future climate change (Stralberg et al. 2011; Gilmer et al. 2012).

Past regional planning programs have mainly focused on regions characterized by large complex systems which serve as the focal point for planning and analysis (e.g., Chesapeake Bay, Florida Everglades, Puget Sound, San Francisco Bay). However, many coastal regions of the world are characterized by a series of small to medium-sized wetlands (e.g., 10s to 100s of ha) where the physical and ecological connections are less continuous and the individual systems are exposed and respond differently to stressors. For example, metapopulations of endemic gobies in Southern California depend on the presence of complexes of small estuaries in relatively close proximity, such that when local stressors affect the populations in one estuary, others persist (Spies et al. 2019). Managing such complex coastal regions requires tools and approaches that allow for an inclusive assessment of all the individual wetlands that comprise the overall regional system. Approaches must allow for consideration of a range of wetland sizes and types. They must also consider the effect of regional restoration plans on both individual wetlands and the overall system in a manner that promotes long-term diversity and resiliency at the regional scale.

Here we present an approach to assess historical losses and future management options for more than 100 individual wetlands along the Southern California (USA) coast ranging in size from a few tenths of a hectare to over 250 ha, an approach that could be replicated in many regions with similar features. This analysis was conducted to support the development of a regional wetland strategy that will guide restoration in Southern California for the next several decades (SCWRP 2018). The need for a regional plan to guide restoration of numerous wetlands of varying sizes in a region with complex coastal morphology and wave climate and intense land use pressures has been discussed for over three decades (Zedler 1996). To date, regional restoration planning has been constrained by the lack of a comprehensive assessment of historical conditions and wetland losses and by the absence of models that provide the ability to assess sea level rise effects across all wetlands in the region. We demonstrate the development and application of historical ecological analysis combined with contemporary mapping and archetype analysis, prediction of future sea level rise effects, and analysis of various management scenarios to provide a series of recommendations for integrated restoration and management planning. Although the specific application of the general approach

presented will vary by region based on available data/information, the general approach of comparing past, present, and alternative future wetland extent and composition is parsimonious for regional planning efforts in that it relies on readily available data sources. This approach should be applicable to other coastal regions of the world characterized by a distributed set of wetlands of various sizes and configurations that challenge more traditional regional restoration planning efforts.

Methods

Study Area

The study area for the Southern California Regional Wetland Restoration Strategy (Regional Strategy; SCWRP 2018) consists of the Southern California coast from Point Conception in the north to the USA–Mexico border in the south (i.e., the Southern California Bight; Fig. 1). This 420 km stretch of coast currently supports approximately 105 individual wetlands and river mouth lagoons, with 90% being less than 100 ha in size. Wetlands include small coastal embayments, river mouth estuaries, emergent marsh complexes, and shallow subtidal basins. The watersheds draining to these coastal wetland systems are home to approximately 19.4 million people (US Census Bureau 2013), and most are encroached upon by urban, agricultural, and recreational facilities.

The Regional Strategy was developed over multiple years with input from scientists, agency staff, and practitioners and

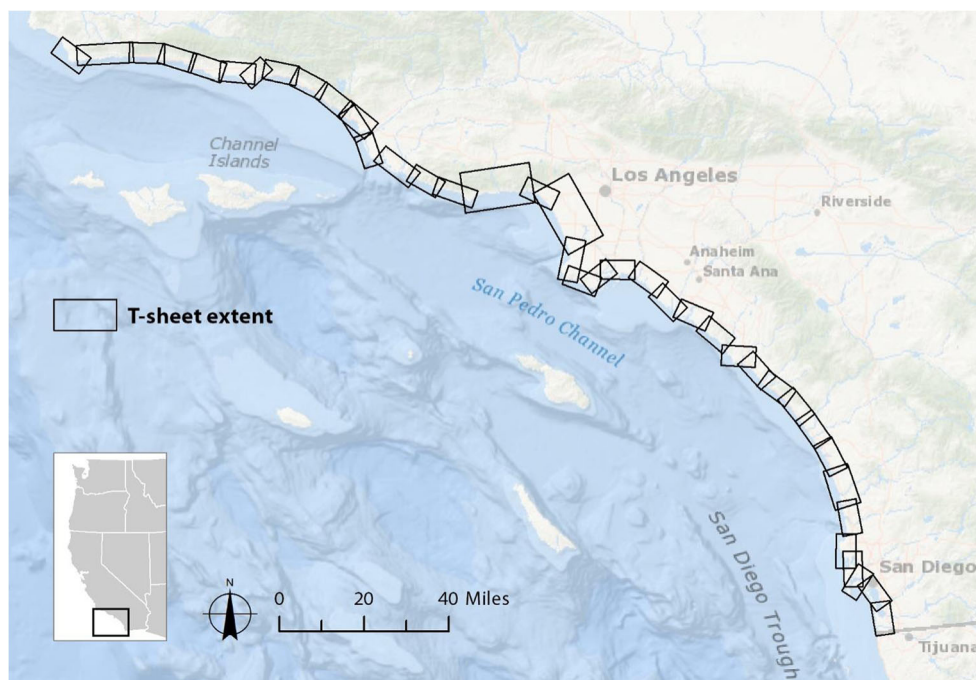
provides a long-term vision and quantitative objectives to guide restoration and management of the 105 wetlands in the region (SCWRP 2018). Recommendations in the strategy are intended to guide prioritization decisions in specific locations as opposed to trying to maximize habitat types at every individual wetland. The plan includes all coastal wetlands in the Southern California Bight because they function as an ecologically interconnected set of systems. The analysis summarized in this paper informed development of the regional objectives and recommendations of specific restoration strategies aimed at achieving the agreed upon objectives.

Analysis of Historical Wetland Losses

Wetland change was assessed by comparing contemporary (ca. 2005) coastal wetland distributions from the National Wetlands Inventory (NWI) to historical (ca. 1850) high-resolution, color digital imagery of 40 historical topographic sheets (T-sheets) covering the same area. The T-sheets were originally produced by US Coast (and Geodetic) Survey between 1851 and 1898 and were obtained from the National Archives and Records Administration in College Park, MD.

The US Coast and Geodetic Survey produced T-sheets for navigation purposes, but they also include mapping of wetlands, streams, and other natural habitats in the coastal zone. They provide the most important single source for understanding the physical and ecological characteristics of the US shoreline prior to Euro-American modification. T-sheets have been produced for the continental USA, Alaska, Hawaiian Islands, Puerto Rico, and US Virgin Islands. Although most

Fig. 1 Study area showing locations of the T-sheets used for mapping of historical wetlands



appropriately used in conjunction with other data sources, such as written accounts, ethnographic records, or other maps, the T-sheets can provide a foundation for regional analysis and a platform on which more detailed investigations can be based (Grossinger et al. 2011; Raabe et al. 2012; Schieder et al. 2018).

Historical and contemporary data were georectified in a GIS using the methods described by Daniels and Huxford (2001) and Smith and Cromley (2006). These methods allow spatial data generated from different datums to be aligned in a standard coordinate system. To ensure no major positional errors, we examined each T-sheet against apparent corresponding features in aerial photography. Comparison of the T-sheet data to stable benchmarks produced an average horizontal error of 12.4 m, which is considered an acceptable offset when working with historical maps and making coarse-scale comparisons to contemporary maps (Daniels and Huxford 2001; Smith and Cromley 2006). All GIS data were projected to NAD 1983 for historical-contemporary comparisons.

We manually vectorized the georeferenced T-sheets through heads-up digitizing, selected coastal features using a consistent set of rules, and classified using a standard system (see below). Because we observed variation in how features were symbolized among different T-sheets (Allen 1997; Askevold 2005), these methods were iteratively refined. Features were digitized at a scale of 1:3000 to 1:5000 and stored in geodatabases in ArcGIS 10.3. Additional detail on historical wetland mapping is provided in Stein et al. (2010, 2014).

Mapping efforts produced a total of over 3300 polygonal and 8000 linear features representing estuarine areas such as subtidal waters, intertidal waters, emergent marsh, and other associated features. Where wetland features (particularly subtidal areas) were contiguous with the ocean, we created a boundary at the ocean opening. We also mapped features immediately adjacent to these estuarine habitats, including beach, dune, forest, freshwater marsh, and creeks but excluded the broad grasslands often indicated adjacent to wetlands. We did not map anthropogenic features shown in the historical surveys, such as jetties, roads, and railroads in the few cases where they crossed wetlands, as this data would not be useful for the change analysis.

Comparison of the historical (ca. 1850) and contemporary (ca. 2005) datasets required resolving differences in the resolution and spatial extent of mapping and in the classification systems. The contemporary mapping provides comprehensive coverage of much of Southern California, while the T-sheets covered only the area within about 2 km of the coast. To perform a meaningful assessment of change over time, only the area common to both datasets was used, primarily the entire surveyed extent of the original T-sheets. Everything in the contemporary dataset which fell outside of the area surveyed from the T-sheet was excluded from the analysis.

A classification crosswalk was generated to create a relationship between the historical and contemporary datasets (Table 1). As mentioned in the previous sections, the historical data has been classified based on the T-sheet classification; however, the contemporary data has been classified using a modified version of the Cowardin classification system (Cowardin et al. 1979). Differences in how the two classification systems classify wetland features made the task of creating an accurate and effective crosswalk challenging. This is because the historical data is classified based on physical features depicted in the T-sheets, while the Cowardin system is based on the frequency of flooding and dominant plant type. Due to these differences, classifications within the two systems do not always have a 1:1 relationship and are not always mutually exclusive.

To align the datasets, a simplified version of the Cowardin classification system was used in both the historical and contemporary datasets. The simplified Cowardin classification used only the system, subsystem, and class levels to maintain an accurate comparison. These align with two major elements documented by the T-sheet surveyors that are relevant to contemporary wetland classification: position on a moisture/inundation gradient and dominant vegetative character. Additional classes in the contemporary dataset were disregarded. The historical classification was then crosswalked to this simplified Cowardin classification based on the T-sheet features. This approach created the 1:1 relationship between the contemporary and historical data necessary for the change analysis but resulted in some loss of information from the contemporary maps. Features mapped within each dataset were grouped into the following classes for purposes of historical-contemporary comparisons: estuarine subtidal, estuarine vegetated, estuarine unvegetated, marine Pacific Ocean, marine beach, palustrine vegetated, palustrine unvegetated, lake, and riverine (Table 1). Change in overall extent and distribution was assessed in addition to changes in specific habitat types (as a way of evaluating type conversion).

Analysis of Wetland Archetypes

The Regional Strategy aims to support restoration of an integrated set of 105 coastal wetlands of different sizes and settings. This requires a clear and relatively concise organizational structure for creating a cohesive strategy that accommodates the diversity of systems in the region yet provides the necessary flexibility for site-specific planning to proceed in consideration of local constraints and opportunities. To accomplish this objective, we grouped historical and contemporary wetlands into *archetypes*, which represent systems with similar form and structure that are expected to function similarly and respond to physical drivers and external stressors in a similar manner. This facilitates our ability to extrapolate knowledge about a given system to similar systems in the region (i.e.,

Table 1 Cross walk between T-sheet (this paper) and Cowardin, et al. (1979) wetland classification for use in the change analysis

Cowardin System, Subsystem, and Class (code)	Simplified Cowardin Classification used for Analyses	T-sheet Summary	T-sheet Data Classification
Marine Subtidal Unconsolidated Bottom (M1UB)	Marine Pacific Ocean	Pacific Ocean	Open Water Subtidal
Marine Intertidal Unconsolidated Shore (M2US)	Marine Beach	Beach	Beach
Estuarine Subtidal Unconsolidated Bottom (E1UB)	Estuarine Subtidal	Subtidal Water Open Water	Open Water Subtidal Channel Subtidal, Open Water Outlet Closed
Estuarine Intertidal Emergent (E2EM)	Estuarine Vegetated	Vegetated Wetland	Vegetated Wetland (not including Non-estuarine)
Estuarine Intertidal, Unconsolidated Shore (E2US)	Estuarine Unvegetated	Intertidal Flat Salt/Unvegetated Flat Open Water	Unvegetated Intertidal Channel Intertidal Unvegetated (not including Non-estuarine) Open Water Intertidal/Supratidal
Riverine	Riverine	River/Stream Gully	Channel Fluvial Gully
Palustrine (Unconsolidated Bottom (PUB)	Palustrine Unvegetated	Open Water	Open Water Non-estuarine
Palustrine Unconsolidated Shore (PUS)	Palustrine Unvegetated	Unvegetated flat	Unvegetated Non-estuarine
Palustrine Emergent (PEM)	Palustrine Vegetated	Vegetated Wetland	Vegetated Wetland Non-estuarine

archetypes) and to consider trade-offs that balance site-specific and regional restoration needs. The archetypes we developed are specific to the Southern California Bight. Different archetypes will be appropriate in other parts of the USA, but the general methodology developed here to analyze future changes will still be applicable.

Archetypes were defined using contemporary wetland data as described in Doughty et al. (2019) and SCWRP (2018). Briefly, we compiled 40 variables related to physical conditions/drivers for each wetland (Table S1). These variables generally fell into one of five categories: catchment properties (proxy for inputs of water and sediment); wetland dimensions, such as size, slope, ratio of dimensions, proportion of subtidal versus intertidal area; inlet dimensions and condition; and wetland volume/capacity.

Of the 105 contemporary wetlands, we had sufficient data for 46, which were retained for the cluster analysis. Data were transformed for normality using approaches appropriate for each data type (typically log, square root, or arcsine root). A K-means cluster analysis was run using a “self-organizing map” option to filter out any variables that did not significantly contribute to the model solution (Hartigan and Wong 1979). We used the same clustering approach defined in Doughty et al. (2019) to define seven archetypes that encompass all wetlands in the study area: small creeks, small lagoons, intermediate estuaries, large lagoons, large river valley estuaries, fragmented river valley estuaries, and open bays and harbors. Intermediate estuaries, which are intermittently opening and

closing estuaries or bar-built estuaries are noteworthy because they represent a significant component of coastal wetlands in Southern California (Zedler 1996). Although a distinct class, it is important to note that most other archetypes include wetlands that have seasonally closing mouths (Jacobs et al. 2011). Finally, we mapped habitat data from the National Wetlands Inventory (NWI) and the California Vegetation Classification (CalVeg) onto the clusters to produce habitat associations for each archetype. We used the classification crosswalk previously described to assign an archetype to each historical wetland (Table 2).

Prediction of Future Changes Associated with Sea Level Rise

We predicted future changes in regional wetland area using a rule-based model that quantifies potential habitat conversion within individual wetlands. The model, described in detail in Doughty et al. 2019 and available online (Doughty 2018), uses hypsometric data, i.e., the measure of land elevation in relation to sea level, to standardize the quantification of habitat change across a region. The approach is consistent with the conceptual model presented by Cahoon et al. (2019) which uses the combination of elevation capital and accretion rates to predict marsh response. The model estimates habitat changes as the combined effects of changes in elevation and water levels for each wetland, which are driven by sea level rise (SLR), accretion, and estuary mouth dynamics over a given

Table 2 Archetypes and example coastal wetlands.

Archetype	General Description	Example Wetlands
Small Creek	Small creek; minimal subtidal habitat area; generally higher gradient	Aliso Canyon Creek, Leo Carrillo
Small Lagoon	Small coastal lagoon without an associated creek	Dume Lagoon, Andree Clark Bird Refuge
Intermediate Estuary ¹	Intermittently closing river mouth estuaries; lacking extensive floodplain or open basin; minimal side channels	Malibu Creek
Large Lagoon	Open basin with extensive subtidal habitat; fringing intertidal; typically, with little fluvial input	Carpinteria Salt Marsh
Large River Valley Estuary	Large, depositional river valleys; basins with fringing marsh; complex lower floodplain; may intermittently close	Goleta Slough, Tijuana River Estuary
Fragmented River Valley Estuary	Currently fragmented large depositional river valley; opportunities for reconnection	Ballona Wetlands, Los Cerritos Wetlands
Open Bay/Harbor	Open water harbors, bays, lagoons; large area, wide & low-lying mouth; may have fringing wetland habitat	San Diego Bay

¹ Wetland of other archetypes may also intermittently close to the tides. However the Intermediate class is characterized by medium size estuaries with mouths that routinely close

time period (Fig. 2). Model rules were developed to ensure that appropriate drivers of elevation and water level changes were applied to each wetland based on system properties and archetype classification. Model inputs were parameterized using available empirical data on accretion and mouth dynamics (i.e., frequency and duration of mouth opening and closing) for the 105 coastal wetlands found in the region. When data was not available for a given site, the archetype classifications serve as a framework to extrapolate data across similar wetland types. Modeling was conducted for two sea level rise projections, 0.6 m by 2050 and 1.7 m by 2100, selected to align with California state guidance (California Coastal Commission 2015; Griggs et al. 2017; National Research Council 2012).

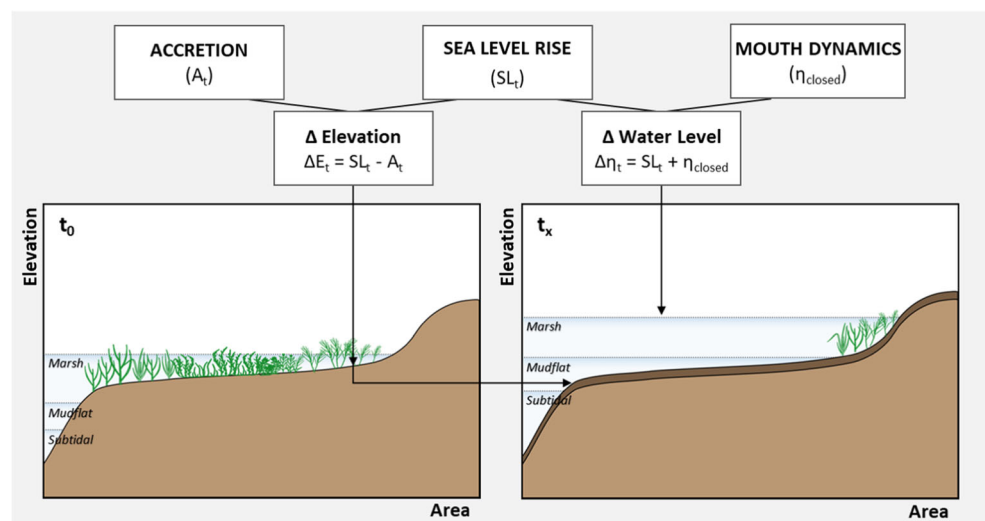
Model results provide estimates of the cumulative area of wetland habitats distributed within elevation ranges on the hypsometric curves for each SLR scenario (Fig. 2). Potential

changes in area were summarized according to three habitat classes, estuarine subtidal, estuarine unvegetated, and estuarine vegetated, to align with the simplified Cowardin classification system (Table 1). Estuarine vegetated wetlands include both low and high tidal marshes. Subtidal water includes embayments and deep channels that do not dry at low tide.

Evaluation of Management Strategies

The SLR model was used to evaluate the potential habitat changes resulting from several management strategies aimed at accommodating or mitigating SLR effects. Strategies were developed in coordination with an interagency workgroup convened as part of the development of the Regional Strategy. Each management strategy was simulated by manipulating one or more of the model inputs, including accretion

Fig. 2 Conceptual diagram of the SLR response habitat change model. Model drivers (sea level rise, accretion, and mouth dynamics) represent the processes inducing change in water levels and elevation. Elevation change (ΔE_t) raises the current marsh hypsometry (t_0 , light brown) to future hypsometry (t_x , dark brown). Water level changes ($\Delta \eta_t$) alter the marsh zones (subtidal, mudflat, and vegetated marsh) delineated by elevation (horizontal lines). Habitat change is calculated as the difference in area under the curve for each marsh zone under current and future conditions



rates, mouth dynamics, and hypsometric data. Facilitation of upland migration of wetlands as a key management strategy was tested for each of the two SLR projections using three scenarios of wetland expansion: (A) no wetland migration, (B) wetland migration avoiding existing developed areas, and (C) wetland migration including developed areas. For the *no wetland migration* scenario, wetlands were constrained to their current boundaries, similar to the approach described above (Section “Prediction of Future Changes Associated with Sea Level Rise”). For the *wetland migration avoiding developed areas* scenario, wetlands were allowed to expand into adjacent areas of suitable elevation that are not currently occupied by homes and businesses. For the *wetland migration including developed areas scenario*, we allowed for the expansion of wetlands into all adjacent areas of suitable elevation, regardless of the current land use. Each upland migration scenario was simulated by expanding the boundary of each wetland based on publicly available GIS data on land use/ownership (CPAD) and elevation (NOAA-CA Coastal Conservancy Coastal LiDAR Project 2009–2013). Hypsometric curves were developed for each of the three expansion boundaries and were used as inputs to the modeling scenarios.

In addition to wetland expansion, we predicted how SLR-induced habitat change might be mitigated by several strategies that reflect adaptation approaches that are being considered and tested. First, we altered accretion inputs to mimic increased sediment delivery by increasing rates to $12.2 (\pm 5)$ mm yr^{-1} and $16.6 (\pm 5)$ mm yr^{-1} to keep pace with SLR projections. Second, we modified the hypsometric curves of each system to simulate one-time thin-layer sediment augmentation to increase intertidal elevation by $23.4 (\pm 10)$ cm. This augmentation depth was selected based on the experimental work being conducted at the Seal Beach National Wildlife Refuge, Seal Beach, CA (USA), as described in Thorne et al. (2019). Third, we tested alternative management of estuary mouth dynamics by either allowing systems to close or actively maintaining systems to be open, which influences the changes in water levels estimated for each system under the SLR projections. Last, we wanted to test potential changes to habitat compositions due to SLR when we reconnect the remaining fragments of wetland complexes that historically comprised complete, hydrologically connected systems. This was accomplished by merging and expanding wetland boundaries, which was informed by the historical analysis described above, and by then developing a hypsometric curve for the complete, reconnected wetland system.

Management strategies reflecting changes to wetland expansion boundaries, accretion, starting elevation, mouth dynamics, and system connectivity were selected for use in the Regional Strategy based on the application of the SLR habitat change model. Although developed for the Regional Strategy, these management strategies are broadly representative of options available to coastal managers worldwide; consequently,

the resultant analysis should be instructive for other regional planning efforts.

Results

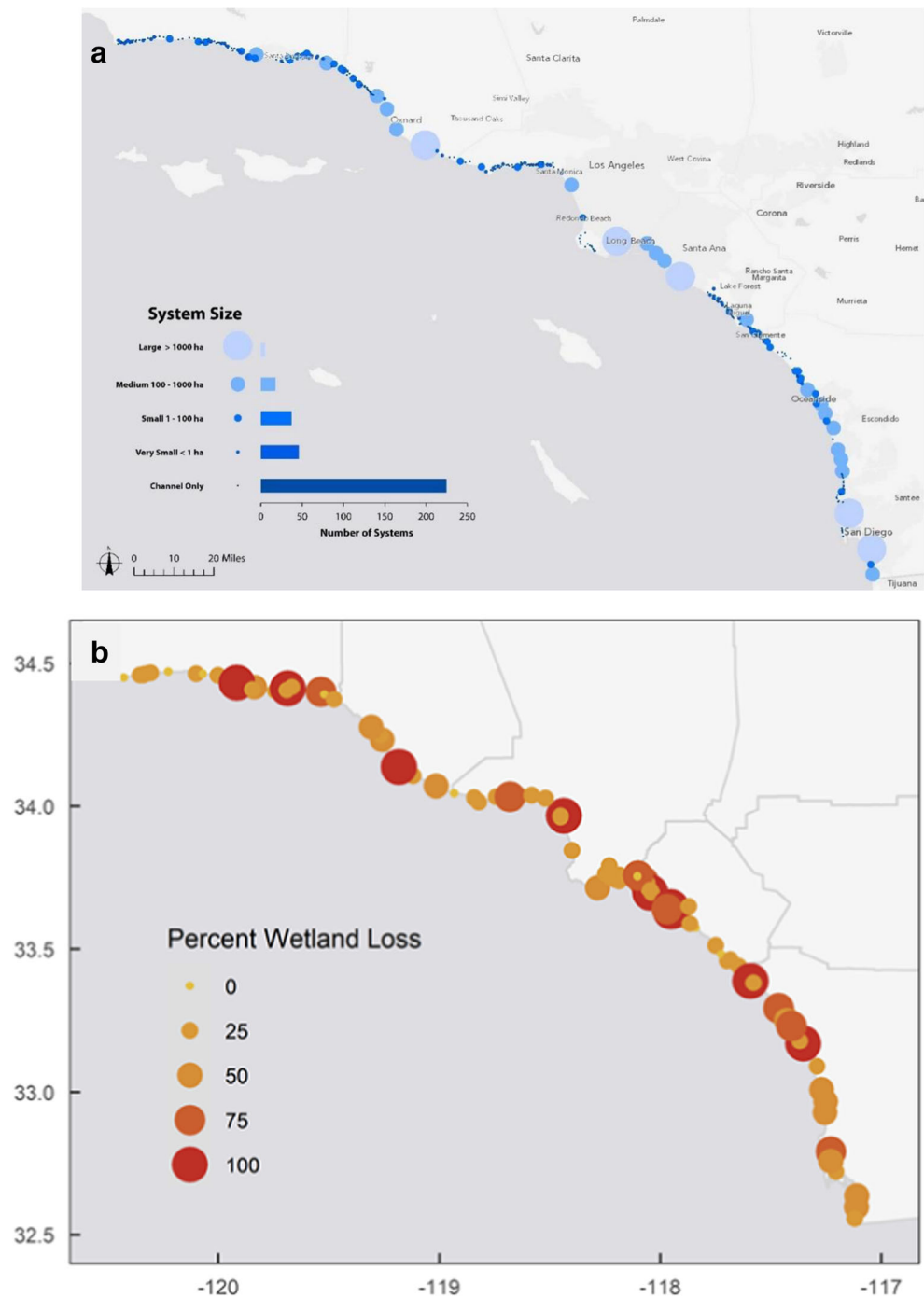
Historical Wetland Losses and Change Analysis

The Regional Strategy study area historically supported approximately 19,500 ha of estuarine habitat along the Southern California coast in the mid-nineteenth century as mapped in the T-sheets. Vegetated wetlands and subtidal water account for most of the historical estuarine area with approximately 7700 ha and 6900 ha, respectively. Intertidal flats, open water, and salt flats together make up the remaining 25% of the total with approximately 4900 ha combined. Much of the historical vegetated wetlands and subtidal water are found in large marsh complexes and bays along the coast. Over half (~57% or ~11,000 ha) of the region’s historical estuarine features were concentrated in the two major open/bay systems at the southern end of the study area, Mission Bay and San Diego Bay.

A total of 331 coastal systems were identified in Southern California’s coastal region. Most systems consisted of only a channel or small and very small coastal wetlands. Of the 308 small and very small systems, 225 were channel only systems that lacked additional estuarine habitats. Only 9 of 308 small systems (3%) were isolated coastal lagoons or wetlands with no associated channels. Of the 299 systems that included coastal streams and were less than 100 ha in size, 73 (25%) of the streams were associated with a small or very small coastal estuary. However, these features were likely variable over time, and this proportion may have fluctuated based on climate and sea level. Individual coastal systems were relatively evenly distributed along the coast with each county having between 60 and 90 systems (Fig. 3). The exception was that the northern region of the study area with rocky headlands contained fewer systems compared to the southern region. On a regional scale, larger systems occur in three areas distributed along the Southern California coastline – south San Diego, along the boundary between Orange and Los Angeles Counties, and in Southern Ventura County. These three nodes are connected by strings of medium and smaller estuaries (Fig. 3).

Since ca. 1850, there has been an overall loss of 9317 ha or 48% of historical estuarine habitats along the Southern California coast. However, losses have not been even across the major habitat types. Estuarine vegetated habitats have experienced the greatest loss in terms of absolute area (–5819 ha, 75% loss), while estuarine unvegetated habitats have experienced the greatest proportional loss of 78% of historical extent. In contrast, the contemporary landscape includes 339 ha more subtidal water, a 5% increase from

Fig. 3 Historical wetland distribution and projected wetland loss with 1.7 m SLR. Top panel (A) shows distribution of 331 historical wetlands. The sizes of the circles represent the relative size distribution of the systems. Inset graph shows distribution of wetland systems by size class. Bottom panel (B) shows locations of 105 contemporary wetlands. The sizes of the circles represent the relative estimates of percent loss

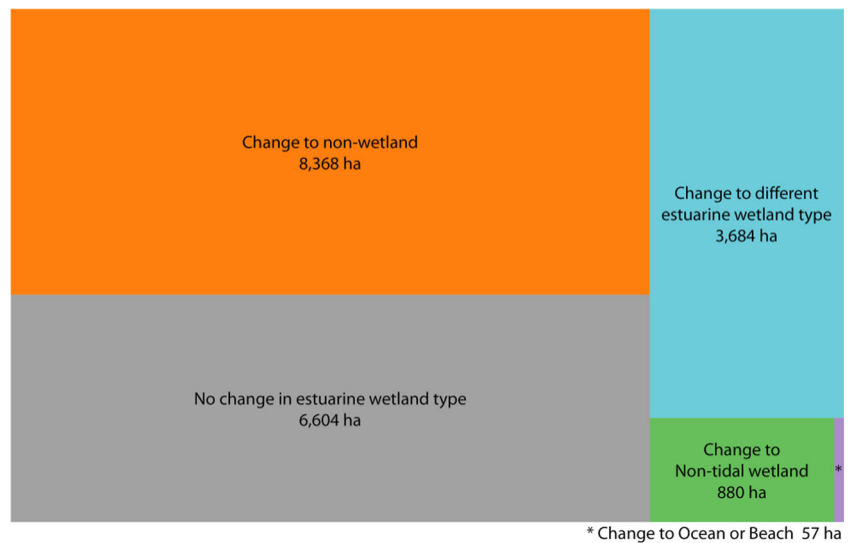


historical extent. These differential losses have shifted the proportional composition of Southern California estuaries. Historically, there was almost an even split between estuarine vegetated (40%), estuarine unvegetated (25%), and subtidal water (35%). Currently the proportional composition is heavily weighted toward subtidal water (71%), while estuarine vegetated (19%) and unvegetated (10%) make up less than one third of the total area combined. Conversion of vegetated and unvegetated wetlands to subtidal habitat has been greatest in the Los Angeles and San Diego regions

where historically large wetland complexes have been converted to commercial ports and harbors.

The largest type conversion has been the change of estuarine habitats to non-wetland features (Fig. 4). Of the 19,500 ha of historical estuarine habitats, approximately 8400 ha or 43% have been converted to non-estuarine features, i.e., urban, agricultural, or open space land uses. Thirty-four percent or 6600 ha of historical estuarine habitats are the same type in the 2005 mapping. However, 74% of this category is due to large

Fig. 4 Tree diagram showing Southern California coastal wetland type conversion between ca. 1850 and ca. 2005



subtidal water features such as Mission Bay and San Diego Bay remaining the same. In contrast, only about 1700 ha of historical vegetated and unvegetated estuarine habitats have remained the same type. Twenty percent of historical estuarine habitats have been converted to a different estuarine type. For example, some areas that were tidal flat in ca. 1850 are now tidal marsh ($\approx 15\%$). A lesser amount, only 880 ha or 4% of historical estuarine habitats have been converted to freshwater wetlands. Finally, a nominal amount of the total historical estuarine extent has been converted to deepwater (subtidal) marine habitats.

In 2005, there were 2081 ha of estuarine habitats (including subtidal water) in the study area that were not

historically present as seen on the T-sheets. Approximately 67% of this “new” estuarine area was converted from the marine category. Most of this was “reclamation” of ocean habitat; however, about 150 ha of beach and dune were also converted to estuarine habitats. Most of this conversion was associated with the creation of the Ports of Los Angeles and Long Beach. Most of the remaining new estuarine area (approximately 600 ha) resulted from the conversion of non-wetland areas including agriculture, undeveloped open space, and developed areas. The remaining 100 ha consist of former nontidal wetlands, such as emergent and woody vegetated wetlands, open water wetlands, and streams/rivers that were converted to contemporary estuarine habitats.

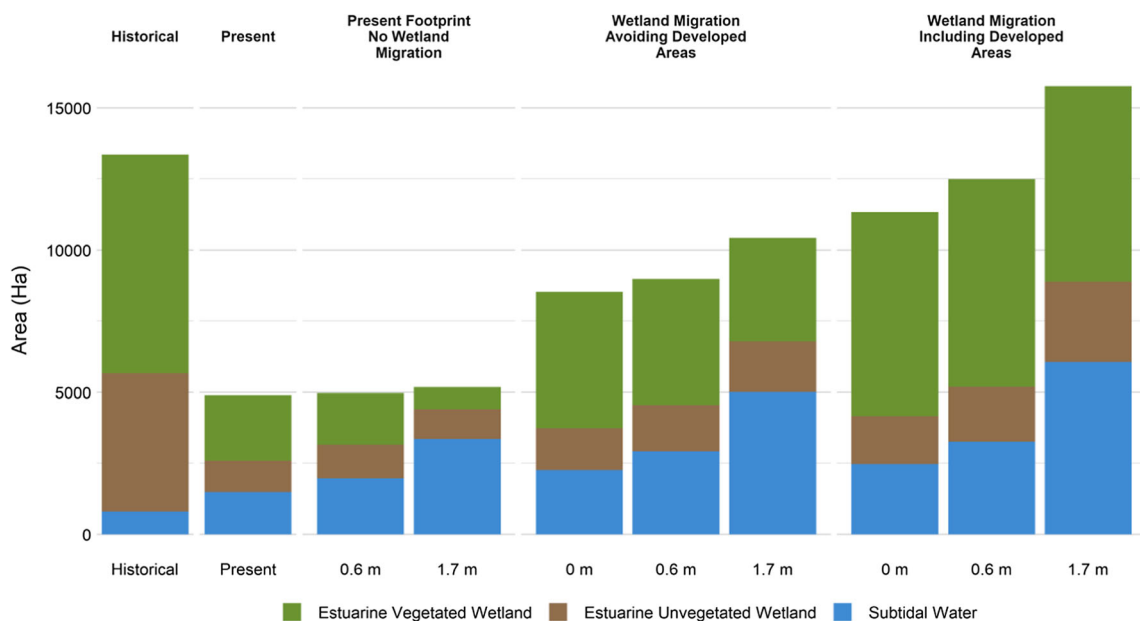


Fig. 5 Potential expansion of wetland area by allowing migration in adjacent areas at suitable elevation, including and excluding areas that are currently developed. Potential for wetland expansion is compared to historical and contemporary wetland distribution

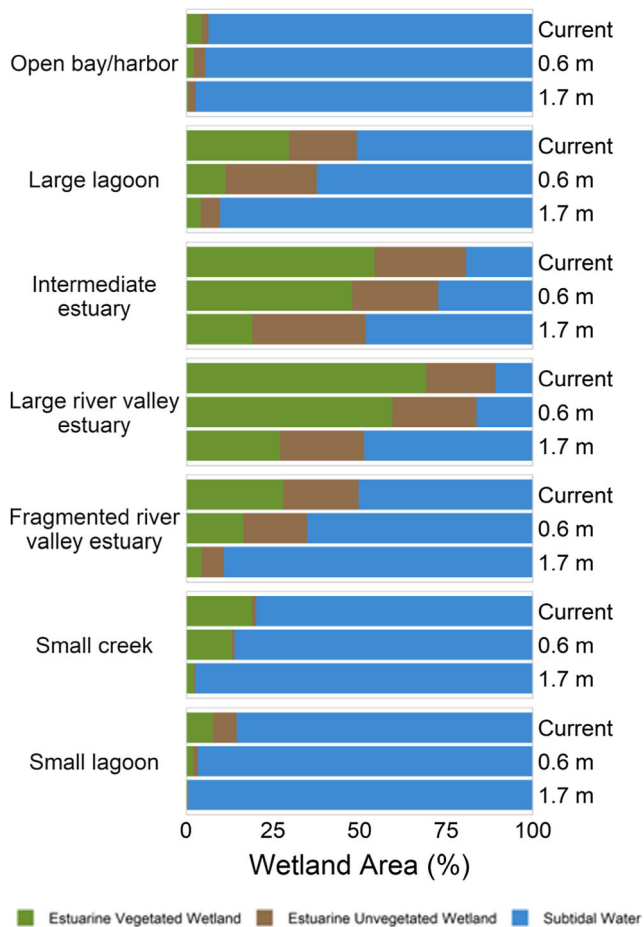


Fig. 6 Current and predicted habitat change for wetland archetypes under two sea level rise scenarios when wetlands are confined to existing boundaries

Future Wetland Loss Due to Sea Level Rise

Absent any intervention, the hypsometric model described above and by Doughty et al. (2019) shows that 407 ha of vegetated marsh and unvegetated flats will be lost with 0.6 m of SLR (by 2050 under current projections) and 1580 ha will be lost with 1.7 m of SLR (by 2100 under current projections) (Fig. 5). The predicted losses represent up to 25% and 69%, of existing vegetated marsh and unvegetated flat areas, which is currently estimated to be 70% of wetland area in the region when large open bays and harbors are excluded. Under this scenario, subtidal areas will increase by 488 ha and 1870 ha with 0.6 m and 1.7 m of SLR, respectively, at the expense of vegetated marsh and unvegetated mudflats.

SLR response was found to vary among archetypes as evidenced by estimates of percent change in vegetated marsh and unvegetated flat (Fig. 6). Large open bays and harbors, which are predominantly subtidal habitats, are expected to experience minimal areal loss of marsh and mudflat due to the relatively small proportion of fringing wetlands characteristic of this archetype. Other archetypes that are large but

have a higher initial proportion of wetland habitats are expected to lose up to 30% of wetland areas with 0.6 m SLR. However, these archetypes could experience rapid declines in wetland areas of up to 80% with 1.7 m SLR. These losses represent conversion of vegetated marsh and unvegetated mudflats to subtidal habitats. Specifically, large lagoons will experience declines of 23% and 80% with 0.6 m and 1.7 m SLR, respectively. Intermediate estuaries exhibit less drastic declines, with 9.4% loss with 0.6 m SLR and 34% loss with 1.7 m SLR. River valley estuaries exhibit the most resilient response to 0.6 m SLR with only 2% change in wetland habitats; however, estimates of loss with 1.7 m SLR increase to 34%, similar to the intermediate estuaries. The fragmented river valley estuary archetype that represents the remnants of once intact river valley estuaries indicates high sensitivity to both 0.6 m and 1.7 m SLR with estimated losses of 29% and 78%, respectively. Archetypes that are relatively small and consist of initially low proportions of wetland habitats are also expected to be highly sensitive to increased sea levels. For example, small creeks will lose 25% of vegetated marsh and mudflats with 0.6 m SLR and 88% with 1.7 m SLR. Small lagoons exhibit the most drastic response to sea level rise with estimates of 80% loss with 0.6 m SLR and 98% loss with 1.7 m SLR.

SLR-induced wetland losses will occur across the entire region (Fig. 3), with the spatial patterns of loss generally reflecting archetype distribution. Large percent losses will occur in the less developed northern part of the region where small creeks and lagoons predominate. However, the central (more urbanized) region south of Los Angeles, with large losses in currently fragmented river valley estuaries, likely reflects their increased sensitivity due to their landscape position, legacy of historical losses, and encroachment by urban development. Ultimately, SLR will serve to exacerbate historical losses and increase fragmentation of the landscape.

Management Options to Mitigate Wetland Losses

Expanding current wetland areas inland should increase their resiliency to SLR. In addition, allowing wetlands to migrate with rising sea levels will offset expected habitat losses. Predicted wetland losses of up to 70% of area with 1.7 m SLR could be offset by allowing expansion of existing wetlands into adjacent upland areas and through active management intervention. With current sea level, realignment of existing levees and roads could allow wetlands to expand into adjacent undeveloped areas with suitable elevations and increase the current coverage of vegetated marsh and unvegetated flats. Most of these areas were historically wetland but have been diked and drained; these represent the greatest opportunities for expansion in response to sea level rise. With 0.6 m of sea level rise, 3060 ha of current upland habitat could become vegetated marsh and flats if wetlands

Table 3 Management alternative options and predicted impact to percent wetland area.

Management Approach	Change in Wetland Area from 2005 (%)	
	0.6 m SLR	1.7 m SLR
Wetland migration only		
No Wetland Migration/ Existing Footprint	-9.7	-34.8
Wetland Migration/ Avoid Developed Areas	-2.6	-18.1
No wetland migration + additional management		
Augmented Accretion	-0.7	-2.4
Sediment Augmentation	-1.6	-27.6
Fragmented System Reconnection	+14.0	-5.0
Wetland migration + additional management		
Augmented Accretion	+2.5	-1.2
Sediment Augmentation	+1.3	-15.2
Fragmented system Reconnection	+29.0	+22.0

Note: Changes to percent wetland area were calculated using different baselines for applicable systems. For example, only intermittently opening and closing systems were considered for mouth dynamics management alternatives and only historically fragmented system complexes were considered for system reconnection

were able to expand into currently undeveloped areas (*wetland migration avoiding developed areas*) (Fig. 5). If wetlands were able to expand into all areas with appropriate elevations (*wetland migration including developed areas*), 6240 ha of upland area could be available for wetland habitat with 0.6 m SLR. With 1.7 m of SLR, 3587 ha of current upland habitat could become vegetated marsh and flats if wetlands were able to expand into currently undeveloped areas (*wetland migration avoiding developed areas*). If wetlands were able to expand into all areas with appropriate elevations (*wetland migration including developed areas*), 7869 ha of upland area could be available for wetland habitat.

In addition to allowing for migration into adjacent areas, targeted restoration and management actions could also offset losses associated with SLR. Increasing annual sediment accretion rates to 12.2 (± 5) mm per year and 16.6 (± 5) mm per year to keep pace with sea level rise would have a moderate effect on habitat change (Table 3). If wetlands were not able to migrate into adjacent areas (no wetland migration/existing wetland footprint), augmenting annual sediment accretion rates to match a sea level rise of 0.6 m (12.2 mm of sediment per year) could reduce wetland loss to 1.6% over the entire region. If marshes were able to migrate into adjacent undeveloped areas (*wetland migration avoiding developed areas*) and sediment accretion rates were augmented to keep pace with sea level rise, an additional 1.3% of vegetated marshes and flats could be saved.

Implementing one-time thin-layer sediment augmentation at a depth of 23.4 (± 10) cm in the manner described in Thorne et al. (2019) would have a comparable effect to increasing the annual sediment accretion rate under 0.6 m of SLR and not allowing wetland migration. However, with 1.7 m of sea level rise, increasing annual accretion rates will increase wetland habitat by 25% more than is possible with the one-time

sediment deposition alone (Table 3). When wetland migration into undeveloped areas is facilitated, augmented accretion could save an additional 14% of wetlands compared to sediment augmentation alone.

Managing tidal mouth dynamics by either allowing inlets to open and close naturally or actively maintaining inlets constantly open will have variable impacts at the regional scale. Habitats may change by up to 40% at individual systems due to changes in mouth management, changes in wetland extent, and associated tidal prism. However, when combined across the region, expected gains and losses balance out and result in no overall effect. In contrast, reconnecting wetland fragments that were historically a single wetland complex could provide an additional 14% of wetland habitat with 0.6 m of sea level rise and under a scenario where no wetland migration could occur. Simultaneously allowing systems to expand into adjacent undeveloped areas while also reconnecting fragmented systems would provide an additional 29% of wetland habitat with 0.6 m of sea level rise. With 1.7 m of sea level rise, system reconnection in conjunction with allowing wetland expansion avoiding developed areas would provide an additional 22% of wetland habitat. Without allowing wetland migration, system reconnection alone would not prevent net losses of wetland habitat with 1.7 m of sea level rise.

Discussion

Projections of 1.7 m of sea level rise threaten a majority of coastal wetlands in California and around the world, with maximum estimated losses ranging from 60 to 90% loss depending on the region and wetland setting, on top of similar losses that have occurred since pre-development periods

(Blankespoor et al. 2014; Schuerch et al. 2018). Despite these dire projections, there are opportunities for management intervention that can reduce projected losses. Immediate and decisive action by the collective management community could restore regional wetland extent and distribution to near historical levels. These opportunities must be pursued in consideration of landscape features together with patterns of current development and infrastructure. Achieving regional restoration goals requires moving beyond site-specific restoration planning to prioritizing opportunities across entire regions that allow for wetland expansion in areas that are most practical and where chances of long-term resiliency are greatest. Regional wetland recovery should prioritize both structural connectivity (i.e., the physical aspects of the landscape that allow movement) and functional connectivity (i.e., the ability for populations and genes to disperse through the landscape; Rudnick et al. 2012). Connectivity is essential to enable species to respond to climate change and other future stressors (Berteaux et al. 2010). Regional analysis can be supported by considering patterns of historical loss and potential future losses through an integrated past-present-future approach, such as the one presented here. It is important that the future orientation of wetlands across a region should not be constrained by historical or current patterns and will likely differ from the current or historic orientation. Achieving this vision requires knowledge of the past and present along with future projections to make informed decisions about regional management priorities and tradeoffs.

Role of Historical Analysis

Historical analysis can help fill critical knowledge gaps that have precluded development of regional restoration plans over the past decades. Understanding historical conditions provides insight into processes that affect the ability of landscapes to support specific wetland types under historical, current, and projected future conditions. This allows integration of the concepts of local habitat succession with the broader perspectives of metapopulation dynamics and island biogeography to account for interactions between individual wetland systems along a defined coastline or bight. This synoptic approach facilitates consideration of key tenets of regional restoration ecology that have proven to be elusive based on observations of contemporary (impacted) landscapes. These concepts include the following recommendations for successful restoration planning (Bedford 1999; Zedler 2000):

- Understand relationships between landscape position and wetland form and habitat composition.
- Determine relatively unimpacted conditions as a reference to guide restoration efforts.
- Consider natural hydrologic regimes and how they vary over seasonal to interannual time frames.
- Assess likely nutrient inputs from contributing watersheds and adjacent land uses.
- Consider spatial relationship of wetlands that facilitate dispersal, colonization, and migration of plant and animal species.

Results of our historical analysis provide insight into the composition and relationships between wetlands that can inform regional restoration planning. Historically interconnected systems of large estuaries interspersed among chains of smaller systems likely functioned as a complex metapopulation of interrelated systems that collectively supported a diversity of natural communities and process along the entire Southern California Bight and allowed exchange of materials and organisms between systems along the coast. Future wetland recovery can attempt to emulate this pattern while attempting to prioritize currently underrepresented habitats and systems, such as tidal flats and seasonally closed lagoons. More importantly, there could be more focus on recreating the mosaic of large wetlands with intervening small river-mouth lagoons that provided nearly continuous estuarine habitat along the Southern California coast. Restoration of small coastal lagoons and estuaries has traditionally been given lower priority because they lack the size, diversity, and charisma of larger coastal wetlands. However, the remnant wetlands along urbanized coastlines, such as Southern California, are often much smaller and more constrained than they were in the past. Emphasizing a series of smaller but intact wetlands that collectively provide desired habitats and functions rather than attempting to create many replicate mesocosms of idealized estuaries within a smaller than historical footprint may ultimately be more sustainable and achieve the goals of compatibility with landscape and hydrologic drivers stressed by Bedford (1999) and Zedler (2000). Historical analysis also suggests that unlike other parts of the world with broad low-lying coastal areas, wetlands along the Southern California coast were largely constrained by the steep topography inherent in the geology of the region. This may limit some future opportunities for wetland migration (in some areas), as is present in other regions, such as the Chesapeake Bay (Schieder et al. 2018).

Future Wetland Losses

We produced a quantitative estimate of relative response to SLR, specific for the Southern California region that is based on the dynamic processes that define local estuaries. The modeling framework incorporates regionally important factors that contribute to SLR response, such as mouth dynamics, which have not been included in previous models (Swanson et al. 2014; Lentz et al. 2016). This approach may be relevant for assessing SLR response in estuaries in other Mediterranean settings across the globe, including South

Africa and Australia, which are subject to similar processes (Jacobs et al. 2011). Based on the use of archetypes, the model should provide a regionally applicable screening tool for application to a wide range of coastal systems, which may have differential responses to SLR (Lentz et al. 2016). The model also has the potential for increased parameterization or the inclusion of site-specific data when it becomes available, which will decrease the uncertainty in model outputs and provide users with improved estimates of SLR response at a given site. Uncertainty is inherent to projected losses due to SLR (Doughty et al. 2019), given data limitations, and errors associated with model input data. Therefore, incorporating estimates of loss for use in regional planning should recognize approximated values as the best available regional guidelines. Because this effort uses site estimates of habitat change to determine future resiliency, it strikes the balance between large-scale vulnerability assessments and site-specific marsh response models. Regional SLR response is often determined using data that is too coarse to capture the vulnerability of individual sites making it difficult to apply the results for local planning. More detailed modeling of marsh response is often conducted at larger, well-studied sites and is too time and labor intensive to repeat for the majority of systems within a region (e.g., Thorne et al. 2016). This means that many (smaller) estuaries are often underrepresented in both local and regional planning efforts. The use of the archetype framework allows us to deal with these data gaps and leverage regional and site assessments. In doing so, we provide increased resolution of SLR vulnerability, at scales relevant to regional and local management. Furthermore, estimates of wetland loss determined using this method corroborate findings from Thorne et al. 2018 who performed detailed process-based modeling for a subset of estuaries in the region (see Doughty et al. 2019 for details). We anticipate that the regional SLR response model will provide screening level assessment that can be used to prioritize and support more detailed site-specific investigations and will provide a platform to prioritize future work based on greatest needs or uncertainties.

Regional Restoration Opportunities

Despite the historical and projected losses, opportunities exist for wetlands to migrate into adjacent undeveloped lands, which would require realignment of physical barriers such as levees, roads, and other infrastructure. Even more opportunities for wetlands to migrate into adjacent land would exist if infrastructure and development were moved. These wetland restoration opportunities vary regionally, with the greatest opportunities to facilitate wetland restoration in the future lying in subregions of the Bight where larger wetlands and lagoons provide greater opportunities for wetland migration into adjacent transition zones. Opportunities also exist in the Santa Barbara, Ventura, and Santa Monica Bay areas that are

dominated by smaller wetland systems but where there is significantly less urbanization and more restorable agricultural land. These are areas where restoration actions could facilitate the migration of wetland habitat and lessen the future impacts of sea level rise. Similar patterns have been predicted for the US Gulf of Mexico coast, where estuaries in low-lying metropolitan areas are expected to be lost because of lack of migration space (i.e., coastal squeeze), whereas those with ample adjacent uplands will better be able to accommodate sea level rise through migration (Borchert et al. 2018). In Jamaica Bay, New York, Cahoon et al. (2019) also predicted that wetlands with high elevation capital and high accretion rates could adapt to sea level rise, where those that did not would likely be inundated over the long term.

Prioritizing wetland restoration through facilitated migration in areas of greatest opportunity would result in a shift in wetland distribution compared to historical. This is exemplified by the Batiquitos Lagoon that historically contained 3% subtidal, 83% mudflat, and 14% marsh and whose future composition is predicted to be 53% subtidal, 17% mudflat, and 30% marsh. However, the overall composition of wetlands across the entire region would be similar to historical and would, therefore, likely support similar plant and animal populations. For example, a mix of archetypes, such as small lagoons and large river valley estuaries, would support both marsh-dependent species such as the Belding's Savannah sparrow (*Passerculus sandwichensis beldingi*) and the Ridgeway's Rail (*Rallus obsoletus obsoletus*) and lagoon-dependent fish species such as the tidewater goby (*Eucyclogobius newberryi*). For the goby, providing a series of small lagoons ranging from 0.5 to 5 ha is more important for supporting stable populations than a few large vegetated estuaries (USFWS 2005). Restoration and management of a series of small lagoons could also provide opportunities for resident and migratory fish to thrive in some systems at certain points of time but colonize other nearby systems if habitat conditions change or degrade where they currently reside. For many estuary-dependent species, the precise location and habitat composition of each individual system are likely less important than the overall regional composition. This "plasticity" in habitat distributions provides opportunities to take a regional approach to prioritizing restoration, focusing actions where they will provide wetlands with the greatest resiliency in the face of climate change while still supporting regionally important species and habitats. Such an approach was demonstrated in the Chesapeake Bay where creating opportunities for wetland transgression has allowed marsh extent to keep pace with sea level rise (Schieder et al. 2018).

Regional restoration planning can become more manageable by utilizing an archetype-based analysis, as was presented here. In addition to providing an efficient way to assess sea level rise effects across all wetlands in the region, archetypes allow general restoration approaches to be developed and

evaluated. Wetland restoration success is largely a function of bio-morphological interactions of tidal ranges, freshwater inputs, salinity gradients, and sediment composition and input (Li et al. 2017). These interactions are, in turn, supported by morphology and landscape setting (Kentula 2002), which are the elements that define archetypes. The efficacy of various restoration and management actions at promoting coastal wetland resiliency to sea level rise can be generalized across archetypes further streamlining planning for regional wetland recovery.

Our estimates of between 25% and 69% loss of existing vegetated marsh and unvegetated flat area loss are similar to projected losses in other coastal regions (e.g., Craft et al. 2008; Lentz et al. 2016) and suggest that our general approach is likely applicable to other areas with relatively open coastlines. The regional hypsometric-based analysis we used may be particularly relevant to regions of the world characterized by small to medium sized estuaries along microtidal wave-dominated open coastlines (e.g., Australia, South America). In these areas, estuarine sediment accumulation is dominated by marine processes and balanced by periodic fluvial discharges that moderate mouth closures and lagoonal water levels (McSweeney et al. 2017). The processes considered in our modeling approach to assess likely losses and investigate restoration and management strategies may transfer well to these coastlines with similar morphologies and sediment dynamics; this should be investigated further.

Sea level rise threatens our economic, ecologic, and social investment in wetland protection and restoration. Higher sea levels will result in wetland loss and habitat type conversion, which will threaten our ability to maintain a network of diverse wetlands along the Southern California coast. However, the worst losses will not occur until sea level rise exceeds 0.6 m (currently projected around 2050). This provides time for deliberate action to acquire uplands adjacent to current wetlands, to implement wetland restoration, and to facilitate wetland management in ways that can better accommodate projected sea level rise.

Application to Other Regions

The past, present, and future approach can be applied to support regional wetland restoration planning in other areas, particularly those characterized by many individual wetlands distributed in relatively close proximity along a defined section of coastline, in contrast to regions characterized by a large central wetland where regional planning may be easier to organize. Large portions of western North America, South America, South Africa, and New Zealand support such distributed wetland networks. The specific analytical approaches may vary by region based on available data and models. For example, T-sheets and sea level response models may not be available in all areas. Nevertheless, the general approach of

developing the best possible understanding of past wetland extent provides critical context to support regional restoration planning. Similarly, even simple estimations of sea level rise effects, e.g., projecting increased ocean elevation onto the land surface, can provide insight into potential future losses that can help prioritize areas and wetland types for restoration. The ability to understand relative historical loss and likely future loss or conversion can be instrumental in guiding discussions about prioritization of resources among many distributed wetlands to ensure that future coastlines continue to support diverse assemblages of interconnected wetland resources.

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