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San Mateo County Wetlands Vulnerability Study

Informing sea level rise adaptation planning through quantitative assessment of the risks and broader consequences of tidal wetland loss: A case study in San Mateo County

Technical Report
Final - January 2019

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Informing sea level rise adaptation planning through quantitative assessment of the risks and broader consequences of tidal wetland loss: A case study in San Mateo County

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Port of Redwood City and Bair Island wetlands. Photo credit: US Army Corps of Engineers Visual Digital Library.

ABSTRACT

Coastal vulnerability assessments are increasing in California as a result of state and local government led climate adaptation efforts. Due in part to the proliferation of fine-scale coastal flood models, standardized approaches have been developed for assessing vulnerability of built assets (e.g., roads, infrastructure) based on likelihood of exposure to flooding and potential for adverse consequences to human health and safety. However, habitat changes and lost ecosystem services are more difficult to quantify because (1) ecosystems are dynamic, requiring more sophisticated analyses of projected temporal changes, and (2) there is no consensus on which services should be quantified or what metrics to use. The disparity makes it challenging for decision makers to integrate natural and built assets into coastal adaptation planning. Risk to natural systems can be underrepresented, skewing prioritization of vulnerable assets toward the built environment, and failing to adequately account for benefits derived from natural ecosystems (e.g., coastal protection, carbon sequestration, biodiversity support). Working in partnership with the County of San Mateo in the San Francisco Bay (California, USA), we quantified projected changes in tidal marsh habitat and in three metrics of ecosystem services under a high sea level rise scenario, and two sediment availability scenarios. We leveraged existing local models, data, and literature to develop spatially-explicit maps of projected future changes in tidal marsh bird indicator species abundance, wave attenuation, and above ground carbon stock in 2040, 2070, and 2100, relative to a 2010 baseline. Maps of projected future changes allowed identification of wetlands currently providing high benefits that are projected to remain high under a range of future conditions (i.e., resilient) as well as those providing high benefits now that are likely to be lost (i.e., vulnerable). Changes in habitat drove the delivery of ecosystem services for tidal marsh bird abundance, above ground carbon stock, and wave attenuation benefits. Accordingly, we observed that our tidal wetland-related benefits showed a neutral or positive change by 2040, but were projected to decrease across a large part of the study area by 2070 in response to projected mid-century acceleration in the rate of sea level rise. Wetlands south of the Dumbarton Bridge, which experience higher sediment availability, were projected to be more resilient overall. In partnership with the County of San Mateo and the California Coastal Conservancy, the results are being integrated into coastal adaptation and climate action planning processes at the county-level and in the broader San Francisco Bay region, and disseminated as a case study approach more broadly.

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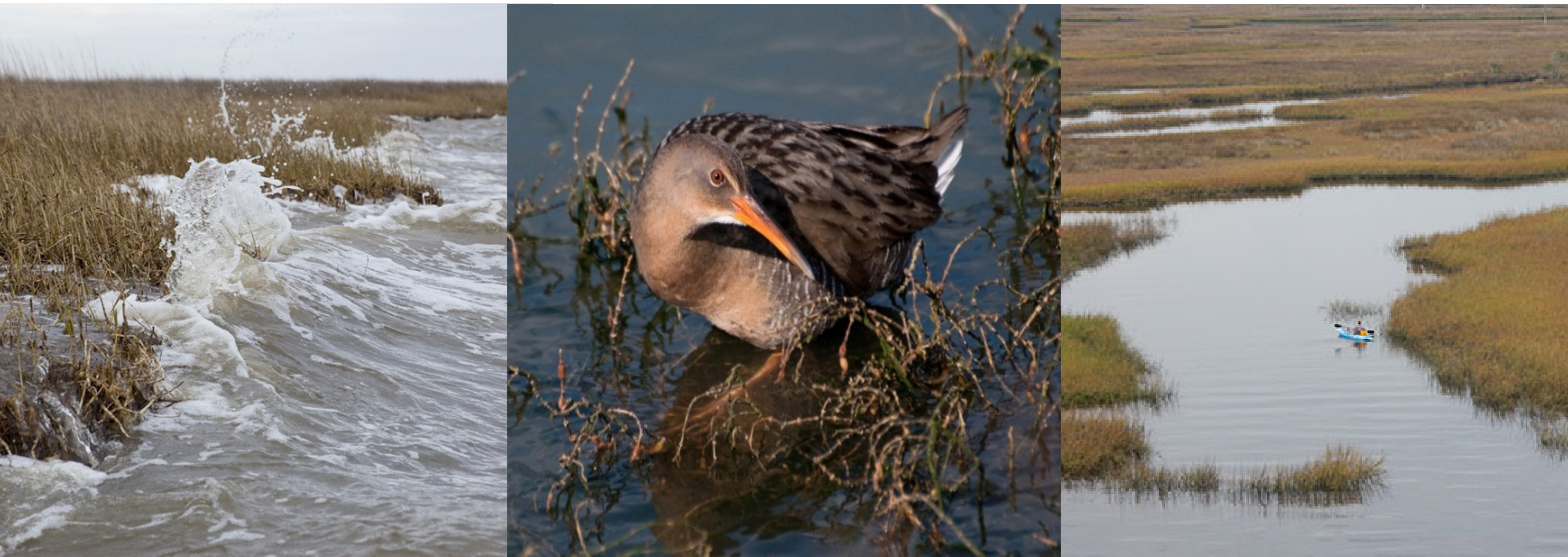

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INTRODUCTION

Rationale

California is a progressive leader among coastal states in recognizing the risks and consequences of changes in sea level and coastal storms, and planning for projected changes in coastal flooding. The projected impact of 0.9-1.4 meters (~3-5 ft) of sea level rise along the coast of California during the 21st century is estimated to affect $67-$100 billion dollars in property and 325,000-500,000 people (Heberger et al. 2009). Local, regional, and state agencies from San Diego to Humboldt Bay have completed 135 sea level rise vulnerability assessments, plans, or strategies (State Adaptation Clearinghouse; resilientca.org) as of the publication of this report, and more are necessary to meet the state's climate adaptation strategy (California Natural Resources Agency 2016).

Vulnerability assessments can rank built assets (e.g., roads, infrastructure) based on likelihood of exposure to flooding and potential for adverse consequences to human health and safety (Arcadis 2015). This quantitative approach is relatively straightforward, in part due to the proliferation of easily accessible flood extent projections under various sea level rise/storm scenarios (e.g., Our Coast Our Future, NOAA Sea Level Rise Viewer) and standard methods for quantifying potential consequences of flooding for built assets (DWR and USACE 2013, FEMA 2015). Ranking allows decision makers to quickly prioritize built assets subject to near-term flooding with the biggest potential impact to human health and safety.

Decision makers also recognize the importance of natural ecosystem functions and services (e.g., White House 2015), and understand that natural systems are also at risk from changes in sea level and coastal storms (California Natural Resources Agency 2016). However, the consequence to natural systems, and the resulting loss in ecosystem services, is often more difficult to quantify, requiring more complex modeling to capture wetland dynamics and challenges with selecting and quantifying ecosystem services across space and time (Craft et al. 2009, Kirwan et al. 2009, Thorne et al. 2015). It is thus understandable that when natural resources are included in vulnerability assessments, analyses tend to be qualitative or expert opinion-based, general rather than site-specific, and only consider limited consequences.

The disparity in approaches for assessing vulnerability of built and natural assets makes it challenging for decision makers to integrate both built and natural assets into coastal adaptation planning. Without a similar framework, the risk to natural systems can be underrepresented, skewing the prioritization of vulnerable assets toward the built environment, and failing to adequately account for the potential adaptation benefits derived from protection and enhancement of coastal ecosystems (e.g., coastal protection, recreation, biodiversity support). The lack of integration during the vulnerability assessment phase hampers the ability of communities to develop adaptation responses that can achieve multiple objectives (i.e., for both built and natural systems) or to accurately assess tradeoffs when weighing adaptation options. We implemented a case study approach to address this gap.

Background

Quantifying the probability of exposure and consequences of coastal flooding on built assets is in many respects more straightforward than for natural resources. First, the elevation of infrastructure remains relatively static through time, so exposure risk can be quantified by a GIS-based overlay of asset locations and readily available, spatially explicit flood extent projections (e.g., http://sealevel.climatecentral.org/matrix/CA.html). In contrast, processes of erosion and deposition are constantly reshaping the topography of natural systems like beaches and coastal wetlands, requiring more sophisticated modeling to forecast changes (Stralberg et al. 2011). Complexity or lack of familiarity with available models, and lack of user-friendly decision-support tools can be a barrier to use of process-based landscape evolution models. Second, flood hazard assessments in the built environment have a clear focus on risks to public safety and property, for which there are standardized metrics to quantify potential consequences (California Building Standards 2013, DWR and USACE 2013, ASCE 2014, FEMA 2015). Though general guidance exists (CEMA and CNRA 2012, California Coastal Commission 2015, BCDC 2016), there is no similar consensus on which of the myriad ecosystem functions and services should be included in a vulnerability assessment. Lastly, despite multiple possibilities for quantitative metrics and valuation approaches (Koch et al. 2009, Barbier and Hacker 2011, King et al. 2015), most remain within the domain of the scientific literature. It is often difficult to extrapolate quantitative measures given the spatiotemporal variability and non-linearity in ecosystem services (e.g., Koch 2009).

For the purpose of our case study, we focused on tidal marsh ecosystems because they are functionally important and particularly at risk from changes in sea level and frequency and severity of storms. Tidal marshes occupy the zone between tidal mud flats and upland areas above the high tide line. They provide critical ecological function in coastal ecosystems and important ecological services to coastal communities on a global, national, and regional scale (Greenberg et al. 2006, Zedler 2010). Benefits include erosion and flood protection, water filtration, recreation, and more (Mitsch and Gosselink 2000). Coastal and estuarine wetlands also face some of the most severe threats from climate change (Michener et al. 1997, Day et al. 2008, Vermeer and Rahmstorf 2009). This is due principally to their sensitivity to changes in inundation patterns and salinity (Kirwan et al. 2010, Zedler 2010, Bayard and Elphick 2011), which are anticipated with climate-related changes in sea level, storms, precipitation, and run-off (Knowles et al. 2006, Day et al. 2008, Cloern et al. 2011).

Local context: San Francisco Bay Area

Cause for concern is especially high in the San Francisco Estuary for two principal reasons. First, tidal marsh habitat supports ecologically distinct populations of plant and animal species, including many endemic species that have evolved adaptations to this saline environment (Greenberg et al. 2006). Second, tidal marsh habitat has been severely altered and degraded, with more than 80% of the historic habitat in the San Francisco Estuary lost since 1800 (Nichols et al. 1986, Takekawa et al. 2006, Goals Project 2015). As a result of the loss of tidal marsh habitat and subsequent population declines of endemic species, management activities in tidal marsh ecosystems are now constrained to ensure no impacts to sensitive tidal marsh species and require considerable investment to increase populations. Remaining habitat has been subject to changes in salinity, invasion by non-native species, fragmentation, and encroachment by urban development (Goals Project 2015). Climate change impacts will further exacerbate these existing stressors and can mean the difference between long-term sustainability and loss of ecological function (Nur and Herbold 2015).

San Mateo County is particularly vulnerable to changes in coastal flooding resulting from sea level rise/storms. The County has the state's largest population projected to be at risk from 0.9m (~3ft) of sea level rise by 2100 (Hauer et al. 2016) and has significant infrastructure and assets in low-lying areas. As an initial step in its resilience strategy, the County assessed the exposure, vulnerability, and consequences of shoreline inundation—including built, human, and natural assets (County of San Mateo 2018). Maintaining natural resources is a high priority for the County and for the San Francisco Bay region (Goals Project 2015). The County's tidal marshes were among the highest ranked for conservation priority across the estuary (Veloz et al. 2013). While the first phase of the County of San Mateo's assessment does highlight where wetlands are exposed to rising tides, it does not account for potential tidal marsh accretion. It also considers the potential consequence of wetland loss in terms of the habitat for endangered species, lacking an approach that can account for the variation in habitat quality in the region or broader ecosystem benefits such as carbon sequestration or coastal defense. This makes it more challenging to prioritize the vulnerability of natural and built assets together or to quantify the multiple benefits and trade-offs of various adaptation strategies.

Despite these challenges, there is strong consensus by the public, scientists, and decision makers on the importance of tidal wetlands and their value as the front-line of defense for Bay Area communities facing impacts from sea level rise. In June of 2016 nearly 70% of voters in the 9-county Bay Area voted to pass Measure AA, a parcel tax that will fund long-term wetland restoration in the region. Additionally, the Baylands Ecosystem Habitat Goals Update (Goals Project 2015), which was the result of collaboration by 21 management agencies working with a multi-disciplinary team of over 100 scientists, emphasized the value and urgency of restoring tidal marsh in the Bay in the face of climate change. Furthermore, sea level rise vulnerability assessments and adaptation planning efforts have been completed or are underway in almost all of the 9 Bay Area counties, as well as bay-wide through the San Francisco Bay Conservation and Development Commission's Adapting to Rising Tides Bay Area project.

OBJECTIVES

The project's overarching objective was to demonstrate an approach for better quantifying benefits of and risks to natural resources and the services they provide in the context of a sea level rise vulnerability assessment. By doing this, we addressed a critical challenge in coastal adaptation planning: linking the natural and built environment to ensure that adaptation strategies provide the broadest benefits at the lowest costs. In partnership with the County of San Mateo and the California Coastal Conservancy, our results will be integrated into coastal adaptation and climate action planning processes at the county-level and in the broader San Francisco Bay region, and disseminated as a case study approach more broadly statewide.

Our goals were to:

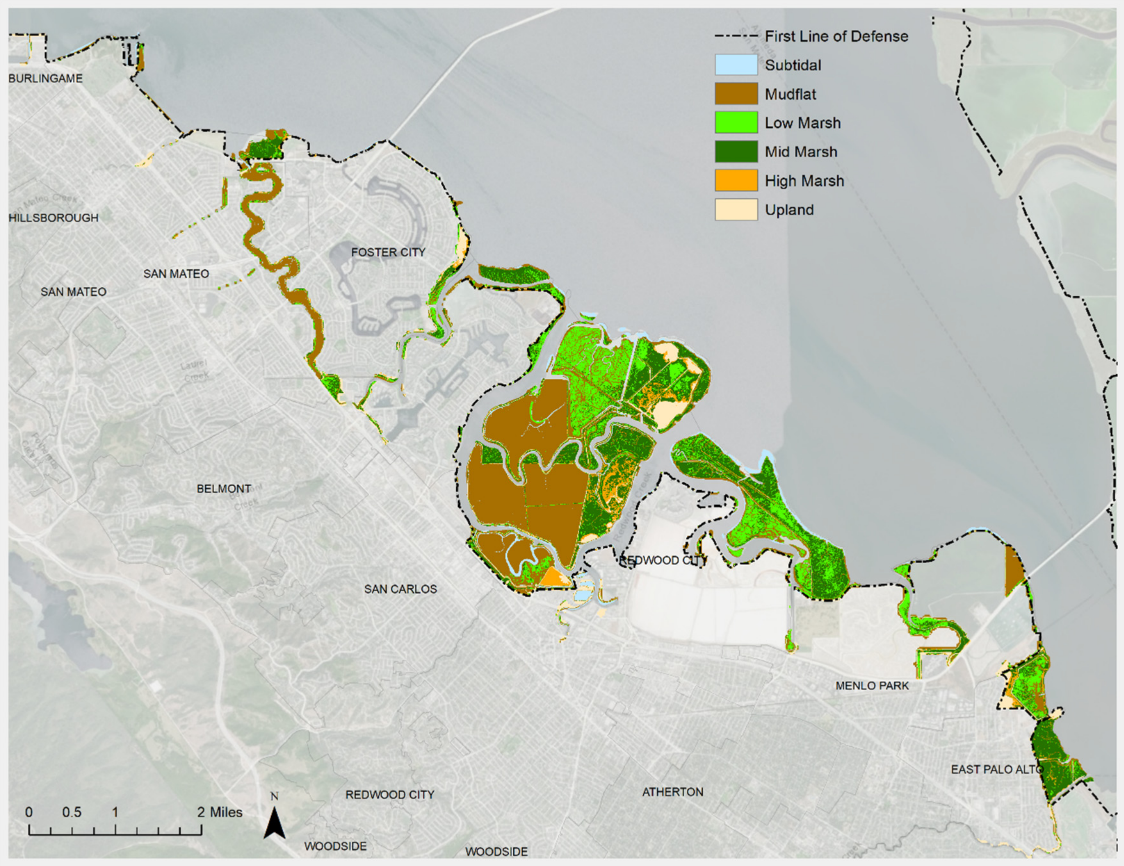
1. Quantify changes in projected functions and services (i.e., multiple benefits) of tidal wetlands under different sea level rise/sediment scenarios by leveraging existing models, data, and literature.
2. Engage with decision makers to integrate this more detailed, data-driven risk assessment of tidal wetlands with concurrent vulnerability and adaptation planning efforts occurring at the local and regional scales.

METHODS

Study area

We conducted the study on the San Francisco Bay wetlands of San Mateo County (California, USA; Figure 1), from Coyote Point (City of San Mateo) south to the County boundary at San Francisquito Creek (City of East Palo Alto). The majority of existing tidal wetlands occur on the outboard side of levees adjacent to the cities of Redwood City, Menlo Park, and East Palo Alto. Most of the wetlands are protected as part of the Don Edwards San Francisco Bay National Wildlife Refuge Complex (including Bair Island, Greco Island, Ravenswood ponds, Faber-Laumeister Tracts) or the Ravenswood Open Space Preserve.

Figure 1. The study area included the San Francisco Bay wetlands of San Mateo County, from Coyote Point (City of San Mateo) south to the County boundary at San Francisquito Creek (City of East Palo Alto). Existing tidal wetlands occur primarily on the outboard side of levees. The "first line of defense" identifies the first feature (e.g., levee) along the shoreline that provides protection against coastal flooding (modified from SFEI 2016).



Quantifying changes in projected wetland functions and services

Focusing on tidal wetlands, we quantified projected changes in a selection of functions and services that (1) represent a range of ecological and societal benefits, and (2) could best leverage existing, locally-relevant data, models, and literature to provide the best available science within the time constraints of decision making. We assessed six future sea level rise and sediment scenarios (Table 1) that aligned with the County's vulnerability assessment (County of San Mateo 2018) and supported needs identified by our stakeholder Steering Committee. Ecosystem benefits quantified included projected changes in area of tidal marsh habitat, abundance of tidal marsh indicator bird species, coarse-level changes in above ground carbon stock, and wave attenuation benefits.

Table 1. Modeled scenarios, including output year with corresponding sea level rise (SLR), and suspended sediment concentration assumption. Sediment assumptions varied spatially, with "low" sediment from 50–150mg/L, and "high" sediment from 150–300mg/L (see text for details).

Year	SLR (cm)	Suspended Sediment
2040	25	High
		Low
2070	100	High
		Low
2100	225	High
		Low

Marsh accretion and habitat change

To provide spatially-explicit projections of future tidal wetland elevations for our study area, we refined the existing Marsh98 accretion model developed for San Francisco Bay (Orr et al. 2003) and hybridized for spatial application to the entire San Francisco Bay geography (Stralberg et al. 2011), with updated sea level rise projections for California (Cayan et al. 2016, Griggs et al. 2017). The Stralberg et al. (2011) modeling approach was most recently used to inform the *Baylands Ecosystem Habitat Goals Science Update* (Goals Project 2015), which updated the regionally comprehensive vision and strategies for wetland restoration in the San Francisco Bay in light of climate change. Key inputs to the refined model included an initial elevation surface relative to a tidal datum, suspended sediment concentration, organic accumulation rate, projected sea level rise, and assumptions on the timing of levee breaches as part of a planned restoration of former salt ponds.

Initial elevation surface

Vertical accretion rates based on a mass-balance approach depend on the depth of the water column, requiring data on the elevation of a given wetland surface relative to the tidal frame (Orr et al. 2003). Thus, we compiled a 2-m resolution Digital Elevation Model (DEM) of current marsh areas from shallow subtidal elevations to upland transition zones, which may become marshes in the future. The DEM was based on the most recent (2010) multi-sourced Light Detection and Ranging (LiDAR) remote sensing data and multi-beam bathymetry data available for the region (Foxgrover and Barnard, 2012). Elevations were then converted to a local mean-higher-high water (MHHW) tidal datum using methods described in Stralberg et al. (2011).

Suspended sediment concentration

Accretion rates also depend on the available sediment suspended in the water column. We used a range of low and high suspended sediment concentrations (SSC) based on data compiled by Stralberg et al. (2011) for the entire San Francisco Bay. We contacted local experts and confirmed that no new data were available for our study area (J. Callaway and K. Thorne, pers. comm). Based on Stralberg et al. (2011), we applied a low SSC of 50 mg/l and a high SSC of 150 mg/l to areas north of the Dumbarton Bridge within our study area. For areas south of the Dumbarton Bridge, we applied a low SSC of 150 mg/l and a high SSC of 300 mg/l. Sediment values across the boundary of these two regions were spatially smoothed using a 500m moving window average to reflect a more gradual transition.

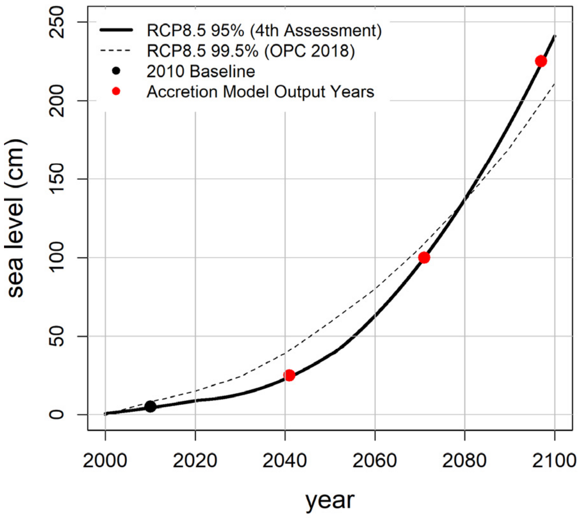
Organic accumulation rate

Organic matter accumulation also affects the rate of vertical accretion (mm/yr), and data across the Bay Area ranged from 1-3 mm/yr (Stralberg et al. 2011). The model is largely insensitive to these small organic matter accumulation rates (Stralberg et al. 2011), so for the purposes of this study we applied a “high” value of 3 mm/yr to be present universally across the study area.

Projected sea level rise

When we began this project, the State of California was in the process of updating 21st century sea level rise projections as part of two related efforts: California’s 4th Climate Change Assessment (http://www.climateassessment.ca.gov), and via a process to update the state’s coastal planning guidance led by the Ocean Protection Council (http://www.opc.ca.gov/updating-californias-sea-level-rise-guidance/). When we began our modeling, only the sea level rise projections from the 4th Climate Change Assessment (Cayan et al. 2016) were available. Based on recommendations to 4th Assessment researchers and input from our Steering Committee, we selected the high emissions Representative Concentration Pathway (RCP) 8.5 scenario (Moss et al. 2010) 95% probability curve from the CanESM2 Global Climate Model, and used the hourly projections for the San Francisco tide gage (Figure 2). The 4th Climate Change Assessment projections were subsequently finalized in Pierce et al. (2018). We note that the probabilistic curves developed for California’s 4th Climate Change Assessment were slightly higher than those that were used in the updated State of California Sea Level Rise Guidance (OPC 2018), due to differing assumptions of the contribution from Antarctic and Greenland ice loss.

Figure 2. Projected sea level rise (solid black line) for the San Francisco tide gage used in our marsh accretion modeling. Curves are based on California’s 4th Climate Change Assessment (Cayan et al. 2016). The “medium-high risk aversion” scenario curve (dashed line) from the updated State of California Sea Level Rise Guidance (OPC 2018; made available after our work) is included for reference. RCP = Representative Concentration Pathway.



Restoration assumptions

We also accounted for the timing of planned levee breaches that will return tidal action to a series of former salt ponds at the Ravenswood complex of the San Francisco Bay National Wildlife Refuge (part of the South Bay Salt Pond Restoration Project) (Figure 3). Members of our Steering Committee who lead this effort (J. Bourgeious and L. Materman) estimated the timing of levee breaches, and we then incorporated this information in our marsh accretion model by allowing the surfaces of the restored ponds to begin accreting only after the breach year. For all years prior to the levee breaching, we masked out the pond areas (i.e., the ponds only contribute to tidal wetland habitat after they are restored). The red area in Figure 3 was assumed to begin accretion in year 2019, and the blue area in year 2028.

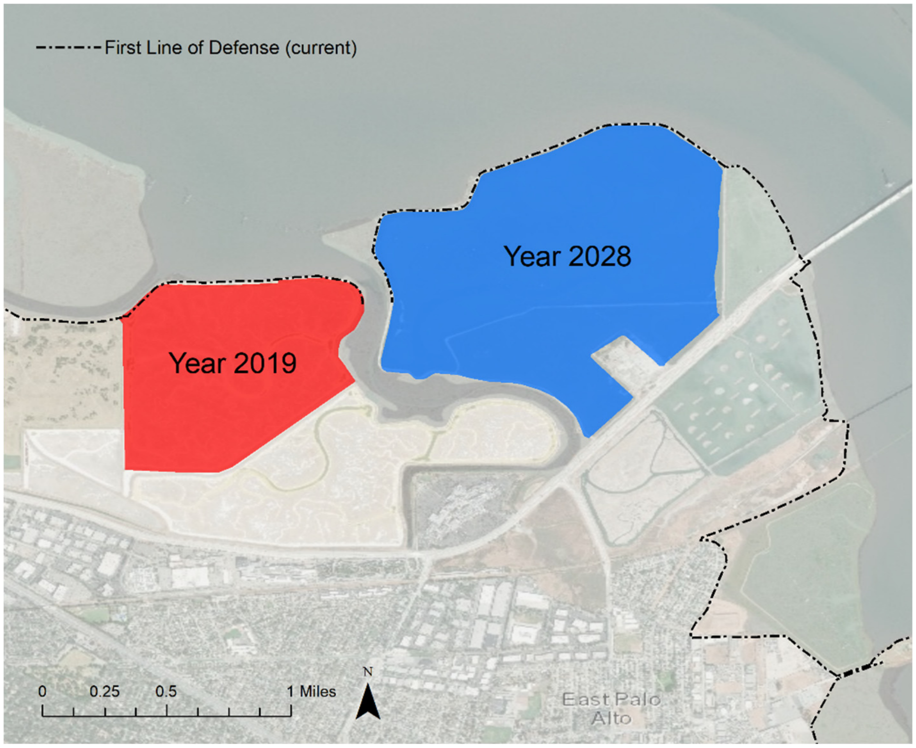


Figure 3. Location and timing of planned restoration that will restore tidal action to former salt ponds as part of the Ravenswood complex of the South Bay Salt Pond Restoration Project. Area in red was assumed to begin accretion in year 2019, and area in blue was assumed to begin accretion in year 2028. The ponds are located just north of the Dumbarton Bridge (City of Menlo Park, California). The "first line of defense" identifies the first feature (e.g., levee) along the shoreline that currently provides protection against coastal flooding (SFEI 2016).

Vertical accretion and habitat change

We ran the accretion model from a year 2010 baseline (initial elevation surface) to year 2096 when the sea level rise curve reached 225cm. For ease of communication we refer to this as the 2100 scenario. The model adds the corresponding depth-dependent mineral sediment accumulation plus organic accumulation at yearly time steps, producing a new elevation surface relative to the projected MHHW level at yearly timesteps. We then output DEM raster surfaces for our year 2040 (25cm SLR), 2070 (100cm SLR), and 2100 (225cm SLR) time points of interest (Table 1).

Based on relative elevation within the tidal frame, we classified output elevations for our 6 scenarios (Table 1), plus the 2010 baseline into habitat types, following Stralberg et al. 2011 (Table 2) for mapping habitat change and for use as inputs to the tidal marsh bird abundance, carbon stock, and wave attenuation models.

Table 2. Habitat classes based on elevation relative to mean higher high water (rMHHW), following Stralberg et al. (2011).

Habitat type	Elevation range (rMHHW)
Upland	>0.3m
High Marsh	0.2 to 0.3 m
Mid Marsh	-0.2 to 0.1 m
Low Marsh	-0.5 to -0.3 m
Mudflat	-1.8 to -0.6 m
Subtidal	<-1.8 m

Abundance of tidal marsh bird indicator species

We used existing models for tidal marsh bird indicator species developed for San Francisco Bay by Veloz et al. (2013) to estimate the abundance of five tidal marsh bird species within the study area: Ridgway's rail, black rail, common yellowthroat, marsh wren, and song sparrow. We then took a weighted geometric mean of all 5 species to generate a metric of tidal marsh bird indicator species abundance. Species were weighted as follows: Ridgway's rail = 5x, black rail = 4x, common yellowthroat = 3x, marsh wren = 1x, and song sparrow = 2x. We briefly describe the methodology below and refer the reader to Veloz et al. (2013) for further details.

We included several elevation-based metrics as covariates in our bird abundance models, following Veloz et al. (2013). We estimated the mean, majority and standard deviation of elevation for all of the 2 x 2 m cells within a 50 m radius of the center of each cell (100 m radius for Ridgway's rail to account for their larger territory size). We calculated the percent of high marsh, mid marsh and low marsh within a 50 m radius of each grid cell (100 m radius for Ridgway's rail). We used interpolated maps of spring and summer salinity to calibrate our model (Veloz et al. 2013). We used projections of changes in salinity from the USGS CASCaDE model (Cloern et al. 2011) to estimate changes in salinity with climate change and sea level rise. All covariates were developed for the 2010 baseline and the 6 future scenarios from the accretion model (Table 1).

Other covariates used in the model were assumed to remain constant through future scenarios. These included a set of distance metrics: distance to bay, distance to urban areas, and distance to channels. We also included the tidal range and the density of channels in a 50 m radius around each cell (100 m radius for Ridgway's rail).

We used annual surveys of tidal marsh birds throughout the San Francisco estuary to estimate the abundance of each species at each survey location. These estimated abundances were used as a response variable in a boosted regression tree model (Elith et al. 2008) to predict abundance to all tidal marsh cells within the study extent. Accuracy estimates for each of the models was provided in Veloz et al. (2013).

Above ground carbon stock

To determine a coarse-scale estimate of carbon sequestration benefits, we developed a model based on a subset of field-based, above ground biomass harvest data synthesized by Byrd et al. (2017) and a subset of spatially explicit covariates from the bird models. We used distance to bay, distance to channel, channel density, tidal range, summer salinity, and elevation in a boosted regression tree model to predict above ground tidal marsh vegetation biomass within the study area. The correlation between observed and predicted average biomass was 0.72 ± 0.04 based on a 10 fold cross validation of model training data. Based on Byrd et al. (2017) we estimated above ground carbon (g/m^2) as 0.441 times the total biomass in each cell for all tidal marshes in the study area for current (2010 baseline) and 6 projected future conditions (Table 1).

Wave attenuation

We modelled wave attenuation using the Federal Emergency Management Agency's (FEMA) Wave Height Analysis for Flood Insurance Studies (WHAFIS; Version 4.0, FEMA 2007a) and wave runup (RUNUP) models (Version 2.0, FEMA 1991). As the name suggests, WHAFIS is typically used to assess flood insurance rates using 10- and 100-year floods (FEMA 1988) but is increasingly being used to evaluate the effects of waves under different sea level rise scenarios (e.g., ESA PWA 2012). This flexibility also allows the assessment not only of different sea-level rise scenarios but the potential effects of changes to the elevation profile due to different levels of accretion, planned levee removal, and/or marsh restoration.

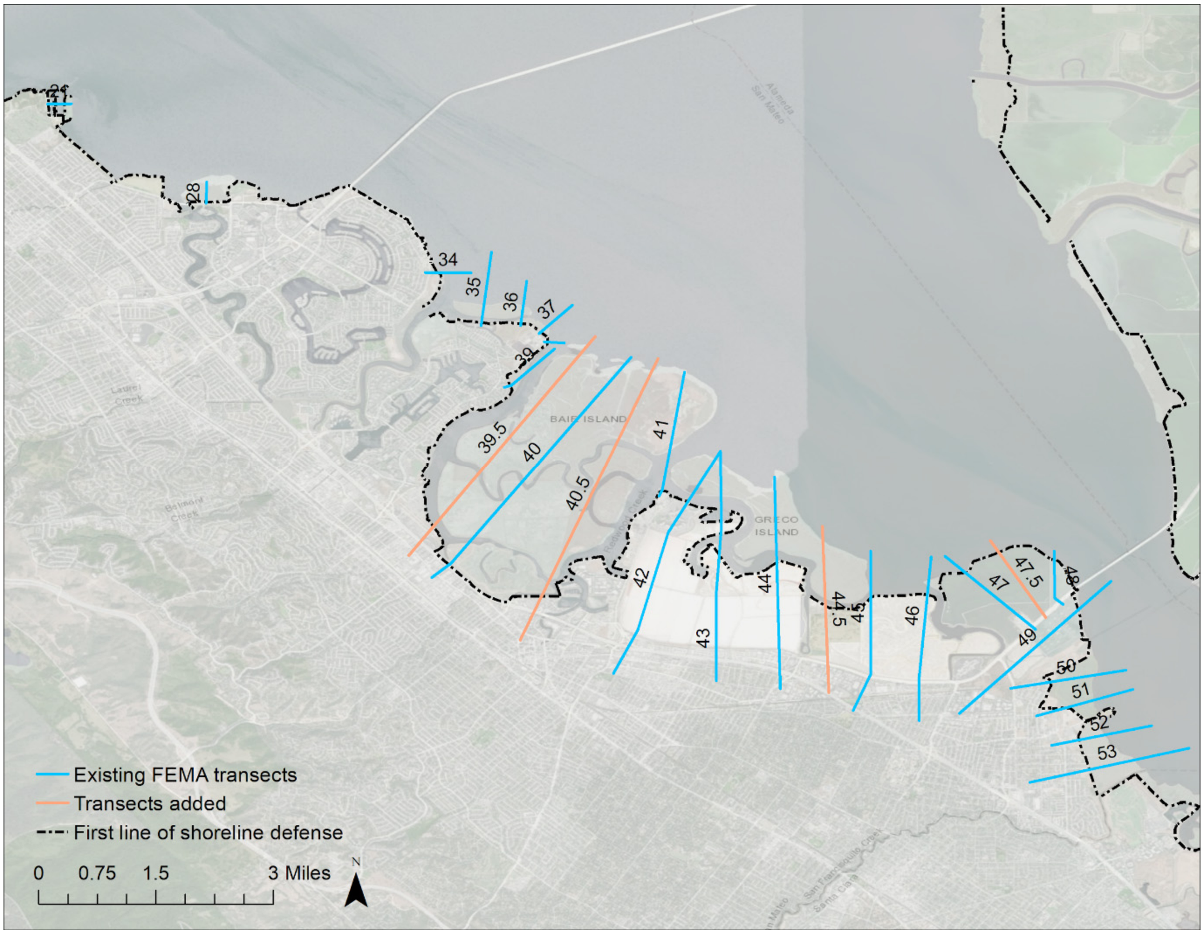
Transects

WHAFIS is a one-dimensional model, producing results along individual transects rather than a two-dimensional map. Based on input from our Steering Committee, we used transects from the most recent flood insurance study of the area (FEMA 2017) and added a few additional transects to get better spatial coverage across our tidal wetlands of interest (Figure 4).

Elevation

We created inputs for the WHAFIS model using the results of our marsh accretion modelling (see above), which included the planned restoration of existing salt ponds (Figure 3). Water depth calculated as MHHW was used as the stillwater elevation. We extracted the elevation at points every five meters along each transect. Each point was assigned to one of the cover classes required for WHAFIS (e.g., overwater fetch or marsh vegetation) based on the combination of elevation and vegetation assumptions from our habitat classes (Table 2).

Figure 4. Location of transects used for our wave attenuation modelling in San Mateo County, California. Transects in blue were taken from the most recent FEMA flood insurance study (FEMA 2017) of the region; transects in orange were added by us to give better coverage of some of the marshes. The "first line of shoreline defense" is the first shoreline feature (e.g., levee) that provides protection against coastal flooding (modified from SFEI 2016).



Vegetation

Marsh vegetation has a major impact on wave attenuation, making waves slower, shorter, and less energetic (FEMA 2007a) and so was important to include in our projections of future wave attenuation. Current vegetation in the study area consists primarily of pickleweed (*Salicornia pacifica*) and native Pacific cordgrass (*Spartina foliosa*; Wardman 2011; Point Blue Conservation Science, unpublished data). Specific vegetation parameters used to calculate wave attenuation were taken from the FEMA study done by Wardman (2011; Table 3).

Table 3. Base vegetation parameters for use in Pacific-coast WHAFIS modelling from Wardman (2011).

Species	Effective Drag Coefficient	Unflexed Stem Height (ft)	Stem Density (#/sq. ft)	Base-Stem Diameter (in)	Mid-Stem Diameter (in)	Top-Stem Diameter (in)	Front Area Ratio
Pacific Cordgrass *(Spartina foliosa)*	0.1	3.5	6	0.5	0.5	0.5	1.59
Pickleweed *(Salicornia pacifica)*	0.1	2	28	0.4	0.4	0.125	0.1

For future scenarios, we assumed the vegetation likely to be present based on our elevation-based habitat class (Table 2) as follows: high marsh = pickleweed, mid marsh = mix, low marsh = cordgrass, mudflat = none. We used these basic assumptions in the absence of specific knowledge about what the future species composition of these marshes will look like.

Input wave parameters

WHAFIS must be parameterized with initial wave height, wave period, wind speed, and wind direction (FEMA 2007b). These parameters were taken from the USGS Coastal Storm Modelling System (CoSMoS; Barnard et al. 2009) accessed using the *Our Coast Our Future* tool (www.ourcoastourfuture.org). As CoSMoS is a two-dimensional model, it captures the spatial variability in the bay and so gave us transect-specific starting parameters. We used data from the daily, annual, 20-year, and 100-year storm scenarios for each of the three sea level rise scenarios modelled (25, 100, and 225 cm; see Table 1). For the 1-, 20-, and 100-year storms, the storm surge as calculated by the CoSMoS model was added to the base amount of sea level rise to serve as the projected future stillwater elevation.

Spatial interpolation

To produce a two-dimensional map of predicted wave height in the 6 future scenarios, we interpolated the results of our WHAFIS modelling between each transect. We interpolated using co-kriging with the elevation surface as a covariate for the 2010 baseline and each future scenario (Table 1). The interpolation was performed using the default parameters of the Geostatistical Analyst extension's co-kriging tool in ArcGIS 10.5 (ESRI 2017). Data extraction and the creation of the input cards for WHAFIS were performed in R Version 3.4 (R Core Team, 2017) using the raster (Hijmans 2017) and rgdal (Bivand et al. 2017) packages.

We calculated a wave attenuation metric as the inverse of wave height: the taller the waves the less attenuation benefit. The attenuation benefit was calculated as follows:

$$attenuation\ benefit = 1 - \frac{ScenarioWaveHeight}{MaxWaveHeight}$$

The smaller the scenario wave heights (*ScenarioWaveHeight*), the larger the numerator in the equation and thus the larger attenuation benefit. The maximum wave height (*MaxWaveHeight*) is the maximum wave height across all seven scenarios (2010 baseline + 6 future scenarios).

Multi-benefit metric

We developed a composite index that spatially integrates the bird, carbon, and wave attenuation ecosystem benefits. The multi-benefit metric was calculated as the geometric mean of bird abundance, carbon stock, and wave attenuation benefits. Based on input from our Steering Committee, we weighted the wave attenuation benefit more heavily (2x). The geometric mean ensures that all three benefits contribute to the metric at the same scale, regardless of the units with which the individual metrics were measured.

Analysis

Because our interest was in understanding how (direction) and where (spatial distribution across the landscape) tidal wetland-related ecosystem services change with rising seas, we produced maps showing change relative to the 2010 baseline condition for each of the three individual metrics (birds, carbon, waves) and the composite multi-benefit metric for our six future sea level rise and sediment scenarios (Table 1).

Integrating results with concurrent local/regional adaptation planning efforts

Project Steering Committee

To guide the project and facilitate integration of results with concurrent local and regional planning efforts, we developed a project Steering Committee made up of representatives from the key wetland and shoreline land managers located within our study area. In addition to project partners from the County of San Mateo and the State Coastal Conservancy, our Steering Committee included representatives from the cities of Redwood City, Menlo Park, and East Palo Alto, the San Francisco Bay National Wildlife Refuge, South Bay Salt Pond Restoration Project, and the San Francisquito Creek Joint Powers Authority (see Acknowledgements). We communicated with the Steering Committee via email and phone discussions as needed to decide on key model input assumptions, and convened the Steering Committee in-person a total of three times:

1. Initially to review the proposed work plan, to decide on future scenarios and key model input assumptions, and to identify potential planning efforts to prioritize for outreach and integration of project results
2. For a project status update midway through the project, and to provide input on proposed output products and deliverables that would best support existing planning efforts
3. To review draft results, and discuss deliverables and broader dissemination of results. This included feedback and guidance to improve effectiveness of communicating project results to decision makers, and a prioritized list of desired products that would support members' own communication needs and facilitate broader dissemination of results.

Broader engagement

Our partnership with the County's Office of Sustainability allowed leveraging of ongoing stakeholder coordination and public outreach efforts as a vehicle for integrating project results with other County departments and municipalities. We provided project updates, background information, and presentation material to support engagement in:

1. Sea Level Rise Workgroup meetings, which included representatives from all 20 cities in the County
2. Technical and Policy working groups, comprised of internal and external partners (i.e., key city and local/state/federal agency decision makers), that met periodically to support the County's Sea Level Rise project
3. Sustainability staff participation in the Regionally Integrated Climate Action Planning Suite (RICAPS) initiative to support development of Climate Action Plans and greenhouse gas inventories

4. Education and outreach via the County's Youth Exploring Sea Level Rise Science (YESS) program

Our match funding also allowed us to present the study at a variety of other local, regional, state, and national forums, which reached both technical science and management/decision-making audiences. We provide a summary of broader engagement in the Outcomes and Conclusions section.

RESULTS

Through 2040, habitats were projected to accrete and transition to higher elevation habitat classes (e.g., mudflat to vegetated marsh) under the high sediment scenario, and to at least maintain the current proportion of habitats under the low sediment scenario (Figures 5 and 6). However, with the projected acceleration in the rate of SLR after mid-century (Figure 2), the majority of wetlands within the study area were projected to be unable to keep pace with rising seas, transitioning to mudflat elevations under the high sediment scenario, or to a mix of subtidal and mudflat habitats under the low sediment scenario by 2100. A notable exception to this trend is the region south of the Dumbarton Bridge, where sediment assumptions were two to three times higher, and maintained higher elevation habitat classes for longer. Areas that retained vegetated marsh by 2100 under the high sediment scenario were either currently at the highest (upland) elevation or were located in the higher sediment region south of the Dumbarton Bridge.

Changes in habitat drove the delivery of ecosystem services for tidal marsh bird abundance, above ground carbon stock, and wave attenuation benefits. Accordingly, we observed that our tidal wetland-related benefits showed a neutral or positive change by 2040, but were projected to decrease across a large part of the study area by 2070 (Figures 7-12, Appendix B). Areas that currently (2010 baseline) support the highest multi-benefit index values were those that occur at highest elevations (i.e., currently support vegetated marsh), and these high elevation areas were observed to have the largest loss of benefits by the 2070 scenarios. We also noted that the remaining high elevation areas in 2100 were projected to support an increase in benefits relative to the 2010 baseline. Lastly, we observed a net positive effect on ecosystem services of restoring the Ravenswood ponds to tidal action regardless of future scenario.

Figure 5. Projected habitat change through time under the "high" sediment scenario.

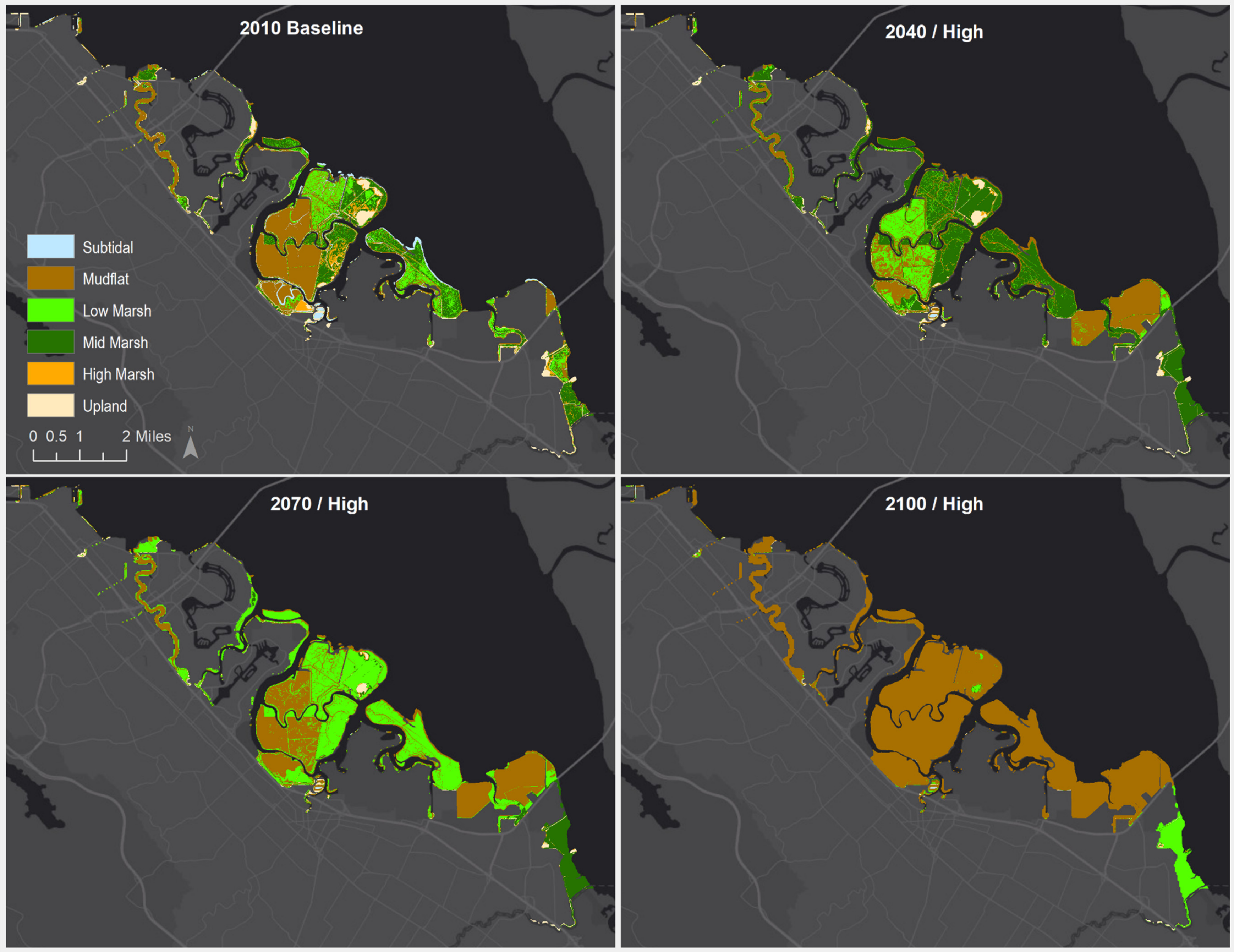


Figure 6. Projected habitat change through time under the "low" sediment scenario.

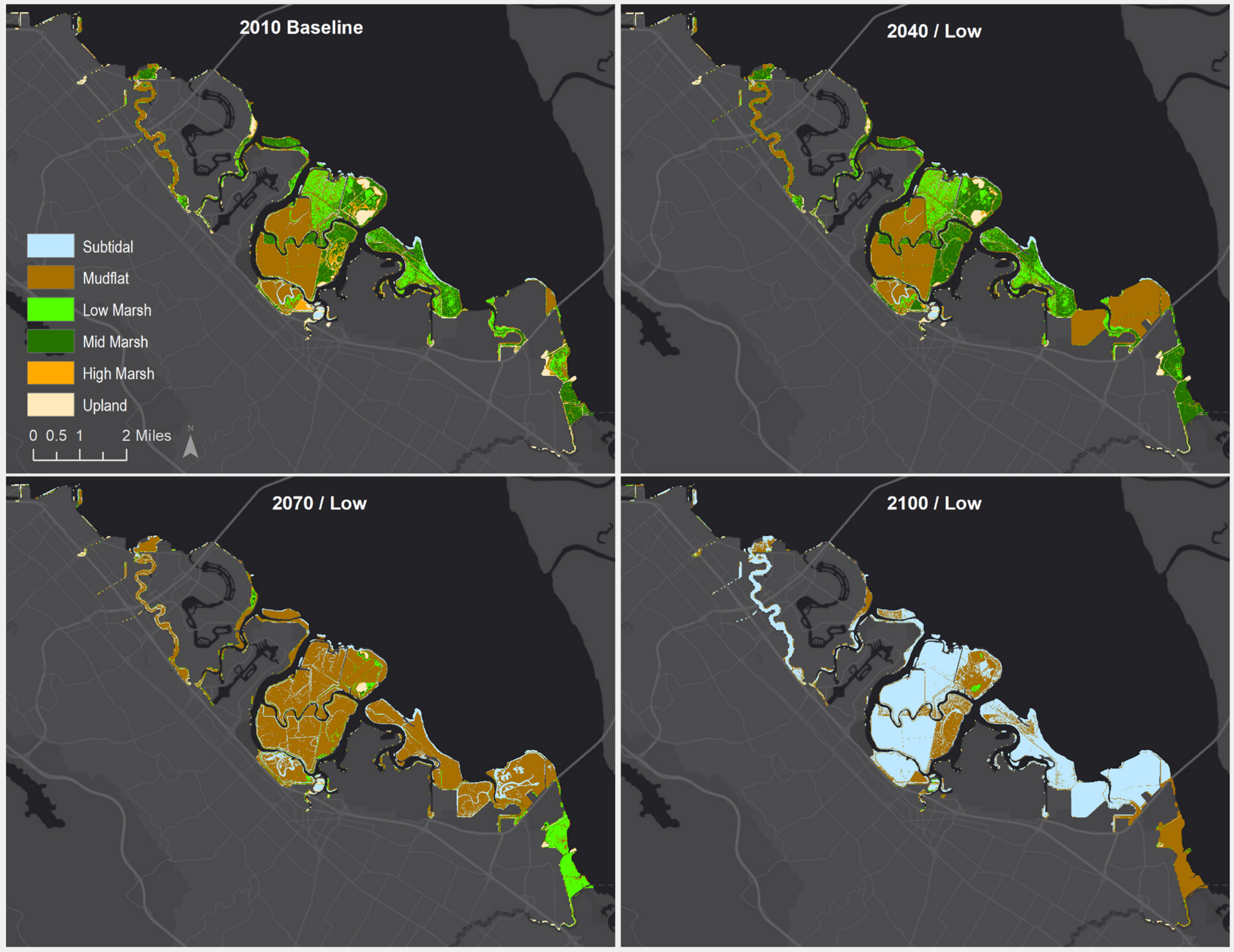


Figure 7. Baseline daily (high tide) wave height (in feet) and projected change in daily wave height through time under the "high" sediment scenario. See Appendix Figure B-1 for "low" sediment scenario comparison.

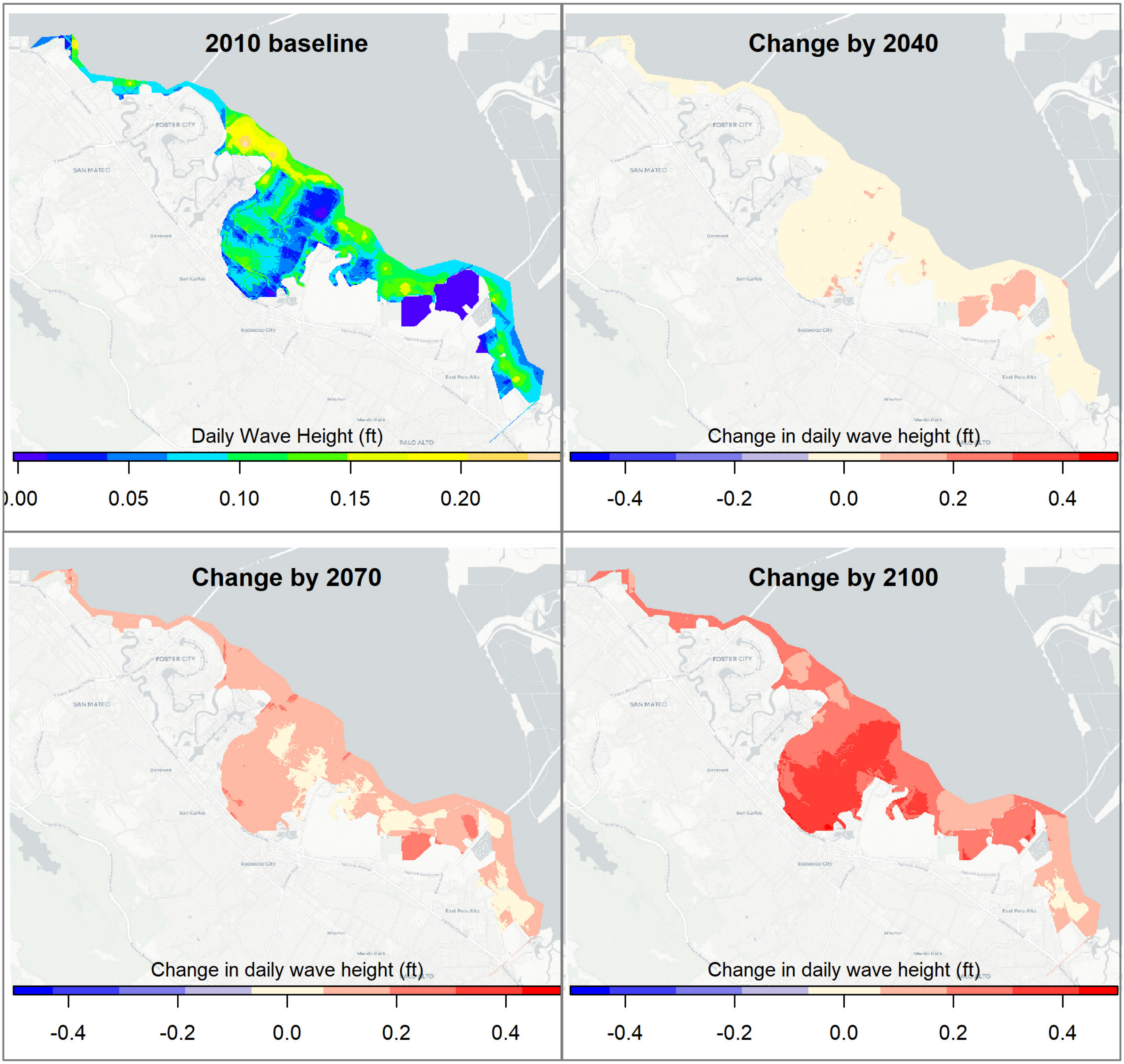


Figure 8. Baseline annual storm wave height and projected change in annual storm wave height through time under the “high” sediment scenario. Note the scale range differs from Figure 7. See Appendix Figure B-2 for “low” sediment scenario comparison.

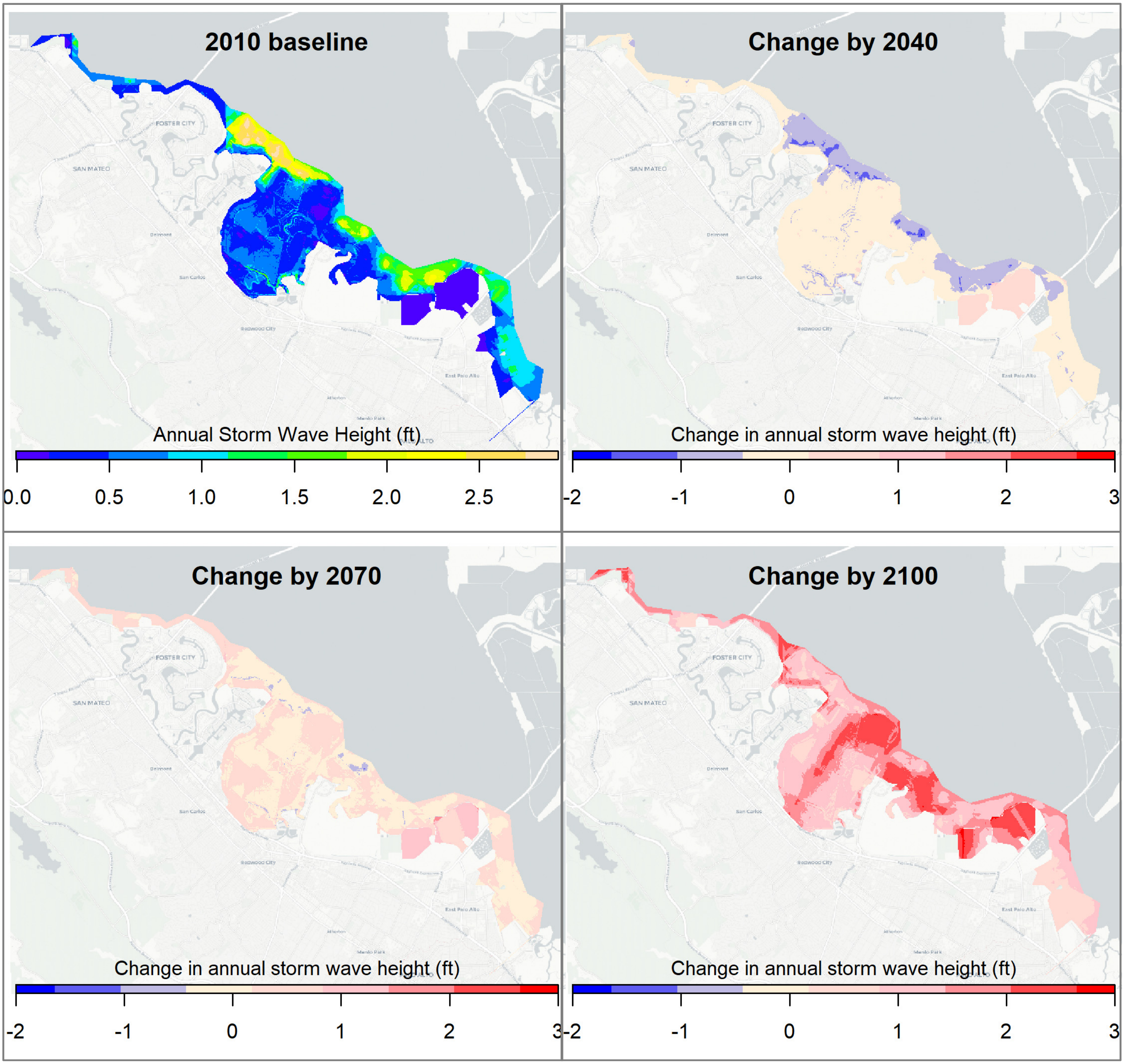
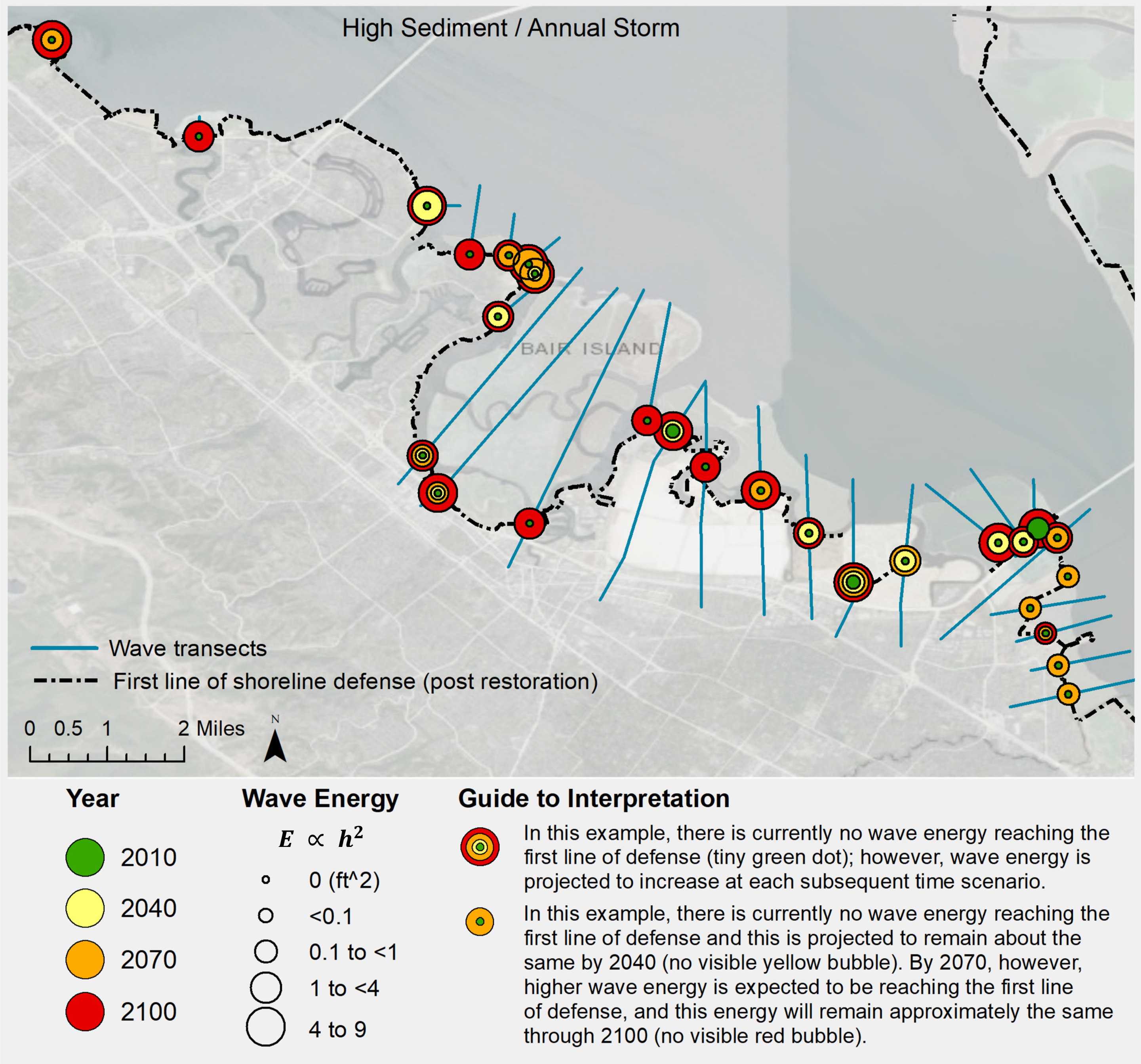


Figure 9. Metric of wave energy at the first line of defense (typically a levee) through time, under the high sediment scenario and an annual storm condition. The projected future year is coded by color, and the size of the circle indicates the magnitude of wave energy (*E*), calculated as the square of wave height (*h*) at the first line of defense. Larger circles indicate more wave energy at the first line of defense, thus more potential for erosion and increased maintenance cost of shoreline protection structures. In all cases, we observed an increase in wave energy at the first line of defense through time, though the magnitude varied spatially. Note that >85% of transects were projected to overtop at the first line of defense in this scenario by 2070 due to Total Water Levels exceeding the elevation of the first line of defense (Appendix A). First line of defense was modified from SFEI (2016).



In this example, there is currently no wave energy reaching the first line of defense (tiny green dot); however, wave energy is projected to increase at each subsequent time scenario.

In this example, there is currently no wave energy reaching the first line of defense and this is projected to remain about the same by 2040 (no visible yellow bubble). By 2070, however, higher wave energy is expected to be reaching the first line of defense, and this energy will remain approximately the same through 2100 (no visible red bubble).

Figure 10. Baseline above ground carbon stock and projected change in carbon stock through time under the “high” sediment scenario. See Appendix Figure B-3 for “low” sediment scenario comparison.

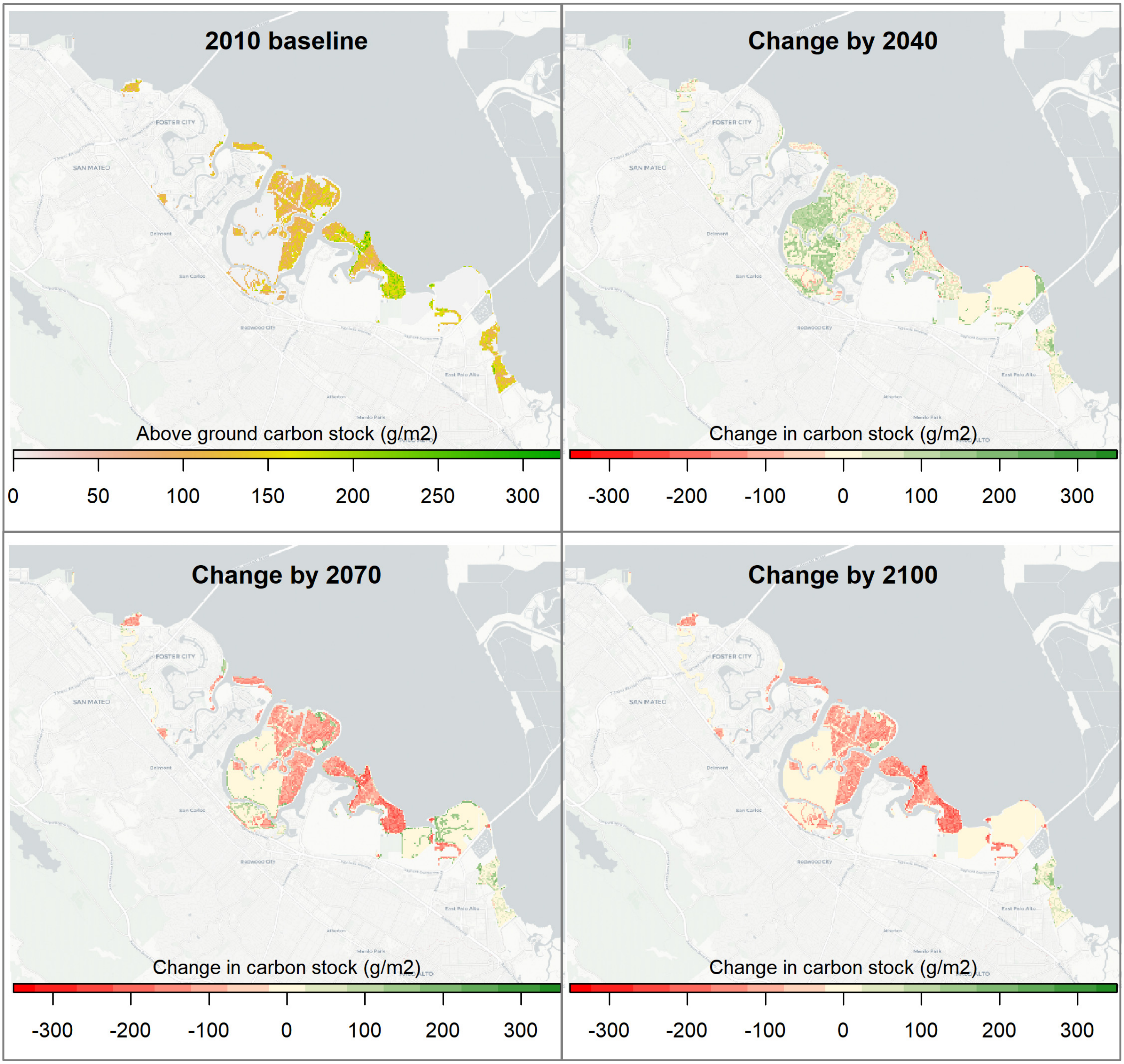


Figure 11. Baseline tidal marsh bird abundance and projected change in bird abundance through time under the "high" sediment scenario. See Appendix Figure B-4 for "low" sediment scenario comparison.

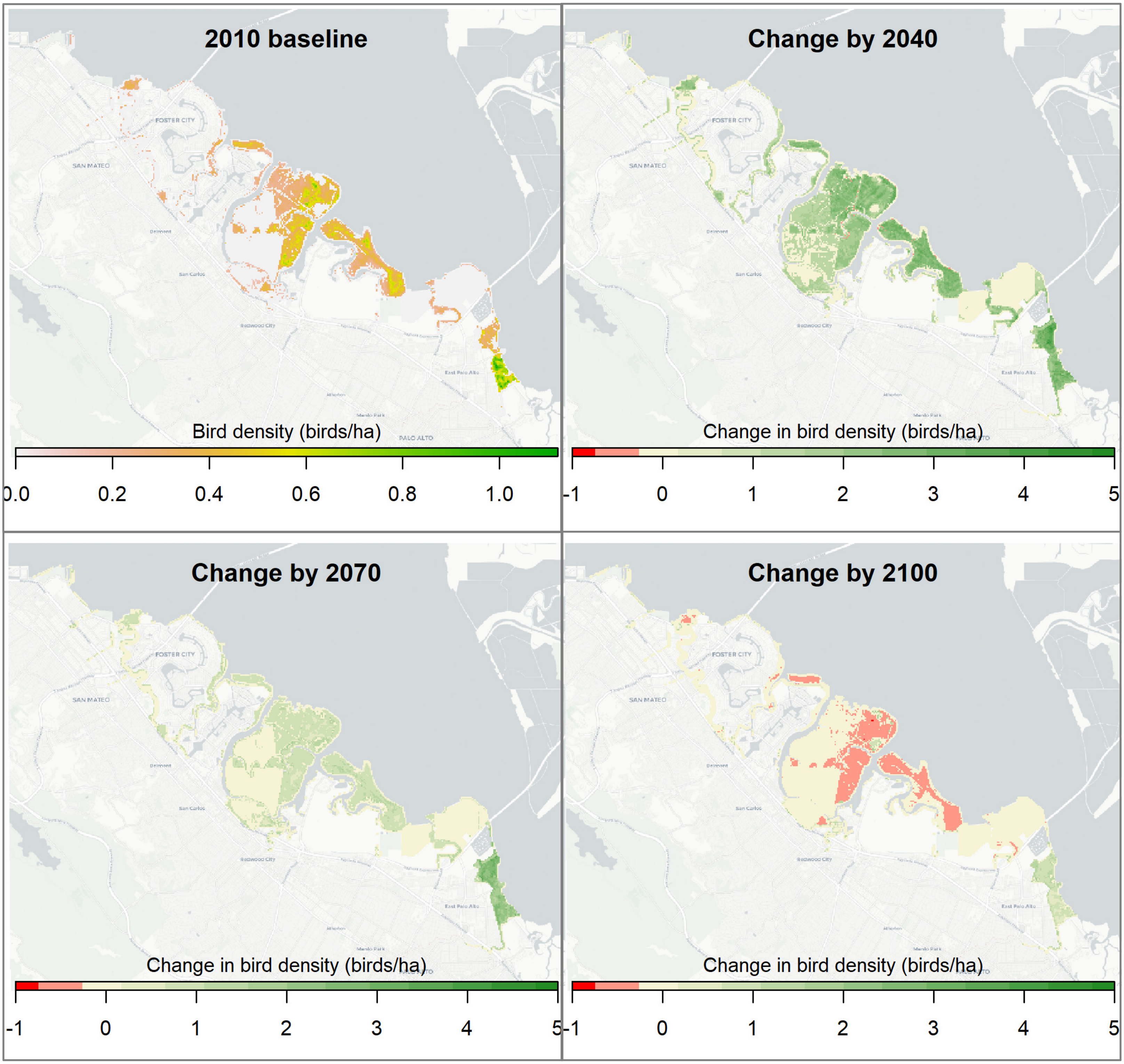
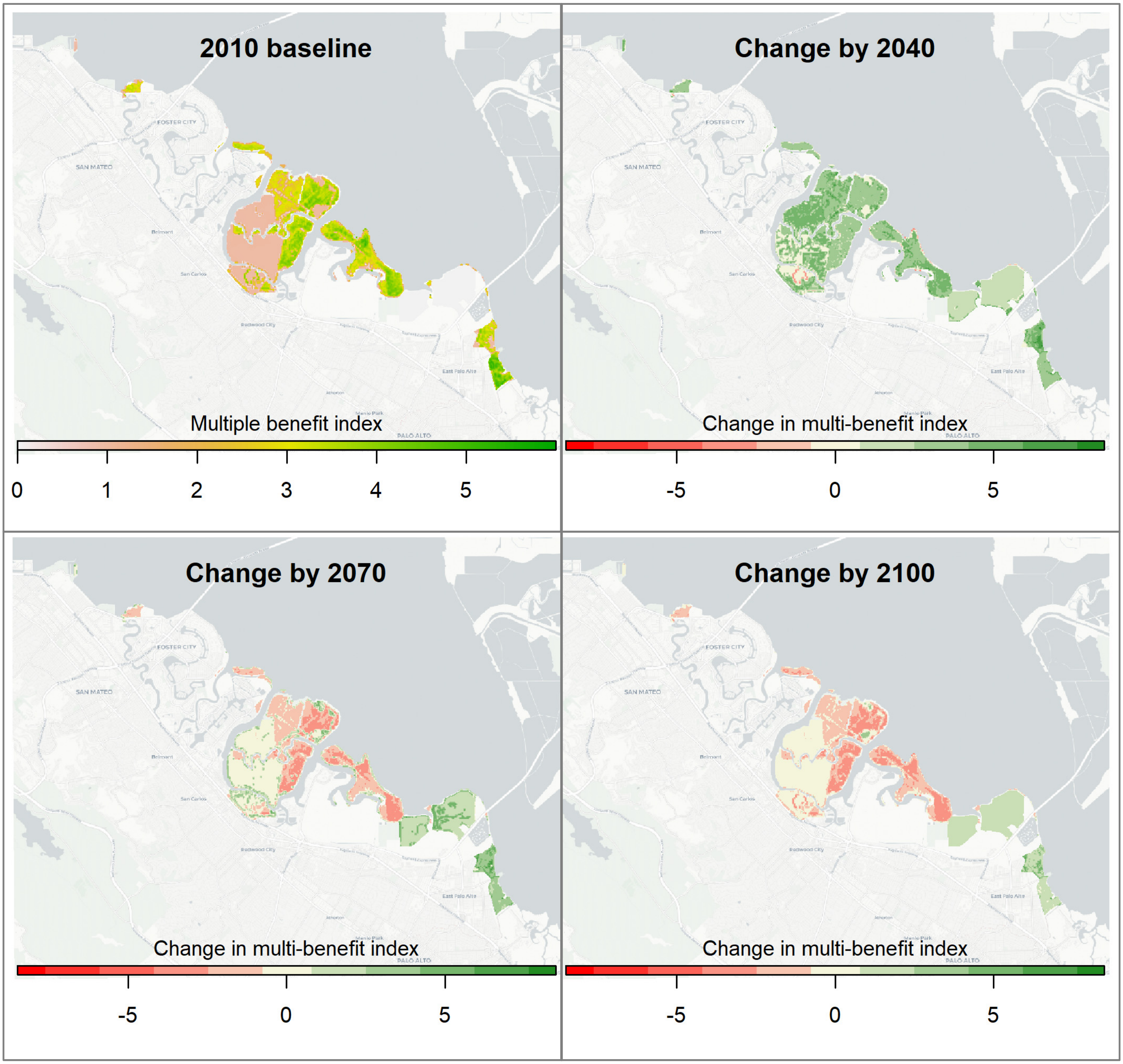


Figure 12. Baseline multi-benefit metric (bird abundance + carbon stock + wave attenuation x2) and projected change in multiple benefits through time under the "high" sediment scenario. See Appendix Figure B-5 for "low" sediment scenario comparison.



OUTCOMES AND CONCLUSIONS

Results to inform adaptation planning

Results of our wetland vulnerability study can be used to inform adaptation planning by identifying where and when multiple benefits of wetlands (i.e., the suite of biodiversity, carbon sequestration, and coastal protection ecosystem services assessed in our study) are projected to be vulnerable or resilient in the face of rising seas, so that we may plan for and prioritize appropriate actions. For example, one could examine the change in spatial distribution of multi-benefit "hot spots" to prioritize where and what types of adaptation actions could be implemented based on how benefits are projected to change in the future.

To illustrate such an example, we classified areas where, in a given high sediment scenario, the value of multiple benefits were "high" (>50th percentile) or "low" (<50th percentile). We then mapped the projected change in these hot spots in 2100 relative to the current 2010 baseline (Box 1). Areas with relatively low current and future benefits (indicated in tan in Box 1) might be managed to achieve other ecosystem services (e.g., services provided by mudflats rather than vegetated marsh). Areas in red indicate locations that provide high tidal wetland ecosystem service benefits now, which are projected to be lost with sea level rise by 2100. These red areas might be prioritized for adaptation interventions such as sediment augmentation to maintain marsh elevations. Areas in dark green indicate locations that one might define as "resilient"—they provide relatively high tidal wetland ecosystem service benefits today and are likely to maintain their relative importance in the future landscape. Areas in light green indicate locations that provide relatively little ecosystem service benefits today relative to other wetlands in the current landscape, but that are projected to be of higher relative importance in the future landscape. Both green areas might be prioritized for protection from other stressors (e.g., invasive species, erosion).

Box 1 is intended only as a simple example to illustrate potential use of our results. More relevant prioritizations could be done based on input from stakeholders on what they value or desire for the future of their shoreline.

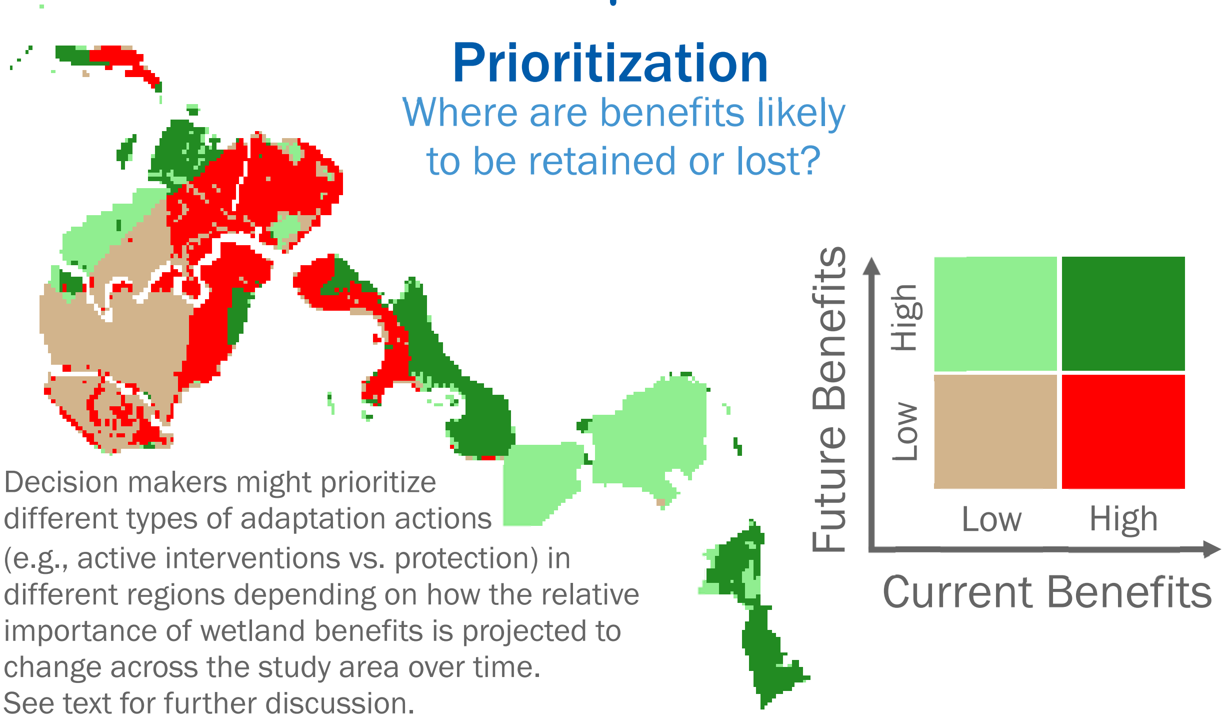
BOX 1. Example of how our tidal marsh vulnerability results could be used to prioritize where and what types of adaptation actions could be considered based on how benefits are projected to change in the future.

Wetland Vulnerability Assessment

Projected change in ecosystem services

Prioritization

Where are benefits likely to be retained or lost?



Decision makers might prioritize different types of adaptation actions (e.g., active interventions vs. protection) in different regions depending on how the relative importance of wetland benefits is projected to change across the study area over time. See text for further discussion.

Inform Adaptation Planning

What types of adaptation actions should be prioritized in different wetland areas in order to maximize benefits in the face of rising seas?

Broader engagement

In addition to the three in-person meetings with our 10-person Steering Committee, we developed, delivered, or contributed to a total of 11 local, regional, state, and national forums for broader engagement and dissemination of results over the course of this project, reaching a total of 152 high school students and 560 technical experts and decision makers (Table 4). This broader engagement and outreach was supported by our leveraged match funding.

With support from project partners, we anticipate several additional outcomes that will support integration of results into ongoing or future planning efforts within the San Francisco Bay Area, as well as broader dissemination of the case study approach:

- Development of a peer-reviewed publication
- Completion of non-technical project communication materials (e.g., 2 pager, slide deck, StoryMap or web page for access to products)
- Spatial data from model output results will be incorporated into San Mateo County's GIS data portal for broader use by local stakeholders for adaptation planning activities (http://seachangesmc.com/vulnerability-assessment/)
- Outreach on available project output data and products to support specific planning efforts identified by our Steering Committee. Some of this outreach has already begun, including:
    - Integration of project results into adaptation strategy "scenarios" being developed as part of a partnership between the County of San Mateo, the Natural Capital Project, and the San Francisco Estuary Institute

Table 4. Summary of broader engagement and dissemination of results through the end of September 2018.

Date	Forum	Estimated # Attendees	Audience	Location	Presenter
Sept 21, 2018	San Francisco Bay Restoration Authority Governing Board Meeting	25	Decision makers	San Francisco, CA	Hayden/ Veloz
Sept 2018	Youth Exploring Sea Level Rise Science at 3 San Mateo County high schools	152	High school students	Pacifica, Half Moon Bay, and Woodside, CA	Nuñez
Sept 10, 2018	Bay-Delta Science Conference	30	Technical experts, managers, decision makers	Sacramento, CA	Hayden
May 30, 2018	Sea Change SMC stakeholder meeting	80	Local government staff and decision makers	Redwood City, CA	Hayden
Mar 30, 2018	Floods, Drought, Rising Seas: Challenges and Opportunities for Water Management in San Mateo County	20	Technical experts, managers, decision makers	Redwood City, CA	Hayden
Mar 30, 2018	Floods, Drought, Rising Seas: Challenges and Opportunities for Water Management in San Mateo County	300	Technical experts, managers, decision makers	Redwood City, CA	Papendick
Feb 20-21, 2018	2nd National Living Shorelines Technology Transfer Workshop	25	Technical experts, managers, decision makers	Oakland, CA	Malinowski
Nov 9, 2017	Coastal & Estuarine Research Federation Biennial Conference	30	Technical experts, managers	Providence, RI	Hayden
Oct 10, 2017	13th Biennial State of the San Francisco Estuary Conference	20	Technical experts, managers, decision makers	Oakland, CA	Hayden
Aug 2017	County SLR team	15	County department heads	Redwood City, CA	Papendick
Spring 2017	County SLR team	15	County department heads	Redwood City, CA	Papendick

Conclusions

Integrating ecosystem processes (i.e., marsh accretion) and services (e.g., biodiversity, carbon sequestration, coastal protection) provided the County of San Mateo with a more nuanced picture of the relative risks and consequences of wetland vulnerability from rising seas. Spatially-explicit modeling of where and how multiple-benefits are projected to shift with rising seas allows decision makers to better integrate natural and built assets into adaptation planning by providing information that can (1) support timing and prioritization of adaptation actions, (2) account for the potential benefits derived from natural and nature-based adaptation strategies, (3) develop adaptation responses that can achieve multiple objectives (i.e., for both built and natural systems), and (4) more accurately assess tradeoffs when weighing adaptation options.

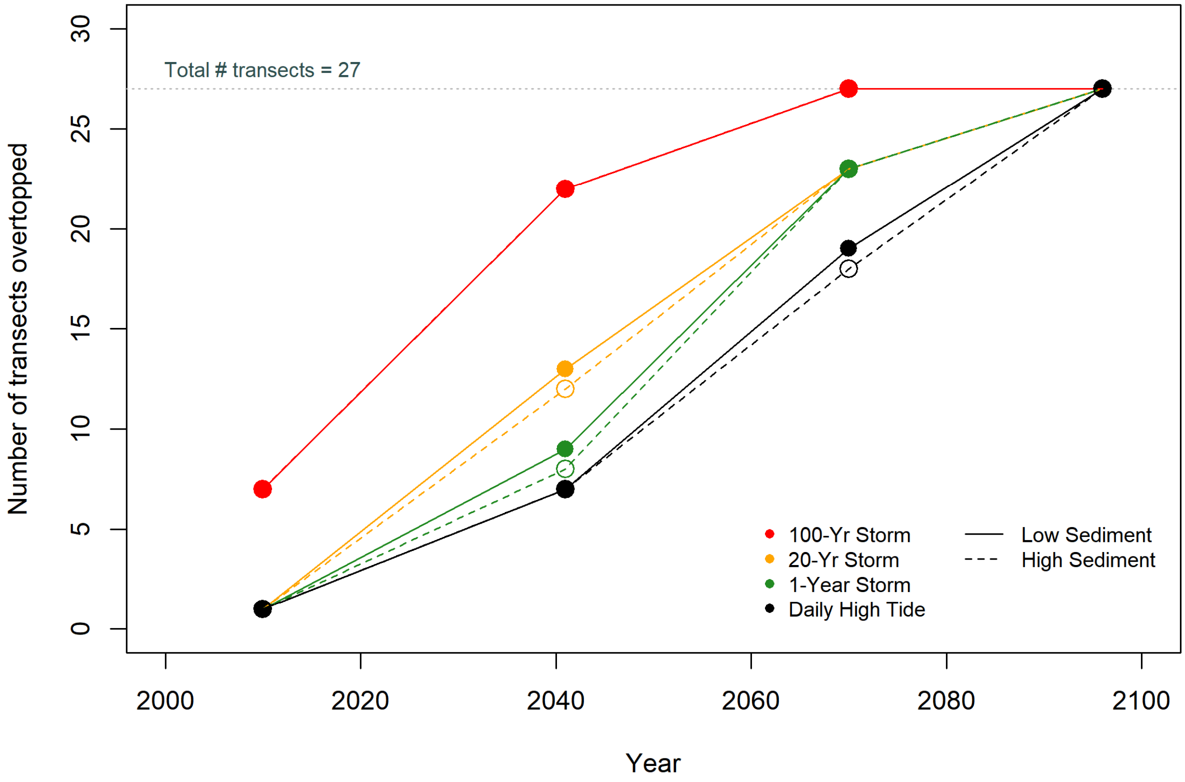
We did not find tradeoffs among the particular ecosystem service metrics we analyzed, but rather that the various metric values were correlated. Loss of tidal marsh habitat coincided with a reduction in above ground carbon stock, wave attenuation, and tidal marsh bird population size, as would be expected. This suggests that in more data-limited regions, focusing on habitat change or a single ecosystem service metric prioritized by local stakeholders might be adequate to understand broad future trends, as long as other (non-quantified) benefits were clearly recognized and incorporated into cost/benefit decisions. We acknowledge, however, that other than wave attenuation we did not include metrics that might better represent the ecosystem services provided by mudflat or subtidal habitats. As vegetated marsh habitat shifts to mudflat or subtidal with rising seas, there will likely be tradeoffs—i.e., loss of marsh-dependent services but gains in mudflat/subtidal-dependent services.

Our study also illustrated the importance of incorporating stakeholder input to produce locally-tailored information. Assessing vulnerabilities necessarily requires selection of what “assets” (in our case ecosystem services) to include. Similarly, the audience for the assessment needs to align with the choices about what level and types of threats are assessed. In our study, the Steering Committee provided valuable guidance in selecting future scenario parameters and in capturing the relative importance of our quantified services to local stakeholders. These choices (e.g., higher weighting of wave attenuation benefits), will change the result of any integrative assessment.

Our case study provides a framework that others can modify and improve upon to better incorporate natural resources into their vulnerability and adaptation planning efforts. It was intended to address the statewide need for a more integrated approach to assessing vulnerability of built and natural assets. This type of accounting is critical to be able to effectively prioritize the potential adaptation benefits derived from protection and enhancement of coastal ecosystems (e.g., coastal protection, recreation, biodiversity support), benefits that are often omitted from traditional cost-benefit analyses when weighing adaptation options. As more refined models, tools, or data become available, they can be leveraged in a similar approach and would certainly be needed to inform site-specific implementation design.

APPENDIX A: Wave transect overtopping summary

Figure A-1. Number of wave transects (Figure 4) where the first line of defense (SFEI 2016) was projected to be overtopped by the Total Water Level (stillwater level + storm surge + wave runup) under each future year/sediment scenario (Table 1) and projected future wave climate for a daily high tide, 1-year, 20-year, and 100-year coastal storm (based on USGS CoSMoS model).



APPENDIX B: Additional “low” sediment scenario figures

Figure B-1. Baseline daily (high tide) wave height (in feet) and projected change in daily wave height through time under the “low” sediment scenario. See Figure 7 for “high” sediment scenario comparison.

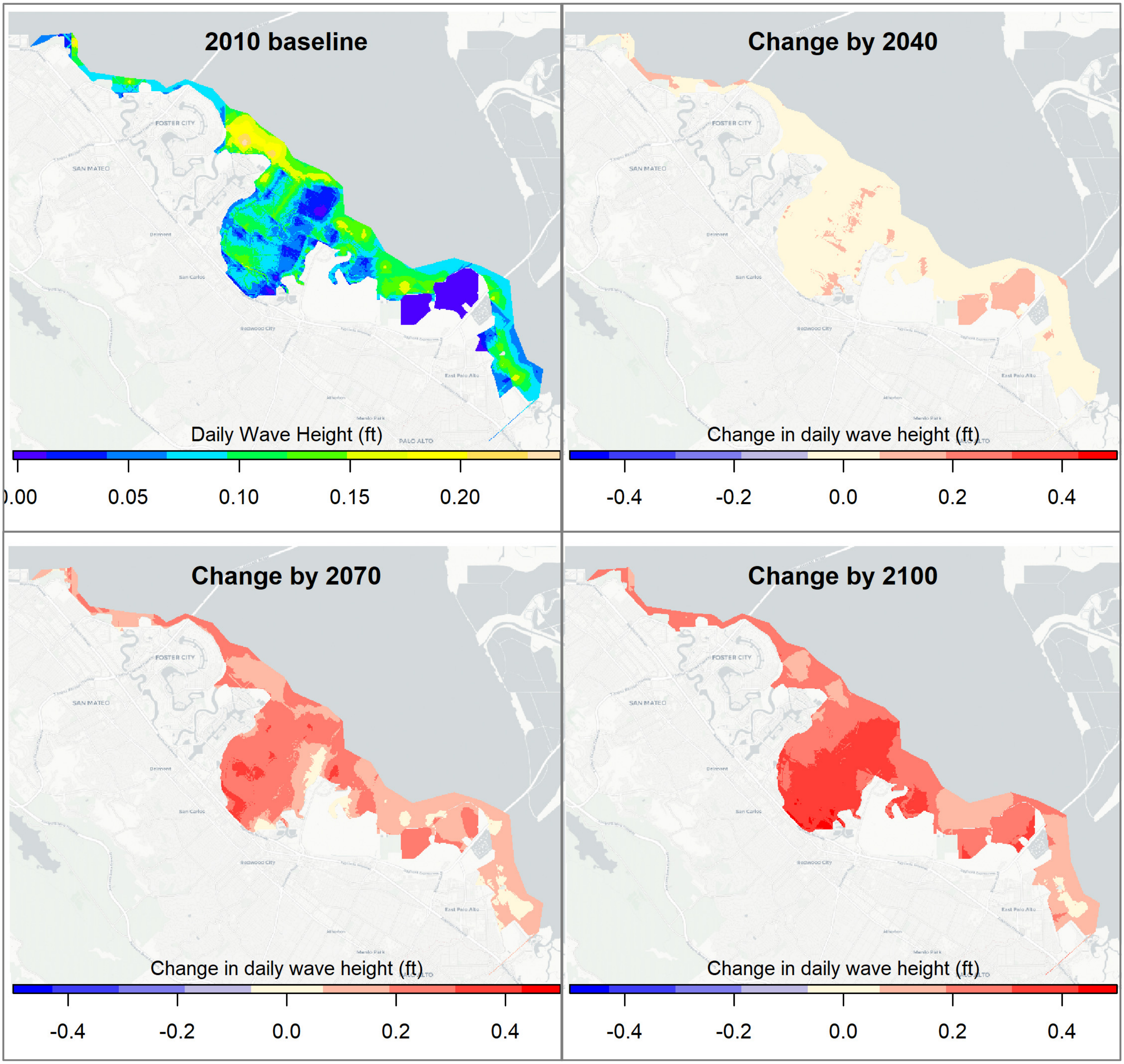


Figure B-2. Baseline annual storm wave height and projected change in annual storm wave height through time under the “low” sediment scenario. Note the scale ranges differ from Figure B-1. See Figure 8 for “high” sediment scenario comparison.

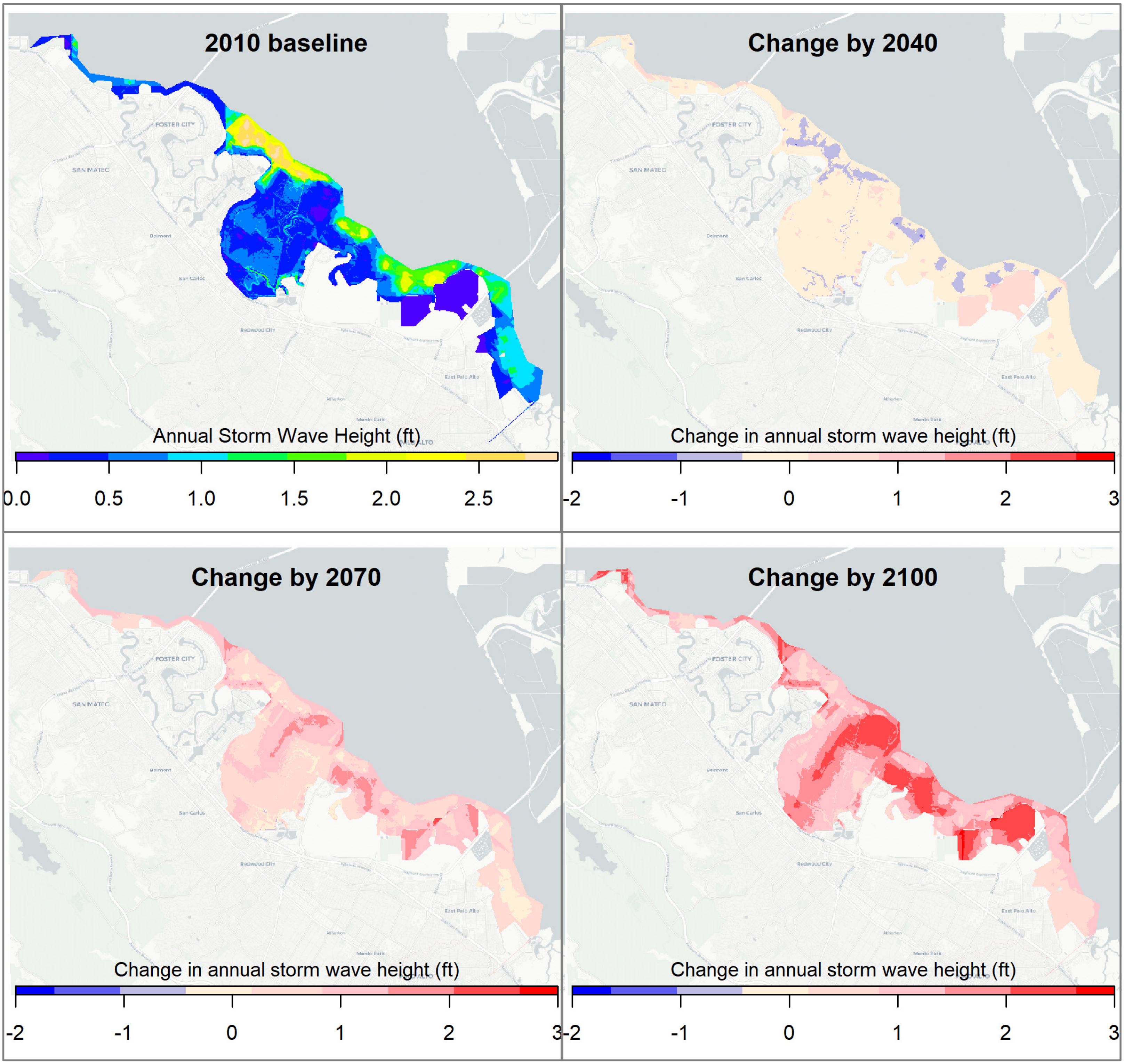


Figure B-3. Baseline above ground carbon stock and projected change in carbon stock through time under the “low” sediment scenario. See Figure 10 for “high” sediment scenario comparison.

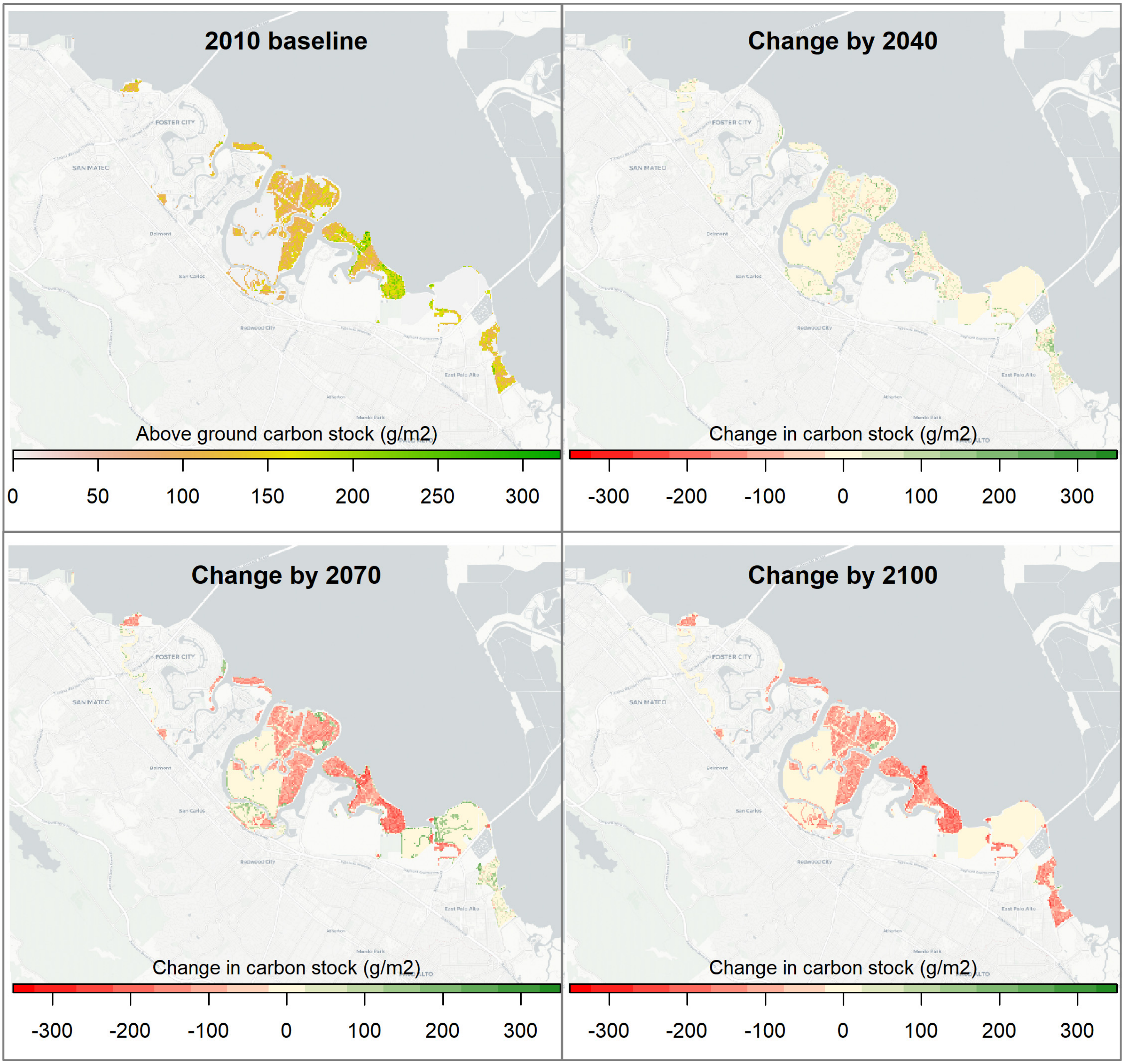


Figure B-4. Baseline tidal marsh bird abundance and projected change in bird abundance through time under the “low” sediment scenario. See Figure 11 for “high” sediment scenario comparison.

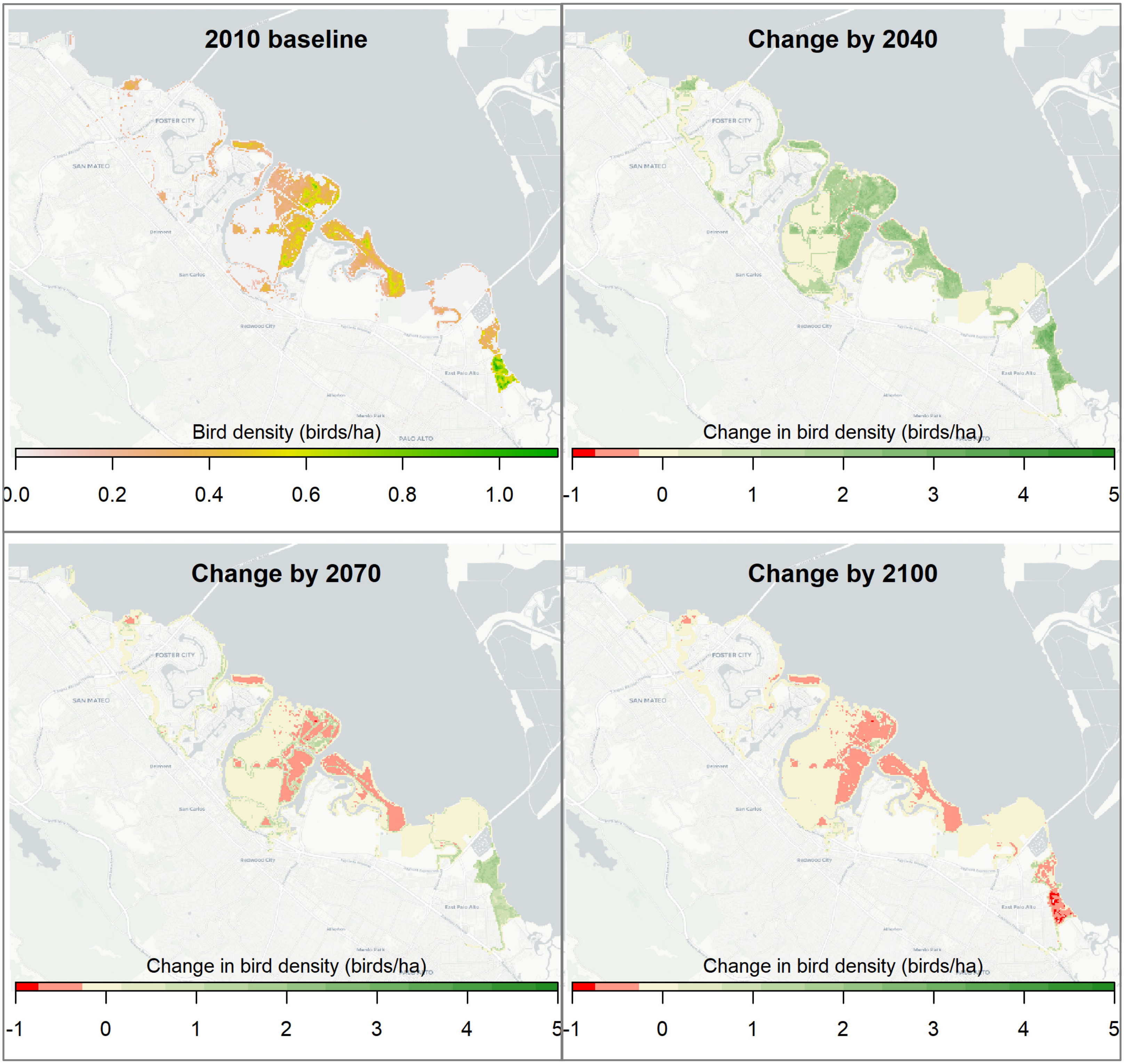
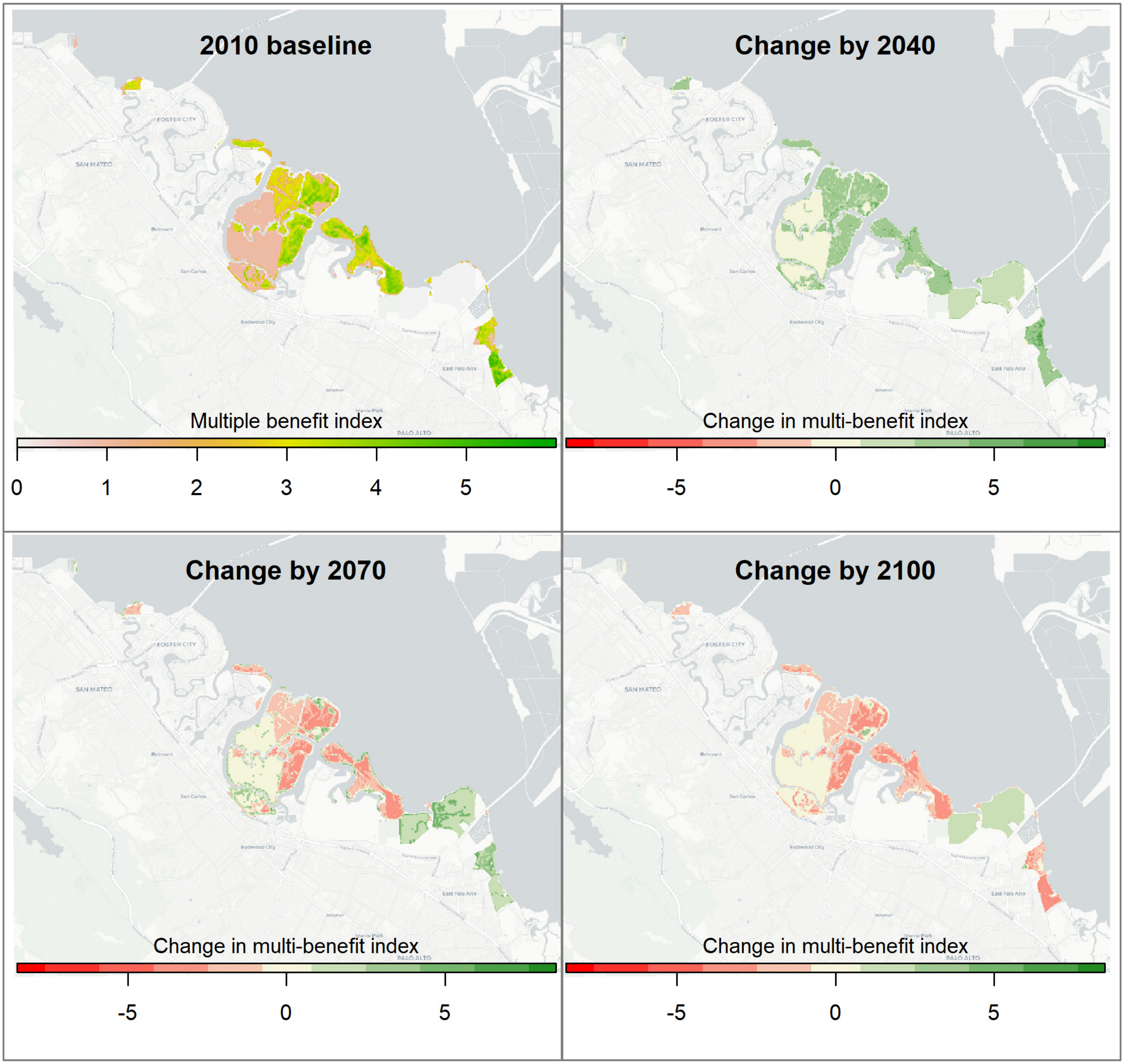


Figure B-5. Baseline multi-benefit metric (bird abundance + carbon stock + wave attenuation x2) and projected change multiple benefits through time under the "low" sediment scenario. See Figure 12 for "high" sediment scenario comparison.



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