Final Report for Sea-level Rise Response Modeling for San Francisco Bay Estuary Tidal Marshes

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Final report for sea-level rise response modeling for San Francisco Bay estuary tidal marshes

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Executive Summary

- San Francisco Bay estuary contains the largest remaining expanse of tidal salt marsh on the Pacific coast of the United States. We collected baseline elevation, tidal inundation and vegetation data at 12 marsh sites to examine potential effects of climate change. We used Real-Time Kinematic Global Positioning System (RTK GPS; $\pm$ 2 cm vertical accuracy) to survey elevation. Vegetation was surveyed within 0.25 m^2 quadrats for species composition, percent cover, and height. We established water level monitoring stations at all sites to capture local annual variation in tidal inundation and to determine elevation relative to site-specific tidal datum.

- Study sites included San Pablo Bay National Wildlife Refuge, China Camp State Park, Corte Madera Ecological Reserve, Fagan Ecological Reserve, Cogswell Marsh, Arrowhead Marsh, Colma Creek Marsh, Laumeister Marsh, Coon Island Marsh, Black John Marsh, Petaluma Marsh, and Gambinini Marsh. Across all sites, 19.94 km^2 of marsh was surveyed or roughly 12% of the remaining tidal marshes in the San Francisco Bay estuary.

- Ground elevation data was interpolated in ArcGIS 9.3 (Kriging method) into continuous 3 x 3 m grid cell raster. Mean root-mean-square error for all interpolations was < 0.10 m.

- Sediment cores collected along elevation transects at four representative sites (China Camp, Coon Island, Petaluma, and Laumeister) were used to determine historic accretion rates with horizon marker dating techniques (^{210}Pb, ^{137}Cs) (Callaway *et al.* 2012). Percent organic matter, porosity, compaction and decomposition were incorporated with accretion rates, elevation, and tidal range data input into a Wetland Accretion Response Model for Ecosystem Resilience (WARMER). Results at the representative sites were extrapolated to the remaining eight sites.

- Across all sites, 7,437 elevation points were surveyed with 88% of the data between 1.5 and 2.1 m (NAVD88). Sites were located at different elevations within the San Francisco Bay tidal range. Sites ordered by decreasing mean elevation were: Fagan (highest mean elevation), Laumeister, Gambinini, Coon Island, Petaluma, San Pablo, Black John, China Camp, Cogswell, Arrowhead, and Colma (lowest mean elevation).

- A total of 3,302 vegetation plots were surveyed across all sites. Low plant species richness was recorded with 21 plant species identified within plots across all sites. The plant community composition also reflected variation in tidal inundation and water salinity. For example, the highest species diversity was found in marshes along the Napa River presumably due to lower water salinity levels.

- Pickleweed (*Sarcocornia pacifica*) was the most common species recorded in 91% of the plots, followed by *Schoenoplectus* spp. (12%), *Distichlis spicata* (9%), *Spartina* spp. (9%), *Jaumea carnosa (7*%), *Grindelia stricta* (7%), and *Frankenia salina* (4%).

- Plant communities were categorized based on observed elevation relative to local tidal datum to develop marsh zones for sea-level rise response model interpretation. Upland transition was defined by *Baccaris pilurais* (> 1.0 m relative to MSL). High marsh was defined by *Jaumea carnosa, Distichlis spicata*, and *Frankenia salina* (0.1 – 1.0 m MSL). Mid marsh was defined by a transition of high marsh species and the upper edge of *Spartina* spp (0.45 – 0.7 m MSL). *Sarcocornia pacifica* was found over a large elevation range and therefore was present in both high and mid marsh categories. Low marsh was defined by *Spartina* spp (0.2 – 0.34 m MSL). Mudflat was defined by anything less than 0.2 m MSL.

- Results from the WARMER modeling suggested that 95% (1,942 ha) or nine of the sites would become mudflats by 2100 with a 1.24 m sea-level rise. Three sites with the remaining 4% (85 ha) is projected to be low marsh habitat dominated by *Spartina* spp. by 2100. All upland transition, high and mid marsh habitats were projected to be lost by 2100.

- Accretion rates used in the WARMER model were relatively high in south San Francisco Bay (Callaway *et al.* 2012), and those marshes withstood sea-level rise longer with areas transitioning from high to low marsh vegetation by 2100 (e.g. Cogswell, Laumeister, and Colma).

- Napa River sites were parameterized with higher sediment accretion rates and higher starting elevations with WARMER and showed the maintenance of high marsh until 2030 (+0.24 m SLR) for Coon Island and 2040 (+0.32 m SLR) for Fagan marsh. Between 2040 (+0.32 m SLR) and 2060 (+0.57 m SLR) mid marsh vegetation was maintained. Low marsh was dominate to 2090 (+1.05 m SLR), at which time both marshes transitioned to mudflats.

- All other marsh sites had relatively low accretion rates relative to sea-level rise. WARMER projected all of these marshes to transition to mudflat by 2100. Corte Madera, China Camp, and San Pablo Bay NWR marshes lost all high marsh by 2030 (+ 0.24 m SLR), briefly transitioned to mid and low marsh plant communities, but ultimately transitioned to areas dominated by mudflat by 2080 (+ 0.85 m SLR). The three marshes located on the Petaluma River (Gambinini, Petaluma, and Black John) lost most high marsh habitat by 2030 (+ 0.24 m SLR) and transitioned to mostly mudflat by 2080 (+0.85 m SLR).

- Projected loss of pickleweed (*Sarcocornia pacifica*) habitats by 2100 could affect many tidal marsh wildlife species such as the federally endangered salt marsh harvest mouse (*Reithrodontomys raviventris*) and state threatened California black rail (*Laterallus jamaicensis coturniculus*). Only 4% of the marsh area was projected to support cordgrass (*Spartina* spp.) habitats by 2100 that also would affect distribution of the federally endangered California clapper rail (*Rallus longirostris obsoletus*).

- The modification of the San Francisco Bay estuary makes it especially susceptible to sea-level rise, since there are few areas available for upslope marsh transgression. Seven of the marsh sites we surveyed had adjacent open space, but five marshes were surrounded by urban infrastructure prohibiting upslope movement.

Abstract

Coastal ecosystems have been identified by the International Panel on Climate Change (2007) as areas that will be disproportionally affected by climate change. Recent sea-level rise projections range from 0.57 to 1.1 m (Jevrejeva *et al.* 2012) or 0.75 to 1.9 m by Grinsted *et al*. (2010) and Vermeer and Rahmstorf (2009) by 2100, which are contingent upon the ambient temperature conditions and CO_2 emissions. Sea-level rise projections for San Francisco Bay are 1.24 m by 2100 (Cayan *et al.* 2008). The expected accelerated rate of sea-level rise through the 21st century will put many coastal ecosystems at risk, especially those in topographically low-gradient areas.

Sea-level rise response modeling was conducted at 12 tidal salt marshes around San Francisco Bay estuary where marsh accretion and plant community state changes were assessed to 2100. Detailed ground elevation, vegetation, accretion, and water level data were collected at all sites between 2008 and 2011 and used as model inputs. A modification of the Callaway *et al.* (1996) model, the Wetland Accretion Rate Model for Ecosystem Resilience (WARMER), was developed to run sea-level rise response models for all sites (Swanson et al. *submitted*). Our results showed that the vast majority, 95.8% (1,942 ha), of the marshes in our study were projected to lose marsh plant communities by 2100 and transition to mudflats. Three marshes were projected to maintain marsh vegetation to 2100, but they only comprised 4.2% (85 ha) of the total marsh area surveyed.

1. Introduction

Climate change effects for coastal ecosystems include projected changes in mean and extreme ambient temperatures, precipitation patterns, ocean temperature and acidity, extreme storm events and sea-level rise (SLR; Cayan *et al.* 2005; Hansen *et al.* 2006; IPCC 2007). Projections of mean sea-level rise (SLR) to the year 2100 are characterized by high uncertainty because of the difficulty in modeling melting ice sheet dynamics and other ocean processes. Global sea-level has risen 1.8 mm/year between 1961 and 1993 and 3.1 mm/year since 1993 (IPCC 2007). While earlier SLR projections ranged from 0.19 - 0.58 m (IPCC 2007), more recent projections range from 0.6 - 1.6 m (Jevrejeva *et al.* 2010) and 0.9 - 1.3 m (Grinsted *et al*. 2010) by 2100. Vermeer and Rahmstorf (2009) projected SLR up to 1.9 m by 2100 contingent upon CO_2 emissions and ambient temperature conditions. Local rates of observed SLR in San Francisco Bay estuary (SFBE) have been 2.2 cm per decade for a total of 19.3 cm between 1900 and 2000 (Cayan *et al.* 2006). SFBE projected SLR is up to 1.24 m by 2100 depending on CO_2 emissions (Cayan *et al.* 2008).

Although global in distribution, the extent of tidal salt marshes is limited to the low-energy intertidal zones of temperate estuaries, with 16,000 km^2 found in North America (Greenberg *et al*. 2006). Marshes are dominated by plant communities that have varying tolerance to tidal inundation and salinity, resulting in zonation along the elevation gradient (Mancera *et al*. 2005). These low-lying areas are particularly vulnerable where variation in tidal depth and duration plays a major role in structuring these plant communities (Brittain and Craft 2012). Marshes will be affected by climate change through accelerating SLR (Holgate and Woodworth 2004, Kemp *et al.* 2011), shifting precipitation patterns (Hamlet and Lettenmaier 2007, Bengtsson *et al.* 2009), erosion (Leatherman *et al*. 2000), and changing frequency and intensity of storms (Emanuel 2005, Webster *et al.* 2005, IPCC 2007). Marshes can keep pace with changes in local sea level through accretion processes that include sediment deposition and organic matter accumulation (Morris *et al*. 2002, Geden *et al.* 2011), if suspended sediment concentrations and organic production are high enough (Kirwan and Gutenspergen 2010). However, marshes may be lost if SLR outpaces vertical accretion processes, resulting in the loss of marsh plant communities (Morris *et al.* 2002, Callaway 2007).

We evaluated SLR effects for tidal salt marshes with a site-specific, bottom-up approach. We included plant community state changes which can help inform effects on resident wildlife species. The scope of our quantitative assessments of SLR impacts on wildlife in tidal marshes was developed at an ecologically relevant parcel scale, which will help inform local management strategies and climate change adaptation plans (Fig. 1). The coupling of a bottom-up approach that includes modeling of marsh physical process and plant communities with top-down SLR models allowed the assessment of marsh plant community state changes through 2100 (Fig. 2). The objectives of the study were to: (1) establish baseline conditions for all marsh sites, (2) develop a simulation model for tidal marshes, (3) synthesize results into site-specific parcel-scale plant community state change models, and (4) compare SLR vulnerability across the range of study sites.

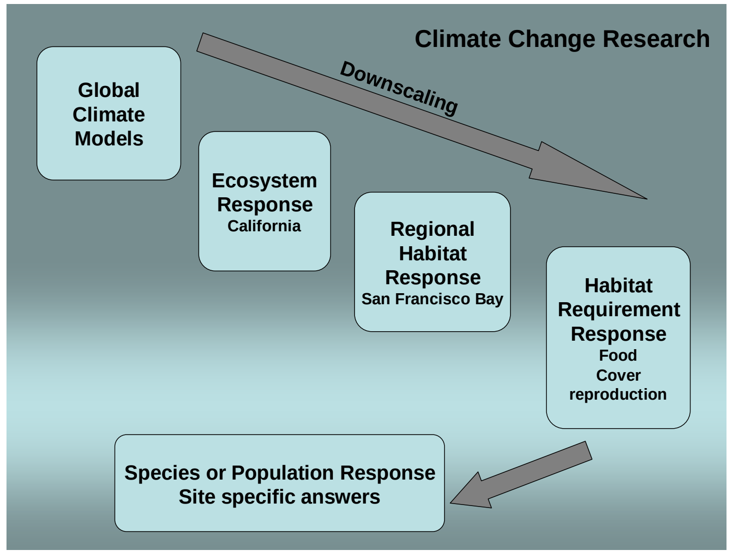


Figure 1. Climate change research requires the downscaling of global climate models to site specific habitats and wildlife species.

1.1 Study Area

The San Francisco Bay estuary (SFBE; California, USA) has been heavily affected by human development which has resulted in the loss of 80% of the historic tidal salt marshes, greatly impacting the local marsh wildlife (Goals Project 1999). Eleven wildlife species of concern are named in the multi-species tidal salt marsh recovery plan for northern and central California (USFWS 2009), and SFBE comprises the single largest habitat block remaining (Takekawa *et al.* 2006). The SFBE marshes support a variety of habitats for federal and state protected endemic rail species (Rallidae) such as the California clapper rail (*Rallus longirostris obsoletus*), the California black rail (*Laterallus jamaicensis coturniulus*), and the salt marsh harvest mouse (*Reithrodontomys raviventris*) (Takekawa *et. al.* 2011, Tsao *et al*. 2009, Spautz *et al.* 2006). The estuary is located on the Pacific Flyway and is a Western Hemisphere Shorebird Reserve Network site of hemispheric importance used by migrating and wintering birds (Accurso 1992). Bird species such as sparrows (Alameda Song Sparrow *Melospiza melodia pusillula*, Suisun Song Sparrow *M. m. maxillaris*, and San Pablo Song Sparrow *M. m. samuelis*) and Salt Marsh Common Yellowthroat (*Geothlypis trichas sinuosa*) are found here.

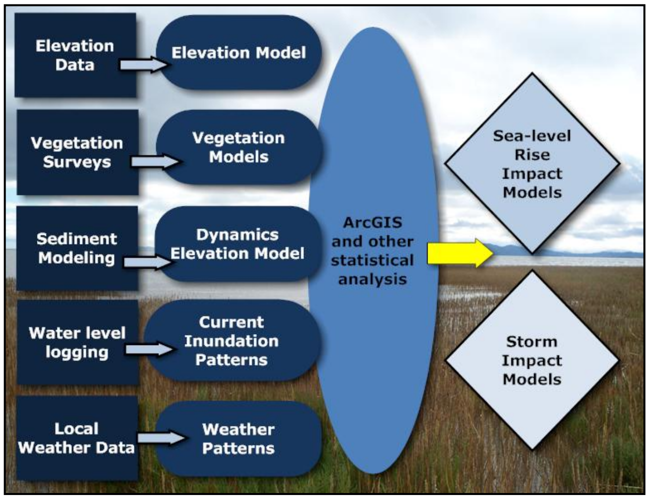


Figure 2. USGS climate change research program conceptual model for a bottom-up local level approach.

Twelve marsh sites covering 19.94 km^2 (about 12% of the remaining marsh in the SFBE) were sampled and modeled for SLR response (Fig. 3). Four sites were located in the southern portion of SFBE (Arrowhead, Cogswell, Laumeister, and Colma) and three sites were located within San Pablo Bay (Corte Madera, China Camp, and San Pablo). Two marshes were sampled along the Napa River (Fagan and Coon Island) and three sites along the Petaluma River (Black John, Petaluma, and Gambinini). Marsh sites varied in age, position within the tidal range, and adjacent land cover type and encompassed a wide variety of land owners, including federal and state agencies, as well as NGOs and private landowners.

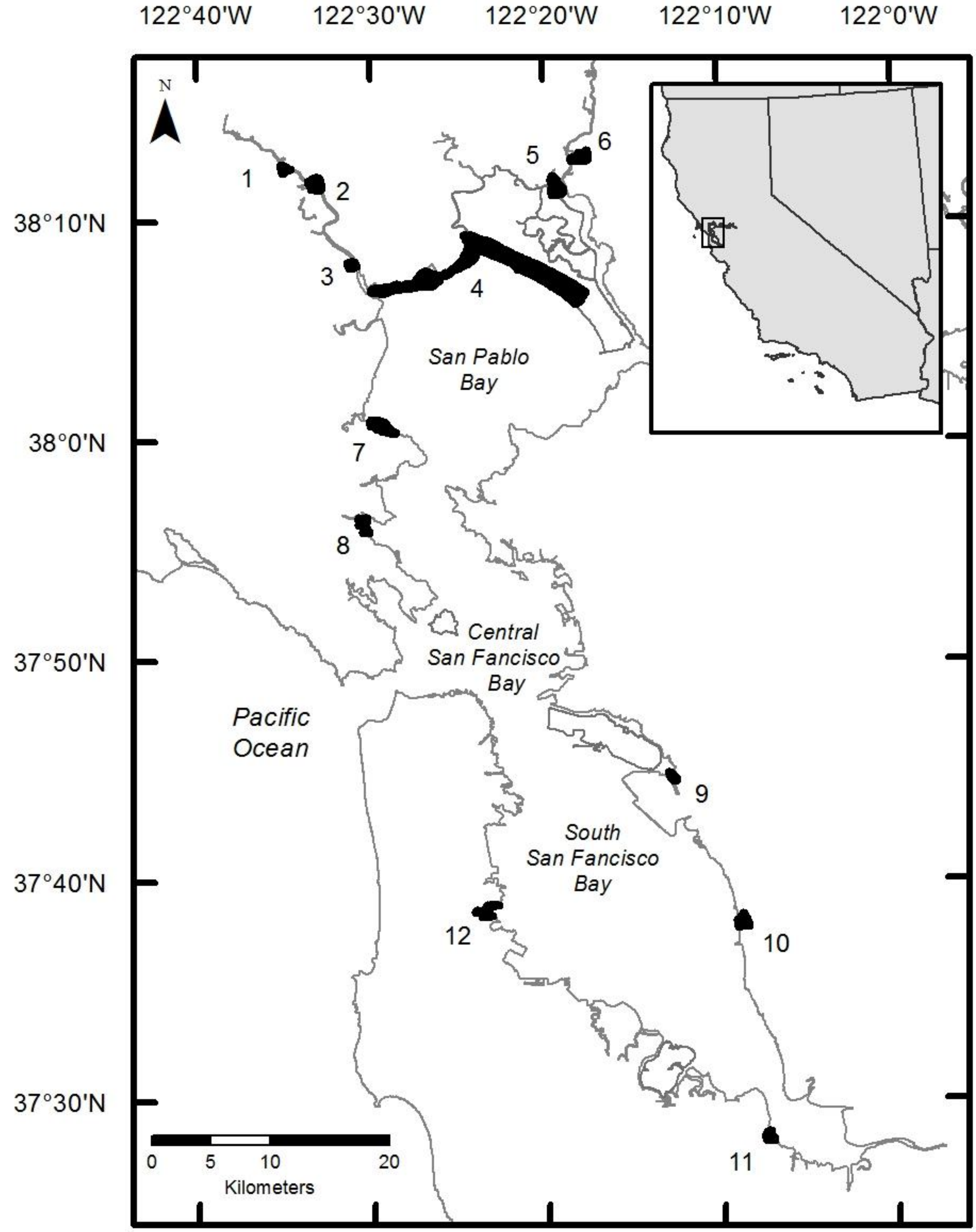
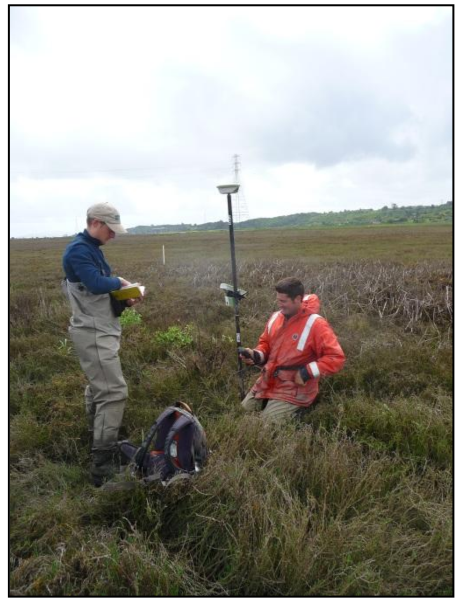


Figure 3. SFBE marsh study sites: 1 = Gambinini; 2 =. Petaluma; 3 = Black John; 4 = San Pablo Bay NWR; 5 = Coon Island; 6 = Fagan; 7 = China Camp State Park; 8 = Corte Madera; 9 = Arrowhead; 10 = Cogswell; 11 = Laumeister; 12 = Colma.

2. Methods

2.1 Elevation surveys

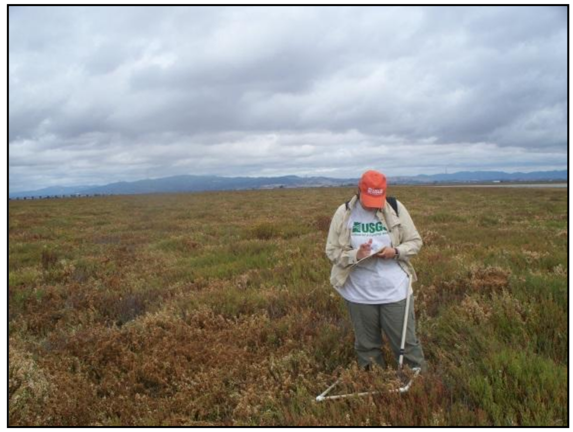


Elevation data collection

We conducted survey-grade elevation surveys at marshes throughout the SFBE between 2008 and 2010 using a Leica RX1200 Real Time Kinematic (RTK) Global Positioning System (GPS) rover (± 1 cm x, y, ± 2 cm z accuracy; Leica Geosystems Inc., Norcross, GA). The rover positions were received in real time from the Leica Smartnet system via a CDMA modem (www.lecia-geosystems.com). We used the WGS84 ellipsoid model for vertical and horizontal positioning. Positions were referenced to a National Geodetic Survey (NGS) benchmark (X 552 1956 Mare Island). The average measured vertical error for the benchmark throughout the study was ± 2.5 cm, similar to the stated error of the RTK GPS. Elevation was surveyed along transects perpendicular to the major sediment source (San Francisco Bay, Napa River, Petaluma River), with a survey point taken every 25 m; 50 m separated transect lines. The Geoid03 model was used in calculating elevations from orthometric heights (NAVD88; North American Vertical Datum of 1988) and all points were projected to NAD83 UTM zone 10 using Leica GeoOffice (Leica Geosystems Inc, Norcross, GA, v 7.0.1). Orthometric heights were calculated based on NAVD88 and the NGS Geiod03 Model (NAVD88; North American Vertical Datum of 1988).

2.2 Elevation modeling

We synthesized the survey data to create an elevation raster in ArcGIS 9.3 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (3 x 3 m cell size). We used the exponential model for Ordinary Kriging and adjusted model parameters to minimize the root-mean-square error (RMS), an internal measure of model performance. Lag size and number of lags were optimized for the site (lag size x lag number < ½ maximum distance among points, ERSI); an anisotropy adjustment was applied because of a trend in the elevation data. Resultant models were externally cross-validated by comparing models created with 70% of the data with the remaining 30% of the points. We then used the elevation models as the basis for subsequent analysis, such as tidal inundation patterns, WARMER modeling, and vegetation correlations. The mean and range of elevation was calculated by randomly sampling locations from the interpolated model at a density of 3/ha to produce an unbiased sample for each site. We used a one-way ANOVA and the Tukey HSD test to analyze site elevations for significant differences.



Vegetation data was collected concurrently during elevation surveys.

2.3 Vegetation surveys

We recorded plant species diversity concurrently with elevation surveys at 50% of the elevation points within a 0.25 m^2 quadrat. We measured height (mean, maximum, measured within 0.05 m) and estimated percent cover for each species. We combined all recorded *Spartina* spp. in analysis due to the difficulty in distinguishing native, hybrid and non-native species. We categorized plant species into low, mid, high-marsh, and upland transition by measured elevation relative to mean sea level (MSL; m), which were used to relate to changing elevations with SLR. We used the vegetation and elevation relationships to predict transitions or state changes of wildlife habitats to assess vulnerability and better understand outcomes for habitat persistence to 2100.

2.4 Water level monitoring

We deployed water level data loggers (Model 3001, 0.01% FS resolution, Solinst Canada Ltd., Georgetown, Ontario) at all sites over the study period. Each site had 1 to 4 loggers (n = 28) depending on its size. Loggers were placed at the mouth and upper reaches of second-order channels (tidal creeks) to capture the local tidal cycle and inundation patterns. We collected continuous data every six minutes throughout 2009 and 2010 to develop local hydrographs and inundation rates. In addition, water conductivity was collected at a subset of sites; however, this data has not been analyzed. Loggers were surveyed with the RTK GPS at the time of deployment and at each data download to correct for any movement. Water levels were corrected for local barometric pressure with data from independent barometric loggers (Model 3001, 0.05% FS accuracy, Solinst Canada Ltd., Georgetown, Ontario).

Water level data was collected at all sites throughout the study period.

The local water level data was used to develop elevation and tidal datum relationships for all sites. Water level peaks throughout 2010 were averaged to create mean high water (MHW) and mean higher high water (MHHW) datums relative to NAVD88 for each site. The development of local mean sea level (MSL) and mean low water (MLW) tidal datums were not possible because of the relatively high elevation of the water loggers in the marsh channels, therefore MSL was determined using VDatum v 2.3.0 (http://vdatum.noaa.gov). All results are reported relative to local MHW calculated from local water data. For SFBE, MHW and MHHW are the most important metrics for understanding plant marsh communities and wildlife habitats.

3. The Wetland Accretion Rate Model for Ecosystem Resilience (WARMER)

We developed the model WARMER, a 1-D cohort model of wetland accretion based on Callaway *et al.* (1996) to examine SLR projections for SFBE marshes. WARMER calculated elevation changes relative to MSL based on projected changes in relative sea-level, subsidence, inorganic sediment accumulation, aboveground and belowground organic matter productivity, compaction, and decay (Fig. 4) for a representative marsh area. Each modeled cohort provided the mass of inorganic and organic matter accumulated at the surface in a single year and any subsequent belowground organic matter productivity (root growth) less decay. Cohort density, a function of mineral, organic and water content, was calculated at each time step to account for decay of organic material and autocompaction of the soil column. The change in relative elevation was then calculated as the difference between the change in modeled sea-level and the change in height of the soil column, which was estimated as the sum of the volume of all cohorts over the unit area model domain.

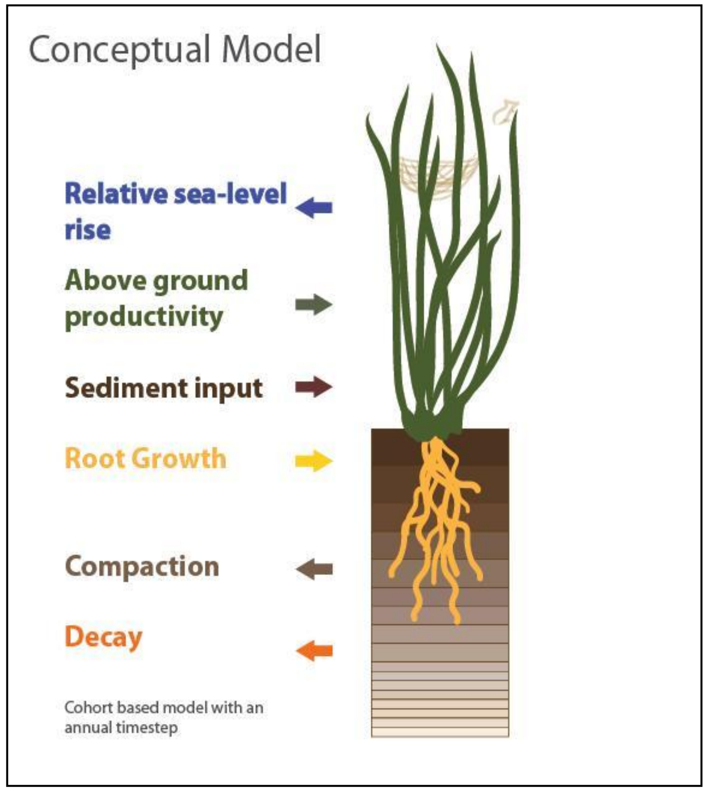


Figure 4. WARMER 1-D conceptual model

WARMER expanded upon the Callaway *et al.* (1996) model by including: (1) feedback between organic matter accumulation and elevation; (2) development of a non-linear relationship between inorganic matter accumulation and elevation; and (3) incorporation of a temporally variable SLR. The elevation of the marsh surface, E, at time t relative to local MSL was estimated as:

where **E(0)** is the initial elevation relative to MSL, **SLR(t)** is the sea-level at time t relative to the initial sea level and $\mathbf{V_i(t)}$ is the volume per unit area, or height, at time **t**, of the cohort formed during year **i**. The total volume of an individual cohort was estimated as the sum of the mass of water, calculated from the porosity of the cohort, sediment and organic matter divided by the cohort bulk density.

We developed WARMER models from the elevation, vegetation, and water level data collected at each site (*see* 2.1 - 2.3). For this study, accretion rates for four marshes (Coon Island, a portion of Petaluma Marsh, China Camp Marsh and Whale's Tail Marsh were determined from ^{210}Pb and ^{137}Cs dating of sediment cores (Callaway *et al*., 2012; Swanson *et al*. submitted). Accretion data from the most comparable of these four sites to calibrate the accumulation and sediment properties at the remaining sites for WARMER modeling (*see* Appendix). All results were presented as elevation relative to MHW.

3.1 Model inputs

3.1.1 Sea-level rise scenario

In WARMER, we incorporated a recent forecast for San Francisco Bay SLR (Cayan *et al*., 2009) based on a moderate emissions scenario (A2 in IPCC Fourth Assessment Report, Bindoff *et al*. 2007) which forecasts 1.24 m of SLR by 2100 (Fig. 5). The average annual SLR curve was used as the input function for the WARMER model. We assumed that the tide range remains constant through time, with only MSL changing annually.

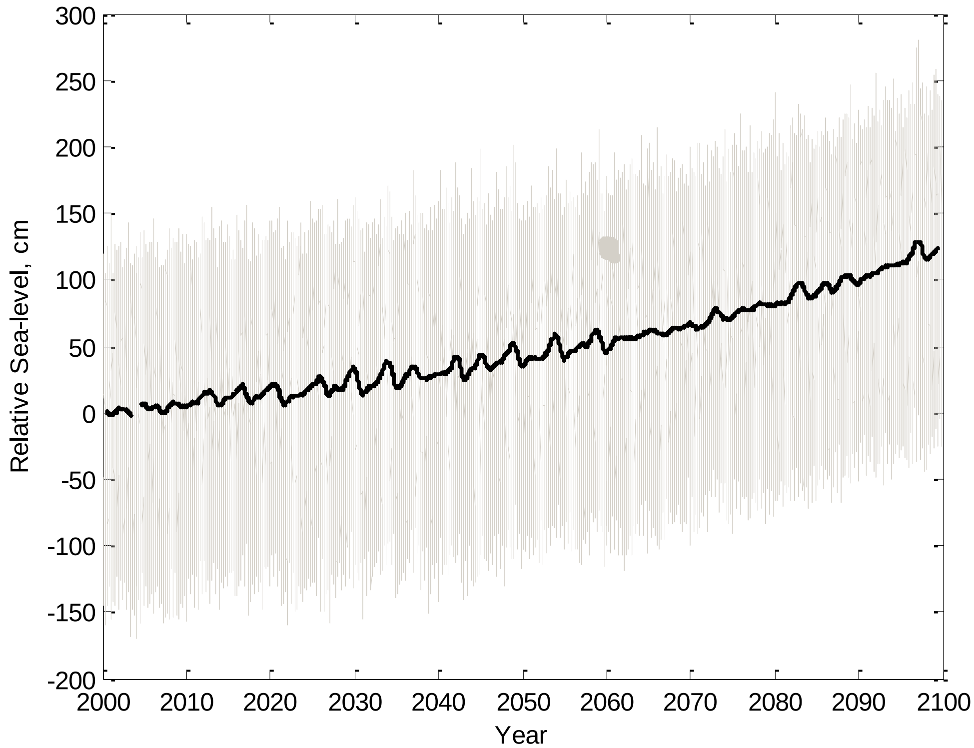


Figure 5. Hourly water level prediction from Cayan *et al.* (2009) with a 1-year running mean of hourly data.

3.1.2 Inorganic matter

Sediment flux from the water column to the marsh surface at a given elevation, z, was estimated as the product of suspended solids concentration, SSC, and settling velocity summed over all times that elevation z is inundated. For the case of constant SSC and settling velocity, the mass accumulation was directly proportional to the inundation frequency and calibrated without any direct measurement of concentration or settling velocity. This sediment flux at a given elevation, z, measured in mass per unit area per year, $M_s(z)$, was equal to:

where ***f*(z)** was the inundation frequency as a function of elevation, and $\boldsymbol{SSC * w_s}$ was the maximum potential sediment flux determined by calibration to sediment accumulation data.

To calibrate the sediment input function, sediment accumulation rates were determined using the Constant Rate of Supply (CRS) method for ^{210}Pb from sediment cores taken within each of the four reference marshes (Robbins 1978; Callaway et al., 2012). If the CRS method could not be applied because the sediment core did not capture the complete excess ^{210}Pb profile, the sediment accumulation rate was determined using the 1963 peak ^{137}Cs horizon identified in the soil column.

3.1.3 Organic matter

The base organic input function developed by Morris *et al.* (2002) was used in WARMER. However, Morris *et al.* (2002) used *Spartina alterniflora* as the base of the functional relationship although most SFBE marshes are dominated by native *Sarcocornia pacifica* (pickleweed). *S. alterniflora* and its hybrids have invaded parts of the estuary, but they are the target of an intensive control program. Therefore, the Morris et al. (2002) function was adapted for the vegetation in SFBE. The shape of the curve that Morris et al. (2002) developed for *S. alterniflora* marshes was retained, but the elevation range of the vegetation, the roots of the parabolic equation, and the magnitude of organic matter input were adjusted for SFBE marsh vegetation primarily represented by *S. pacifica*. This was accomplished by fixing the roots of the parabolic function at MSL and MAT for each site and then calibrating the magnitude of the predicted organic matter accumulation to measured organic matter input rates from the sediment cores. The parabolic equation describing the annual mass of organic matter accumulated per unit area, $\boldsymbol{M_0}$ was then:

where a and b are constants with units of —— for above- and below- ground production, respectively, fit to the measured organic matter accumulation rates in the surface layer of each sediment core for each marsh at specified elevations. The organic matter accumulation rate was determined from the sediment accumulation rate and the ratio of sediment to organic matter in the surface layer of each sediment core. Organic matter input was divided between above and below ground input with a shoot to root ratio of a/b = 0.57 based on the work of Scarton *et al.* (2002) and Curcó *et al*. (2002) with *Sarcocornia* spp. The mass of organic material generated below ground each year was distributed exponentially with depth and the coefficient of exponential decay, **kdist**, set equal to 1.0 (Deverel *et al*. 2008).

3.1.4 Compaction and decomposition

Compaction and decomposition functions of WARMER followed Callaway *et al.* (1996). Compaction of highly porous marsh sediment was determined by a rate of decrease in porosity from the average measured porosity of the top 5 cm of each sediment core and a lower limit of porosity measured at the bottom 5 cm of each sediment core. The rate of decrease, $\boldsymbol{r}$, in porosity of a given cohort was estimated as a function of the density of all of the material above that cohort:

—— (4)

where $\boldsymbol{p_b}$ is the density of the material above a cohort and $\boldsymbol{k_1}$ was a calibration constant.

Decomposition was modeled as a three-stage process where the youngest organic material, less than 1 year old, decomposed at the fastest rate; organic matter 1 to 2 years old decayed at a moderate rate; and organic matter greater than 2 years old decayed at the slowest rate. Decomposition also decreased exponentially with depth. The percentage of refractory organic material was determined from the organic content measured in the sediment cores. The constants used to parameterize the compaction and decomposition functions follow those used by Deverel *et al*. (2008).

WARMER was run for 243 simulations with a range of values of sediment input, organic matter input, SLR, and initial marsh elevation in order to explore model sensitivity. The values were chosen to reflect the expected and extreme values of sediment and organic matter accumulation, porosity, SLR, and initial marsh elevation measured or anticipated for SFBE (Callaway *et al.,* 2012). Low and high estimates of the magnitude of sea-level rise over the next century (50 and 150 cm; Cayan *et al*. 2009) were included in the modeling.

4. Results

4.1 Elevation

Low slope elevation gradients characteristic of marshes were observed at SFBE sites (Fig. 6). A total of 7,437 elevation points were collected from 2008 - 2010 (Table 1). Overall, elevation had a small range with 88% of surveyed points falling between 1.5 and 2.1 m (NAVD 88; Fig. 7). We found that most of the marshes surveyed were located above MHW. Across all sites mean elevation was 0.03 m (SD = 0.13) above MHW. Mean elevation relative to MHW varied significantly across sites (one-way ANOVA, $F_{11} = 173.61$, $p < 0.0001$; TukeyHSD, $t_{5749} = 4.6236$, $p = 0.04837$, Fig. 8). We found that marshes located along rivers (Gambinini, Petaluma, Black John, Coon Island, and Fagan) had higher elevations than those located along the bay edge (Fig. 8). Grouped by their location within the bay, marsh elevation (relative to MHW) in the South SFBE < San Pablo Bay < Petaluma River < Napa River (ANOVA: $F_3 = 179.28$; $p < 0.0001$). The interpolated elevation models for all sites had a root-mean-square error (RMS) of 0.1 m (Table 2).

Table 1. Summary of the amount of elevation and vegetation data collected for each site. SPB refers to San Pablo Bay, SSFB refers to south San Francisco Bay, and Petaluma and Napa refers to the rivers draining from the north into San Pablo Bay.

Fig. 1 Ref	Region	Site	Area (ha)	Elevation (n)	Mean Elevation (m)	Elevation Range (m)	Vegetation (n)
1	Petaluma	Gambinini	24.8	217	1.9	0.35	110
2	Petaluma	Petaluma	80.6	655	1.8	0.63	356
3	Petaluma	Black John	30.9	213	1.8	0.45	108
4a	SPB	San Pablo East	962.6	434	1.9	0.72	271
4b	SPB	San Pablo West	449.5	962	2	1.49	691
5	Napa	Coon Island	98.7	799	1.8	1.24	364
6	Napa	Fagan	67.9	609	1.9	0.61	308
7	SPB	China Camp	96.7	753	1.8	0.55	422
8	SPB	Corte Madera	76.8	744	1.6	0.59	361
9	SSFB	Arrowhead	17.0	274	1.6	0.37	50
10	SSFB	Cogswell	60.3	523	1.8	0.55	228
11	SSFB	Laumeister	36.8	717	2.1	0.47	72
12	SSFB	Colma	24.6	537	1.4	1.58	-
		Total	2027.2	7437	1.9	1.6	3302

Table 2. ArcGIS elevation model root-mean-square error (RMS) and standard error (SE) by site.

Fig. 1 Ref.	Study Site	Model RMS	Model Avg. SE
1	Gambinini	0.09	0.09
2	Petaluma	0.09	0.09
3	Black John	0.05	0.04
4a	San Pablo East	0.10	0.11
4b	San Pablo West	0.15	0.15
5	Coon Island	0.07	0.05
6	Fagan	0.08	0.08
7	China Camp	0.09	0.09
8	Corte Madera	0.09	0.08
9	Arrowhead	0.07	0.06
10	Cogswell	0.09	0.09
11	Laumeister	0.08	0.08
12	Colma	0.21	0.21
	Mean	0.10	0.09

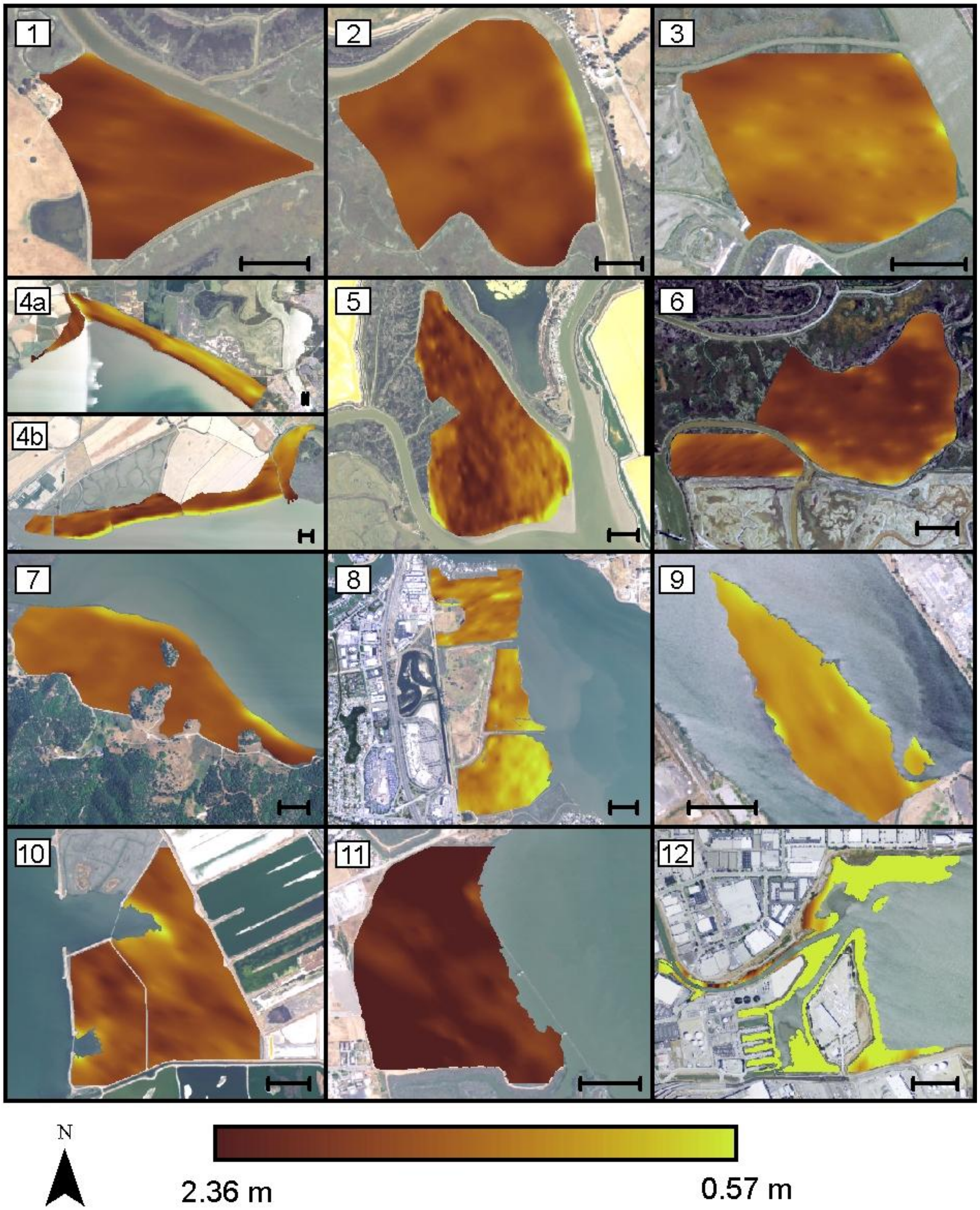


Figure 6. Elevation models for all marsh sites (NAVD88). Model parameters were optimized to reduce RMS. Scale bar = 200 m. 1 = Gambinini, 2 = Petaluma, 3 = Black John, 4a = east San Pablo Bay NWR, 4b = west San Pablo Bay NWR, 5 = Coon Island, 6 = Fagan, 7 = China Camp State Park, 8 = Corte Madera, 9 = Arrowhead, 10 = Cogswell, 11 = Laumeister, 12 = Colma.

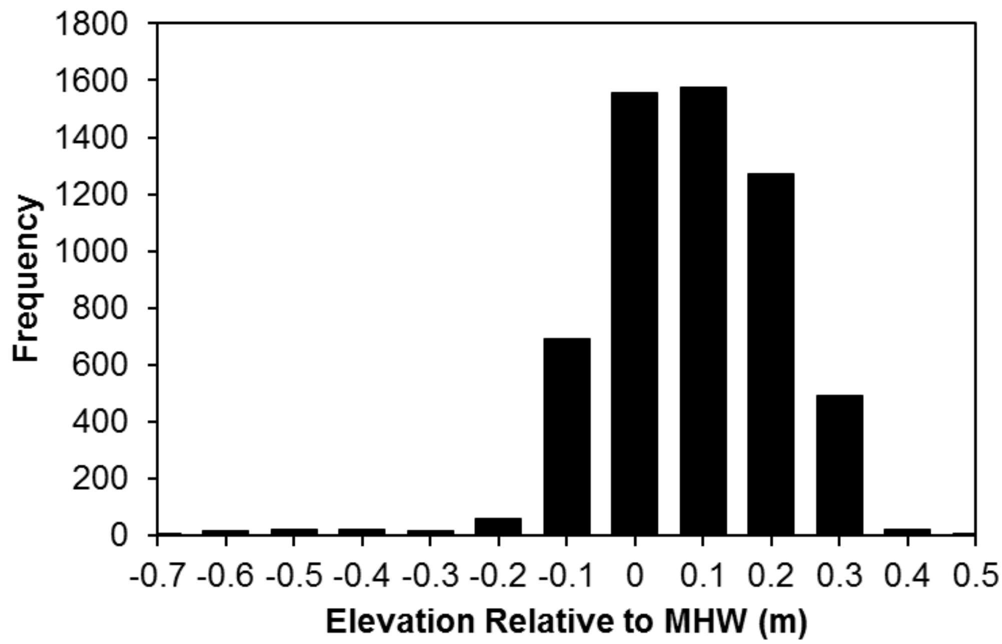


Figure 7. Distribution of marsh elevations relative to mean high water (MHW) for all sites. Random points were sampled from the elevation models at a density of 3/ha to produce an unbiased distribution.

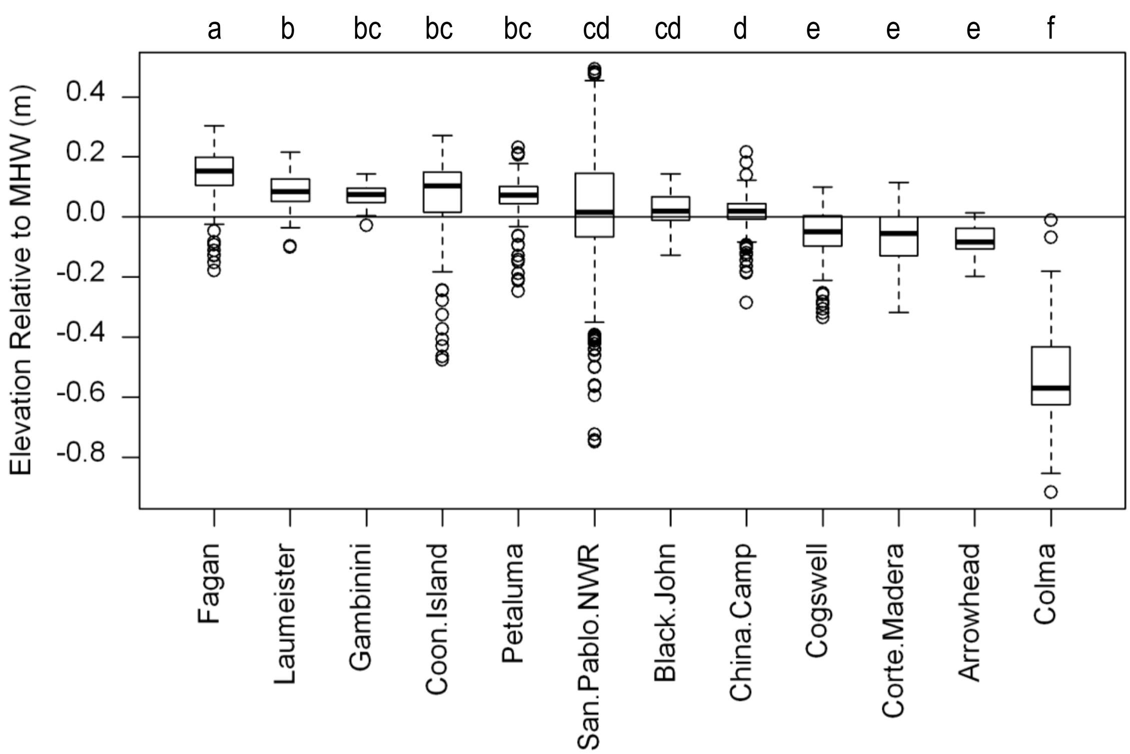


Figure 8. Vegetation relative to marsh (MHW) by site. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers). Circles indicate outliers. Letters denote significant from a TukeyHSD test (alpha = 0.05).

4.2 Vegetation

Vegetation was sampled at 3,302 locations across all marsh sites (Table 1). Distinct zonation in plant communities was observed in relation to MHW as plants are typically restricted by their inundation tolerance and soil salinities (Figure 9). Plant species were categorized into low, mid, and high marsh, and upland transition communities by measured elevation relative to mean sea level (MSL; m). Categories were determined by comparing the elevation mean and standard deviations of each species and grouping overlapping distributions. These communities were then used to interpret changing elevations with SLR (Table 3). Most of the surveyed marshes had representative high marsh vegetation (Table 4).

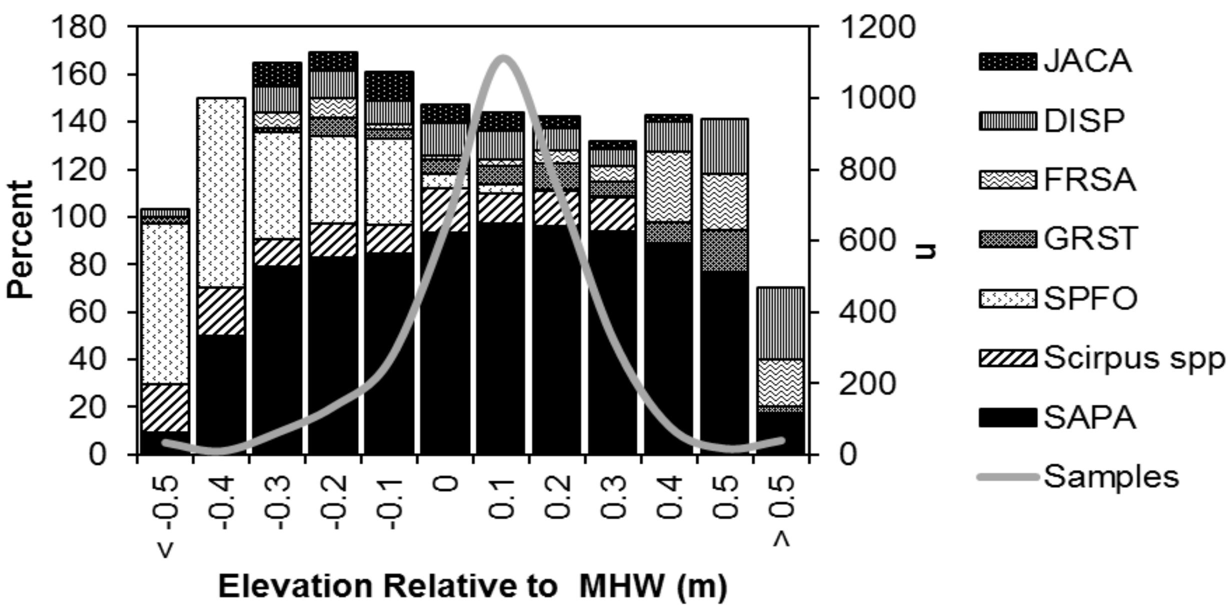


Figure 9. Dominant marsh plant species related to elevation (MHW, m) across study sites. GRST = *Grindelia stricta;* SPFO = *Spartina* spp *.(S. foliosa x S. densiflora).*; SAPA = *Sarcocornia pacifica;* JACA = *Jaumea carnosa;* DISP = *Distichlis spicata*; FRSA = *Frankenia salina*. Grey line represents sampling distribution. Plant canopy cover, which often overlaps, was estimated for each species, thus greater than 100% in a given plot was possible.

Table 3. Plant communities were categorized based on observed elevation distributions to develop marsh zones to model with SLR. Species are ordered by abundance from high to low.

Upland Transition (> 1.0 m MSL)	**High Marsh** (0.7 - 1.0 m MSL)	**Mid Marsh** (0.45 - 0.7 m MSL)	**Low Marsh** (0.2 - 0.45 m MSL)	**Mudflat** (< 0.2 m MSL)
Baccharis pilurais	*Jaumea carnosa*	*Sarcocornia pacifica*	*Spartina* spp.	Sparse *Spartina* spp.
Frankenia salina	*Distichlis spicata*	*Distichlis spicata*		
	Frankenia salina	*Frankenia salina*		
	Sarcocornia pacifica	*Spartina* spp.		

Table 4. Summary of the most common plant species found across all sites. Colma marsh was not surveyed for vegetation due to *Spartina* removal efforts which left most of the marsh unvegetated during our study.

				% Present					
Fig. 1 Ref.	**Study Site**	**SAPA**	***Schoenoplectus* spp.**	***Spartina* spp.**	**FRSA**	**GRST**	**JACA**	**DISP**	**n**
1	Gambinini	99.1	3.6	0.0	6.4	4.5	0.9	8.2	110
2	Petaluma	97.2	6.5	0.0	12.9	6.5	17.4	9.6	356
3	Black John	98.4	46.3	0.0	0.0	14.8	0.0	8.3	108
4a	San Pablo East	85.7	0.9	7.4	0.5	2.8	0.0	0.0	217
4b	San Pablo West	86.8	1.7	9.1	11.1	10.3	4.8	7.7	691
5	Coon Island	87.9	38.5	0.8	0.5	7.4	7.7	1.4	364
6	Fagan	87.3	51.0	0.3	0.3	0.3	0.3	1.9	308
7	China Camp	96.9	1.7	4.3	1.4	8.3	8.1	12.8	422
8	Corte Madera	97.2	0.0	27.4	0.6	5.0	10.2	23.9	361
9	Arrowhead	76.0	0.0	98.0	0.0	0.0	64.0	26.0	50
10	Cogswell	92.5	0.0	9.2	0.0	0.0	0.0	0.0	228
11	Laumeister	86.1	0.0	37.5	1.4	27.8	4.2	40.3	72

Sarcocornia pacifica was the most common species surveyed across sites, occurring at 91% of 3,287 areas. *Schoenoplectus* spp. was the second most common species (12.8%), followed by *Distichlis spicata* (10.3%), *Spartina* spp. (8.9%), *Jaumea carnosa* (7%), and *Grindelia stricta* (6.8%). The sites located along more brackish river water had higher species richness -- Coon Island and Fagan, both on the Napa River, had the highest overall species richness.

All of the surveyed marshes had high *S. pacifica* abundance, the characteristic species of SFBE tidal marshes; however, several species of the marsh community differed by region (Table 3). *Schoenoplectus* spp. commonly associated with brackish conditions were found in the sites along the Petaluma and Napa Rivers but not in the south San Francisco Bay sites. *Spartina* spp. were prevalent at south San Francisco Bay, not present on the Petaluma River, very sparse on the Napa River, and in low abundance at San Pablo Bay sites. These patterns in *Spartina* spp. and *Schoenoplectus* spp. distribution were likely in response to differences in water and soil salinity across SFBE (see Fig. 10).

4.3 Water monitoring

Water loggers recorded tide levels from January 2010 – May 2011 for use in our analyses, but we continued monitoring at a majority of the sites for future analyses. The loggers did not capture the bottom portion of the tidal curve because they were located relatively high in t marsh channels. Peak tide levels for one year (2010 - 2011) were averaged for each site, producing sites-specific tidal datums for mean high water (MHW) and mean higher high water (MHHW, Table 5).

Conductivity measurements at a subset of the sites showed the influence of freshwater runoff on water salinity (Fig. 10). The most prominent pattern was the seasonality, with a peak in October (except for Laumeister) correlating with the end of the dry season in SFBE. Coon Island along the Napa River had the lowest mean salinity in 2010, while San Pablo located on the edge of the bay had the highest. In contrast, Laumeister did not show a seasonal salinity pattern. Laumeister was the only site in south San Francisco Bay where we measured conductivity; thus, it is difficult to know whether it represented a different salinity regime from the San Pablo Bay and northern river sites or whether there may have been problems with the conductivity sensor.

Table 5. Water elevations (m, NAVD88) for each marsh site in 2010. Mean sea-level (MSL) was derived from VDatum (NOAA). Mean high water (MHW) and mean higher high water (MHHW) were calculated from in situ data loggers.

Site	MSL	MHW	MHHW
Arrowhead	1.03	1.71	1.91
Black John	1.06	1.73	1.91
China Camp	1.02	1.77	1.95
Cogswell	1.14	1.86	1.99
Colma	1.03	1.77	1.98
Coon Island	1.03	1.78	1.94
Corte Madera	0.99	1.7	1.87
Fagan	1.07	1.75	1.9
Gambinini	1.07	1.8	1.96
Laumeister	1.21	1.92	2.09
Petaluma	1.04	1.76	1.92
San Pablo Bay NWR	1.04	1.69	1.85

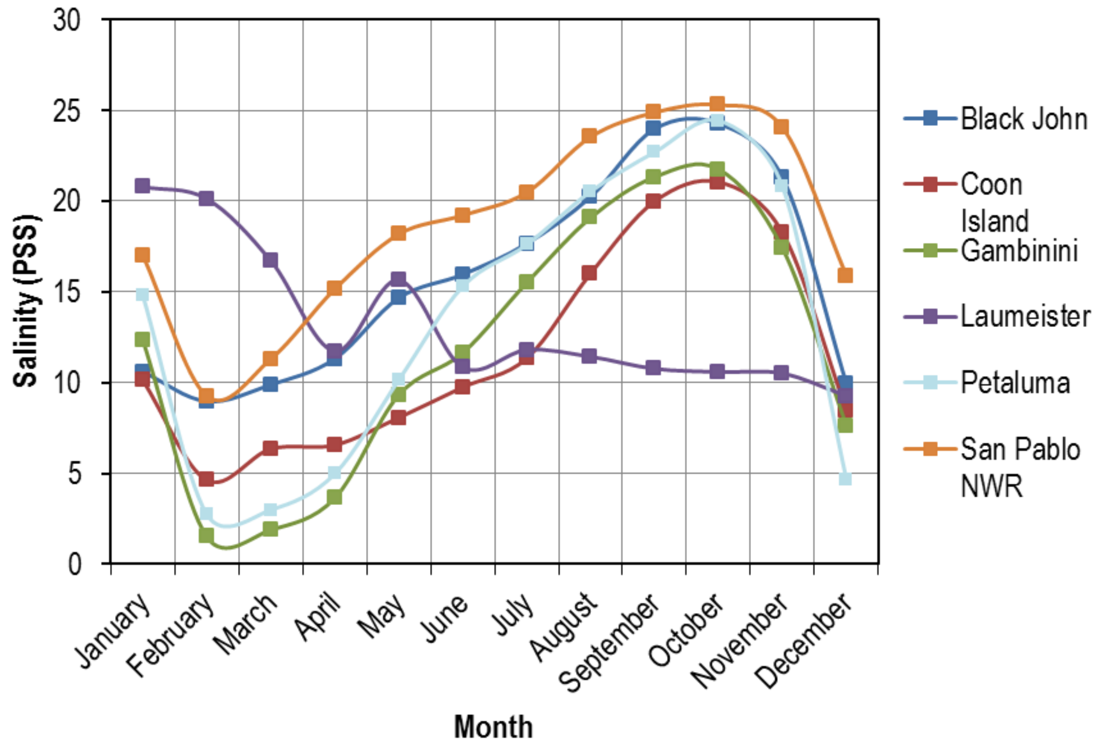


Figure 10. Salinity (Practical Salinity Scale, PSS) throughout 2010 across a subset of study sites. Calculated by taking the monthly mean of salinity from daily high tides. Seawater has a PSS of 35.

4.4 Marsh response modeling

SFBE spatial variability in tidal range, accretion rate, and initial marsh elevation resulted in differential SLR risk (see Appendix for site details). Sediment core data at reference sites (Table 6) was used to inform accretion rates (sediment and organic accumulation) for all sites (Table 7). Measured sediment accumulation used in WARMER showed higher sediment accumulation rates at Laumeister and Coon Island compared to China Camp and Petaluma (Table 5). Sediment accumulation and organic matter accumulation curves were then developed for the reference sites (Fig. 10 & 11).

Generally, sites with lower initial elevations and located lower in the tidal range (e.g. Corte Madera, Colma, Arrowhead) became inundated more frequently and with longer duration than sites with higher initial elevation and located higher in the tidal range (e.g. Laumeister, Gambinini, and Fagan). Accretion rates used in the WARMER model were relatively higher in south San Francisco Bay, thus those marshes withstood SLR to 2100, with areas of transition from high to low marsh vegetation by 2100 (e.g. Cogswell, Laumeister, and Colma). Arrowhead, located in central San Francisco Bay, showed a large transition from mid to low marsh around 2040 (+ 0.32 m SLR), and to mudflat by 2080 (+ 0.85 m SLR).

Table 6. Model inputs used for primary WARMER model sites. Z represents a standardizing metric.

Site	Sediment	Organic matter		Porosity		Decay	Elevation		
	(g/cm2/yr)	*(mg/cm^4/yr)*		(%)		(%)	*(cm above MSL)*		
	M_s(MSL)	a	b	Surface	Depth	Refractory C	Z-2s	Z	Z+2s
China Camp	0.32	-0.00257	-0.00452	82	77	12	64	77	90
Petaluma	0.10	-0.00113	-0.00199	83	80	14	65	77	89
Coon Island	0.59	-0.00142	-0.00250	83	78	55	49	75	101
Laumeister	1.34	-0.00443	-0.00777	76	72	49	69	83	96

Table 7. WARMER model inputs used in extrapolation to the remaining sites. The reference site was chosen based on proximity to marsh. CC: China Camp, PRM: Petaluma, Lau: Laumeister, CI: Coon Island.

	Arrowhead	Black John	Cogswell	Colma	Corte Madera	Fagan	Gambinini	SPB NWR
Reference site	CC	PRM	Lau	Lau	CC	CI	PRM	CC
Max org in (g/cm2/yr)	0.019	0.005	0.029	0.029	0.019	0.005	0.005	0.019
Sediment Ms(MSL) (g/cm2/yr)	0.320	0.097	1.338	1.338	0.320	0.588	0.097	0.320
Surface Porosity (%)	82	83	78	78	82	83	83	82
Depth Porosity (%)	77	80	77	77	77	78	80	77
Refractory Carbon (%)	12	14	55	55	12	12	14	12
Elevation (cm MSL)								
Z-2s	51	58	55	-11	47	65	73	34
Z	63	70	71	31	64	83	81	64
Z+2s	74	81	86	73	81	101	90	93

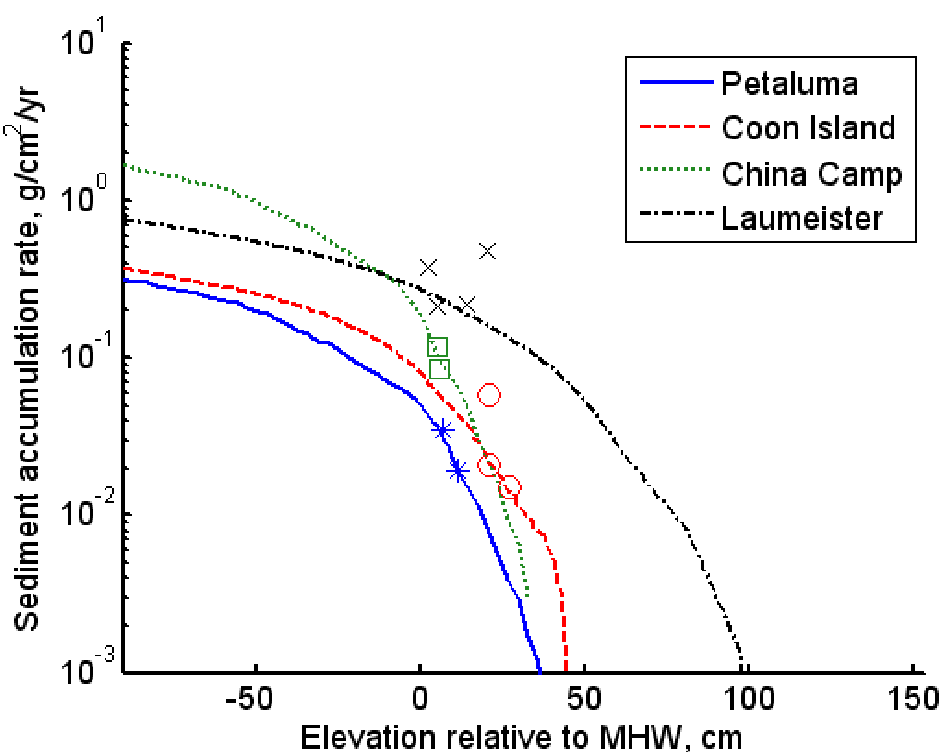


Figure 11. Calculated sediment accumulation curves (lines) and measured accumulation rates (points) for representative marsh sites. Curves are calculated from inundation frequency and calibrated to

accumulation rates measured by Callaway *et al.*(2012). These rates were extrapolated to nearby marshes in the study.

The remaining sites had accretion rates that were relatively low; the WARMER simulations projected that these marshes would transition to mudflat by the end of the century. For example, Corte Madera, China Camp, and San Pablo lost all high marsh by 2030 (+ 0.24 m SLR), briefly transitioned to mid and low marsh vegetation, and ultimately transitioned to areas dominated by mudflats by 2080 (+ 0.85 m SLR). The three marshes located on the Petaluma River (Gambinini, Petaluma, and Black John) also lost most high marsh by 2030 (+ 0.24 m SLR) and transitioned to mostly mudflat by 2080 (+ 0.85 m SLR). As the WARMER model for the Napa River sites was parameterized with higher sediment accretion rates, these sites maintained high marsh until 2030 (+ 0.24 m SLR) for Coon Island and 2040 (+ 0.32 m SLR) for Fagan. Between 2040 (+0.32 m SLR) and 2060 (+ 0.57 m SLR), mid marsh vegetation was maintained for Coon Island and Fagan, respectively. Low marsh vegetation was dominant until 2090 (+1.05 m SLR) at which time both marshes transitioned to predominantly mudflat; both of these sites had higher initial elevations than other marshes.

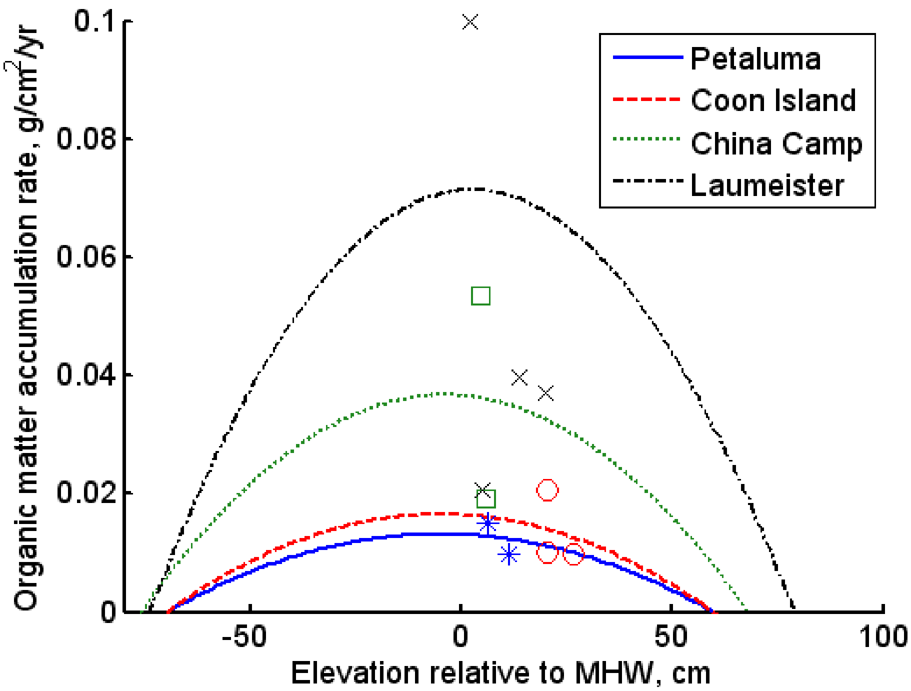


Figure 12. Calculated organic matter accumulation (lines) and measured accumulation rates (points) for representative marsh sites. These rates were extrapolated to nearby marshes in the study.

Nine of the marshes transitioned to mudflat by 2100 (1.23 m SLR), whereas only three marshes maintained vegetation to 2100. All marshes lost upland transition and high marsh by 2100 and mid marsh vegetation was lost at nine marshes by 2100. These results illustrate the spatial variability of SLR impacts across SFBE. The three marshes that maintained marsh vegetation to 2100 comprised only 4% (85 ha) of the total marsh area surveyed. Whereas, a total of 96% (1,942 ha) of the marsh area in our study had transitioned to mudflat by 2100 (Site specific results are described in Appendices A-K).

4.5 WARMER sensitivity analysis

Callaway *et al.* (1996) and Deverel *et al.* (2008) noted that their respective models were sensitive to both initial elevation and porosity. The sensitivity analysis of WARMER showed that the greatest differences in final elevation occurred when SLR and sediment accumulation were varied (Fig. 13). On average, the scenarios with the largest sediment accumulation were able to keep pace with SLR. Scenarios with only 50 cm of SLR by the end of the century had an average increase in elevation of 7%. The small variations in porosity that were observed in the marsh sediment cores did not lead to large changes in final elevation despite the strong non-linearity between porosity and volume. The influence of organic matter accumulation was also small despite varying the observed range of accumulation rates by ~ ±50% in the sensitivity analysis. The scenarios with the lowest sediment accumulation rate did have a larger dependence on initial elevation than the other accumulation rate scenarios. The negative feedback between elevation and sediment accumulation was strong enough to mitigate this influence in the mean

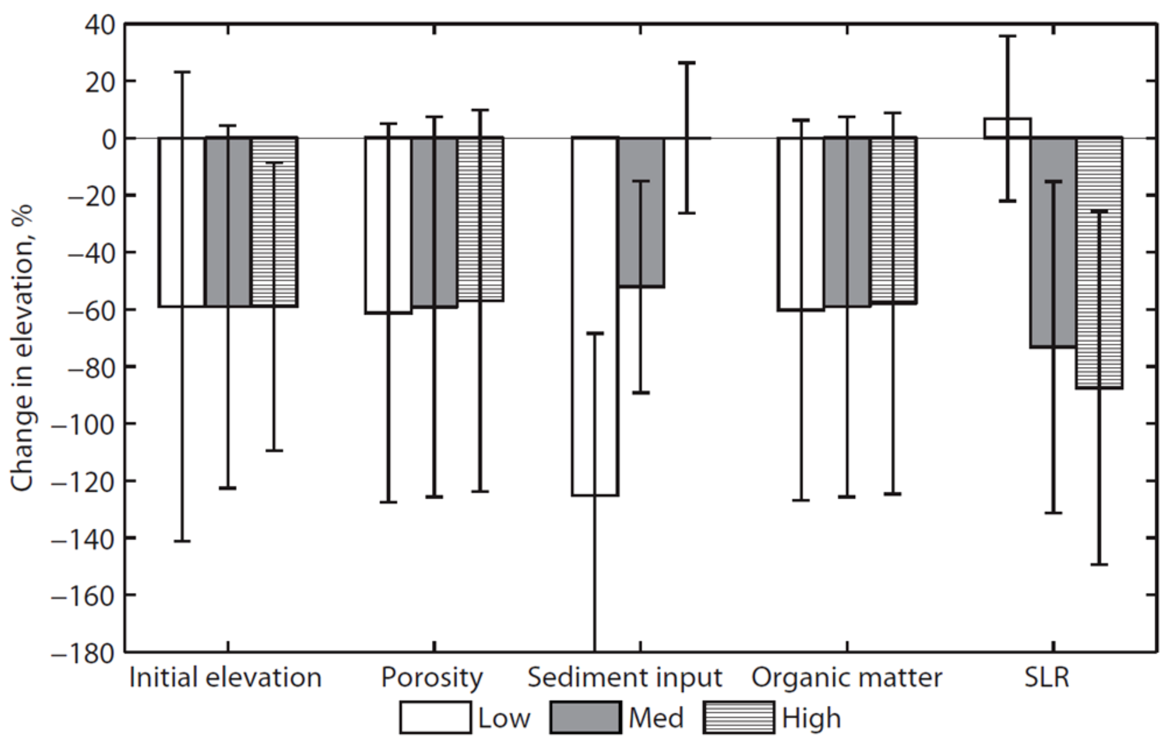


Figure 13. Results of the sensitivity analysis of WARMER. Each bar is the mean final elevation for 81 runs with the indicated parameter. Error bars indicate ± 1 standard deviation from the mean.

and high sediment input scenarios.

The current WARMER model could be expanded and improved for site-specific results. For example, a better understanding on local suspended sediment supply (across the SFBE and marsh sites), settling velocity of suspended sediment and how that relates to vegetation, and temporal variability of deposition rates would improve the accretion function. In addition, the model does not currently address marsh erosion that would also have negative feedbacks to marsh elevation. Any changes in hydrological conditions besides SLR and sediment availability over time were not incorporated into the models.

5. Discussion

Resource land managers responsible for the protection of wildlife species and their habitats were our focus in developing site-specific projections and plant community response to SLR. By identifying SLR habitat thresholds, our project aimed to provide land managers with the science support necessary to make informed decisions and develop climate change adaptation strategies. Our models identified differential risk of individual marshes to SLR in SFBE, including the timing of habitat transitions.

On-the-ground marsh elevation and plant community surveys and tidal regime monitoring provided highly site-specific data important for establishing detailed baseline conditions to develop SLR models. The most common method for obtaining SLR modeling elevation data has been aerial LiDAR (Light Detection And Ranging). However, LiDAR is generally unable to penetrate dense marsh vegetation cover and produces elevation errors 10 - 40 cm greater than ground-based measurements (Foxgrover *et al*. 2011, Schmid *et al.* 2011). The error in LiDAR can represent nearly half of the total marsh slope and can skew SLR response modeling results, especially early in the century through the year 2050. Our results showed that initial elevation, along with tidal range and suspended sediment availability, were key inputs for effectively modeling marsh response from SLR in the SFBE.

Sediment accretion may partially offset increased SLR through 2100. South San Francisco Bay marshes will be able to maintain mid marsh vegetation throughout most of this century with a transition to low marsh vegetation in the later part of the century largely due to their higher sediment accretion rates. In contrast, San Pablo Bay sites will not have high enough accretion rates to maintain elevations at a rate to keep pace with SLR, and they represent some of the largest remaining parcels in the estuary. San Pablo Bay is generally considered to be at a turbidity maximum within the estuary (Rhul *et al*. 2004; Stralberg *et al*. 2011); thus, the limited sediment core data may not reflect the current rate of sediment accumulation there. The accuracy of marsh accretion models is largely dependent on accurate sediment accumulation functions and calibration data. While the accretion models may not accurately reflect the accretion at a specific site, the range of values used does represent a cross section of possible marsh accretion simulations for SFBE. Our results showed that three marshes will maintain marsh vegetation to 2100, but these marshes only comprised 4% (85 ha) of the total marsh area surveyed, while the remaining 96% (1,942 ha) of marsh area in our study would transition to mudflat by 2100.

Urbanization in the SFBE estuary makes it especially susceptible to SLR as there are limited opportunities for upslope transition. Seven of our marsh sites have open space (non-urban) surrounding the sites. With management actions and restoration, these marshes have potential to respond to SLR by moving upslope. In contrast, five sites are surrounded by urban infrastructure and therefore will have no opportunity to move upslope with SLR. If these marshes are unable to transition upslope, due to levees or development, they will become mudflat.

The added effects of climate change on marsh ecosystems may greatly increase threats to already vulnerable wildlife populations and species (Ohlemuller *et al.* 2008). Increased rates of inundation will be ecologically significant for obligate marsh species, especially those that are already limited in number (e.g. California clapper rail) and those that also have low dispersal ability (e.g. salt marsh harvest mouse). Species that rely on marsh habitat for feeding, reproduction, or cover from predators will be negatively affected by SLR. Our projections show the loss of high and mid marsh vegetation by 2050 in most areas. These areas are dominated by *Sarcocornia pacifica,* a plant that is critical for providing habitat structure for the salt marsh harvest mouse, California black rail and nesting song birds. Low marsh vegetation will persist in most areas until 2070 and is dominated by *Spartina* spp. which provides habitat used by the California clapper rail. However low marsh was projected to be lost at 96% of the surveyed areas through 2100, and if representative, it may be result in loss of a significant amount of habitat for the California clapper rail population.

6. Next steps

Our program recognizes the importance of extensive and improved integration of physical and biological monitoring that could facilitate the discovery of important trends and signals for SLR. A better understanding of the spatial variability of available suspended sediment and deposition rates for both organic matter and sediment would greatly improve these site-specific results and is a future direction of the program. We believe this type of baseline data collection can be used to identify and prioritize restoration sites and land acquisitions that may be good candidates for marsh perpetuation in light of SLR. In addition, the continued risk to listed species should be assessed by evaluating movements, nesting requirements, and food availability for species. A better understanding of wildlife response to increased inundation is especially needed. The CERCC program recently has been expanded to Humboldt Bay, Anaheim Bay, and the San Diego estuary, as well as to a range of coastal sites in California, Oregon, and Washington. Consistent with the goal of the USGS Science Strategy, the CERCC program will support models that predict ecosystem change and assess consequences of climate change and its effects on coastal ecosystems, and it will do so at a bottom-up local level appropriate for land managers developing adaptation plans.

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Appendix

Site-specific data is available by request. Contact:

Dr. John Y. Takekawa
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San Francisco Bay estuary Field Station
505 Azuar Dr.
Vallejo, CA 94592
707-562-3003

Appendix A

Arrowhead Marsh

Introduction

Located in central San Francisco Bay, Arrowhead Marsh (hereafter Arrowhead) is a tidal salt marsh which is owned by Oakland Port Authority and managed by East Bay Regional Parks as part of the 741 acre Martin Luther King Jr. Regional Park. Arrowhead is recognized as an important stopover on the Pacific Flyway and is part of the Western Shorebird Reserve Network. Arrowhead is also home to the federally-endangered California clapper rail (*Rallus longirostris obsoletus*) which occupies the low intertidal habitat dominated by cordgrass (*Spartina* spp.)

This study focused on 17.0 hectares of Arrowhead. Elevation and vegetation surveys were conducted in the winter of 2009 using an RTK GPS. To monitor tidal inundation, two water level loggers were deployed from 2009 - 2010. Beginning in 2006, a chemical herbicide (chemical mow) was applied to the western half of the marsh in an attempt to control the invasive *Spartina densiflora* and the *S. densiflora* x *S. foliosa* hybrid. Due to the treatment, vegetation was not surveyed in the western portion of Arrowhead.

Results

Elevation surveys

A total of 274 elevation measurements were taken at Arrowhead (Fig. A-1). The elevation range was 0.87 - 1.84 m with a mean of 1.62 m (NAVD88). Over half (65%) of the survey points fell within 1.55 - 1.70 m, with a 0.15 m range. Arrowhead was the second lowest marsh surveyed in this study with 87% of the elevation points taken located below mean high water (MHW; Fig A-2). Only 13% of survey points were located at elevations above MHW. A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. A-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

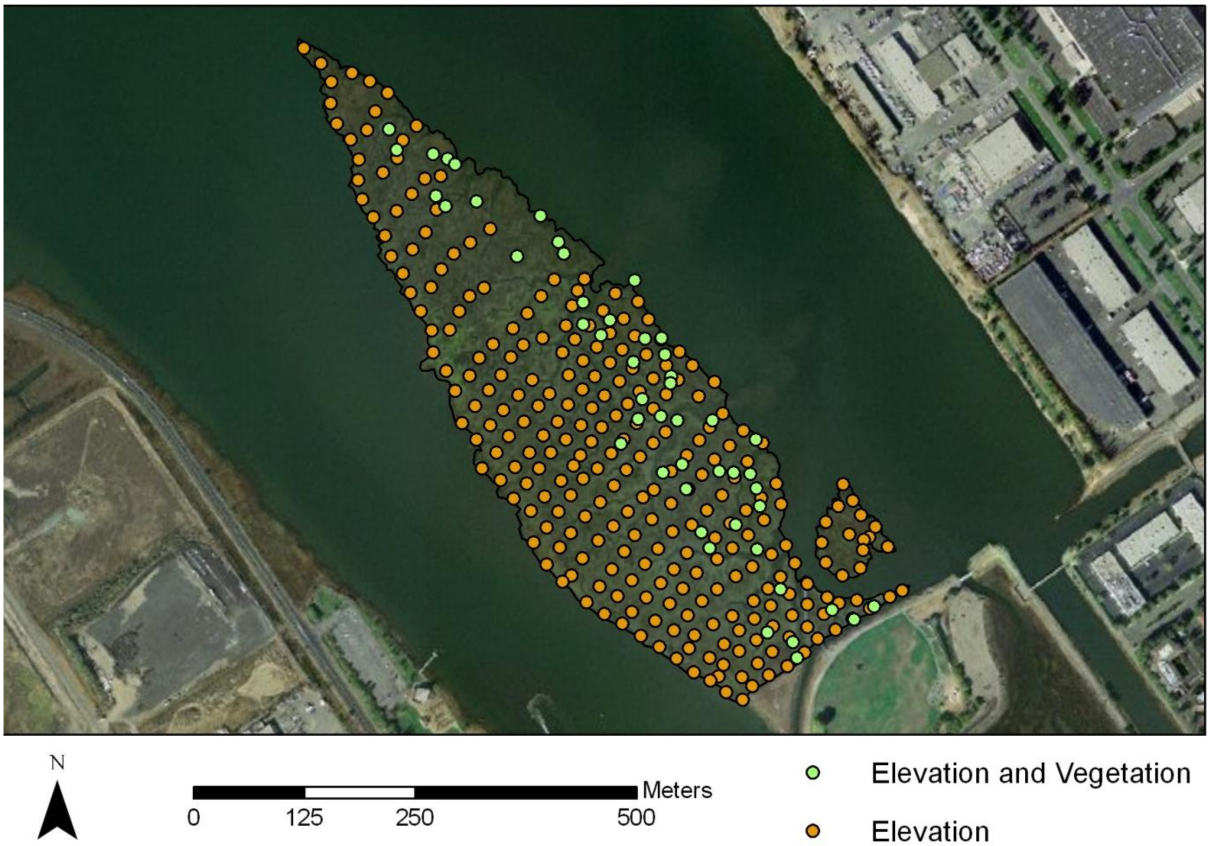

Figure A-1. Arrowhead Marsh with elevation and vegetation survey points collected in 2009.

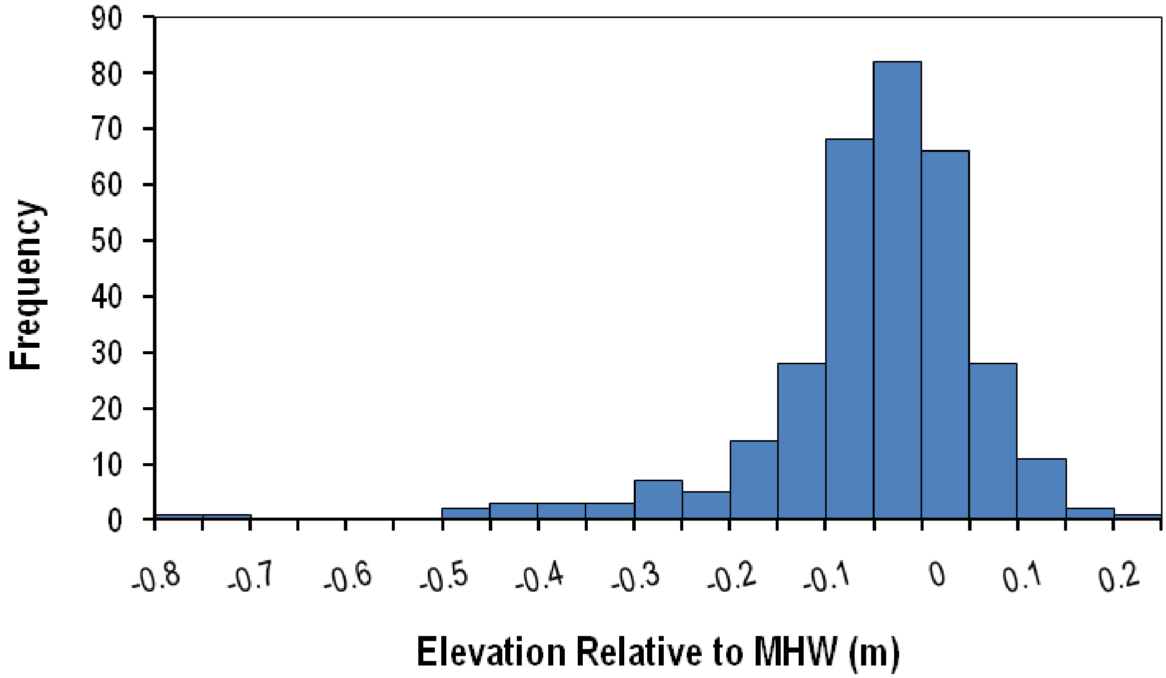

Figure A-2. Distribution of elevation samples relative to local mean high water (MHW) at Arrowhead Marsh.

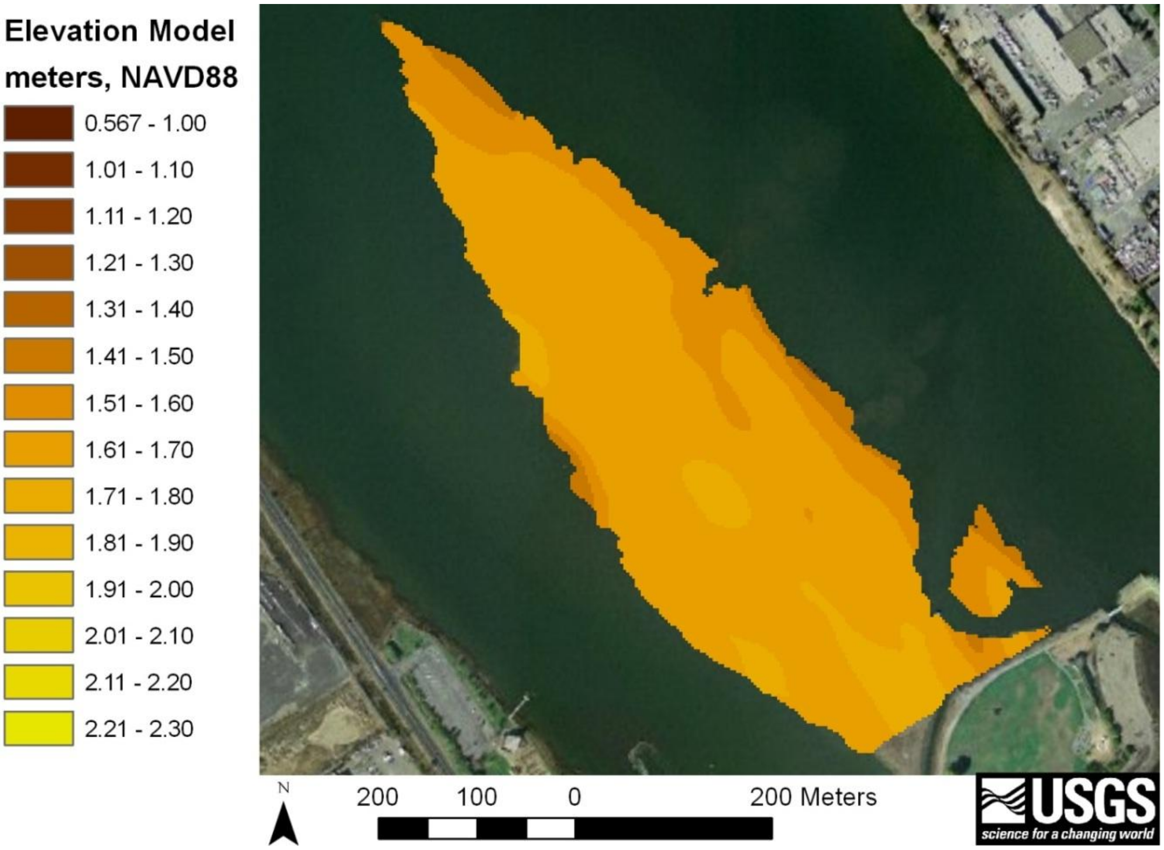

Figure A-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

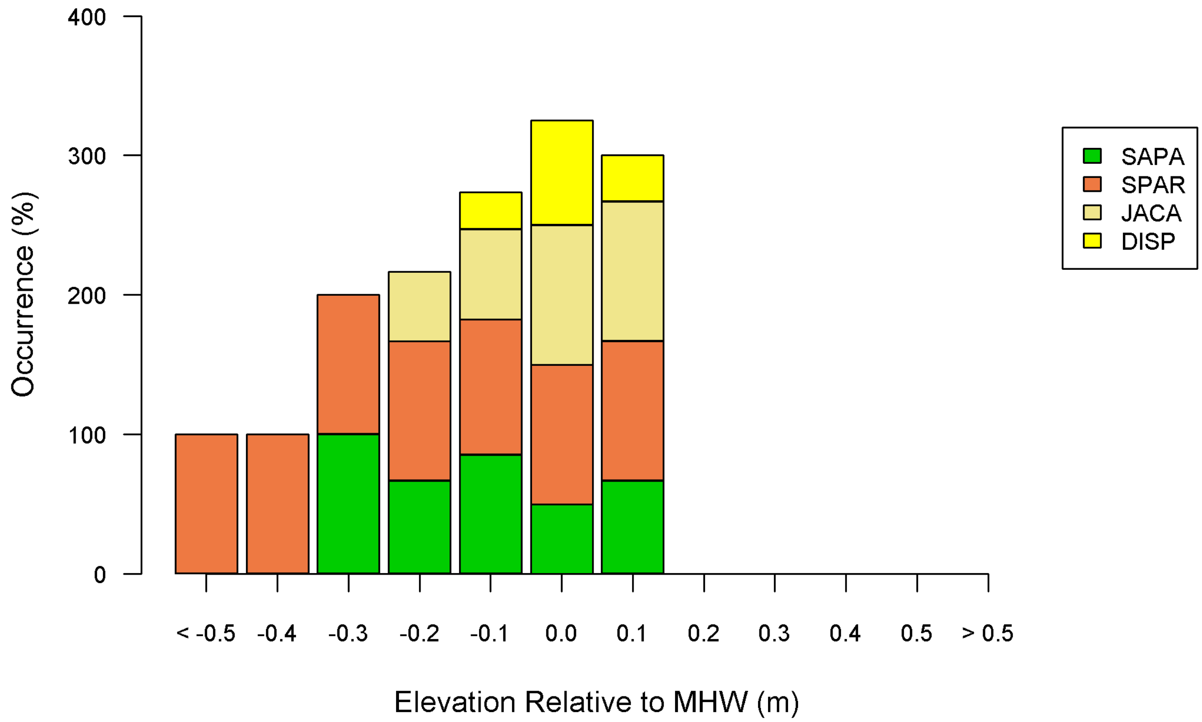

Figure A-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* SPAR = *Spartina* spp.; JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Vegetation surveys

Vegetation surveys were done concurrently with elevation surveys in December of 2009. A total of 50 locations (Fig. A-1) were measured for vegetation composition, height (cm), and percent cover (Table A-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. A-4) was observed within this low slope marsh.

Table A-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species in Arrowhead Marsh.

Species	Elevation (MHW, m)	Elevation SD (MHW, m)	Avg, Height (cm)	Avg. Height SD (cm)	Max Height (cm)	Max Height SD (cm)	% Cover	% Cover SD	n	% Presence
Sarcocornia pacifica	-0.15	0.07	21.63	16.40	25.97	18.88	22.18	17.05	38	76.00
***Spartina* spp.**	-0.17	0.13	41.61	26.40	53.57	33.47	44.86	32.42	49	98.00
Jaumea carnosa	-0.13	0.07	11.88	7.25	14.47	8.58	31.38	25.40	32	64.00
Distichlis spicata	-0.11	0.06	17.00	10.10	19.69	11.46	13.00	13.92	13	26.00

Water level monitoring

Site-specific water level was monitored at Arrowhead for one year from December 2009 – May 2011. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. During 2010, MHW was 1.72 m and MHHW was 1.91 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean elevation) was inundated most often from December 2009 through February 2010 (Fig. A-5). Those months recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in January 2010 was above average throughout the SFBE and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform.

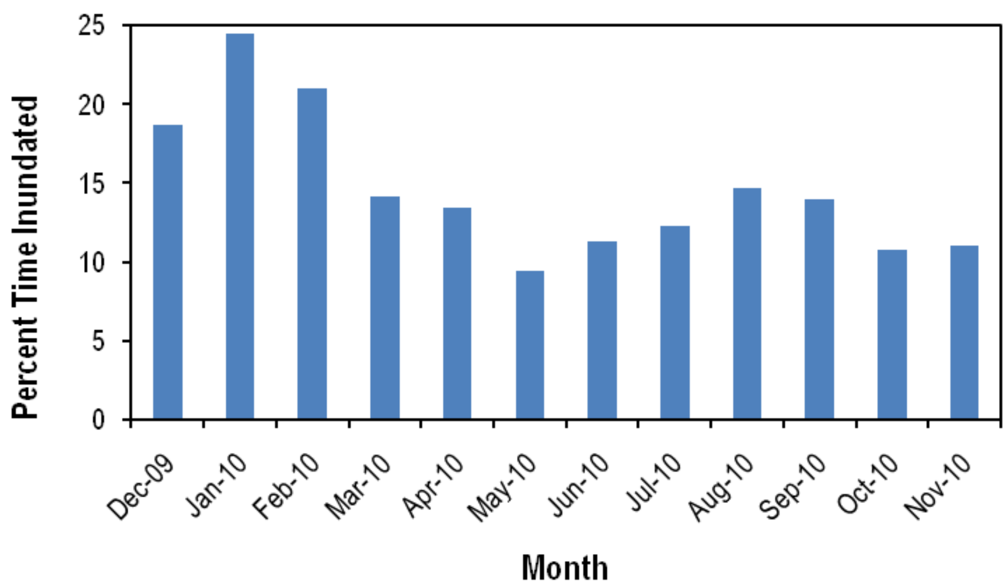

Figure A-5. Percent of time Arrowhead was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

Arrowhead had a low starting elevation and was located low in the tidal range, relative to our other study sites. The WARMER model results indicated that Arrowhead will not keep pace with SLR through this century. WARMER results show a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060 (Fig A-6). By 2080 the marsh is projected to be below MSL and therefore transition to a mudflat (Fig. A-7).

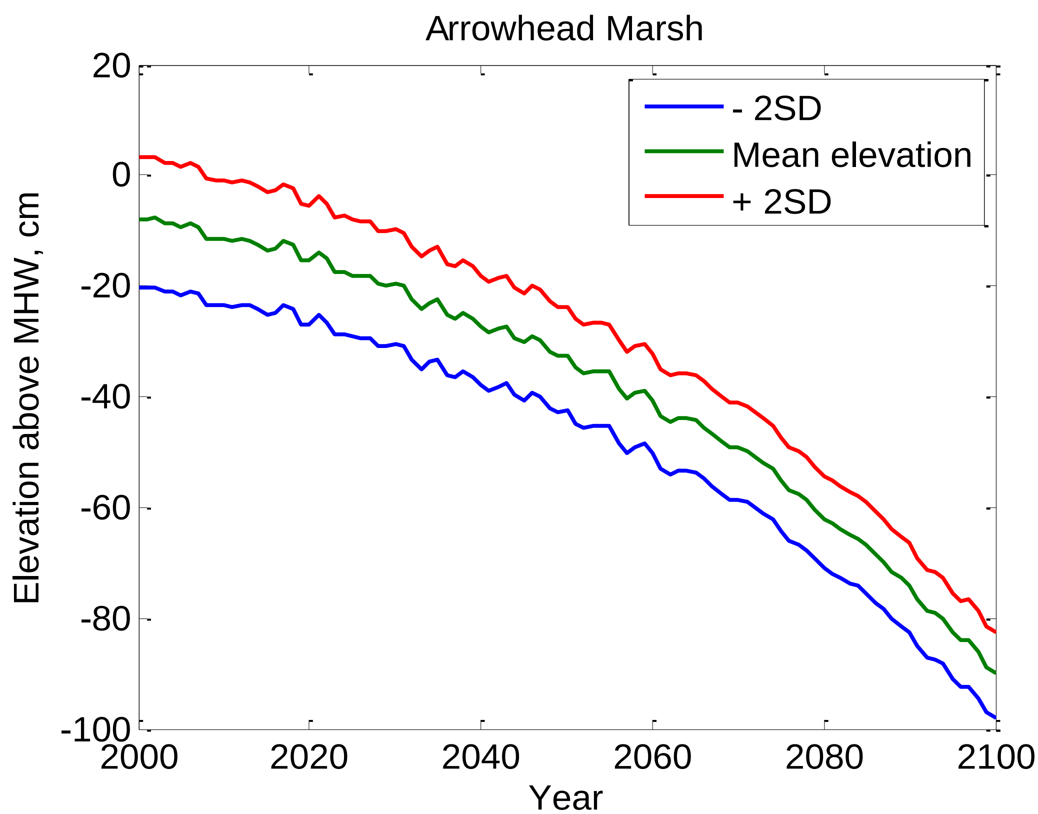

Figure A-6. WARMER scenarios for Arrowhead elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

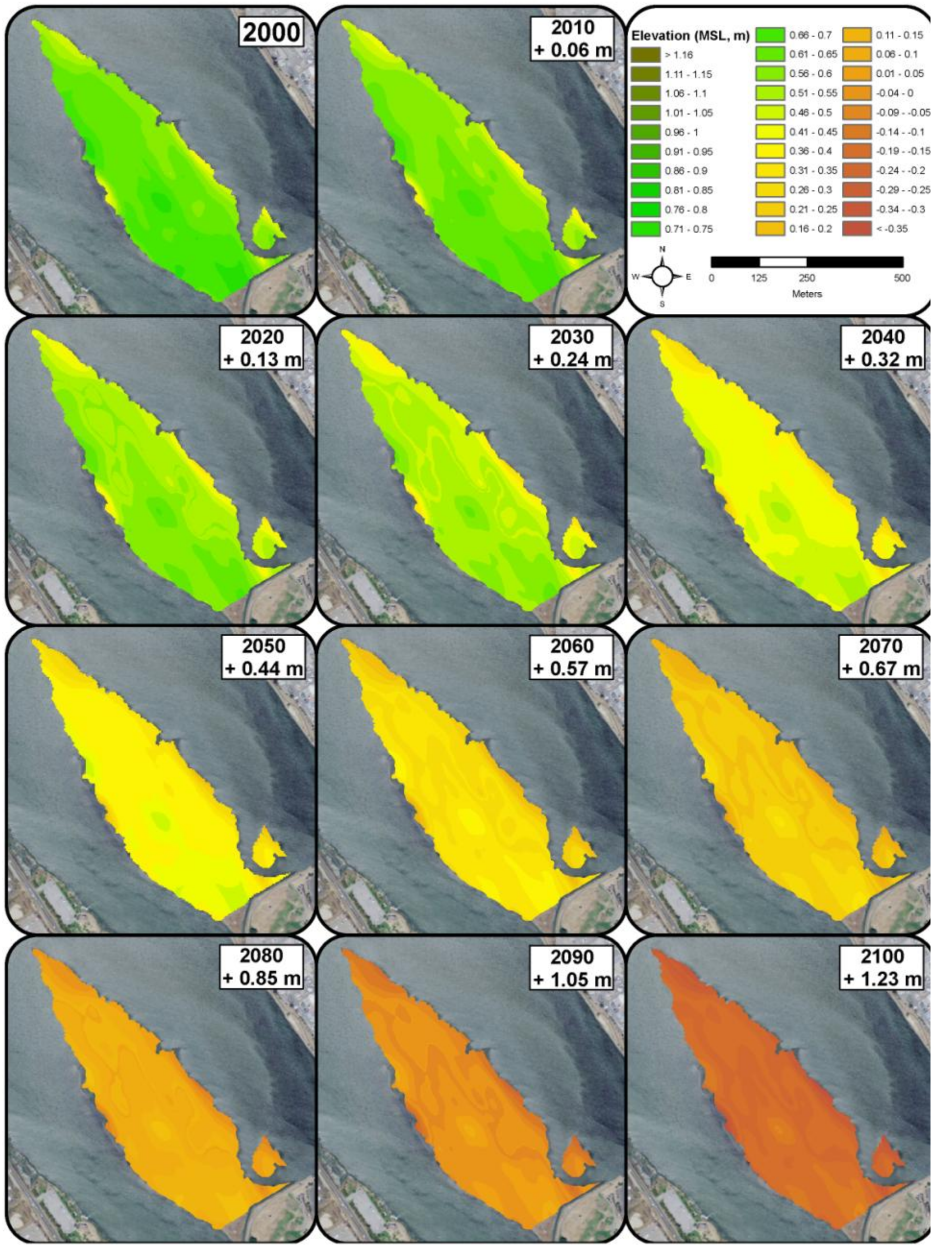

Figure A-7. Spatial WARMER results for Arrowhead. WARMER accounts for changes in relative sea level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. A-8 – A-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently vegetation at Arrowhead is primarily categorized as mid marsh with some high marsh vegetation. All high marsh vegetation is projected to disappear with a + 0.06 m SLR. The largest transition will occur around 2040 (+ 0.32 m SLR), with a projected change from mid to low marsh vegetation. A transition to complete mudflat was projected by 2080 (+ 0.85 m SLR).

The WARMER model parameters for Arrowhead were extrapolated using sediment core data from China Camp marsh; thus, SLR projections should be interpreted with caution as local sedimentation processes may be quite different. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentration data to characterize sediment deposition potential.

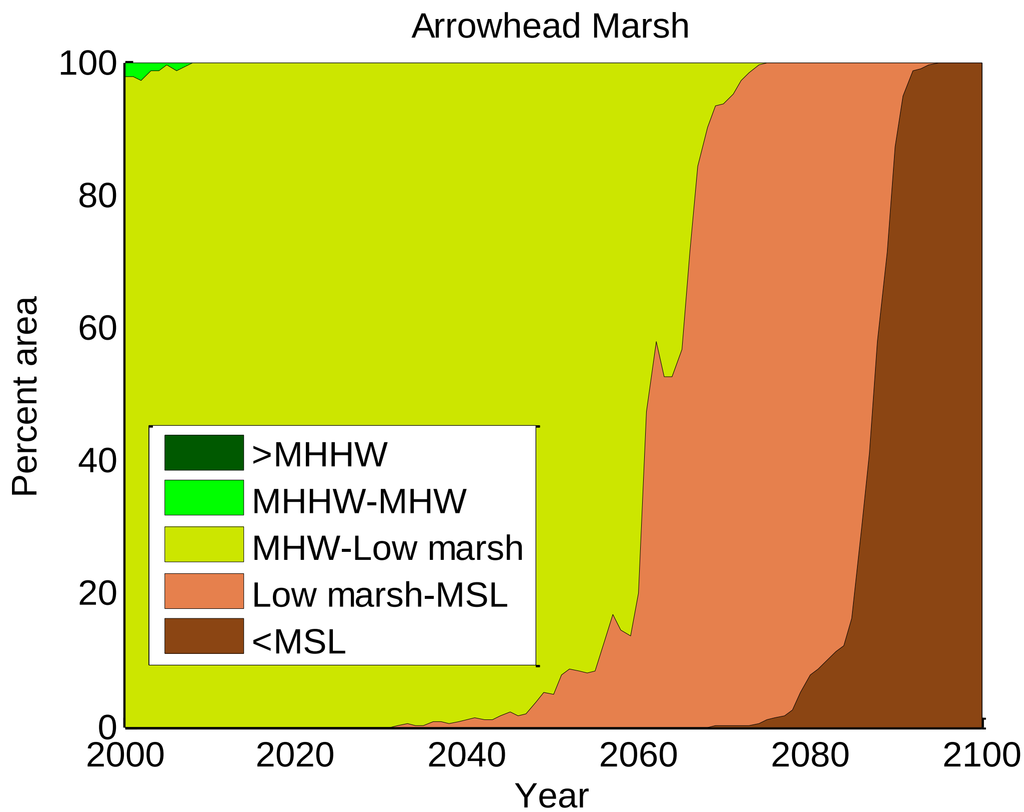

Figure A-8. Area of Arrowhead Marsh within a given tidal range for the duration of the simulation period.

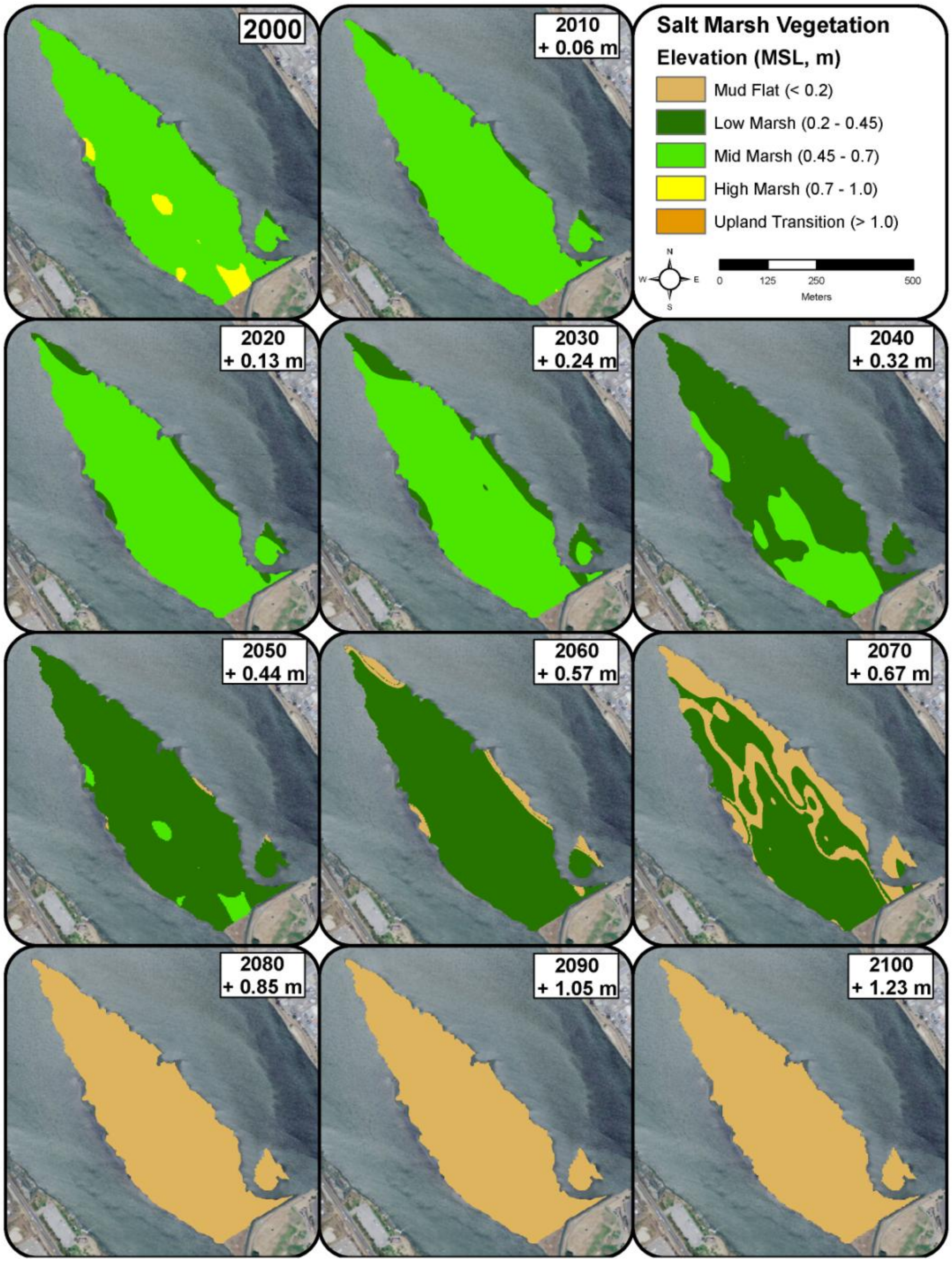

Figure A-9. Arrowhead WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix B

Black John Marsh

Introduction

Black John Marsh (hereafter Black John) is located in Sonoma County at the confluence of Black John Slough, Rush Creek and the Petaluma River. It is owned and managed by the California Department of Fish and Game. It is influenced by both tidal flow and freshwater input from the Petaluma River. Black John is part of the Petaluma Marsh complex, which is the largest marsh complex in California that has never been diked or drained. The land surrounding the marsh is used almost exclusively for agriculture and light grazing. In 2003, the California State Coastal Conservancy funded the acquisition and restoration of a 632 acre parcel just west of Black John, increasing the future potential size of the marsh. Black John is home to several endangered species and species of concern such as California black rail (*Laterallus jamaicensis coturniculus*).

This study focused on 30.9 ha portion of Black John. Elevation and vegetation surveys were conducted in 2010 using an RTK GPS. To monitor tidal inundation and salinity, two water level loggers were deployed in 2009.

Results

Elevation surveys

A total of 213 elevation measurements were taken at Black John (Fig. B-1). The elevation range was 1.18 - 1.97 m with a mean of 1.75 m (NAVD88). Half (50%) of the survey points were within 1.70 - 1.80 m, with a 0.1 m range (Fig. B-2). Over half (67%) of the survey points were located at elevations above mean high water (MHW). A 3-m resolution elevation model was developed in

ArcGIS 9.3 (ESRI, Redlands, CA), using the Kriging method (Fig. B-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

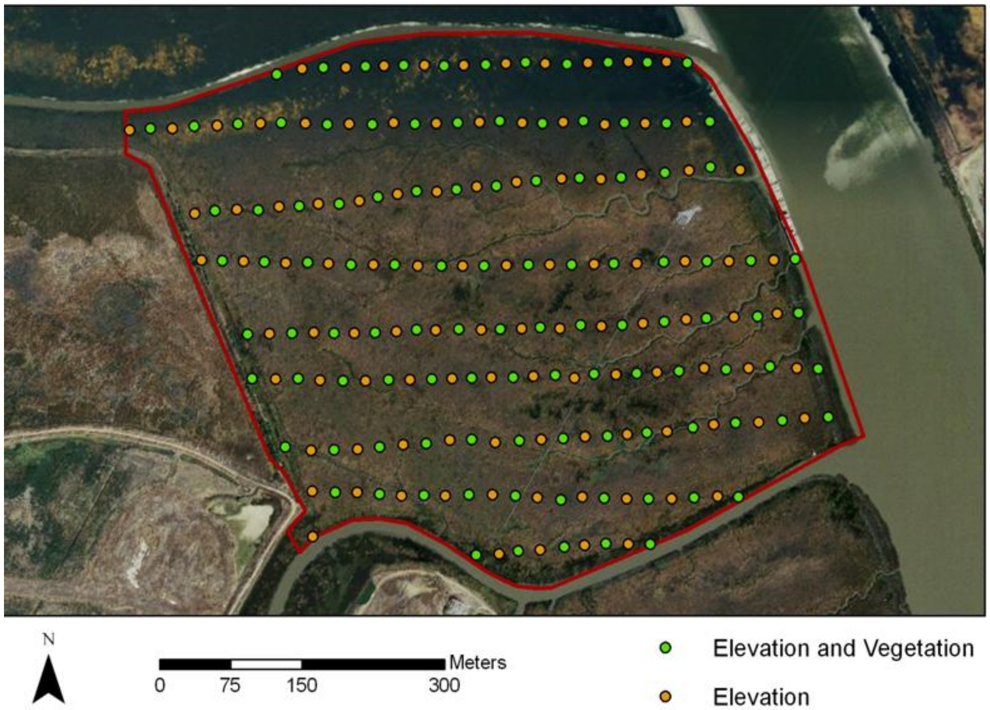

Figure B-1. Elevation and vegetation survey points collected at Black John in 2010.

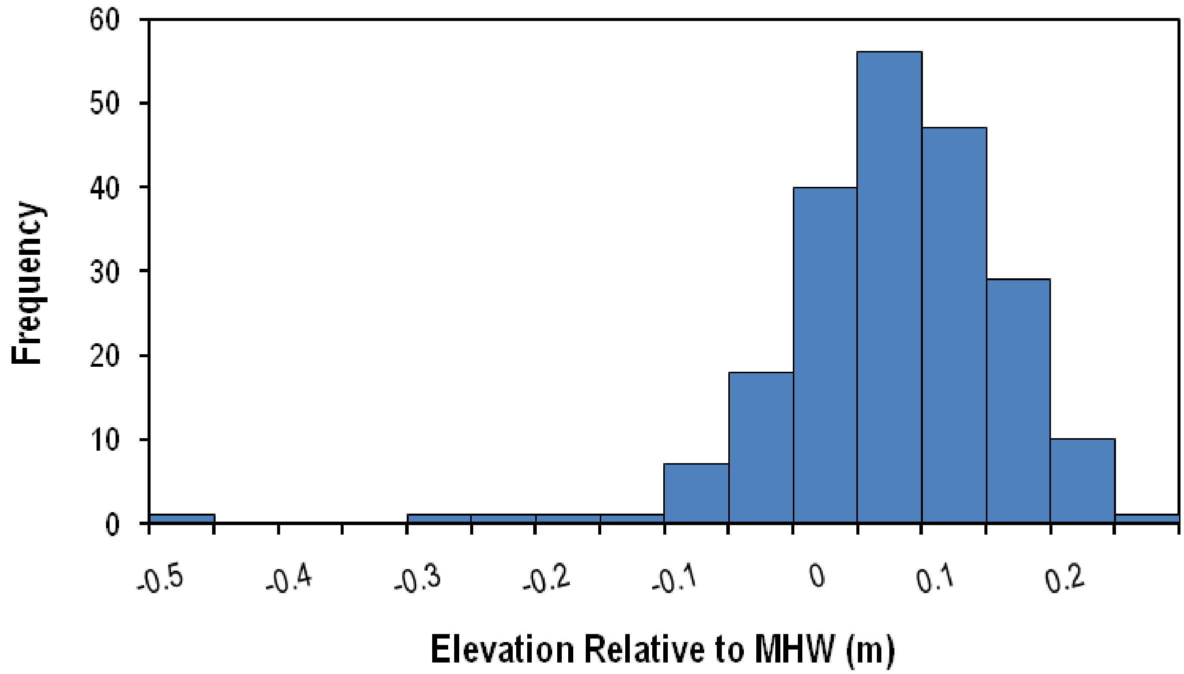

Figure B-2. Distribution of elevation samples relative to local mean high water (MHW) at Black John.

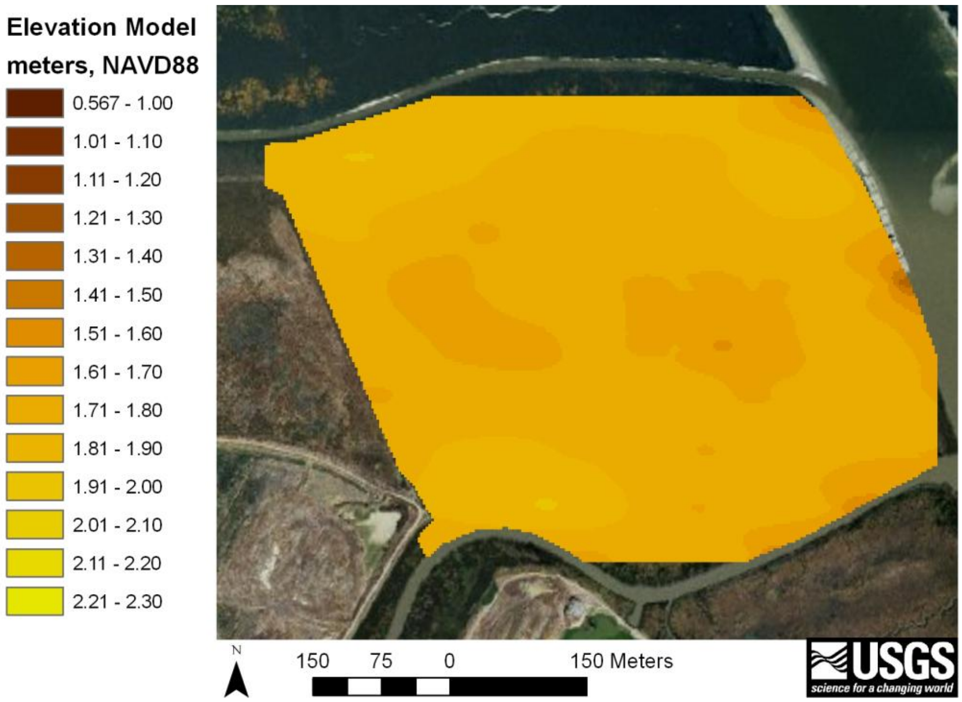

Figure B-3. Elevation model (3-m resolution), developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error.

Vegetation surveys

Vegetation surveys were conducted concurrently with elevation surveys in June 2010. A total of 108 locations (Fig. B-1) were measured for vegetation composition, height (cm), and percent cover (Table B-1). We did not distinguish between *Spartina* spp. or *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. B-4) was observed within this low slope marsh.

Table B-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Black John.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Salicornia pacifica	0.02	0.12	37.59	11.65	51.46	14.62	73.22	30.60	282	91.56
Spartina spp.	-0.29	0.03	47.50	3.54	50.00	7.07	13.00	16.97	2	0.65
Schoenoplectus spp.	0.02	0.10	64.66	17.01	82.18	23.42	13.10	15.46	125	40.58
Grindelia stricta	0.09	0.13	68.09	21.71	83.26	28.38	41.05	25.88	58	18.83
Jaumea carnosa	0.13	-	15.00	-	20.00	-	25.00	-	1	0.32
Frankenia salina	0.16	0.31	27.58	8.81	35.00	11.48	45.42	38.82	12	3.90
Distichlis spicata	0.13	0.24	25.83	9.17	33.47	9.07	38.36	28.66	66	21.43
Lepidium latifolium	0.38	0.34	92.00	21.63	113.38	19.60	35.75	27.76	8	2.60
Atriplex triangularis	0.01	0.05	13.33	7.64	15.00	13.23	8.67	7.09	3	0.97
Baccharis pilurais	0.19	0.34	60.00	22.32	91.67	33.02	28.22	28.85	27	8.77

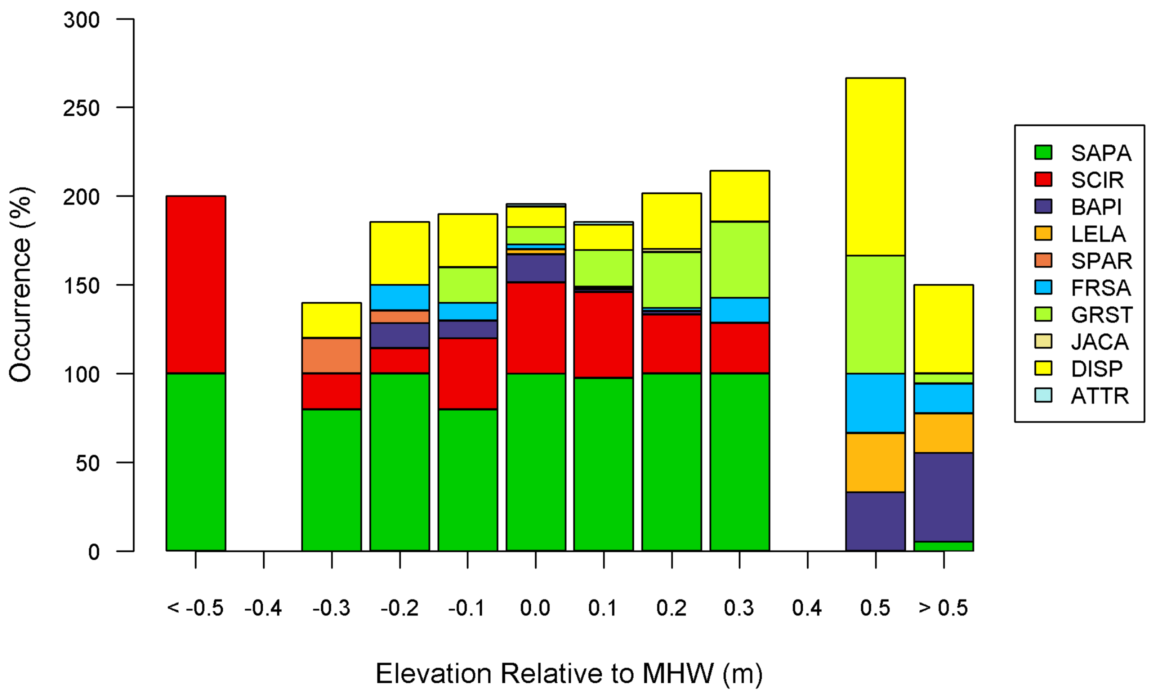

Figure B-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus* spp.*;* BAPI = *Baccharis pilurais*; LELA: = *Lepidium latifolium*; SPAR = *Spartina* spp*;* FRSA = Frankenia salina; GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata;* ATTR = Atriplex triangularis

Water level monitoring

Site-specific water level was measured from December 2009 – May 2010. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. We found mean high water (MHW) was 1.73 m, and mean higher high water (MHHW) was 1.91 m for the site (NAVD88). The salt marsh platform (defined as mean marsh elevation) was inundated most often in January 2010 and February 2010 (Fig. B-5). Those months recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in

January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform. Mean salinity during 2010 at Black John was 15.3 (SD = 6.6) PSS.

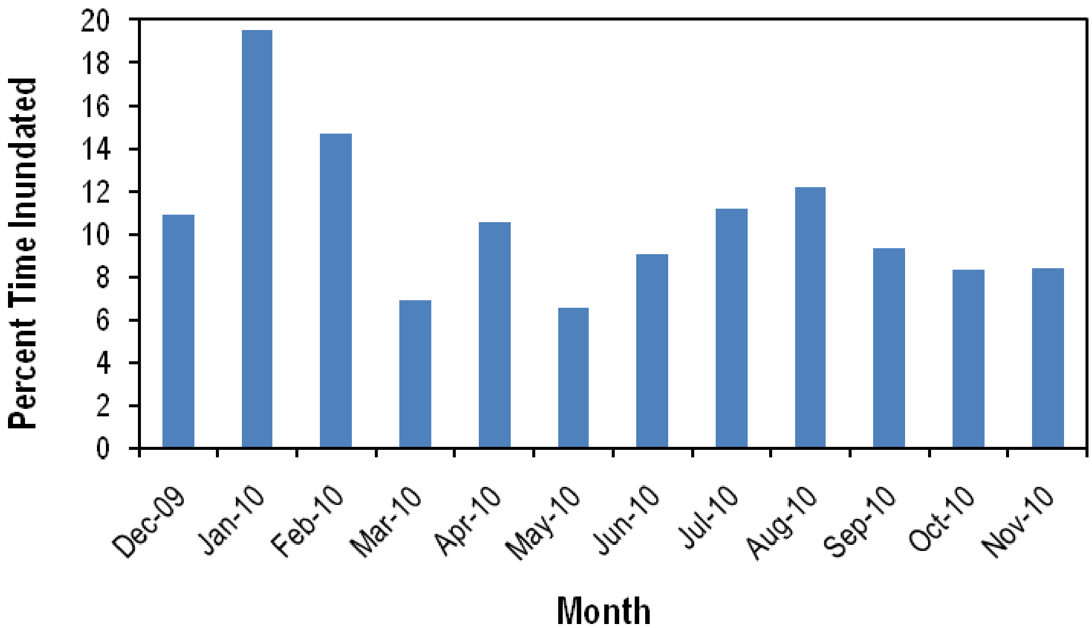

Figure B-5. Percent of time Black John was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

The WARMER scenario indicated that Black John will not keep pace with sea level rise (SLR) through this century. WARMER results showed a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060 (Fig B-6). By 2080 the marsh is projected to be below mean sea level and transition to mudflat (Fig. B-7).

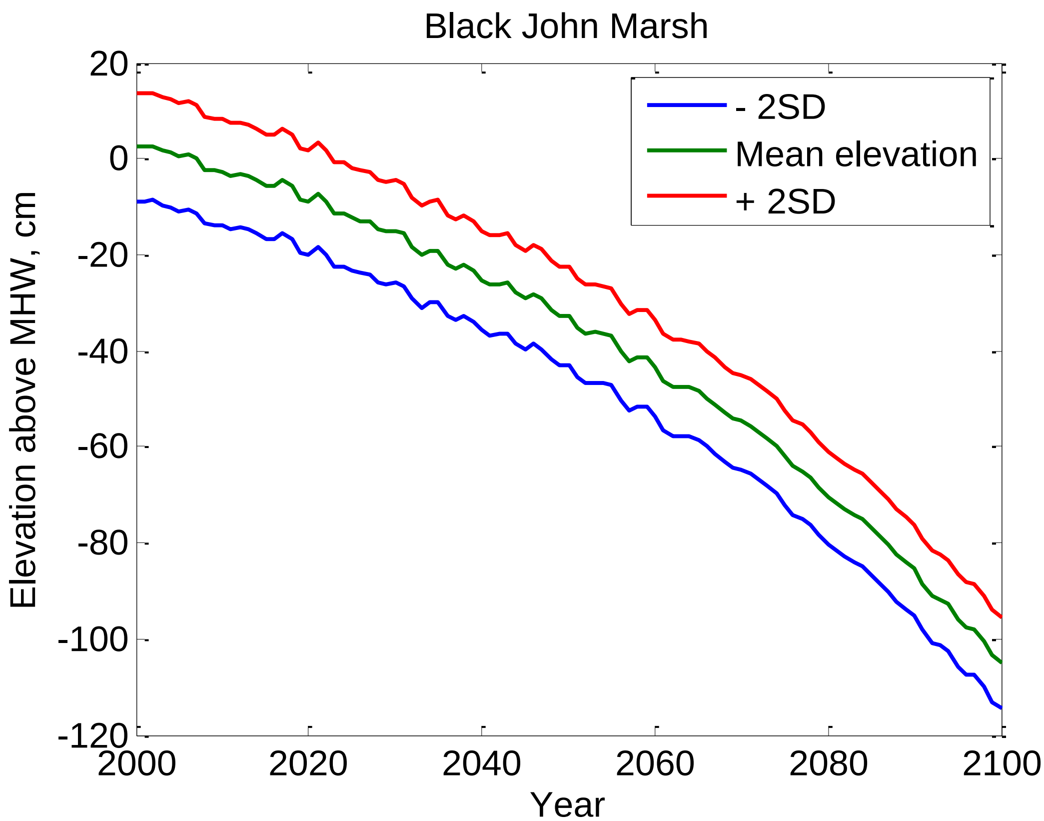

Figure B-6. WARMER scenarios for Black John marsh elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

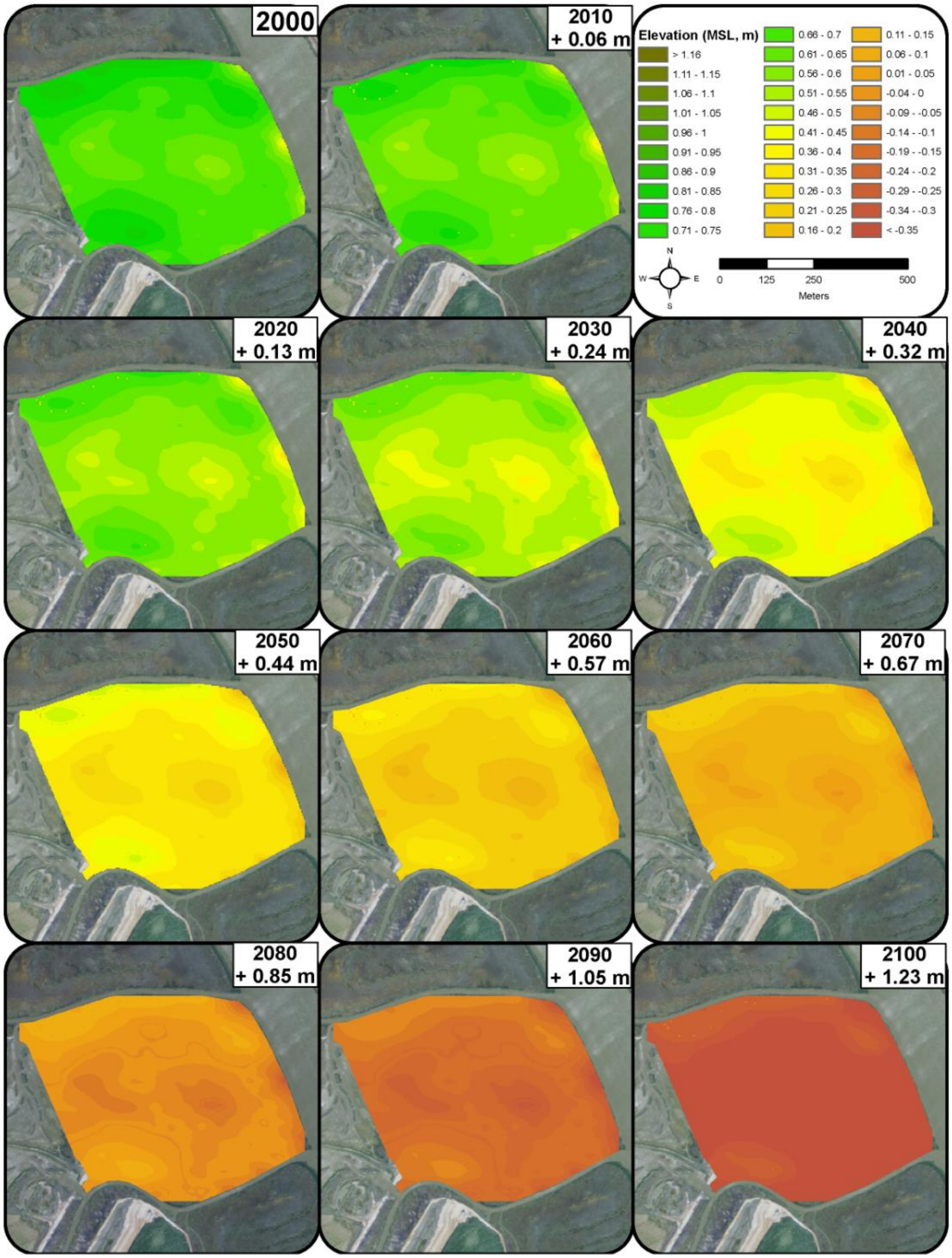

Figure B-7. WARMER results for Black John. WARMER accounts for changes in relative sea level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. B-8 – B-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently, Black John is a mixture of mid and high marsh vegetation. All high marsh vegetation is projected to disappear by 2040 (+ 0.24 m SLR). The largest change is projected to occur around 2040 (+ 0.32 m SLR) at which time the majority of the marsh will transition to low marsh, a habitat zone which currently represents negligible area at Black John. A transition to complete mudflat was projected by 2080 (+ 0.85 m SLR).

The WARMER model parameters for Black John were extrapolated using sediment core data from Petaluma Marsh; thus, predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. In addition, quality control issues with the Petaluma sediment cores resulted in the removal of data that indicated high sedimentation rates. The Petaluma River is a major source of sediment to San Francisco Bay, therefore it is likely that the current inputs to WARMER are underestimating accretion potential at Black John. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentration data to characterize sediment deposition potential.

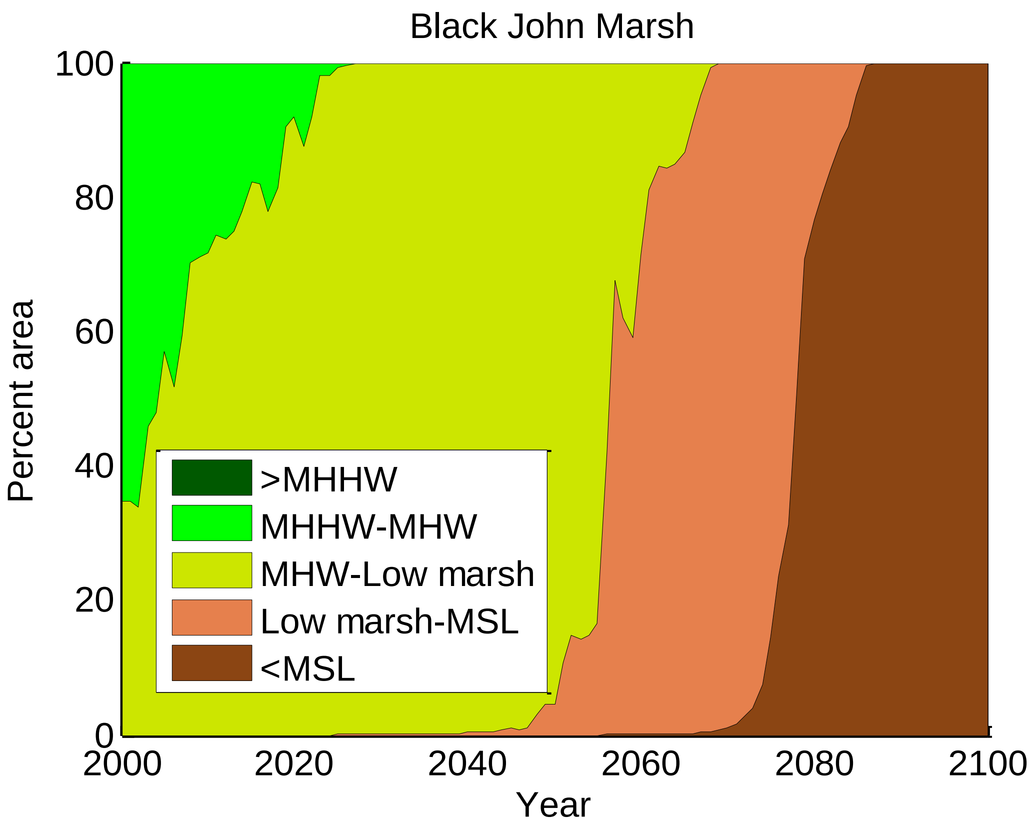

Figure B-8. Area of Black John within a given tidal range for the duration of the simulation period.

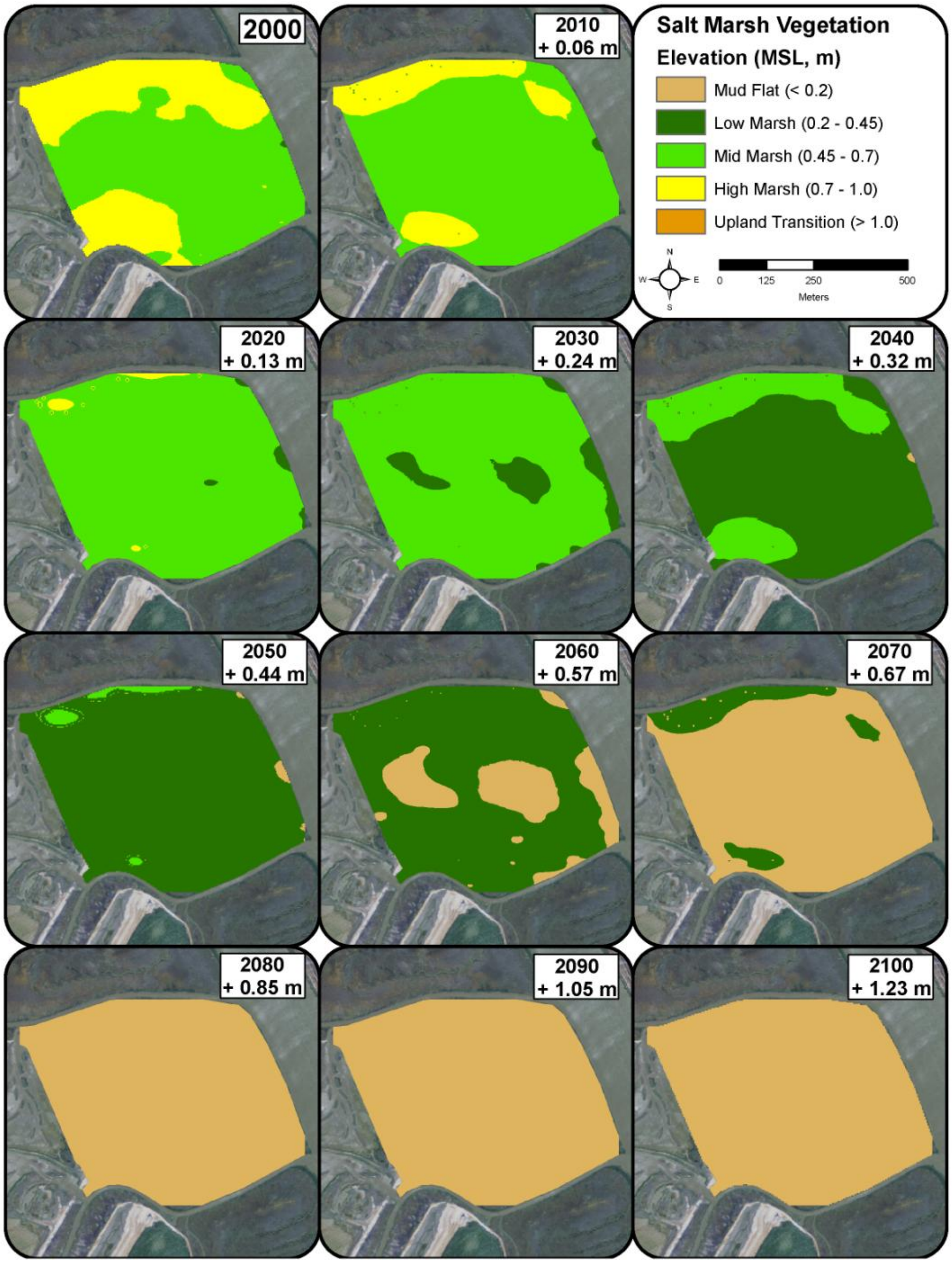

Figure B-9. Black John WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix C

China Camp Marsh

Site Introduction

China Camp State Park (hereafter China Camp) is a 1517 acre park owned and managed by California State Parks. China Camp is located in Marin County and the city of San Rafael. It contains a large expanse of undeveloped historic marsh, with adjacent uplands comprised of oak woodlands. China Camp is part of the NOAA National Estuarine Research Reserve (NERR) network, where it is used as a reference for healthy marsh and a living laboratory for staff and scientists.

China Camp is located adjacent to Gallinas Creek on San Pablo Bay. It is influenced by tidal flow from the San Pablo Bay as well as freshwater flow from Gallinas Creek. China Camp provides habitat for state listed species, such as the California black rail (*Laterallus jamaicensis*) and federally endangered species such as salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsolete).*

This study focused on 96.7 ha of marsh at China Camp. Elevation and vegetation surveys were conducted in 2010 using RTK GPS. To monitor tidal inundation, four water level loggers were deployed in 2010.

Results

Elevation surveys

A total of 753 elevation measurements were taken at China Camp (Fig. C-1). The elevation range was 0.87 - 2.28 m with a mean of 1.79 m (NAVD88). Over half (58%) of the survey points were within 1.75 m - 1.85 m, with a 0.1 m range (Fig. C-2). China Camp was a relatively high marsh with the majority (67%) of survey points located at elevations above mean high water (MHW). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA), Spatial Analyst using the Kriging method (Fig. C-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

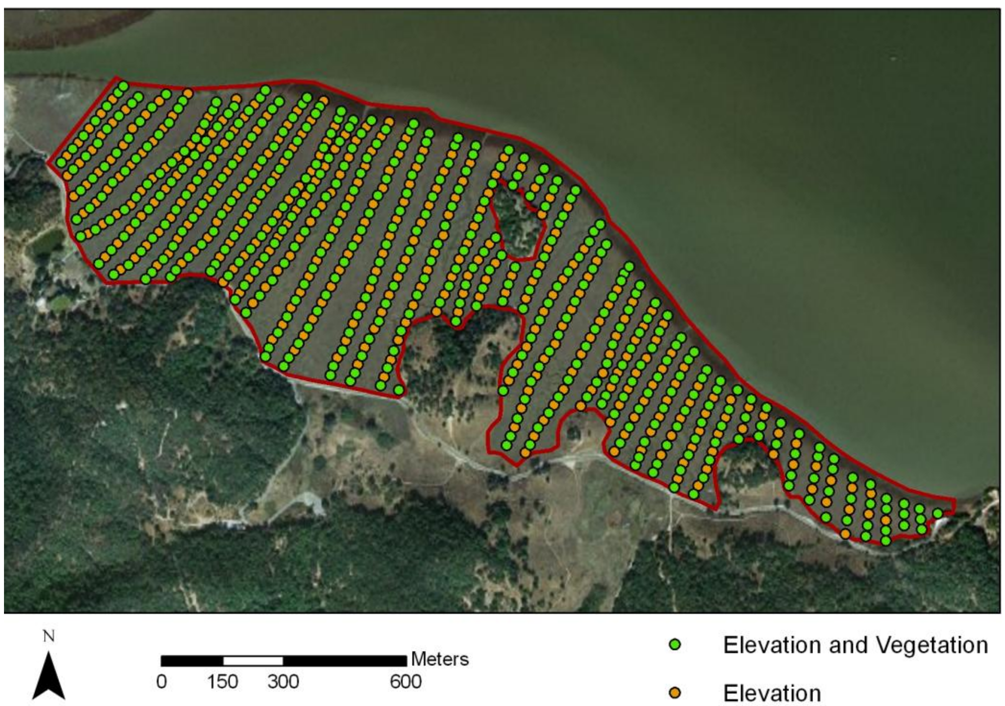

Figure C-1. China Camp with elevation and vegetation survey points taken in 2010

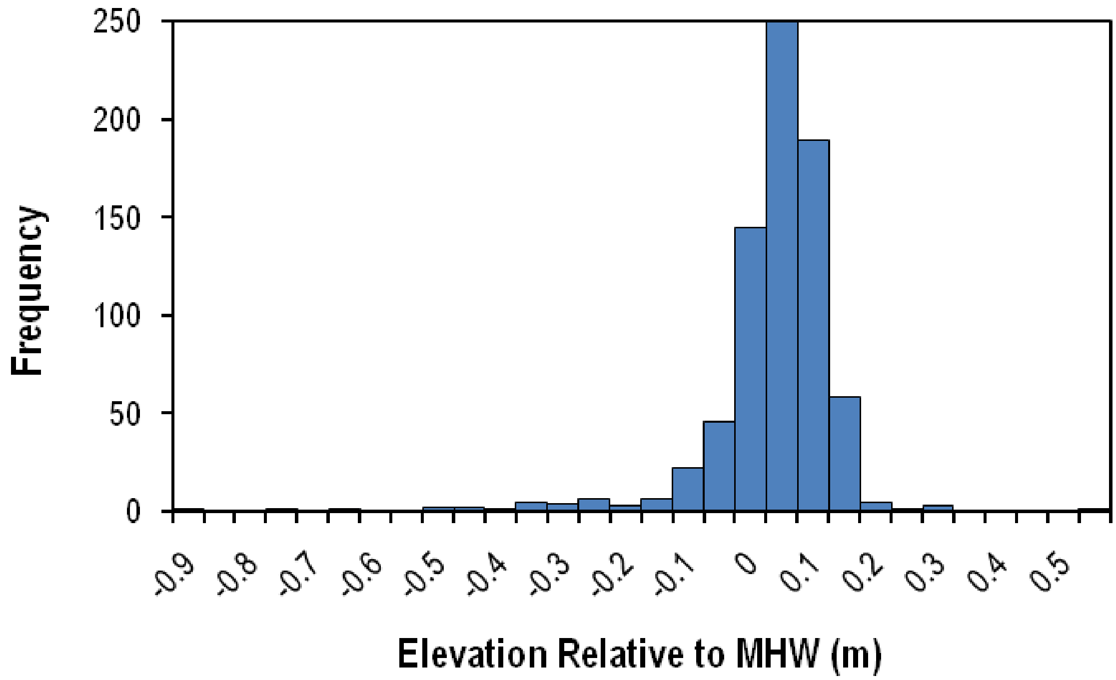

Figure C-2. Distribution of elevation samples relative to local mean high water (MHW) at China Camp.

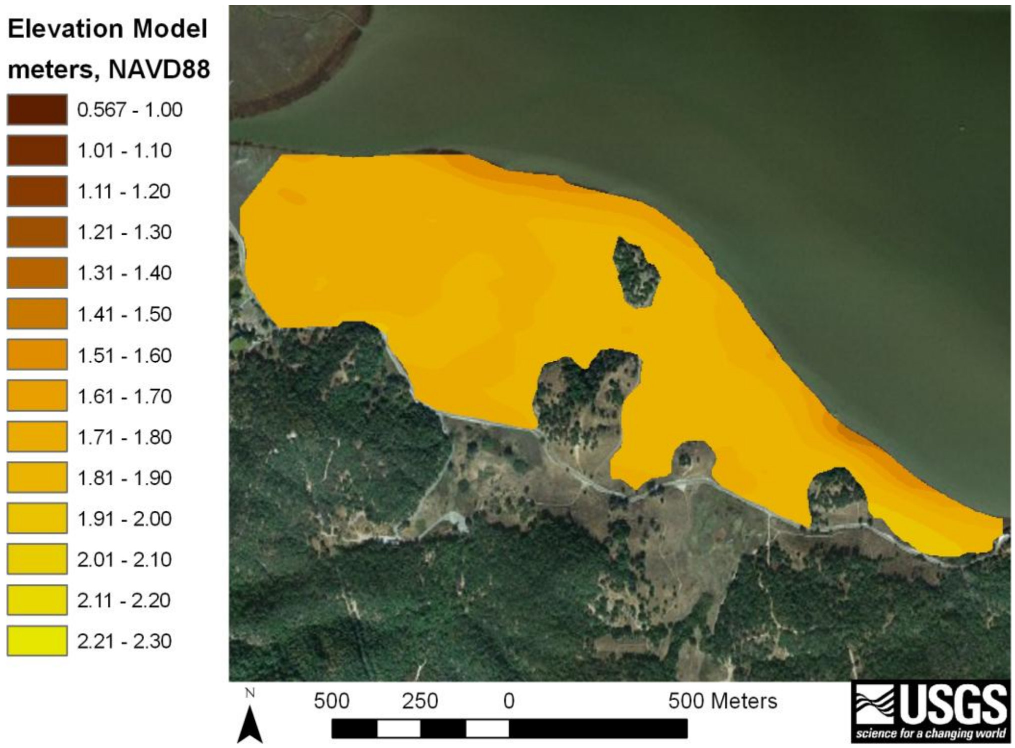

Figure C-3. ArcGIS elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed at China Camp concurrently with elevation in February - March of 2010. A total of 423 locations (Fig. C-1) were measured for vegetation composition, height (cm), and percent cover (Table C-1). We did not distinguish between invasive and native *Spartina* or *Schoenoplectus* in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. C-4) was observed within this low slope marsh.

Table C-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at China Camp.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.01	0.10	29.72	8.78	41.76	10.30	81.45	24.51	408	96.68
Spartina spp.	-0.46	0.21	34.25	13.92	44.08	15.51	12.75	11.33	12	2.84
Schoenoplectus spp.	-0.13	0.16	18.00	21.01	23.00	27.23	16.29	25.84	7	1.66
Grindelia stricta	0.06	0.10	62.03	22.07	66.10	24.87	26.45	20.41	29	6.87
Jaumea carnosa	0.01	0.06	12.76	3.36	16.88	4.32	19.82	26.24	34	8.06
Frankenia salina	0.09	0.04	19.50	5.36	24.33	5.85	24.33	30.64	6	1.42
Distichlis spicata	0.03	0.10	17.85	8.65	22.91	9.40	19.00	26.51	54	12.80
Lepidium latifolium	0.11	0.08	20.40	22.43	24.40	23.29	12.20	11.95	5	1.18

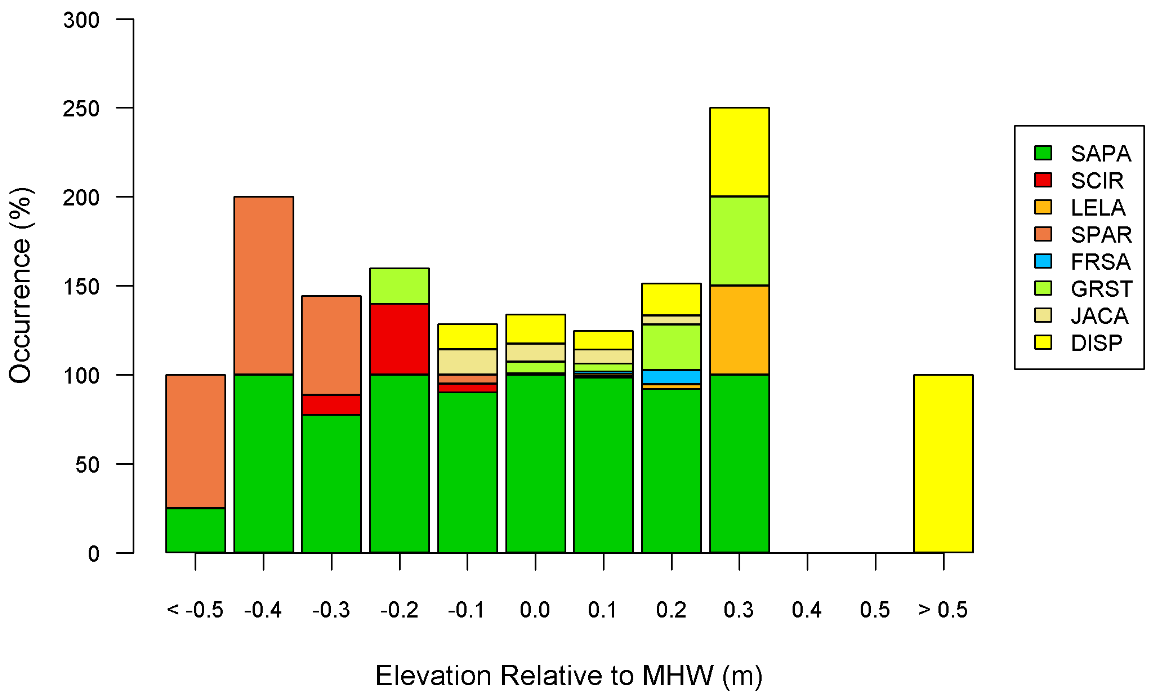

Figure C-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Salicornia pacifica*; SCIR = *Schoenoplectus* spp.; LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.; FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Water level monitoring

Site specific water level was monitored at China Camp for one year, from February 2010 to January 2011. Water level was measured using two data loggers deployed in second order channels. We found MHW was 1.77 m, and mean higher high water (MHHW) was 1.95 m for the site (NAVD88). The marsh platform (defined as mean marsh elevation) was inundated most often in February 2010 (Fig. C-5). We believe these long periods of inundation where the result of above average cumulative rainfall in January 2010 throughout the San Francisco bay area (NOAA).

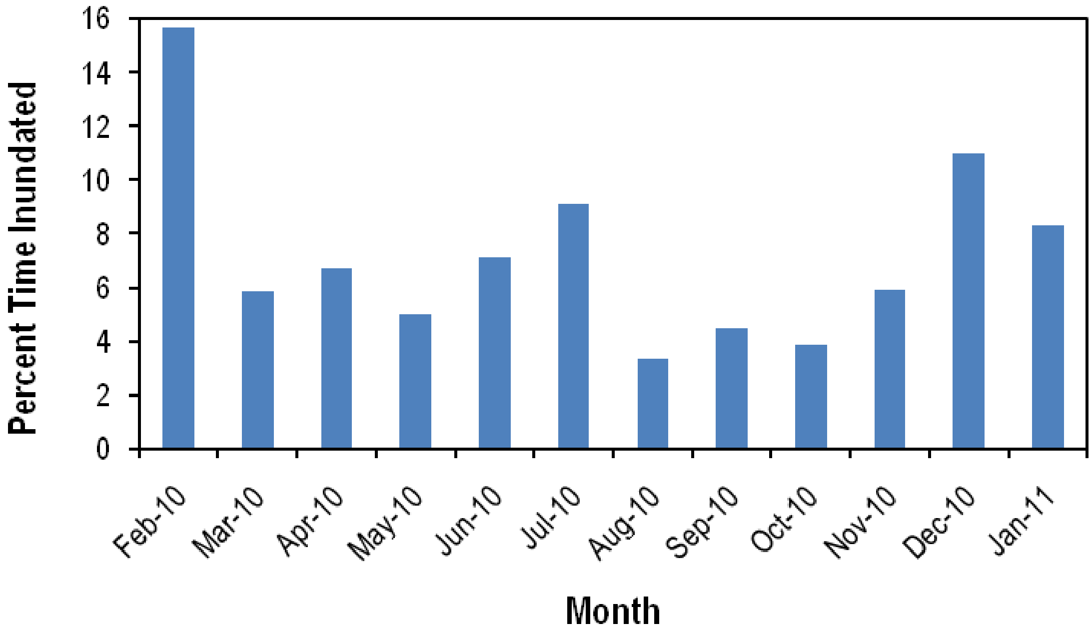

Figure C-5. Percent of time China Camp was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

China Camp SLR response modeling showed that the marsh was able to maintain its elevations through 2030, unlike lower elevation marshes around SFB. However, WARMER projections showed a gradual reduction in elevation relative to MHW over time after 2030, with a more dramatic decline after 2060 (Fig C-6). By 2080 the marsh is projected to be under mean sea level (MSL), and transition to a mudflat (Fig. C-7). Despite its relatively high elevation, WARMER results indicate that China Camp will not keep pace with local SLR through this century.

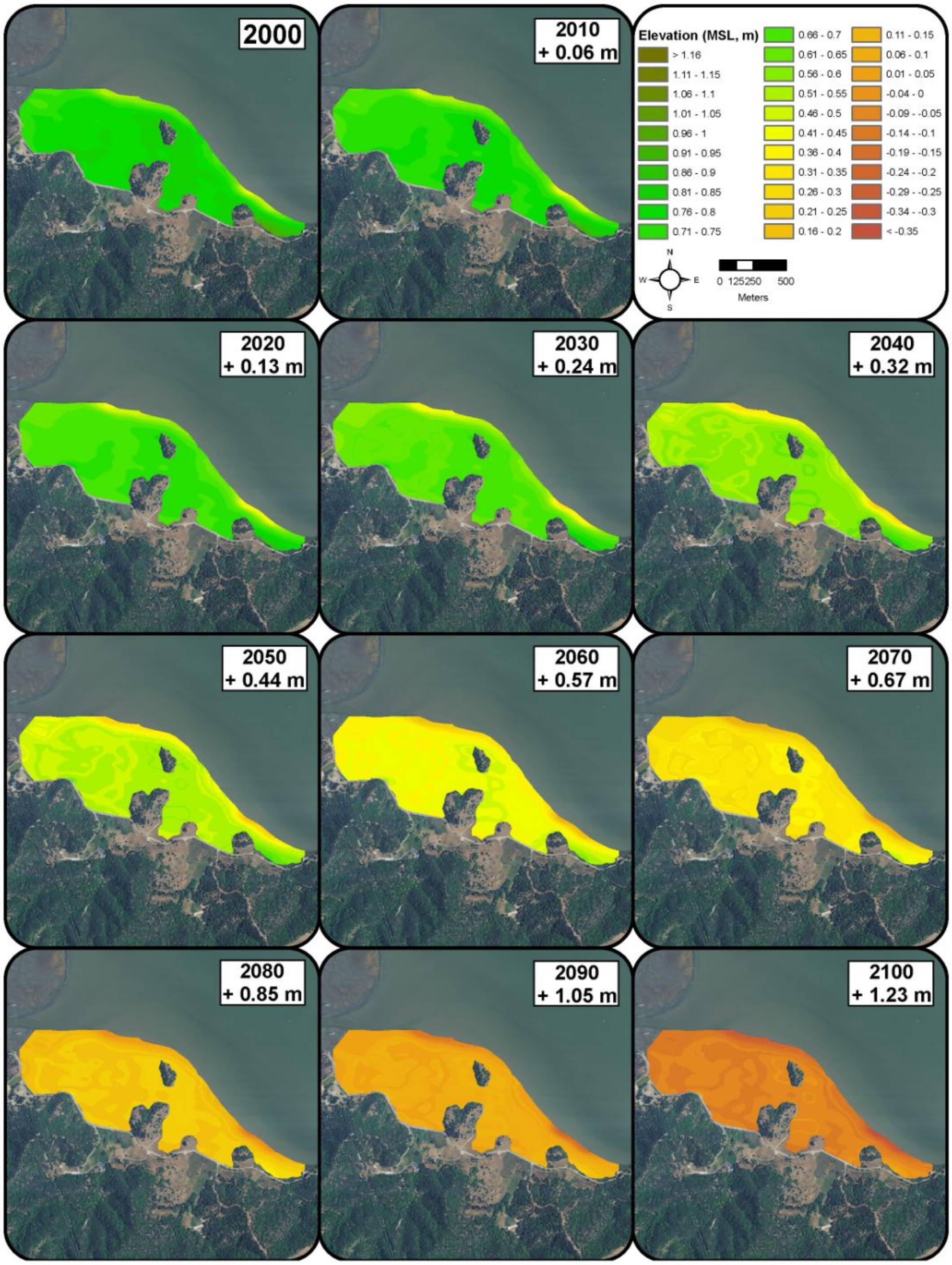

Figure C-6. WARMER results for China Camp. WARMER accounts for changes in relative sea-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

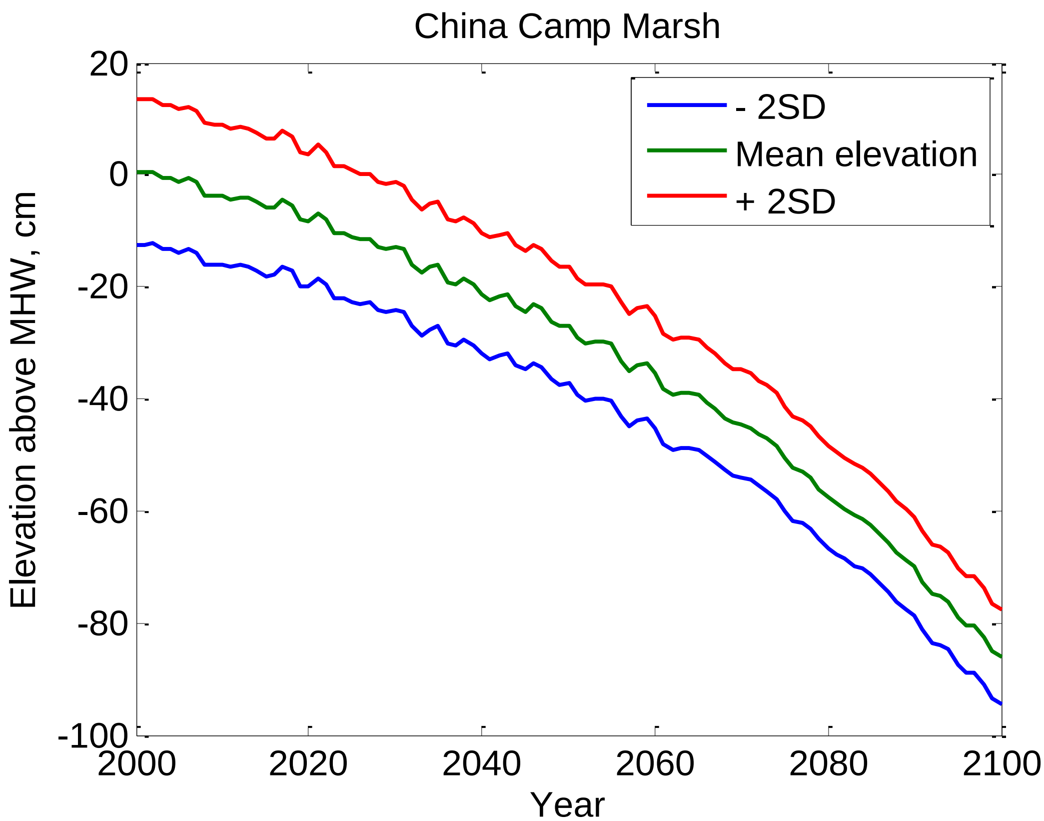

Figure C-7. Modeled WARMER scenarios of marsh elevation change at China Camp. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. C-8, C-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. China Camp is dominated by mid and high marsh plant communities dominated by *Sarcocornia pacifica*, primarily with low marsh vegetation adjacent to the bay. China Camp elevations are between high and mid marsh plant community classifications (Table 4). Therefore, WARMER shows a brief expansion of high marsh habitat in 2020 (+ 0.13 m SLR) which is an artifact of the classification bins based on all vegetation observed in SFBE. Plant communities then return to relatively the same distribution projected in 2000 between 2030 (+ 0.13 m SLR) and 2050 (+ 0.44 m SLR). However, by 2060 (+ 0.57 SLR) most of the marsh will transition to low marsh plant communities. By 2090 (+ 1.05 m SLR) the marsh is projected to transition completely to mudflat.

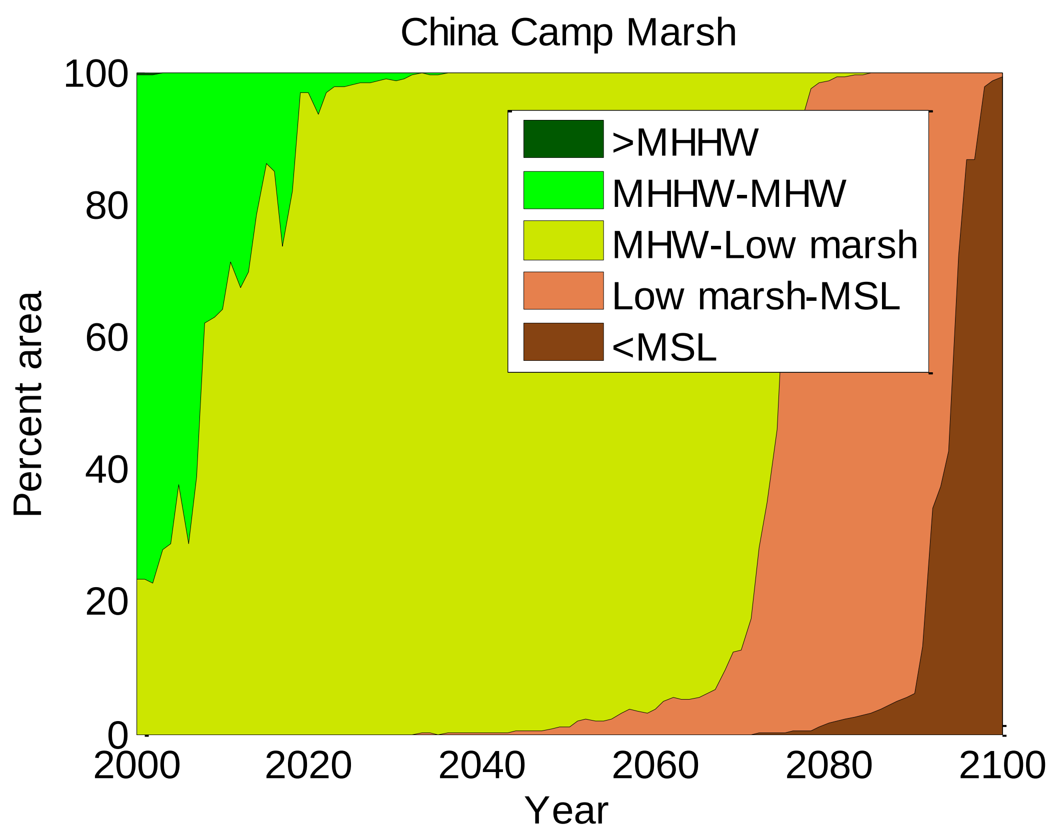

Figure C-8. Area of China Camp within a given tidal range for the duration of the simulation period.

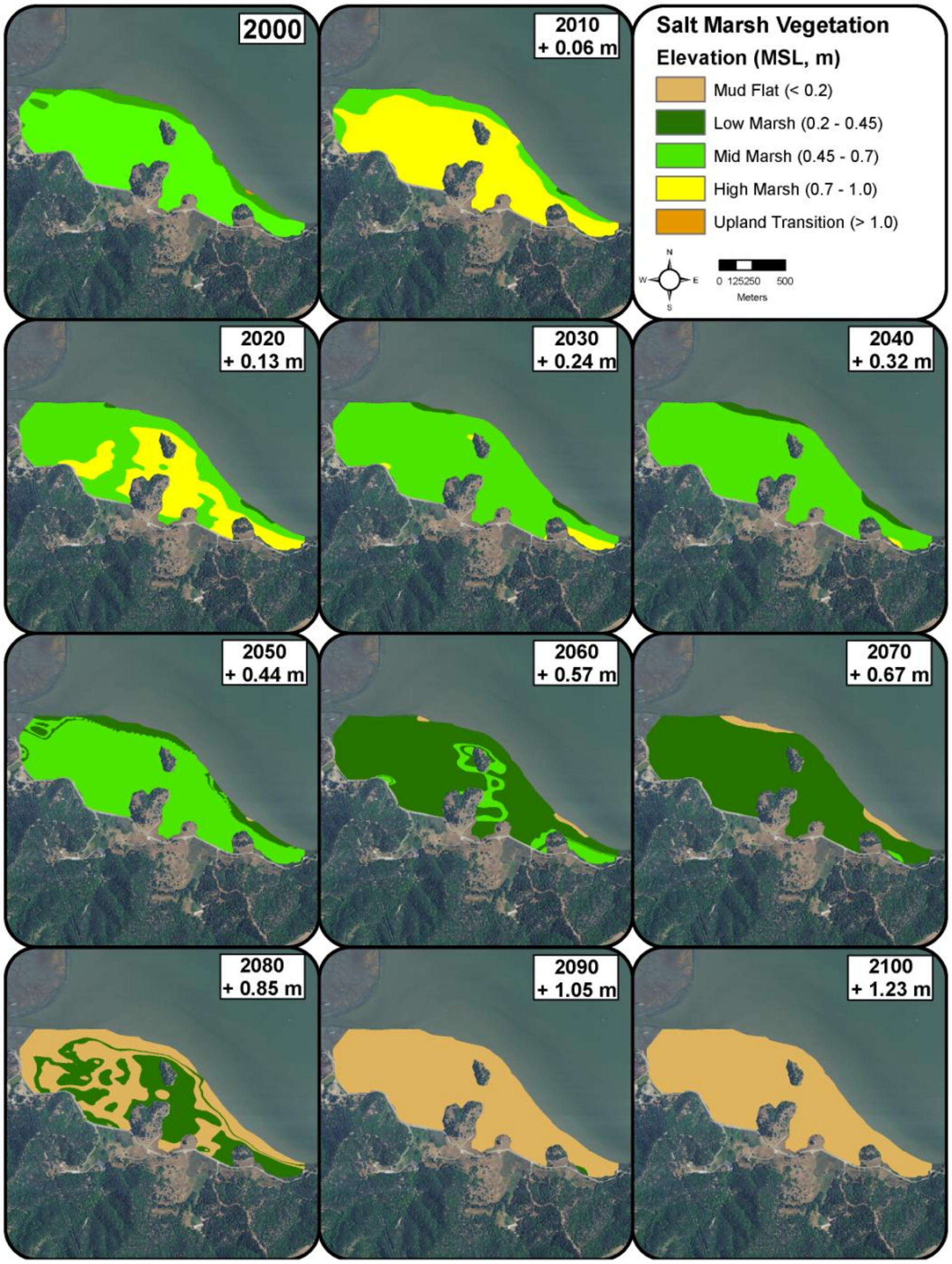

Figure C-9. China Camp WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix D

Cogswell Marsh

Introduction

Cogswell marsh (hereafter Cogswell) is located in Alameda County within the city of Hayward along the eastern shore of south San Francisco Bay. It is located along the Hayward Regional Shoreline and is part of a 250 ha tidal salt marsh restoration and enhancement project that was completed in 1980. It is currently managed by East Bay Regional Park as part of the Hayward Regional Shoreline. This marsh provides habitat for many migratory and marsh species including the federally endangered California clapper rail (*Rallus longirostris obsoletus*).

This study focused on 60.3 ha of Cogswell. Elevation and vegetation surveys were done in 2008 and 2009 using an RTK GPS. To monitor tidal inundation, one water level logger was deployed in 2009 - 2010.

Results

Elevation surveys

A total of 523 elevation measurements were taken at Cogswell (Fig. D-1). The elevation range is 1.66 - 2.71 m with a mean of 1.83 m (NAVD88). Half of the survey points were within 1.75 - 1.90 m, with a 0.15 m range. The majority (64%) of survey points were located at elevations above mean high water (MHW) (Fig. D-2). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. D-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

Figure D-1. Cogswell Marsh with elevation and vegetation survey points taken in 2008 - 2009.

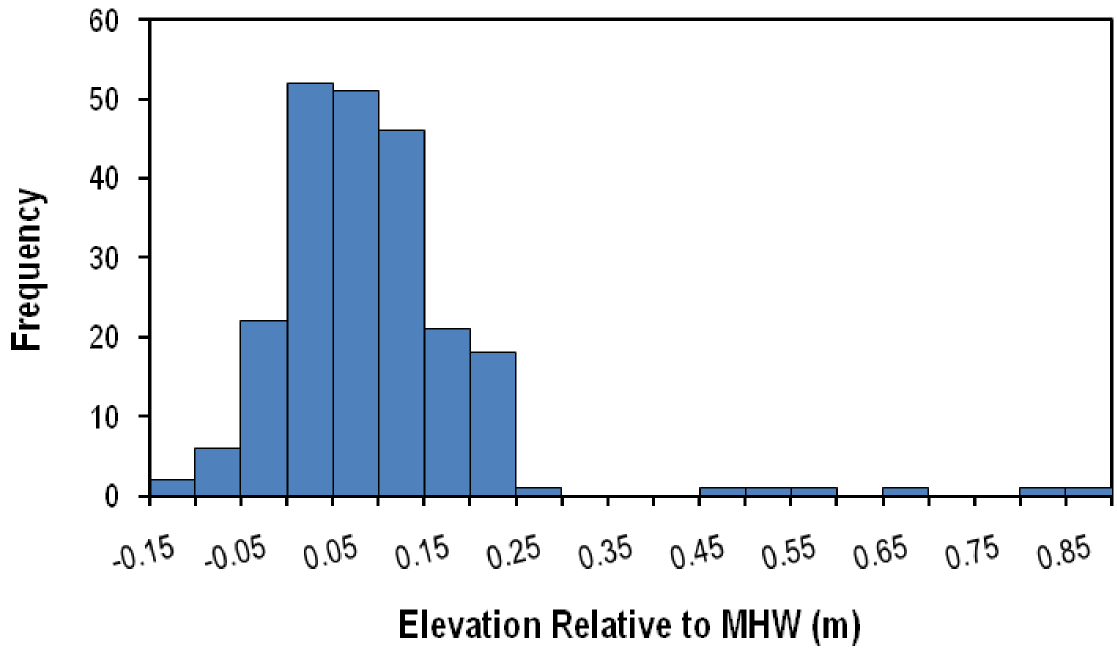

Figure D-2. Distribution of elevation samples relative to local mean high water (MHW) at Cogswell Marsh.

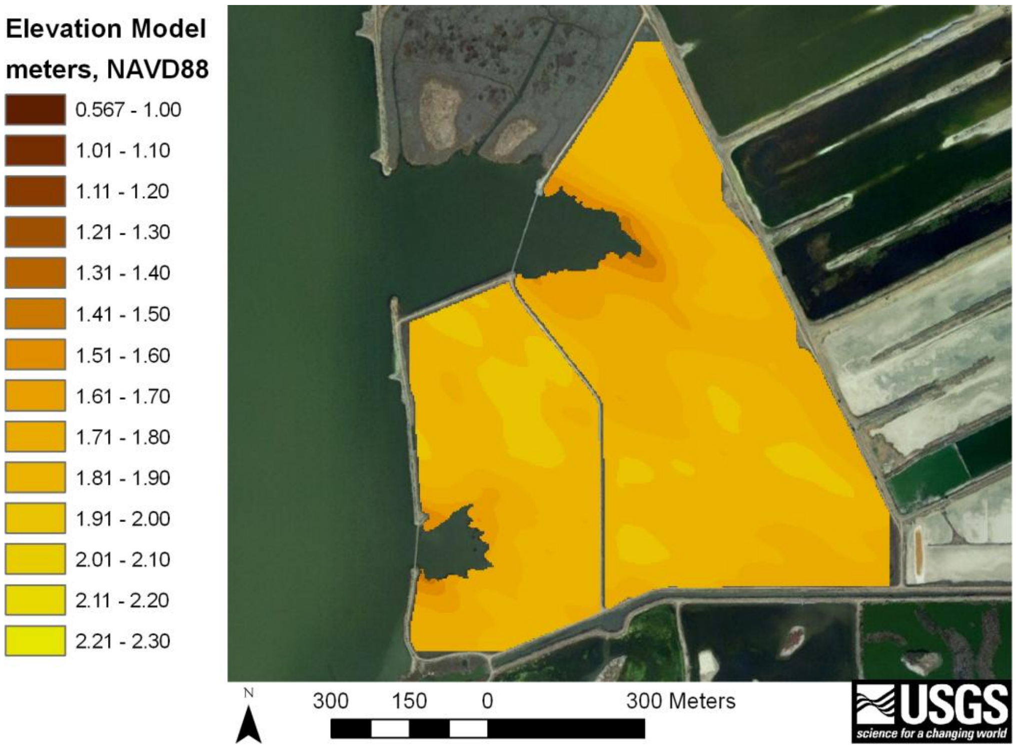

Figure D-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation surveys were conducted concurrently with elevation surveys in April and May of 2008 and 2009. A total of 228 locations (Fig. D-1) were measured for vegetation composition, height (cm), and percent cover (Table D-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. D-4) was observed within this low slope marsh.

Table D-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Cogswell.

Species	*Elevation (MHW, m)*	*Elevation SD (MHW, m)*	*Avg. Height (cm)*	*Avg. Height SD (cm)*	*Max Height (cm)*	*Max Height SD (cm)*	*% Cover*	*% Cover SD*	*n*	*% Presence*
Sarcocornia pacifica	0.05	0.13	30.79	7.84	37.82	10.05	90.39	22.84	211	94.20
Spartina spp.	0.03	0.08	57.19	14.45	69.50	16.78	17.94	12.59	21	9.20

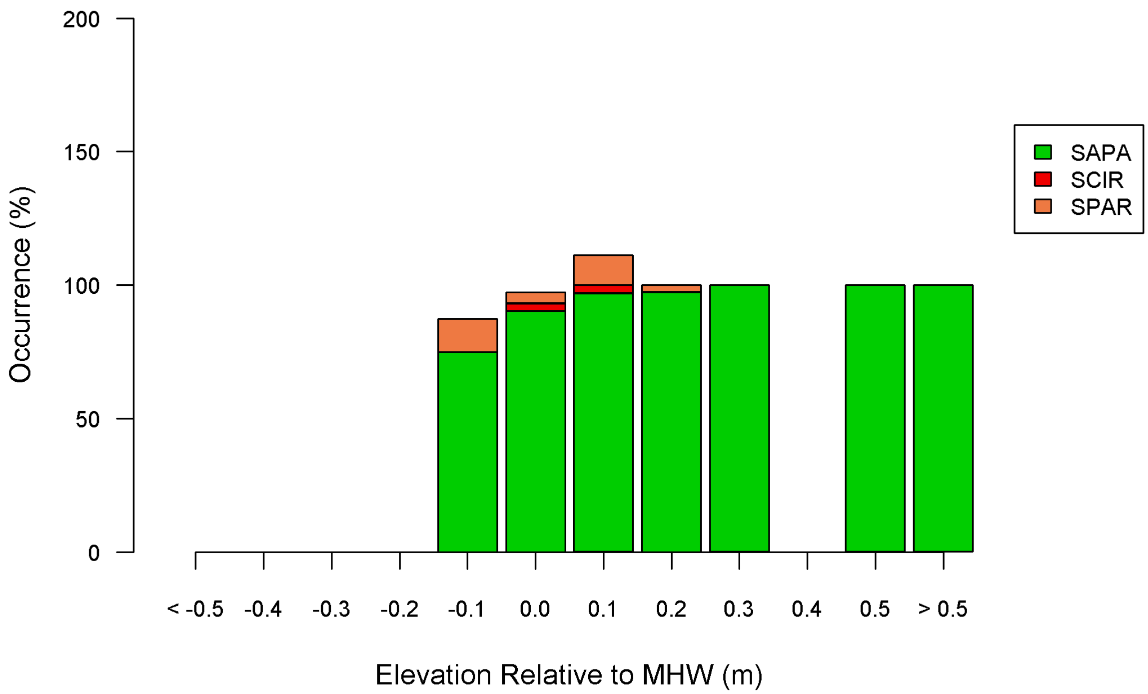

Figure D-4. Stratification of vegetation species was observed relative to MHW Species codes: SAPA = *Sarcocornia pacifica;* SPAR = *Spartina* spp.; and SCIR = *Schoenoplectus* spp.

Water level monitoring

Site-specific water level was monitored at Cogswell from December 2009 to November 2010. Water level was measured using one data logger deployed at the mouth of a second order channel. We found that MHW was at 1.86 m and mean higher high water (MHHW) at 1.98 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean elevation) was inundated most often from December 2009 through February 2010 (Fig. D-5). January and February 2010 recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform.

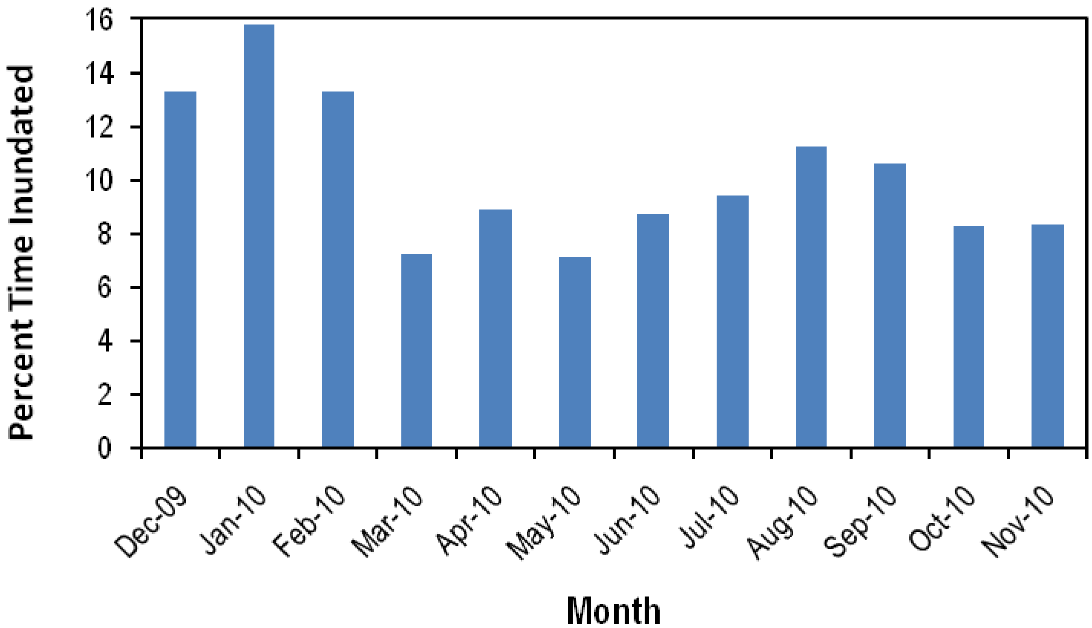

Figure D-5. Percent of time Cogswell was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER results show a gradual reduction in elevation relative to MHW throughout the century with a more dramatic decline after 2060 (Fig D-6). By 2100 the marsh is projected to be below MHW (Fig. D-7). Sites which had higher starting elevations (thus located higher in the tidal range), such as Cogswell, also had higher accretion rates and were less susceptible to SLR.

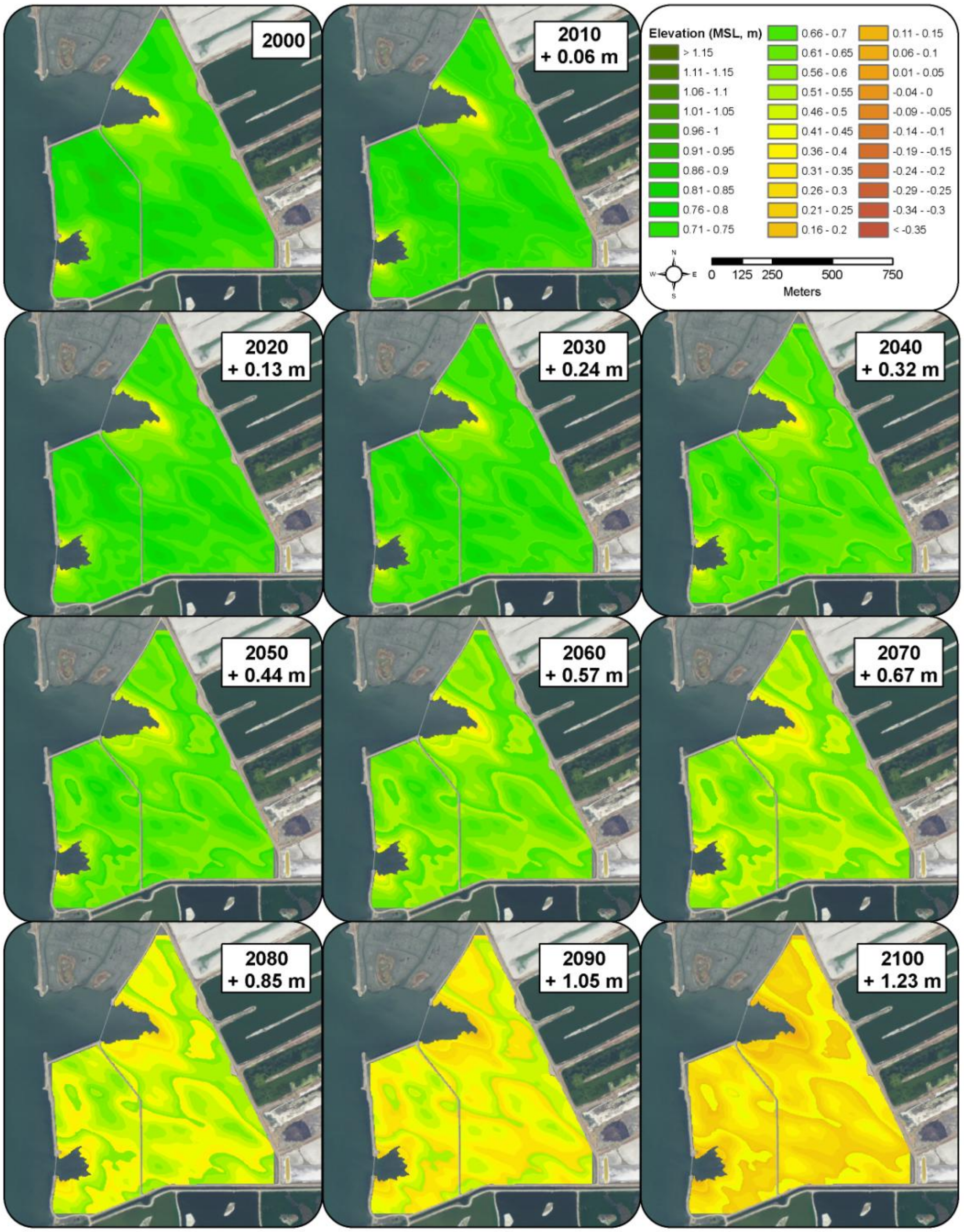

Figure D-6. WARMER results for Cogswell. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

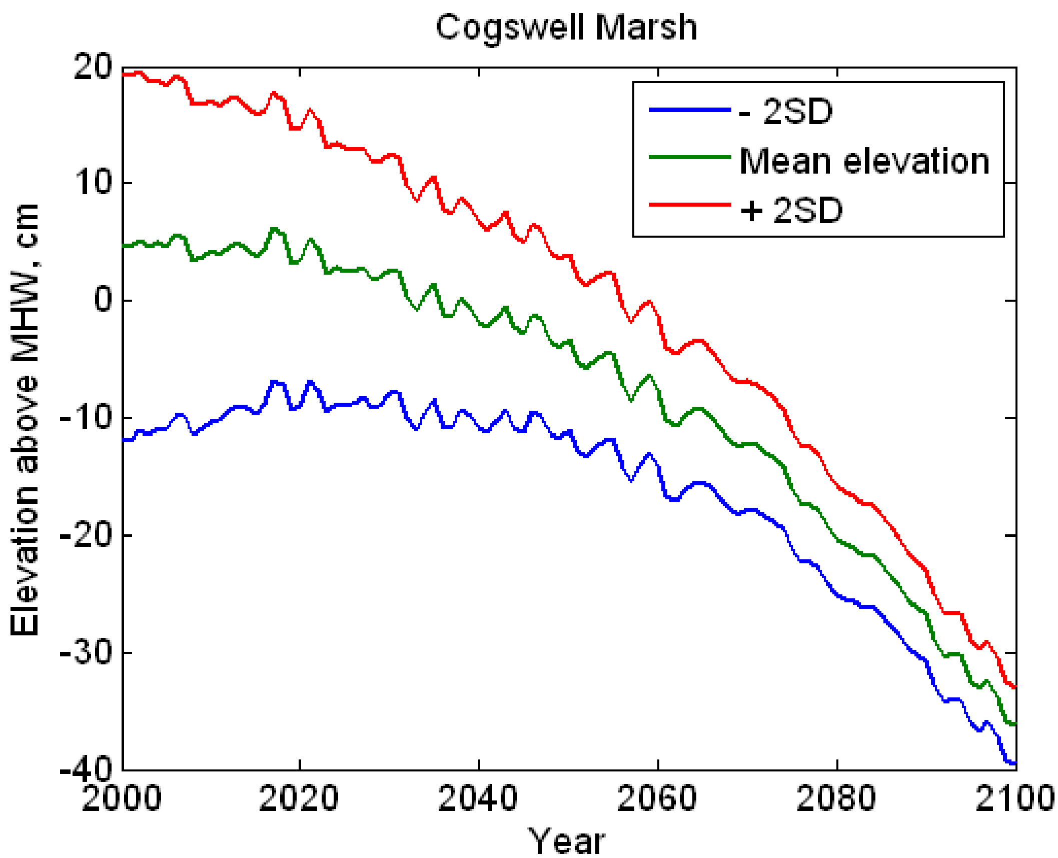

Figure D-7. WARMER scenarios of marsh elevation change for Cogswell. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. D-8 – D-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina spp.* Currently vegetation at Cogswell is predominantly high and mid marsh vegetation. High accretion rates, due in part to high suspended sediment concentrations in South San Francisco Bay, helped maintain the mid marsh habitat at Cogswell through 2070 (+ 0.67 m SLR). Once the rate of sea-level rise increases in the second half of the century, Cogswell is projected to begin decreasing in relative elevation and transition to low marsh habitat by 2100 (+ 1.23 m SLR). Unlike most marshes within this project, Cogswell would not transition to a mudflat by 2100.

The WARMER model parameters for Cogswell were extrapolated using sediment core data near Laumeister marsh; thus, predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentrations, to characterize sediment deposition potential.

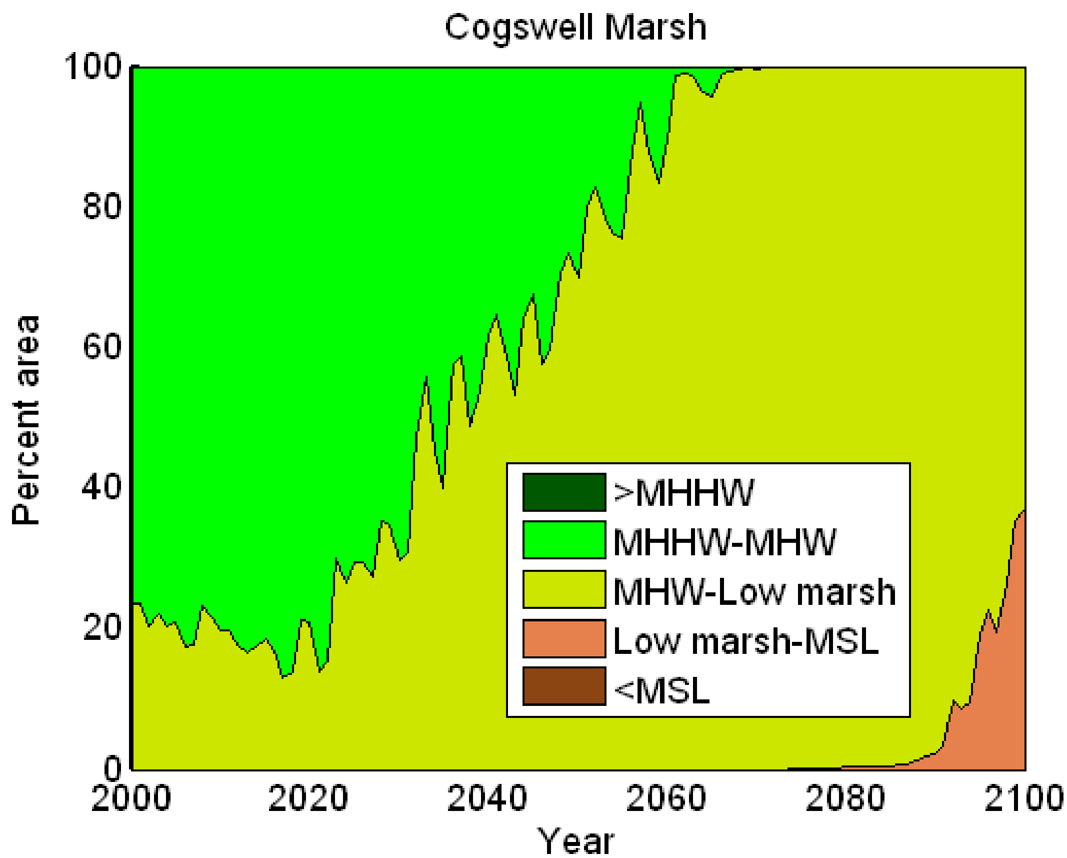

Figure D-8. Area of Cogswell within a given tidal range for the duration of the simulation period.

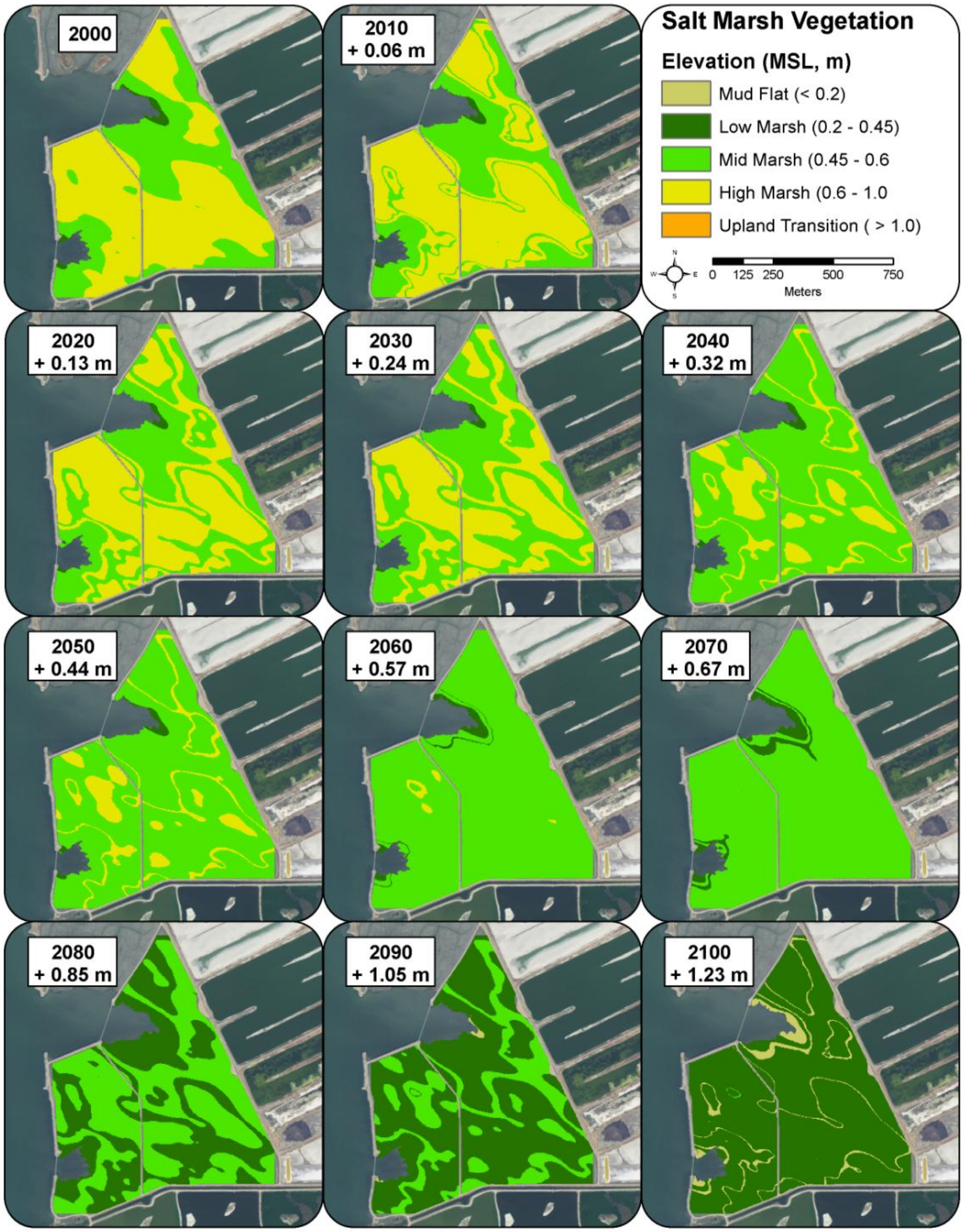

Figure D-9. Cogswell WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix E

Colma Marsh

Introduction

Colma Creek Public Shore contains Colma marsh (hereafter Colma) and is located in south San Francisco Bay just north of San Francisco International Airport. It is fed by Colma Creek which has its headwaters at San Bruno Mountain. Colma is owned and maintained by the Port of San Francisco in San Mateo County. Colma provides important habitat for migratory shorebirds and the federally-endangered California clapper rail (*Rallus longirostris obsoletus*).

This study focused on 24.6 ha of marsh. Beginning In 2006, a herbicide treatment was applied to the marsh in an attempt to control the invasive *Spartina densiflora* and the *S. densiflora* x *S. foliosa* hybrid. As a result of this treatment vegetation at Colma was extremely sparse, therefore vegetation surveys were not conducted. Elevation surveys were done in 2010 using an RTK GPS and to monitor tidal inundation a water level logger was deployed in 2010.

Results

Elevation surveys

A total of 537 elevation measurements were taken at Colma (Fig. E-1). The elevation range was 0.38 - 2.31 m with a mean of 1.38 m (NAVD88). Over half (67%) of the survey points fell within 1.01-1.61 m, with a 0.6 m range. Colma was the lowest marsh surveyed in this study with 87% of the elevation points taken located below mean high water (MHW; Fig E-2). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. 3). This baseline elevation model was used as the initial state in the

WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

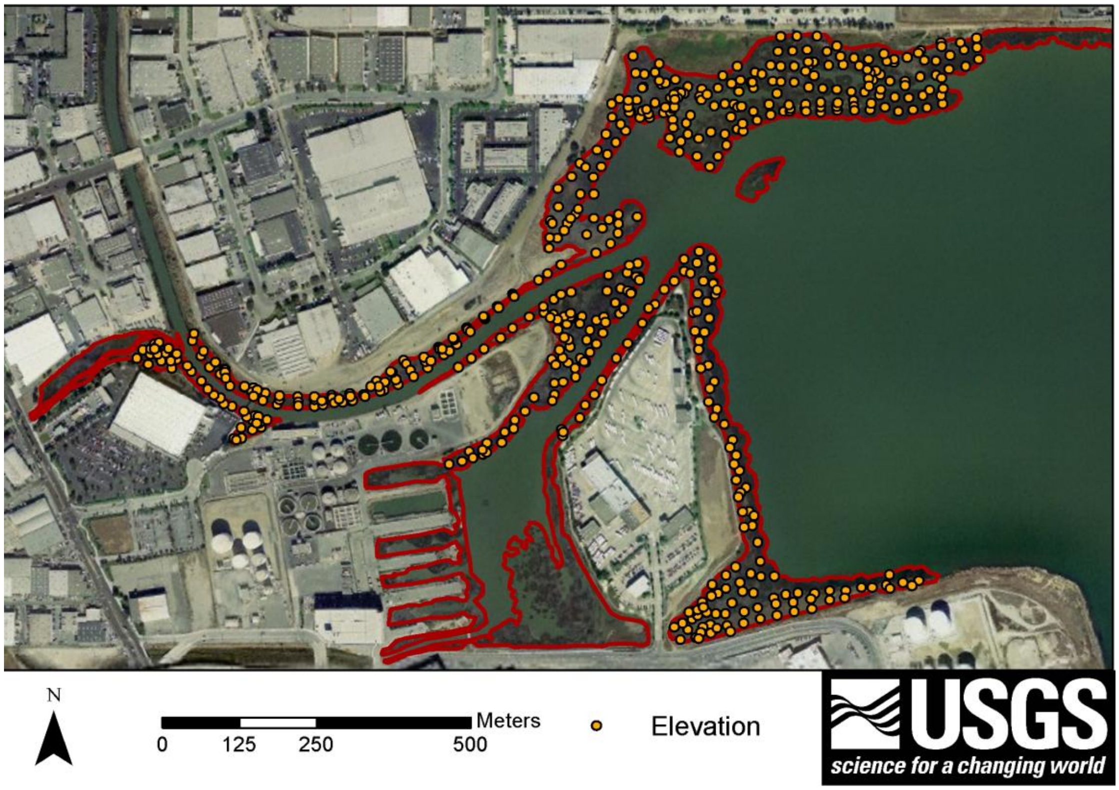

Figure E-1. Colma marsh with elevation survey points taken in 2010.

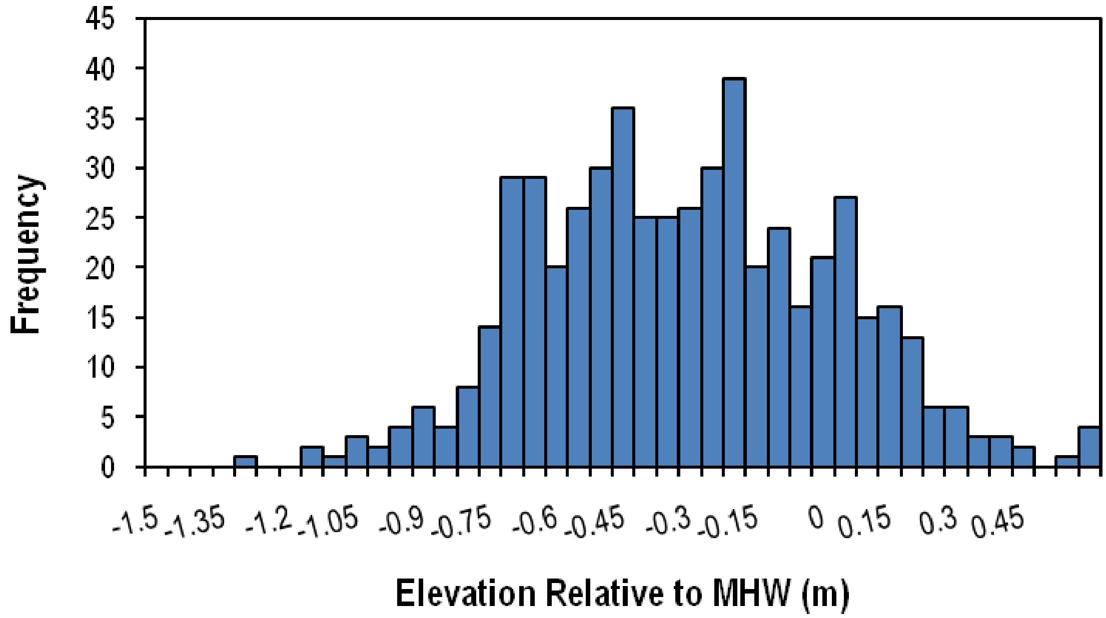

Figure E-2. Distribution of elevation samples relative to local mean high water (MHW) at Colma.

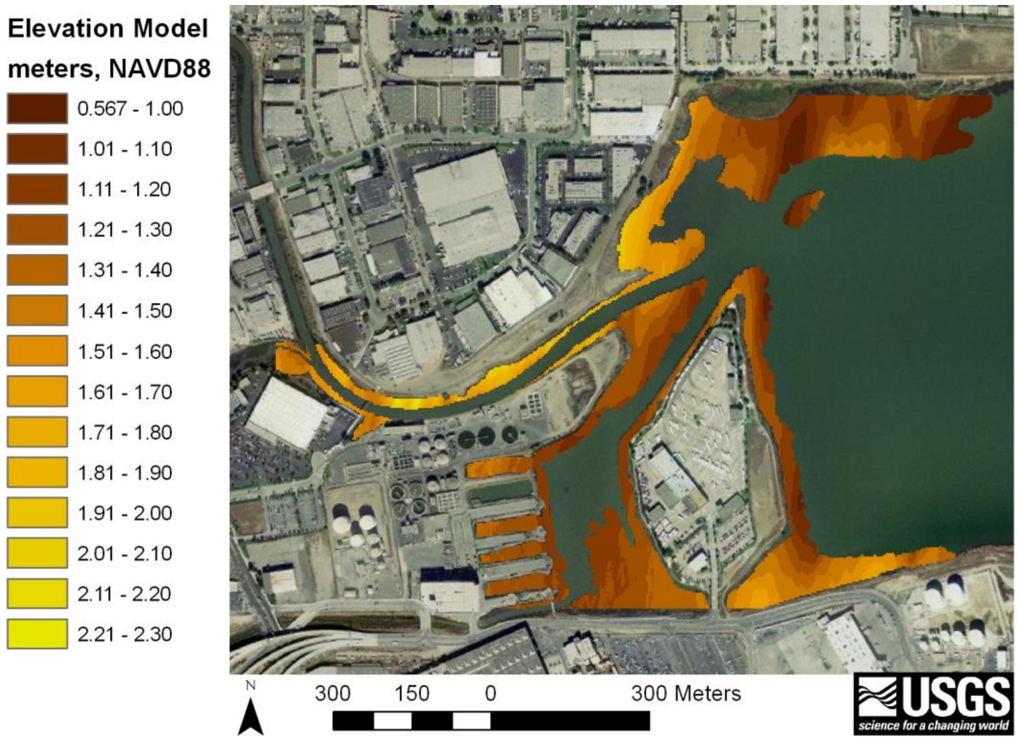

Figure E-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Water level monitoring

Site-specific water level was monitored at Colma in 2010. Water level was measured using one logger deployed in a second order channel. We found MHW at 1.77 m and mean higher high water (MHHW) at 1.97 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean marsh elevation) was inundated most often from January 2010 through February 2010 (Fig. E-5). The loggers recorded above average water levels due to several record-breaking storms that brought low air pressure and substantial rainfall, resulting in higher-than-predicted tides. The cumulative rainfall in January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer than normal periods of the marsh inundation.

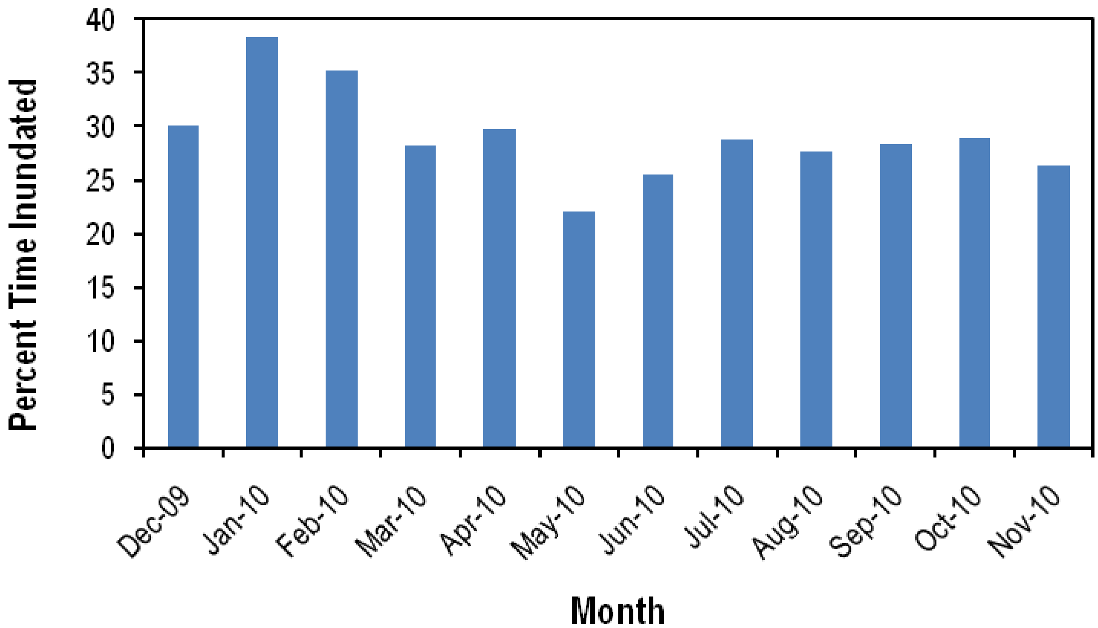

Figure E-5. Percent of time Colma was inundated monthly. Based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER results indicate that Colma will keep pace with local SLR through this century (Fig. E-5 – E-6). Initial elevation is below MHW and is projected to increase slightly to 2060 (+ 0.57 m SLR), and begins to decline (Fig. E-6). Colma does not reach MHW elevations throughout the century. WARMER projects that elevation relative to MSL peaks at ~2050, at which time the SLR curve goes exponential and the marsh begins subsiding (Fig. E-6).

Vegetation data from the other 11 sites were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. D-8 – D-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis* *pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp.

Assuming that high sediment deposition occurs, Colma is projected to transition from a mudflat to mid marsh plant community by 2030 (Figs. E-7 – E-8). By 2100, Colma is projected to be comprised primarily of low marsh. The high suspended sediment concentrations in south San Francisco Bay may allow Colma to maintain its elevation relative to SLR. However, the absence of established vegetation due to the recent herbicide treatment could result in erosion and loss of sediment trapping ability. As a result of the chemical treatment, Colma currently functions as a mudflat.

The WARMER model parameters for Colma were extrapolated using sediment core data near Laumeister marsh, thus predictions should be interpreted with caution as local sedimentation processes are likely very different between these marshes. To improve results, local site-specific sediment core data could be collected, along with suspended sediment concentrations to characterize sediment deposition potential.

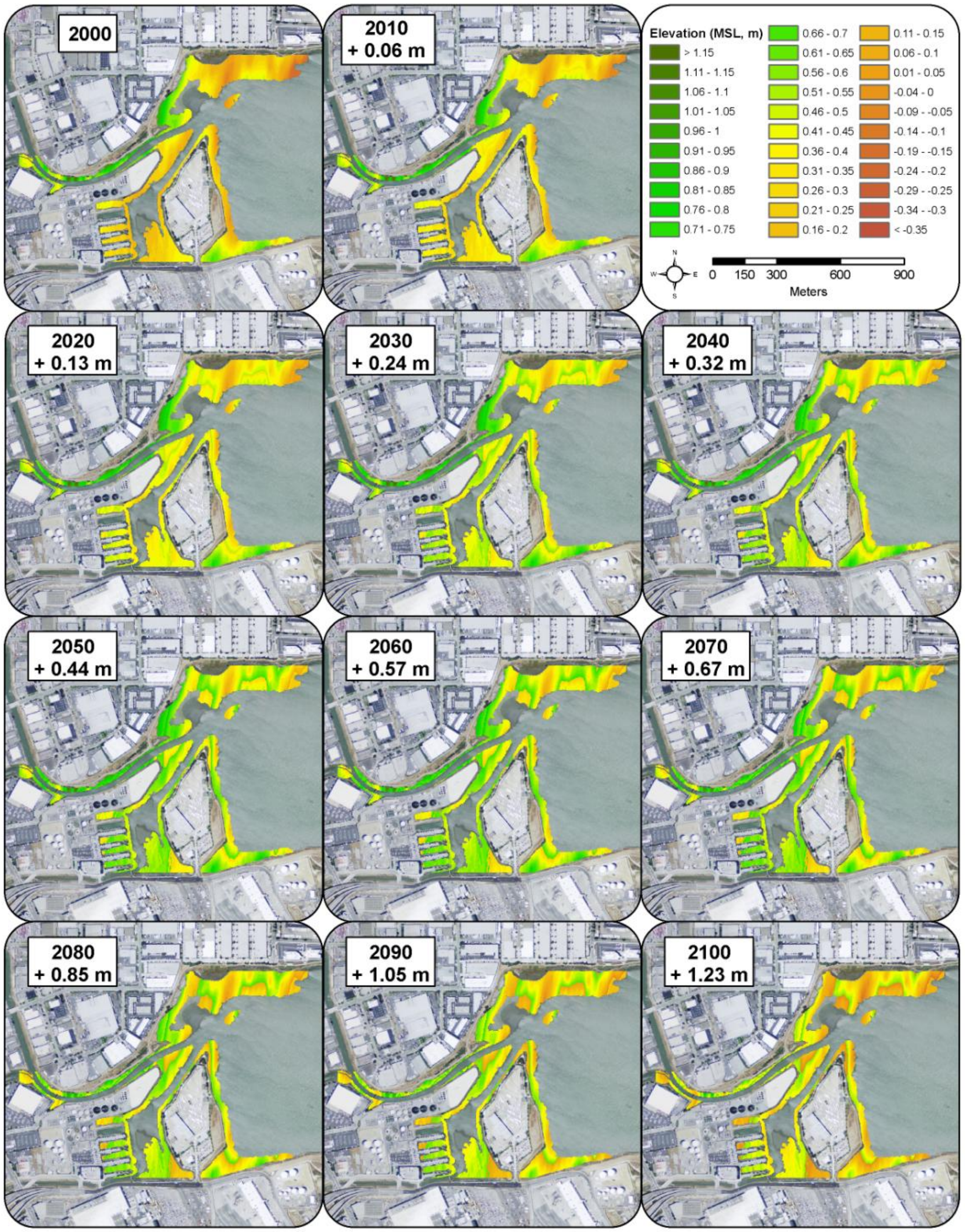

Figure E-5. WARMER results for Colma. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

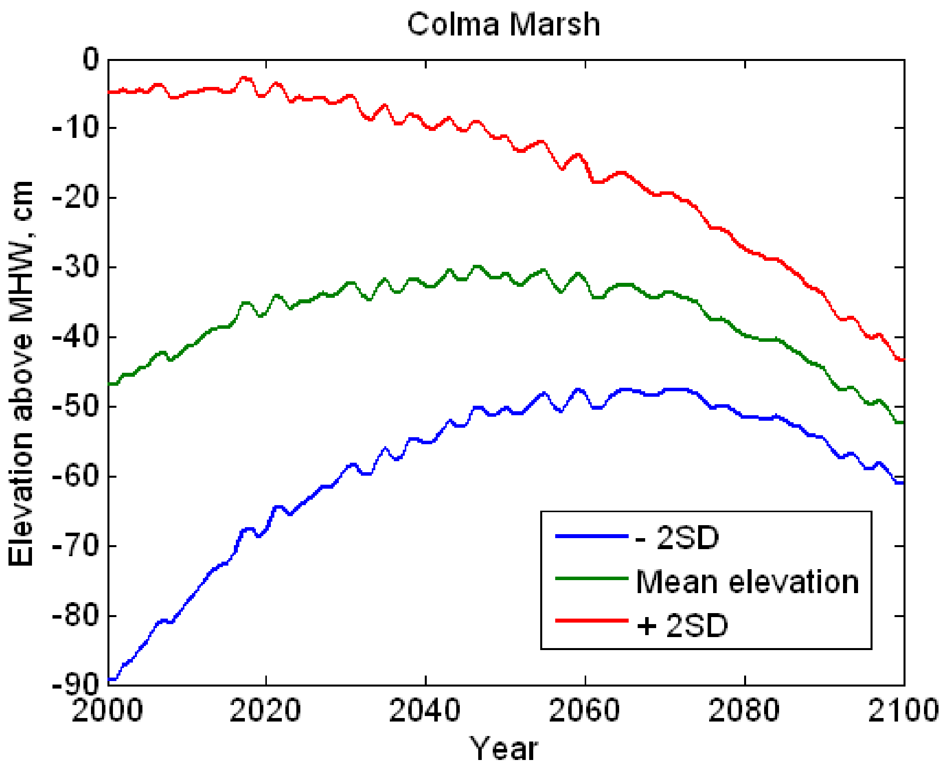

Figure E-6. WARMER scenarios for marsh elevation change at Colma. Elevation above MHW is plotted versus model year with two standard deviations (SD).

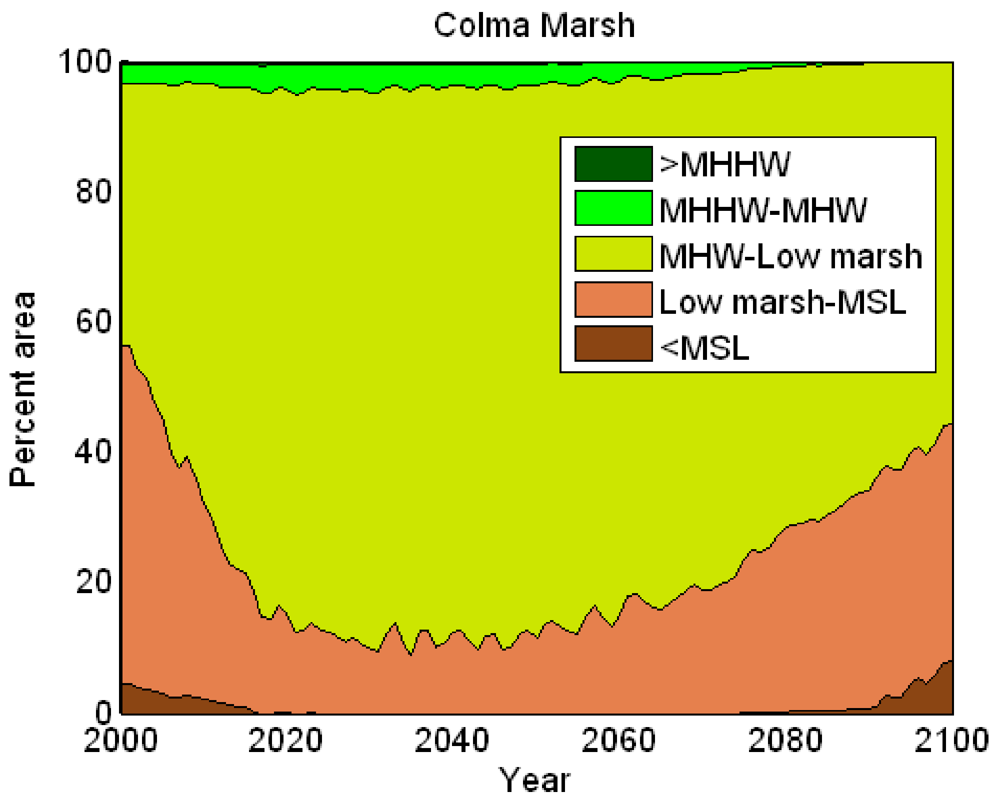

Figure E-7. Area of Colma within a given tidal range for the duration of the simulation period.

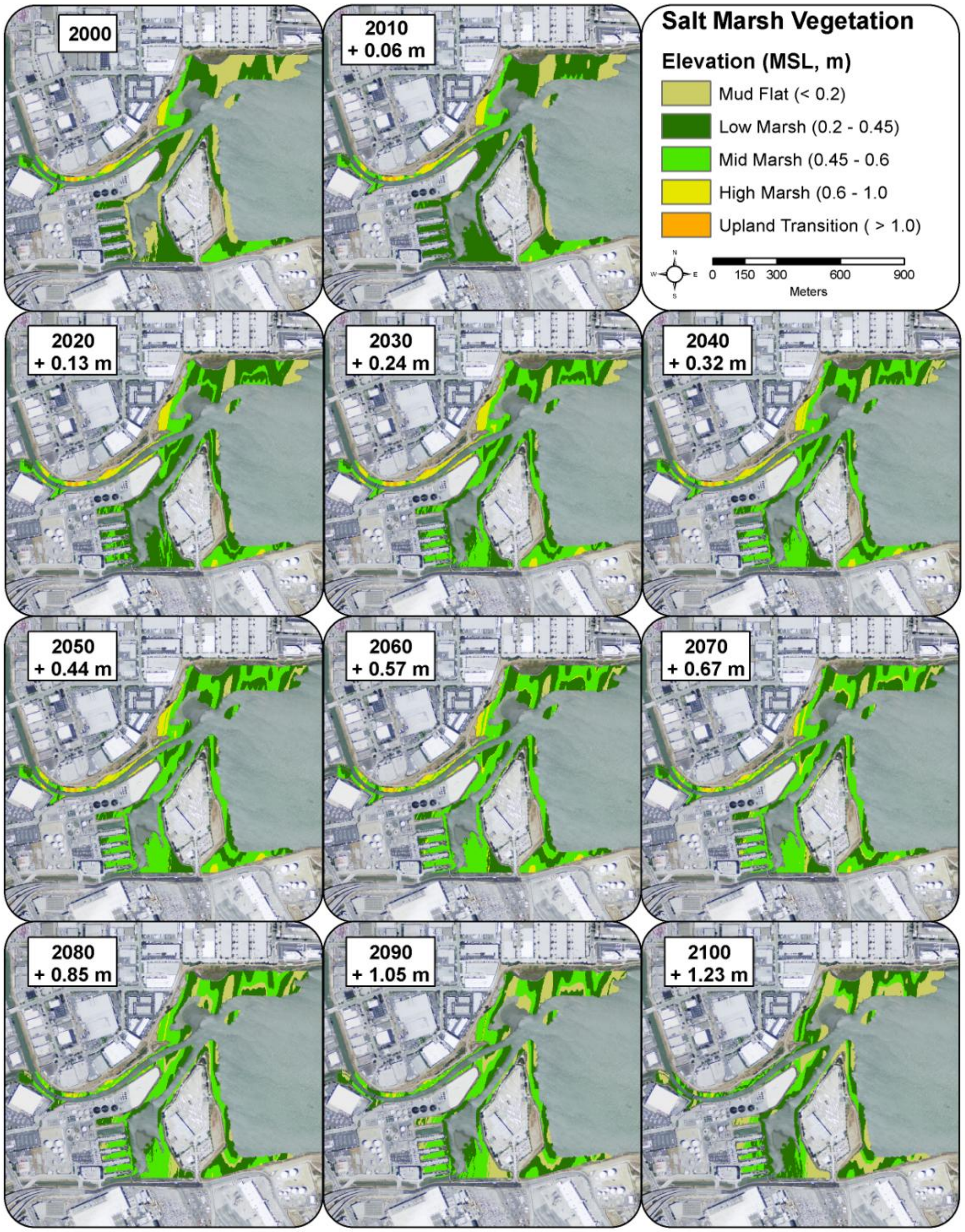

Figure E-8. Colma WARMER results in terms of plant communities which were determined from vegetation data. Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp*.* or *Schoenoplectus* spp*.* in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp*.*

Appendix F

Coon Island Marsh

Introduction

Coon Island marsh (hereafter Coon Island) is located in Napa County along the Napa River and is bordered on the east by Mud Slough. Coon Island is influenced by tidal flow from San Pablo Bay as well as freshwater flow from the Napa River. It is surrounded by salt pond restoration sites in the Napa Sonoma Marshes Wildlife Area. The marsh is owned by California Department of Fish and Game and is home to federally endangered species including the salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsoletus*).

This study focused on 98.7 ha of Coon Island. Elevation and vegetation surveys were done in 2009 using an RTK GPS. To monitor tidal inundation and salinity, two water level loggers were deployed between 2009 - 2010.

Results

Elevation surveys

A total of 799 elevation measurements were taken at Coon Island (Fig. F-1). The elevation range was 0.82 - 2.07 m with a mean of 1.83 m (NAVD88). Over half of the survey points fell within 1.70 - 1.90 m. Coon Island was one of the lower marshes surveyed with the majority (71%) of survey points located at elevations below mean high water (MHW; Fig F-2).

A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. F-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

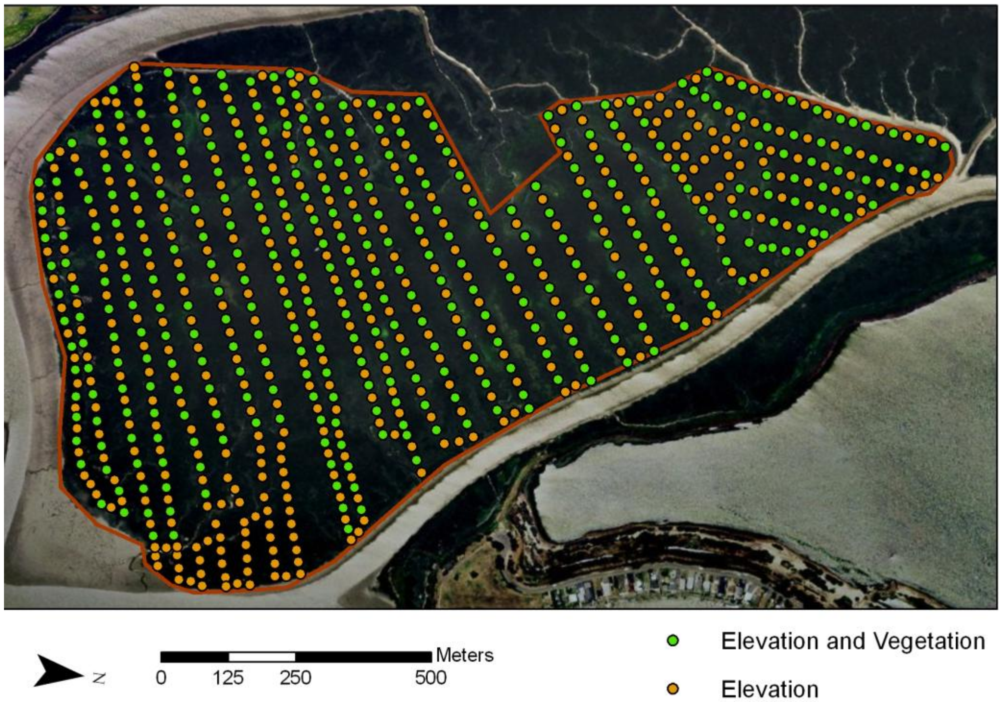

Figure F-1. Coon Island Marsh with elevation and vegetation survey points taken in 2009.

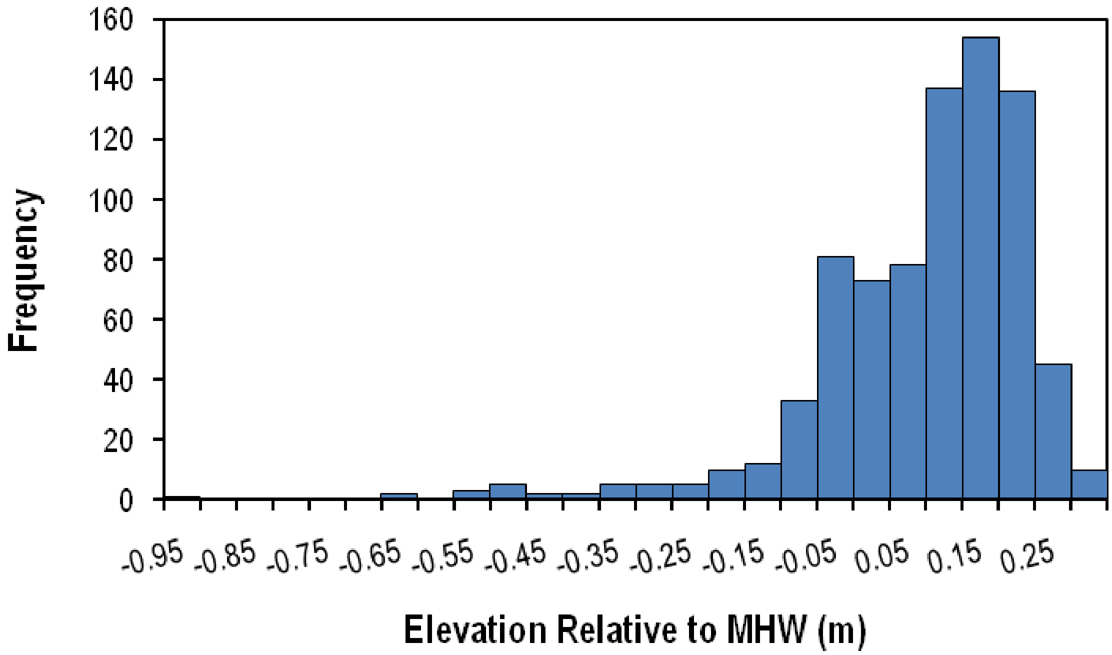

Figure F-2. Distribution of elevation samples relative to local mean high water (MHW) at Coon Island.

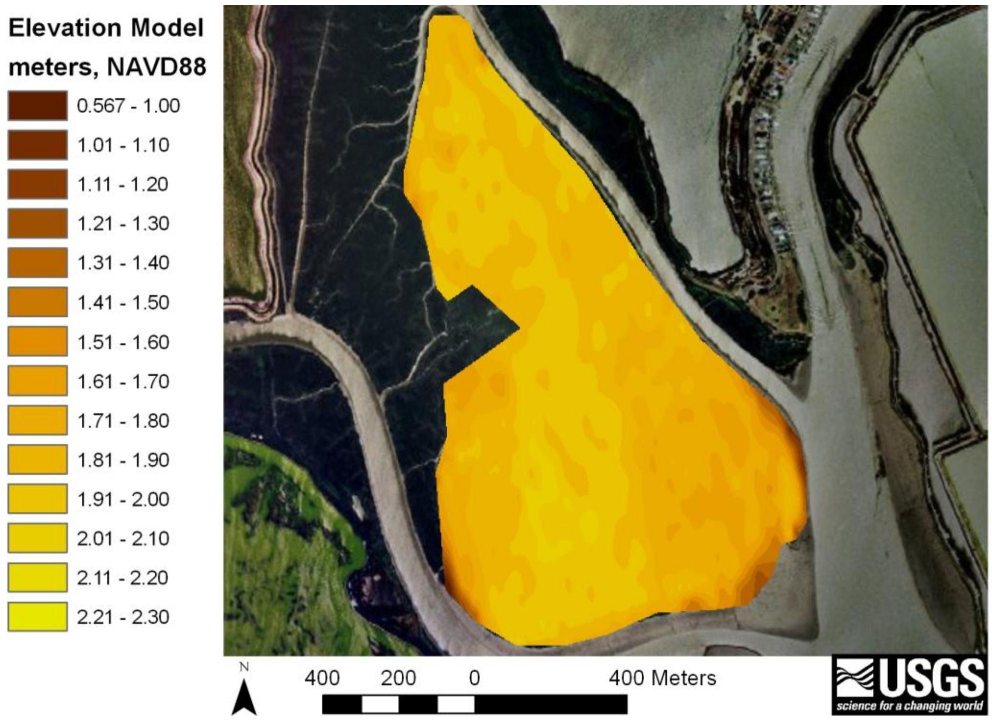

Figure F-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed at Coon Island concurrently with elevation surveys in November - December of 2009. A total of 364 locations (Fig. F-1) were measured for vegetation composition, height (cm), and percent cover (Table F-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. F-4) was observed within this low slope marsh.

Table F-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Coon Island.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.09	0.09	50.11	12.69	57.79	13.74	75.60	27.90	320	87.91
Spartina spp.	-0.37	0.13	91.00	27.62	103.33	20.82	26.67	17.56	3	0.82
Schoenoplectus spp.	-0.02	0.13	86.29	24.84	96.66	26.72	26.57	22.66	140	38.46
Grindelia stricta	0.11	0.06	73.25	24.98	83.75	27.22	32.25	15.60	20	5.49
Jaumea carnosa	0.12	0.10	27.18	8.67	33.46	14.74	36.96	26.56	28	7.69
Frankenia salina	0.12	0.01	35.50	20.51	39.50	21.92	55.00	21.21	2	0.55
Distichlis spicata	0.15	0.03	28.60	9.37	29.80	9.52	1.80	0.45	5	1.37
Lepidium latifolium	0.13	0.07	91.50	10.47	104.61	18.37	25.28	21.84	18	4.95
Atriplex triangularis	0.09	0.08	21.00	4.64	26.20	9.31	11.40	13.50	5	1.37
Baccharis pilurais	0.19	-	60.00	-	95.00	-	60.00	-	1	0.27
Baccharis douglasii	0.14	0.00	75.00	14.14	83.50	19.09	55.00	28.28	2	0.55
Juncus spp.	0.11	0.10	53.00	14.28	59.33	15.13	7.83	10.94	6	1.65

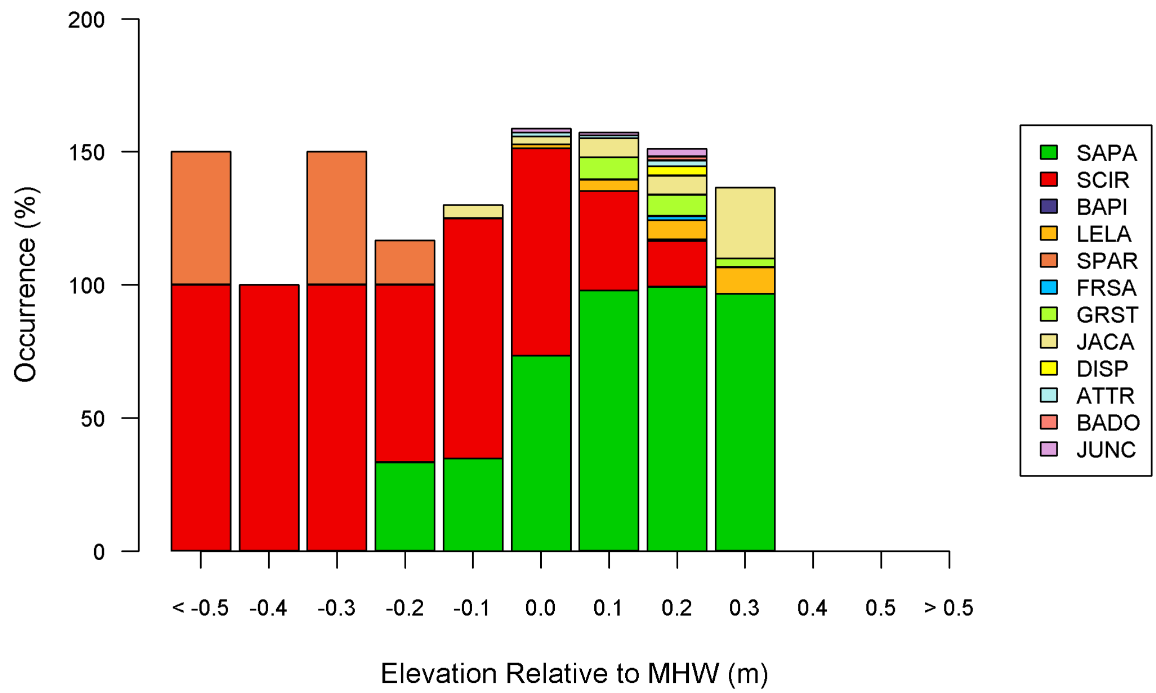

Figure F-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA: = *Sarcocornia pacifica*; SCIR = *Schoenoplectus* spp.*;* BAPI = *Baccaris pilularis*; LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.; FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*; ATTR = *Atriplex triangularis*; BADO = *Baccaris douglasii;* JUNC = *Juncus* spp.

Water level monitoring

Site-specific water level was monitored at Coon Island from December 2009 – May 2010. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. We found MHW was at 1.78 m and mean higher high water (MHHW) at 1.94 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean elevation) was inundated most often from January 2010 through February 2010 (Fig. F-5). Those months recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform. Mean salinity during 2010 at Coon Island was 11.8 (SD = 6.1) PSS.

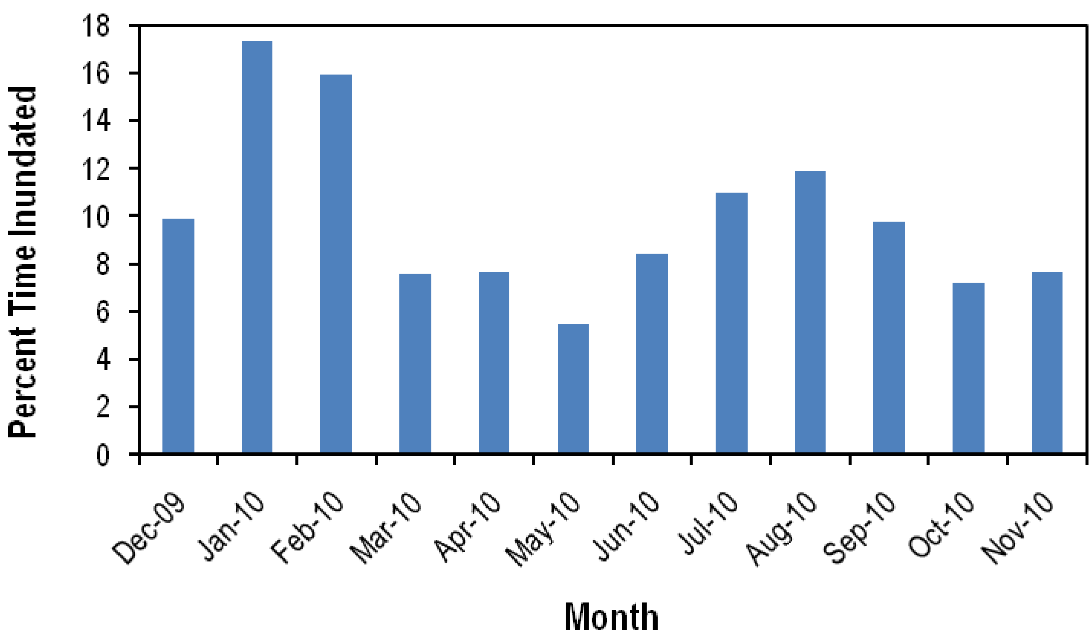

Figure F-5. Percent of time Coon Island is inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER results indicate that Coon Island will not keep pace with local SLR through this century. WARMER projects a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060 (Fig F-6). By 2090 the marsh is projected to be under MSL, and will therefore transition to a mudflat (Fig. F-7).

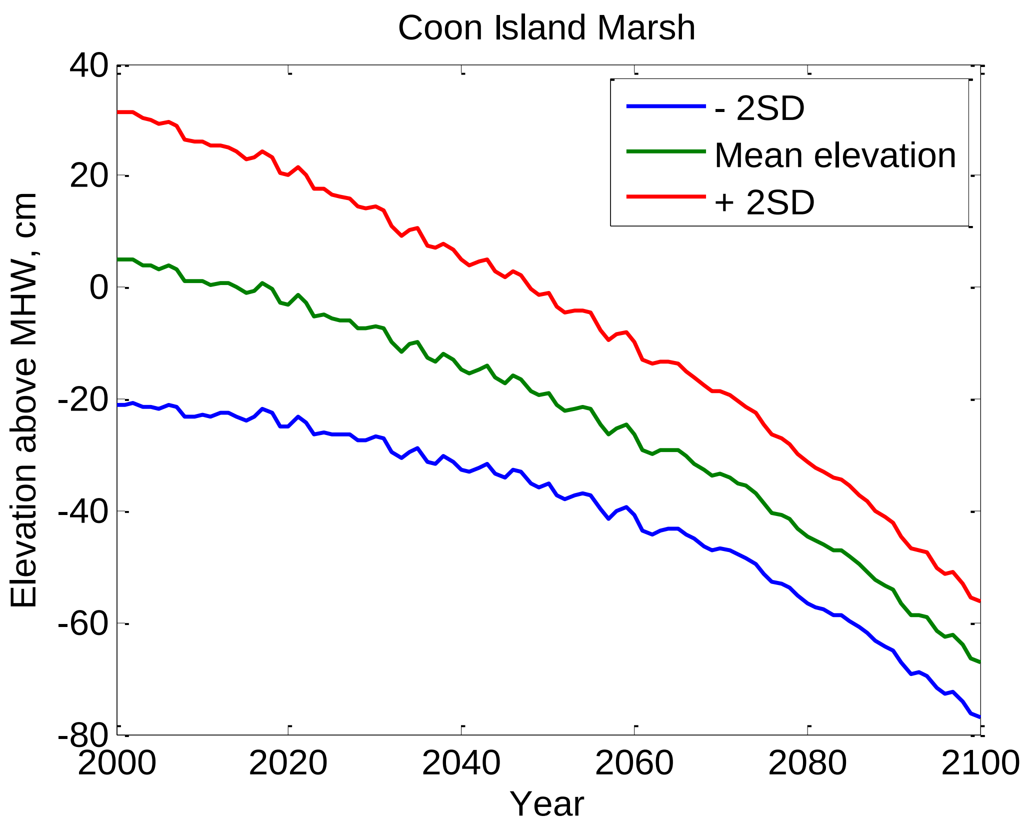

Figure F-6. WARMER scenarios of marsh elevation change at Coon Island. Elevation above MHW is plotted versus model year with two standard deviations (SD).

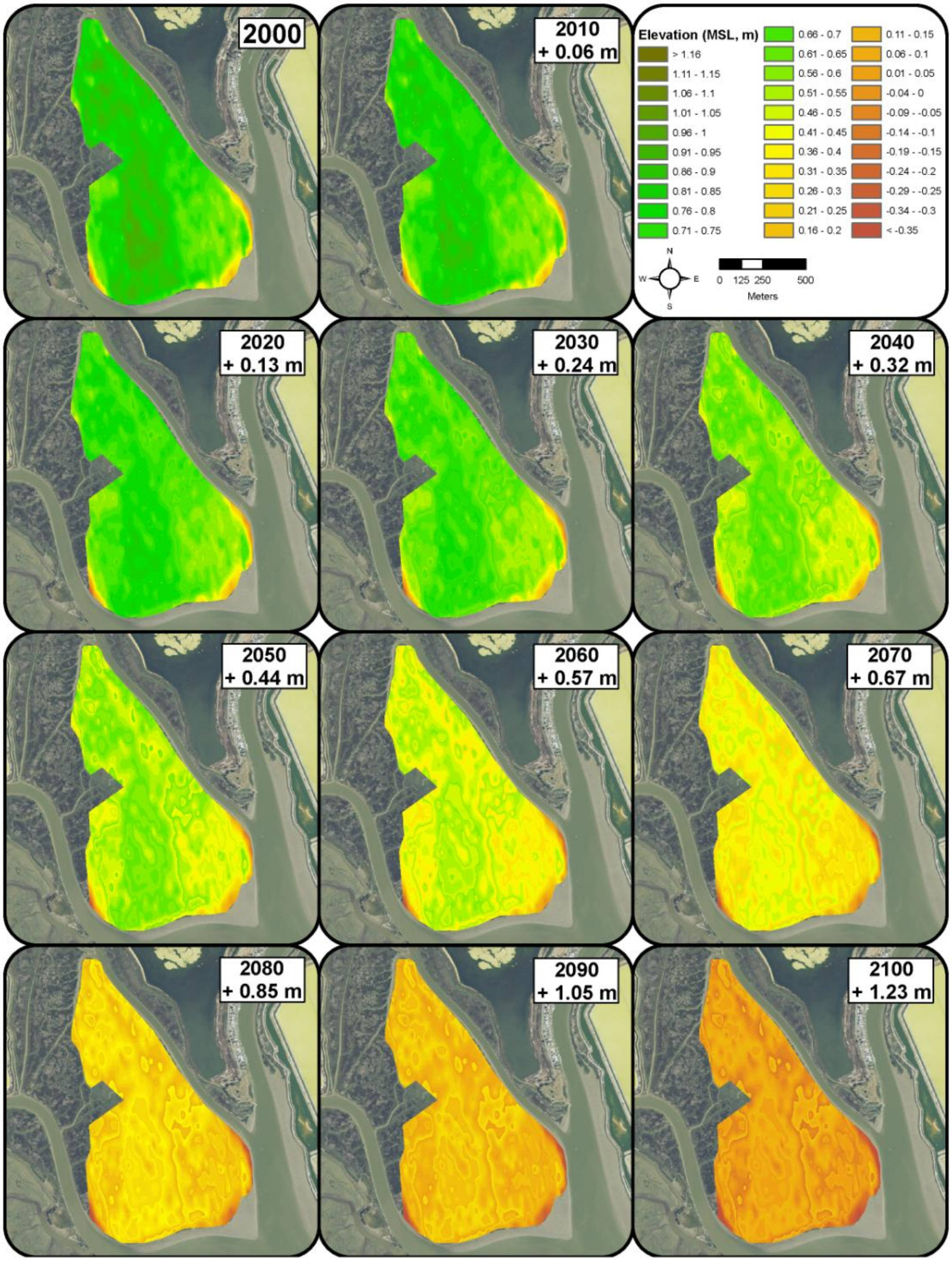

Figure F-7. WARMER results for Coon Island. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity , compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Thus, vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table F-4) and used to interpret the WARMER SLR results (Figs. F-8 – F-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently vegetation at Coon Island is primarily high and mid plant communities. The amount of high marsh vegetation is projected to increase between 2010 (+0.06 m SLR) and 2030 (+0.57 m SLR). By 2060 (+0.57 m SLR) WARMER projects a considerable increase in low marsh vegetation. After 2060 (+0.57 m SLR) the elevation of the marsh rapidly decreases and by 2090 (+1.05 m SLR) the marsh becomes primarily mudflat. The WARMER model parameters for Coon Island were collected using sediment core data from the site.

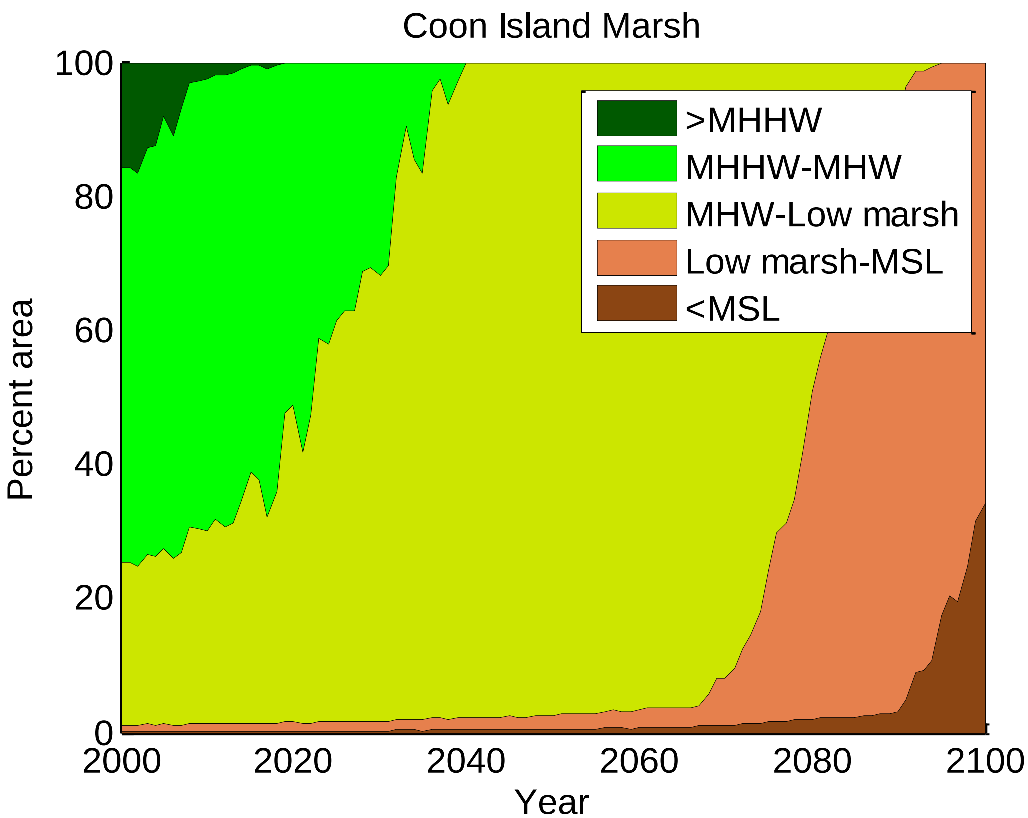

Figure F-8. Area of Coon Island within a given tidal range for the duration of the simulation period.

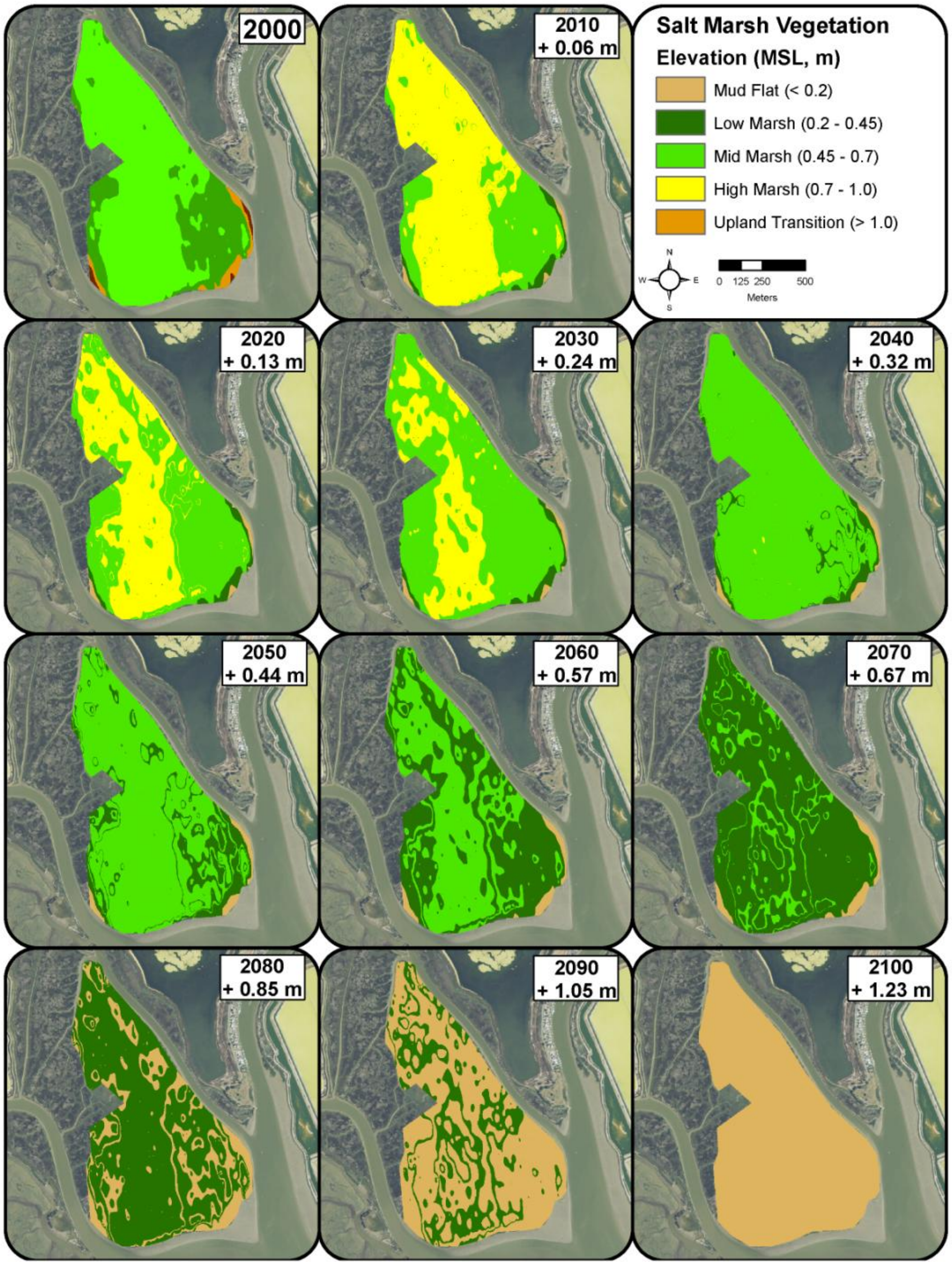

Figure F-9. Coon Island WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix G

Corte Madera Marsh

Introduction

Corte Madera Marsh (hereafter Corte Madera) is located in Marin County along San Pablo Bay and at the mouth of Corte Madera Creek. Corte Madera is part of the 400 ha Corte Madera Ecological Reserve which is owned and managed by the California Department of Fish and Game. It was designated as an Ecological Reserve in 1975 and contains federally endangered California clapper rails (*Rallus longirostris obsoletus*), which occupy the low intertidal zone dominated by cordgrass (*Spartina* spp.). It also contains San Pablo song sparrows (*Melospiza melodia samuelis*) and California black rails (*Laterallus jamaicensis coturniculus*), California species of concern.

This study focused on 76.8 ha of Corte Madera. Elevation and vegetation surveys were conducted in 2010, using an RTK GPS. To monitor tidal inundation, two water level loggers were deployed between 2009 - 2010.

Results

Elevation surveys

A total of 744 elevation measurements were taken at Corte Madera (Fig. G-1). The elevation range was 1.31 - 2.08 m with a mean of 1.63 m and a range of 0.77 m (NAVD88). Over half (80%) of the survey points fell within 1.5 – 1.8 m. Corte Madera was among the lowest marshes surveyed in this study, with 72% of the elevation points taken located below mean high water (MHW; Fig G-2). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. G-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

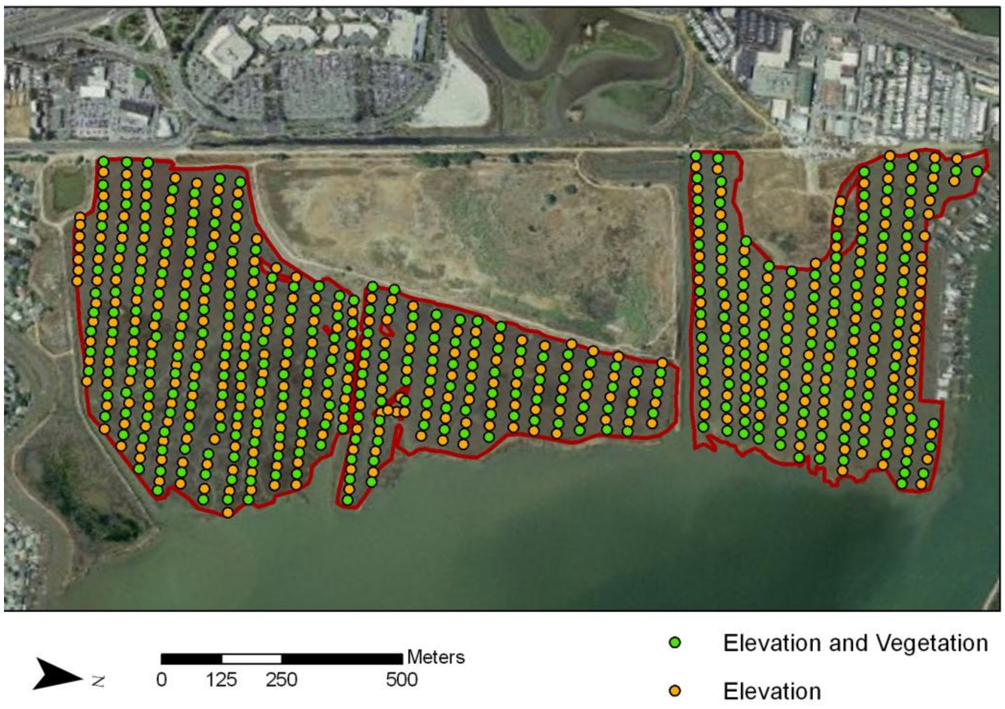

Figure G-1. Corte Madera with elevation and vegetation survey points taken in 2009.

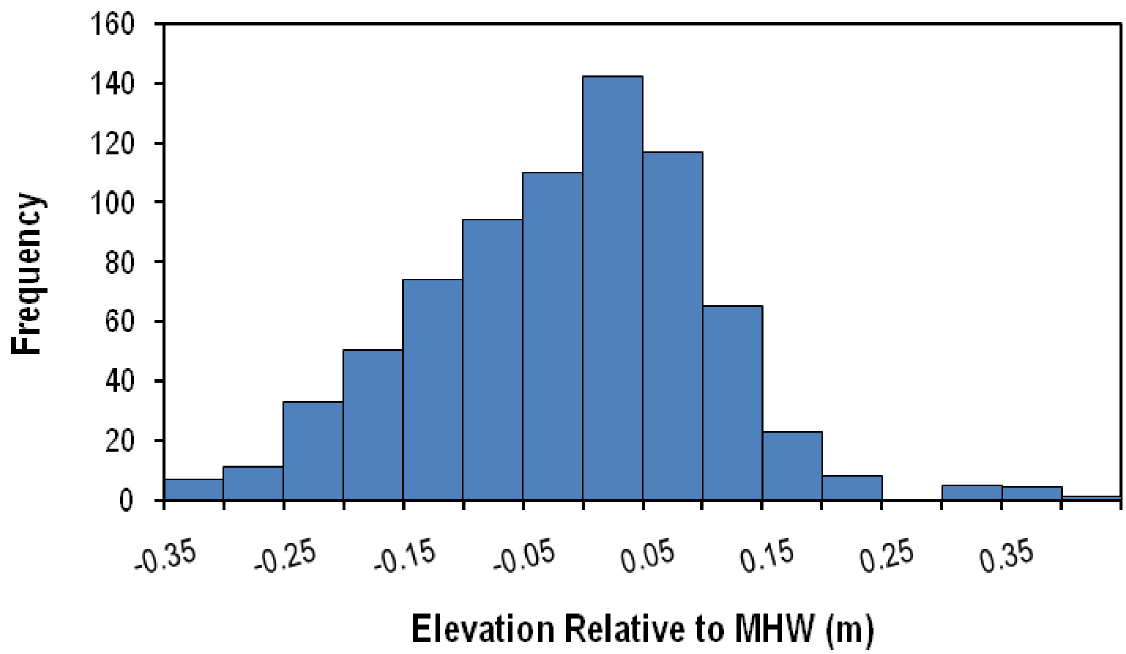

Figure G-2. Distribution of elevation samples relative to local mean high water (MHW) at Corte Madera marsh.

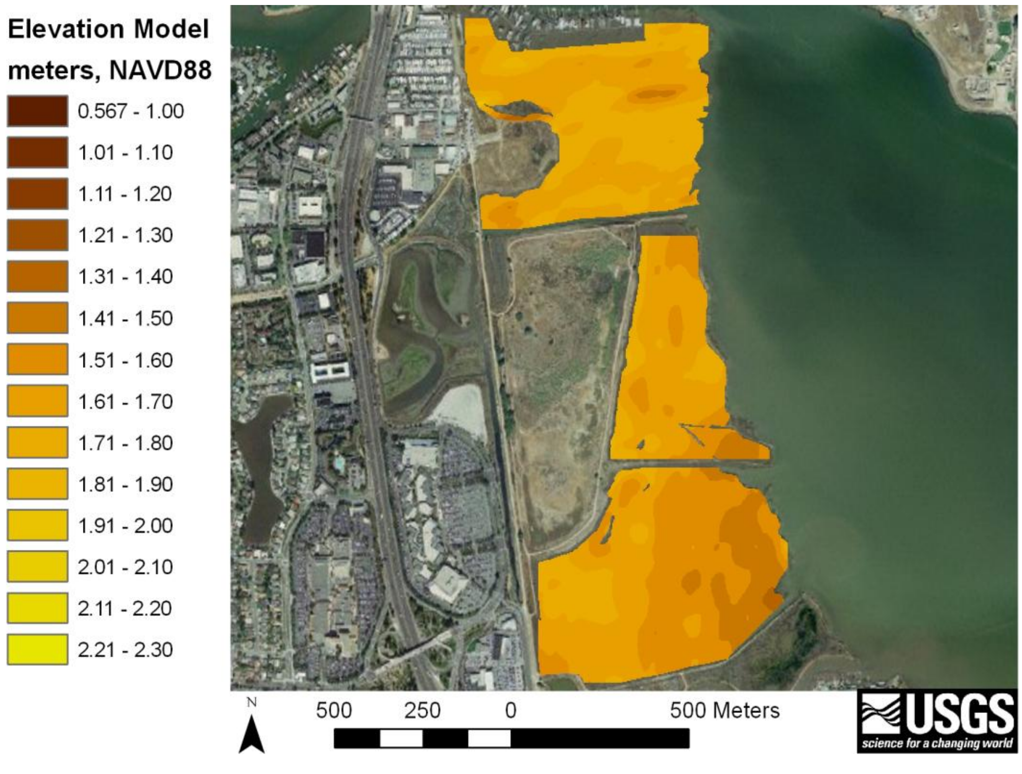

Figure G-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed at Corte Madera concurrently with elevation surveys in March 2010. A total of 361 locations (Fig. G-1) were measured for vegetation composition, height (cm), and percent cover (Table G-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. G-4) was observed within this low slope marsh.

Table G-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species in Corte Madera.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	-0.06	0.12	27.14	7.46	38.10	9.65	70.07	33.92	351	97.23
Spartina spp.	-0.17	0.08	36.43	10.32	51.39	15.19	23.79	25.19	99	27.42
Grindelia stricta	0.08	0.12	41.57	20.80	49.14	21.26	15.14	10.73	14	3.88
Jaumea carnosa	-0.02	0.05	12.14	3.07	15.35	3.02	24.97	30.36	37	10.25
Frankenia salina	0.21	0.19	14.00	9.90	17.50	12.02	9.00	1.41	2	0.55
Distichlis spicata	0.00	0.08	21.16	6.07	28.21	6.65	29.99	27.76	126	34.90
Lepidium latifolium	-0.01	0.08	18.60	7.55	23.70	10.09	11.30	9.20	10	2.77

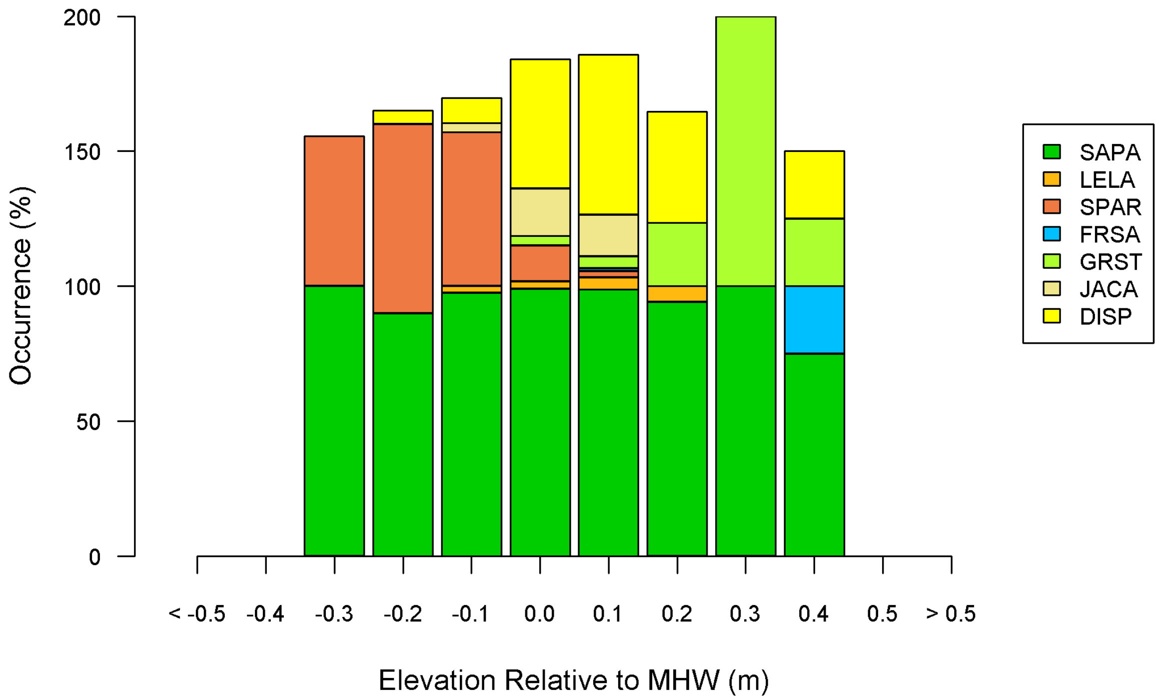

Figure G-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica*; LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.; FRSA = *Frankenia salina;* GRST: = *Grindelia stricta*; JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Water level monitoring

Water levels throughout the year were recorded to evaluate seasonal patterns in tides. Site-specific water level was monitored from August 2010 through July 2011 (Fig. G-5). Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. We found MHW at 1.70 m, and mean higher high water (MHHW) at 1.87 m for the site (NAVD88).

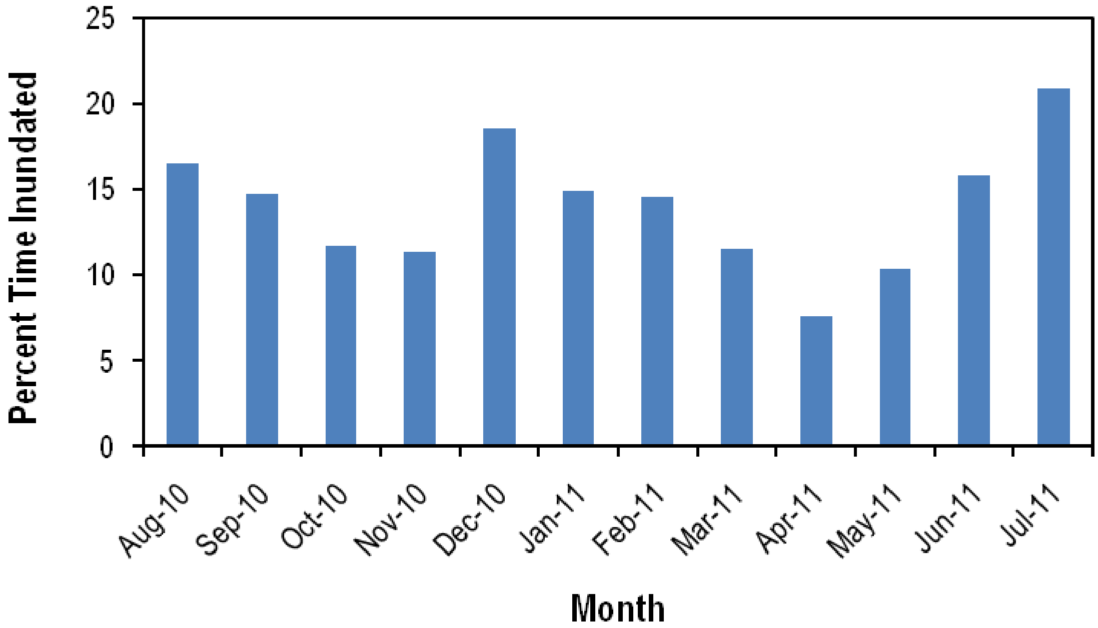

Figure G-5. Percent of time Corte Madera was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

Corte Madera was one of the lowest marshes relative to MHW in this study, second only to Colma marsh. Sites with lower accretion rates and starting elevations and that were located lower in the tidal range, became inundated more frequently, making them more susceptible to SLR. WARMER results indicate that Corte Madera will not keep pace with local SLR through this century. WARMER projects a gradual reduction in elevation relative to MHW through 2100, with a more dramatic decline after 2060 (Fig. G-6). By 2090 the marsh is projected to be under mean sea level (MSL) and transition to a mudflat (Fig. G-7).

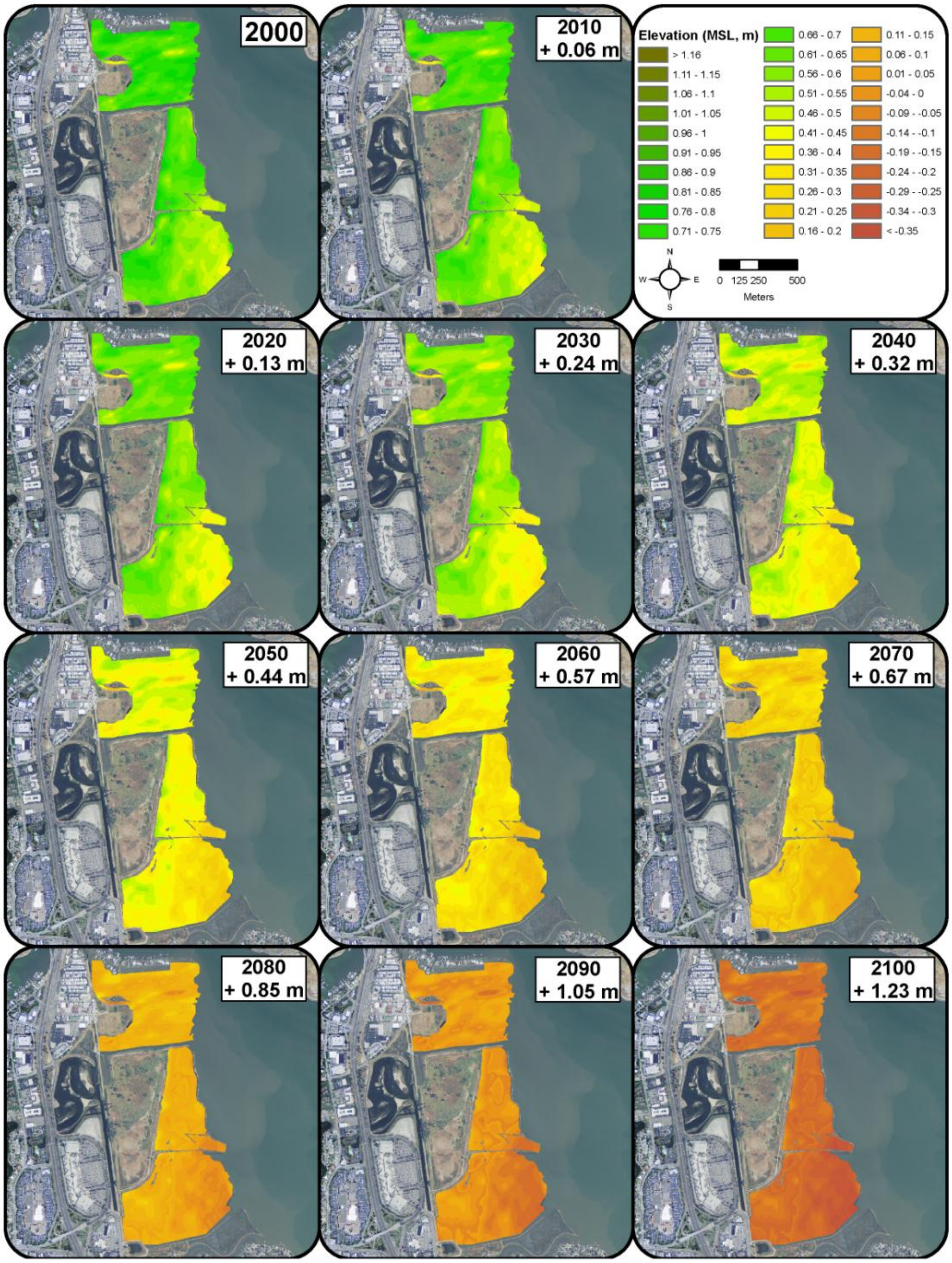

Figure G-6. WARMER results for Corte Madera. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity , compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

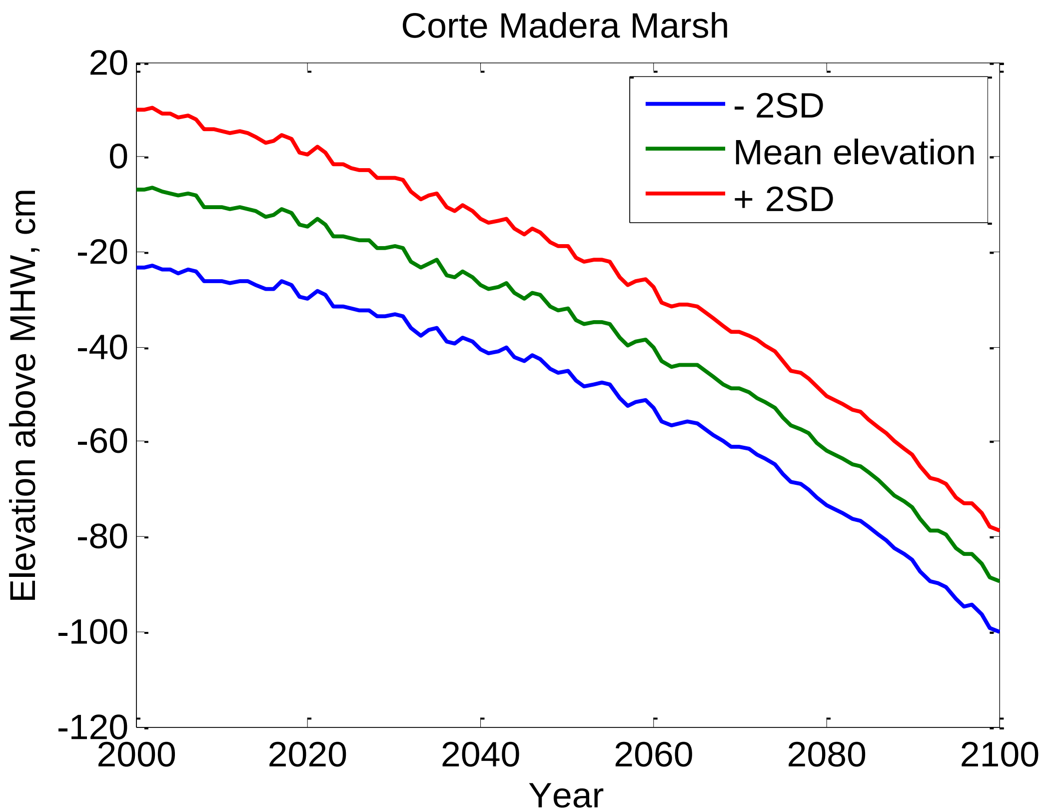

Figure G-7. WARMER scenarios for Corte Madera elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. G-8 – G-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently vegetation at Corte Madera is prominently mid marsh with approximately one quarter high marsh habitat. All high marsh vegetation is projected to disappear by 2030 (+ 0.24 m SLR). Nearly all mid marsh vegetation is projected to disappear by 2060 (+ 0.57 m SLR) and by 2080 (+ 0.85 SLR) Corte Madera is projected to be primarily mudflat.

The WARMER model parameters for Corte Madera were extrapolated using sediment core data from China Camp Marsh, thus predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. To improve results, local site specific sediment core data should be collected, along with suspended sediment concentrations to characterize sediment deposition potential.

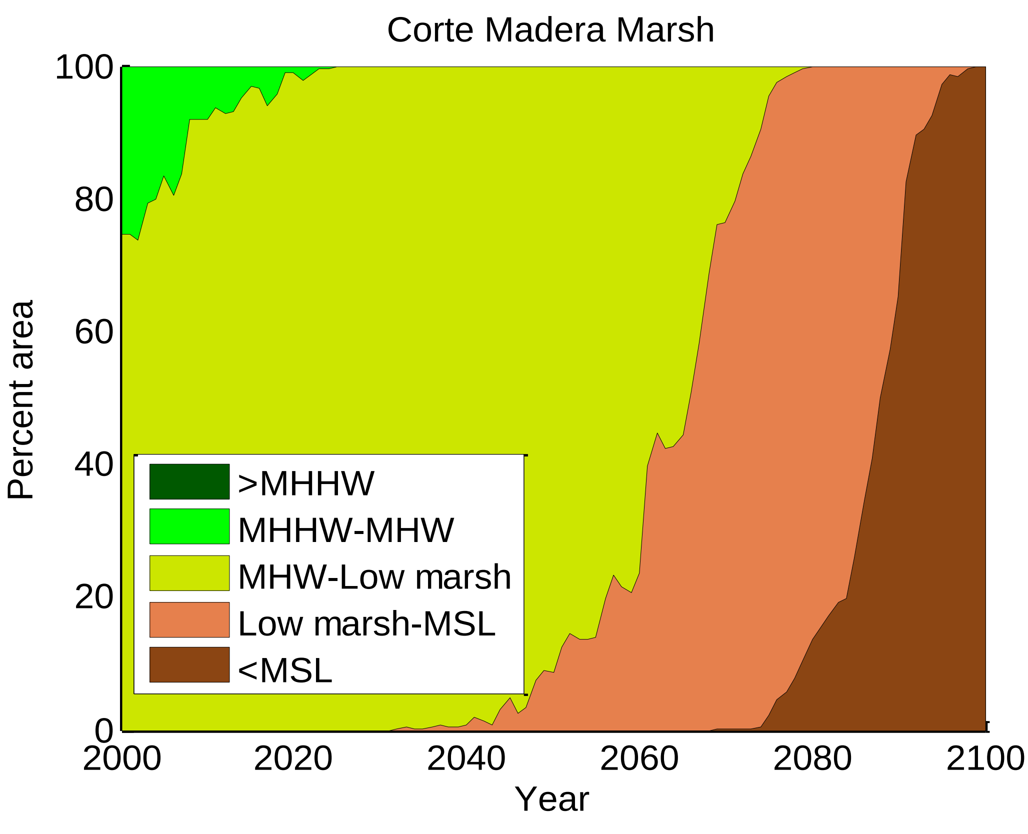

Figure G-8. Area of Corte Madera within a given tidal range for the duration of the simulation period.

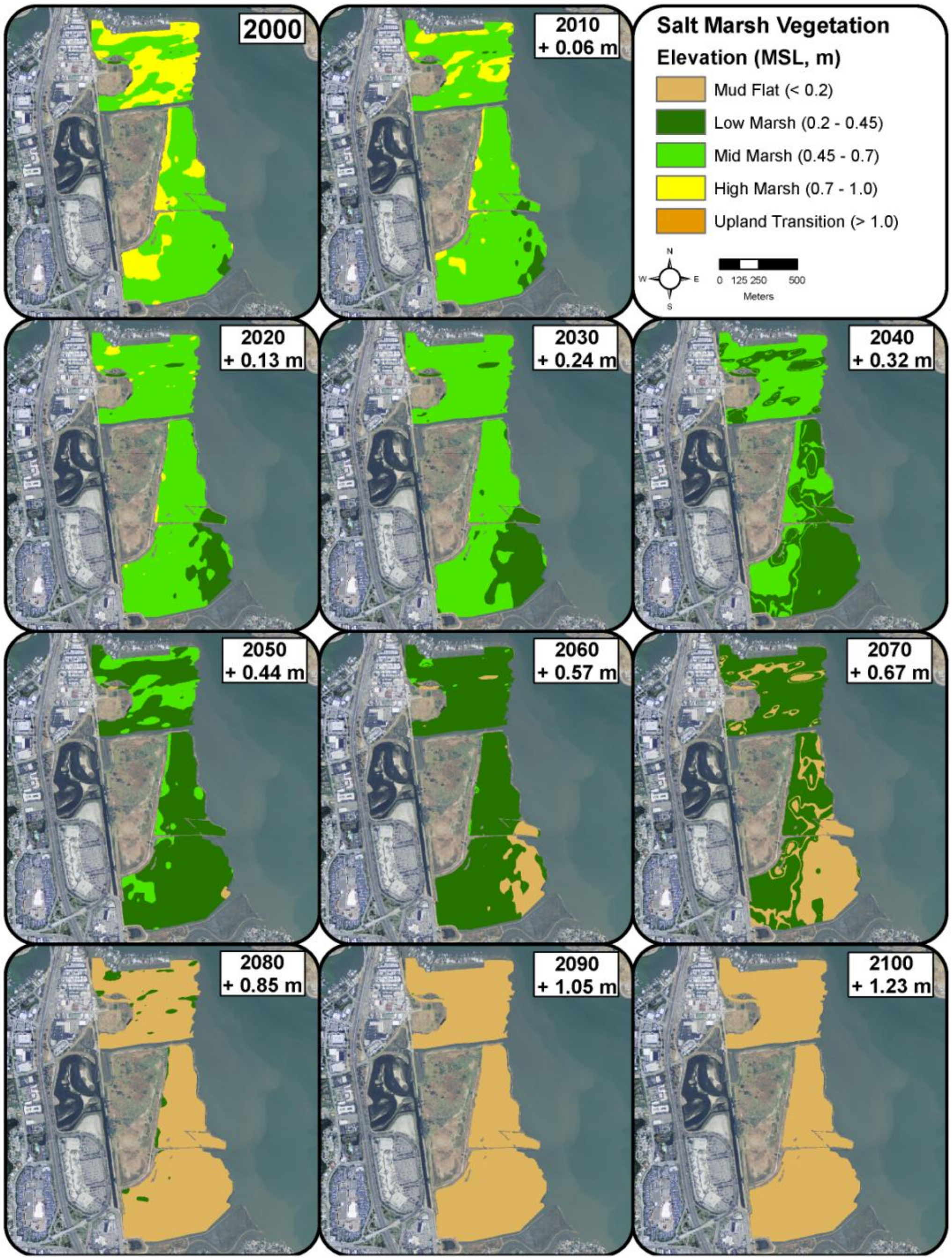

Figure G-9. Corte Madera WARMER results in terms of vegetation category: mudflat, low, mid, or high marsh, or upland transition.

Appendix H

Fagan Slough Marsh

Introduction

Fagan Slough Marsh (hereafter Fagan) is located in Napa County, along the Napa River. It is managed by the California Department of Fish and Game since 1979 and is part of the Fagan Slough Ecological Reserve. The marsh is influenced by tidal flow from San Pablo Bay via Steamboat Slough (north) and Fagan Slough (south) and receives freshwater input from the Napa River. It is surrounded by salt evaporation ponds, private property, and small upland areas with live oaks. Fagan provides habitat for state listed species, such as the California black rail (*Laterallus jamaicensis*) and federal endangered species such as salt marsh harvest mouse (*Reithrodontomys raviventris*) and California clapper rail (*Rallus longirostris obsoletus*).

This study focused on 67.9 ha of Fagan. Elevation and vegetation surveys were conducted in 2010 using an RTK GPS. To monitor tidal inundation, two water level loggers were deployed and monitored between 2010 - 2011.

Results

Elevation surveys

A total of 481 elevation measurements were taken at Fagan (Fig. H-1). The elevation range was 1.16 - 2.25 m with a mean of 1.90 m (NAVD88). Over half (66%) of the survey points fell within 1.9-2.0 m, with a 0.1 m range. Fagan is a relatively high elevation marsh with 88% of survey points located at elevations above mean high water (MHW; Fig H-2). A 3-m resolution elevation model was developed in ArcGIS, Spatial Analyst using the Kriging method (Fig. H-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

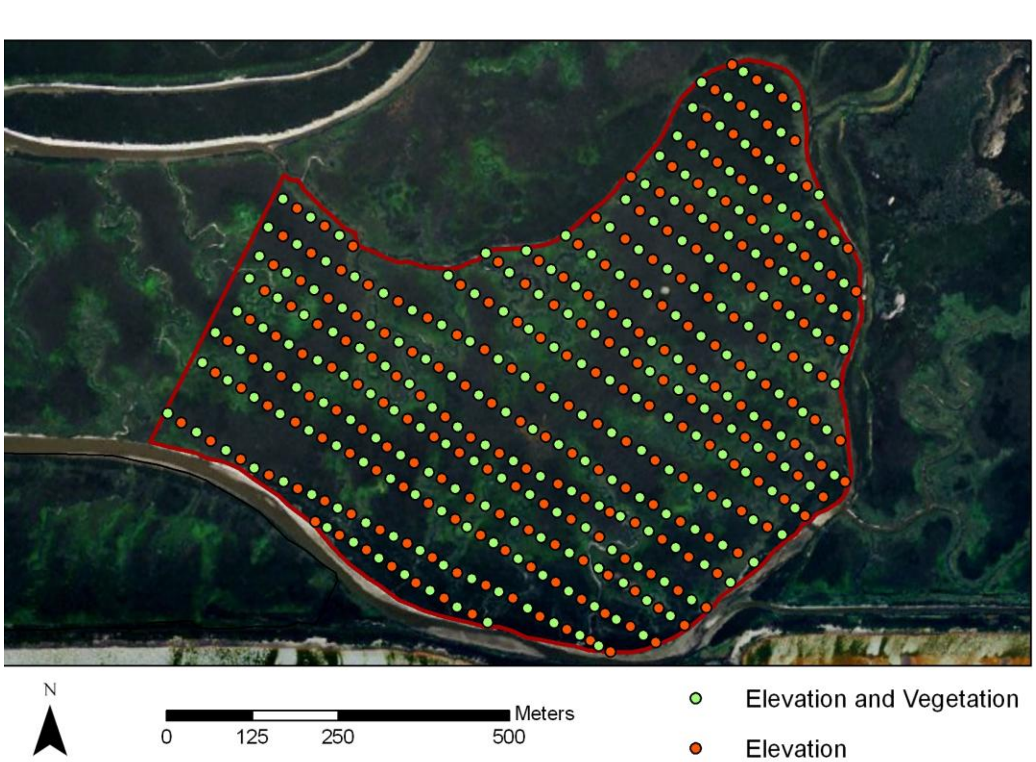

Figure H-1. Fagan Marsh with elevation and vegetation survey points taken in 2010.

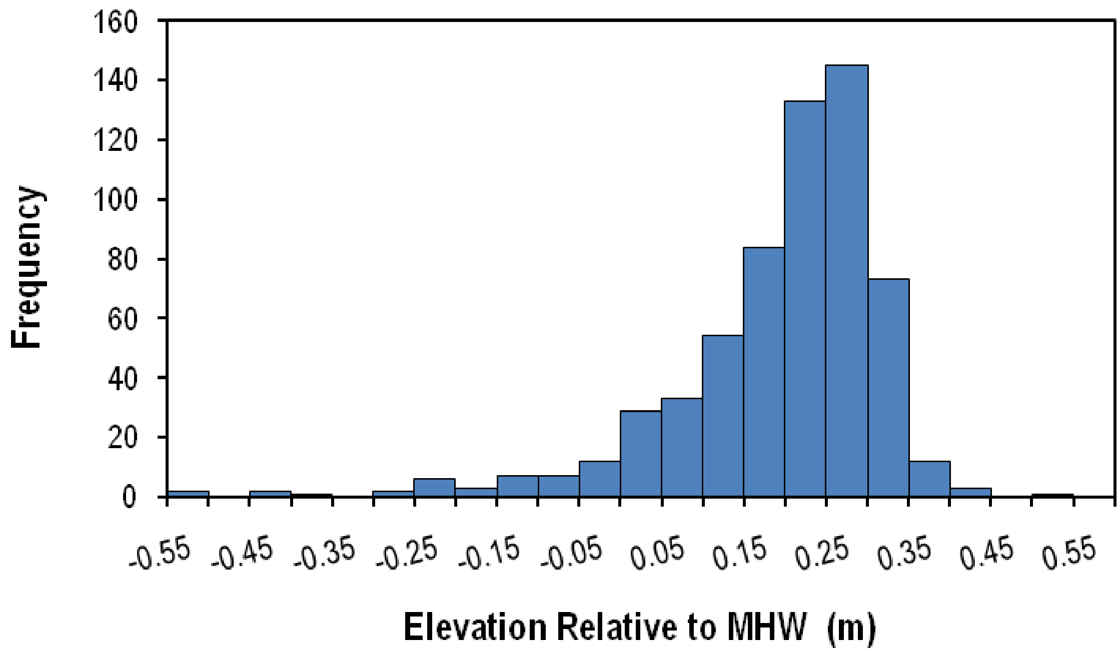

Figure H-2. Distribution of elevation samples relative to local mean high water (MHW) at Fagan Marsh.

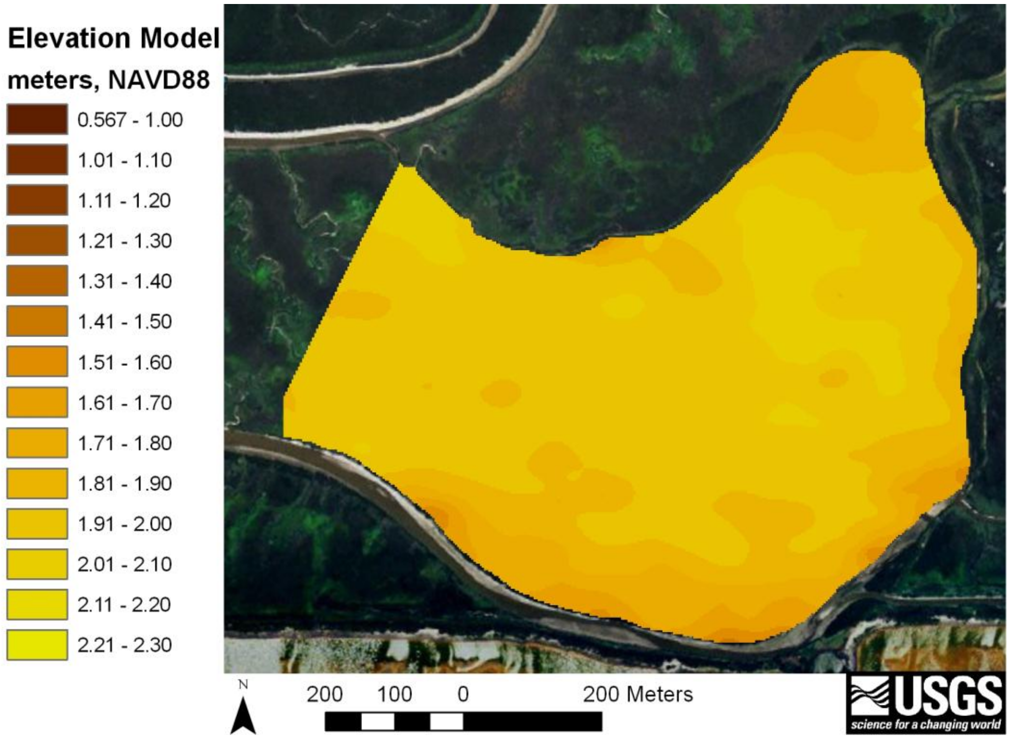

Figure H-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed at Fagan concurrently with elevation surveys in April and July 2010. A total of 241 locations (Fig. H-1) were measured for vegetation composition, height (cm), and percent cover (Table H-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. H-4) was observed within this low slope marsh. Fagan also had relatively high marsh species richness with 17 species recorded.

Table H-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Fagan.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.16	0.11	36.97	10.57	49.24	12.95	61.57	36.47	267	86.69
Spartina spp.	0.03	-	-	-	-	-	35.00	-	1	0.32
Schoenoplectus spp.	0.11	0.14	77.88	30.11	94.56	35.55	15.58	21.08	157	50.97
Grindelia stricta	0.05	0.02	81.50	14.85	81.50	14.85	47.50	60.10	2	0.65
Jaumea carnosa	0.03	-	38.00	-	40.00	-	55.00	-	1	0.32
Frankenia salina	0.16	-	40.00	-	44.00	-	77.00	-	1	0.32
Distichlis spicata	0.20	0.03	26.80	7.36	29.40	6.88	14.00	26.89	5	1.62
Lepidium latifolium	0.14	0.13	92.23	26.66	101.40	27.79	44.02	34.28	53	17.21
Atriplex triangularis	0.09	0.17	27.50	13.50	34.14	16.44	9.57	8.39	14	4.55
Triglochin concinna	0.24	0.04	41.13	8.54	52.25	11.21	27.75	26.86	8	2.60
Typha angustifolia	-0.11	0.21	107.75	22.53	126.67	27.98	26.33	36.27	12	3.90
Potentilla anserina	0.18	0.07	25.87	6.89	30.73	7.50	11.72	13.26	78	25.32
Baccharis pilurais	0.23	0.03	96.50	17.79	96.50	17.79	79.75	28.05	4	1.30
Artemisia spp.	0.13	0.01	33.33	19.73	39.33	17.93	11.33	4.04	3	0.97
Ruppia maritima occidentalis	0.12	0.05	36.50	3.54	36.50	3.54	4.00	1.41	2	0.65
Cotula coronopifolia	-0.11	-	25.00	-	29.00	-	25.00	-	1	0.32
Juncus spp.	0.19	0.06	55.36	15.13	67.00	20.60	7.14	14.77	22	7.14

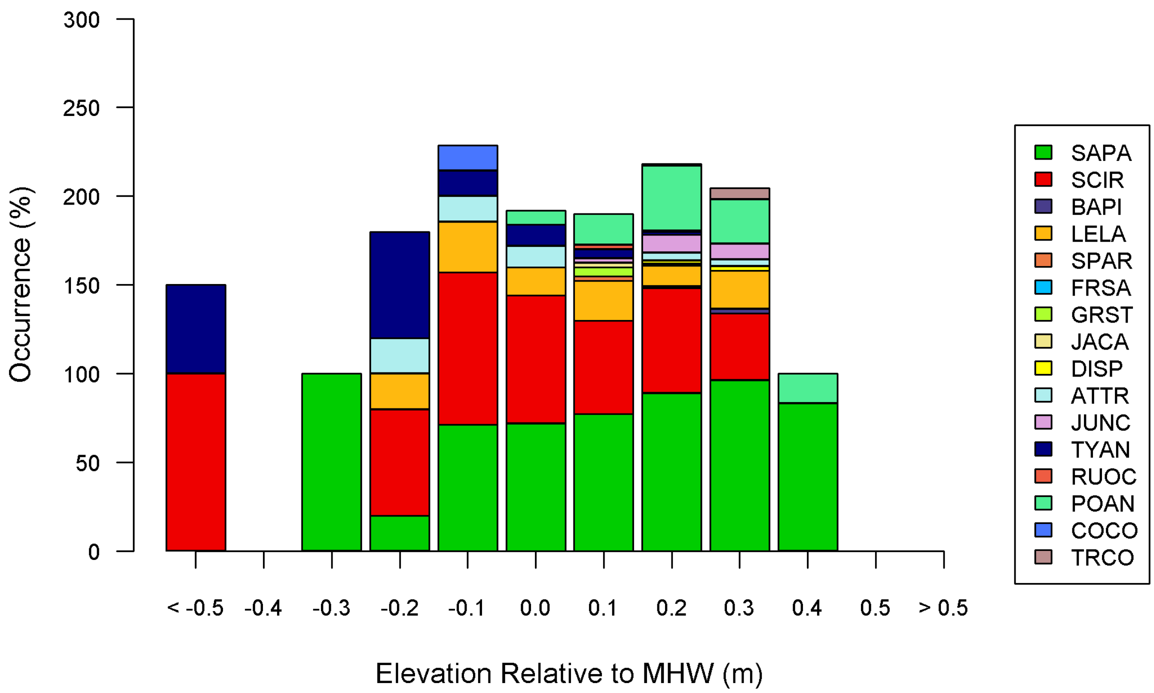

Figure H-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus* spp.*;* BAPI = *Baccaris pilularis*; LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.*;* FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*; ATTR = *Atriplex triangularis*; JUNC = *Juncus* spp*;* TYAN = *Typha angustifolia;* RUOC = *Ruppia maritima occidentalis;* POAN = *Potentilla anserina;* COCO = *Cotula coronopifolia;* TRCO = *Triglochin concinna.*

Water level monitoring

Site-specific water levels were monitored at Fagan from July 2010 - June 2011. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. We found MHW was at 1.75 m and mean higher high water (MHHW) at 1.90 m for the site (NAVD88). Inundation patterns throughout the year were recorded to evaluate seasonal patterns. The salt marsh platform (defined as mean elevation) was inundated most often in June 2011 (Fig. H-5).

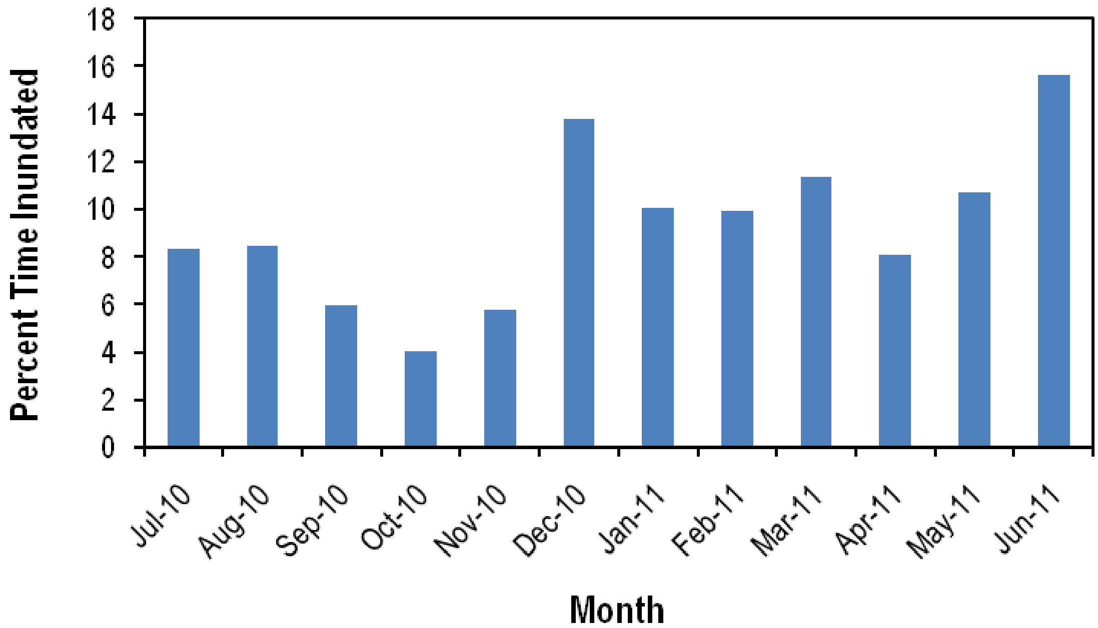

Figure H-5. Percent of time Fagan was inundated monthly. Based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER projects that Fagan will not keep pace with local SLR through this century. WARMER results show a gradual reduction in elevation relative to MHW through the century, with a more dramatic decline after 2060 (Fig. H-6). By 2090 Fagan is projected to be under mean sea level (MSL), therefore transition to a mudflat (Fig. H-7).

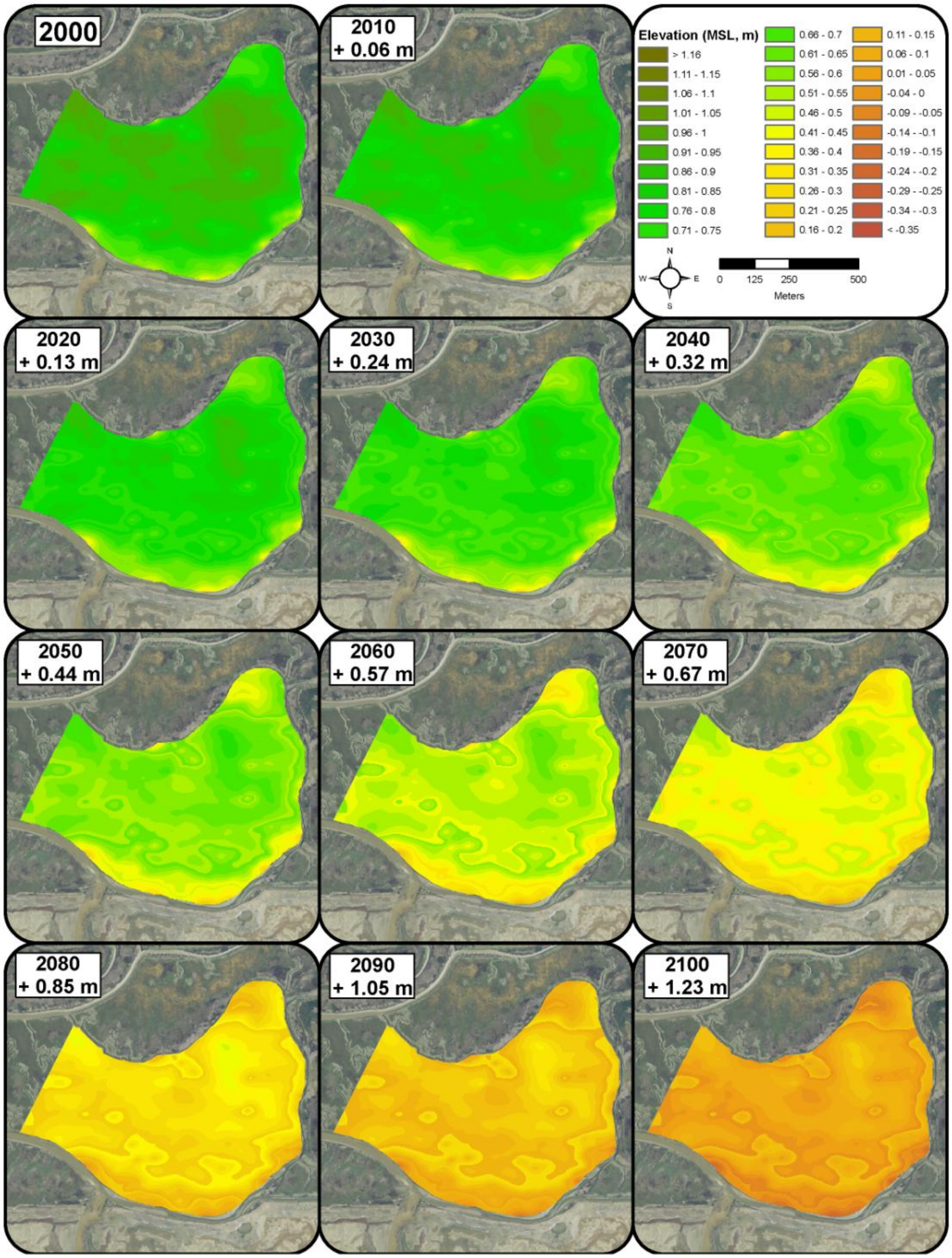

Figure H-6. WARMER results for Fagan. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

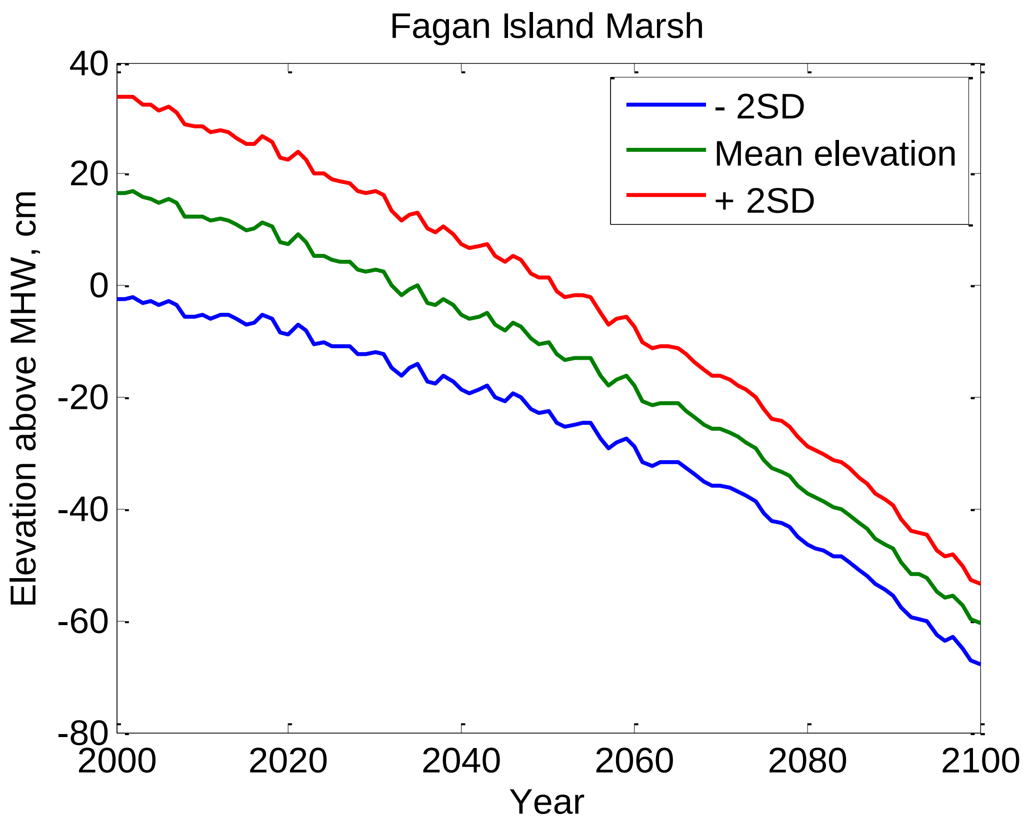

Figure H-7. WARMER scenarios for Fagan elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. H-8 – H-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina spp.* Currently, Fagan is roughly 90% high marsh habitat. The amount of high marsh is projected to steadily decline until 2060 (+ 0.57 m SLR) at which point all high marsh transitions to mid and low marsh. A transition to mud flat is projected by 2090 (+ 1.05 m SLR).

The WARMER model parameters for Fagan were extrapolated using sediment core data from Coon Island, thus predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentrations to characterize sediment deposition potential.

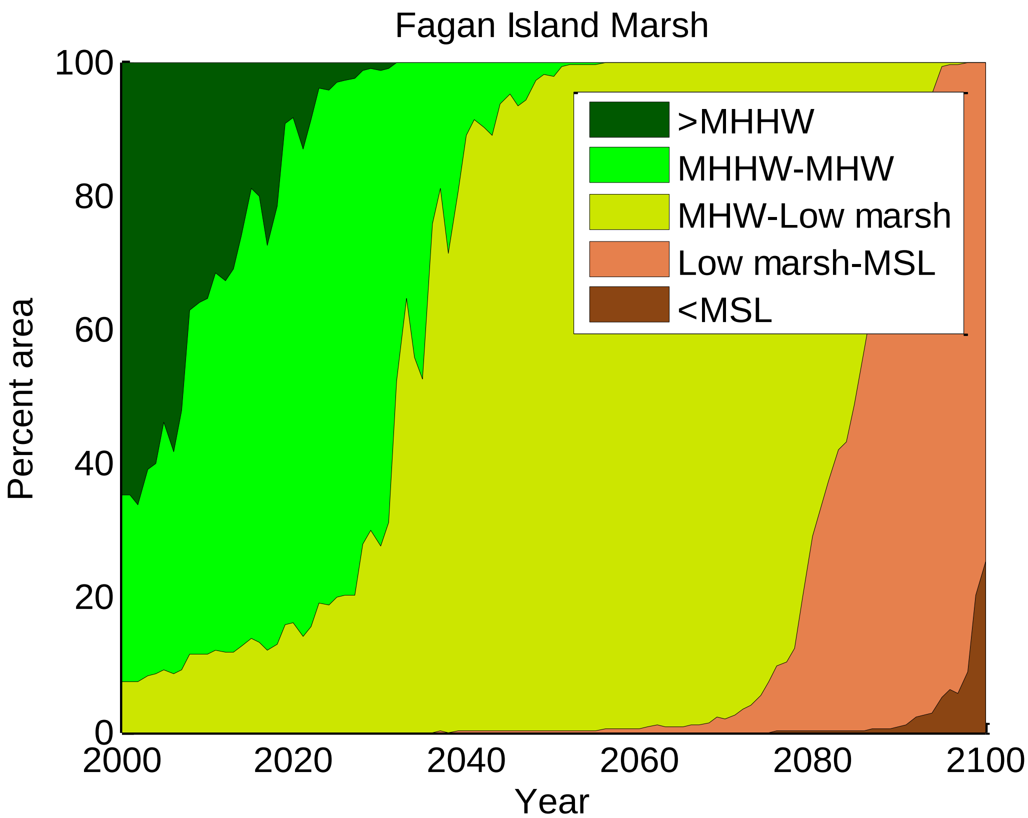

Figure H-8. Area of Fagan within a given tidal range for the duration of the simulation period.

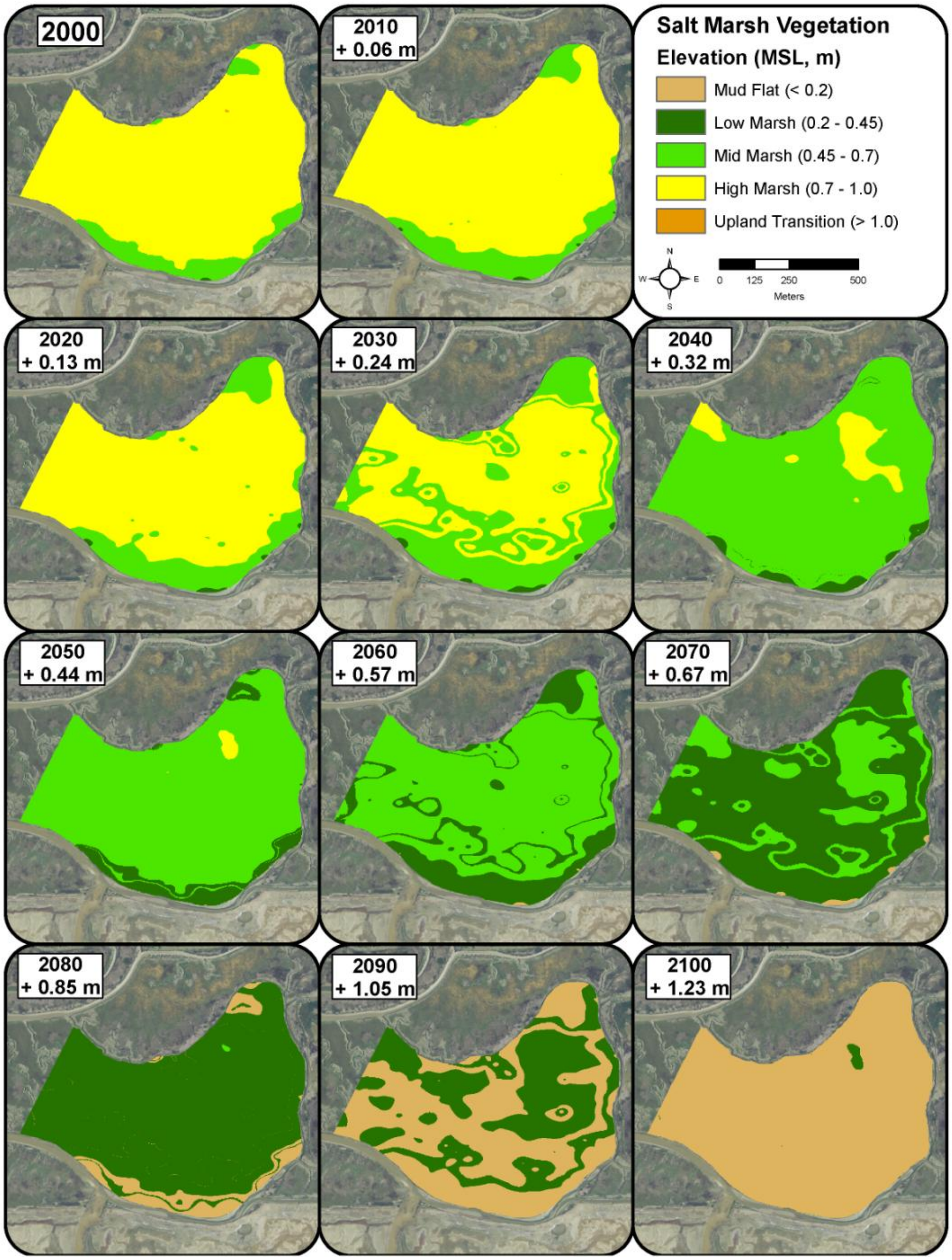

Figure H-9. Fagan WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix I

Gambinini Marsh

Introduction

Gambinini marsh (hereafter Gambinini) is privately owned and located in Sonoma County, along the Petaluma River at the northern tip of the Petaluma marsh complex. The Petaluma marsh complex is the largest marsh in California that has never been diked or drained for agriculture. Due to its proximity to the Petaluma River, Gambinini is influenced by flow from the Petaluma River as well as tidal flow from San Pablo Bay. This marsh is surrounded by oak woodlands and light grazing. This marsh provides important habitat for species of concern including the California black rail (*Laterallus jamaicensis*).

This study focused on 24.8 ha of Gambinini. Elevation and vegetation surveys were conducted in winter of 2009 using an RTK GPS. To monitor tidal inundation and salinity, two water level loggers were deployed between 2009 - 2010.

Results

Elevation surveys

A total of 217 elevation measurements were taken at Gambinini (Fig. I-1). The elevation range was 1.27 - 2.10 m with a mean of 1.86 m (NAVD88). Over half (70%) of the survey points fell within 1.80 - 1.95 m, with a 0.15 m range (Fig. I-2). The majority (81%) of survey points were located at elevations above mean high water (MHW). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. I-3).

This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

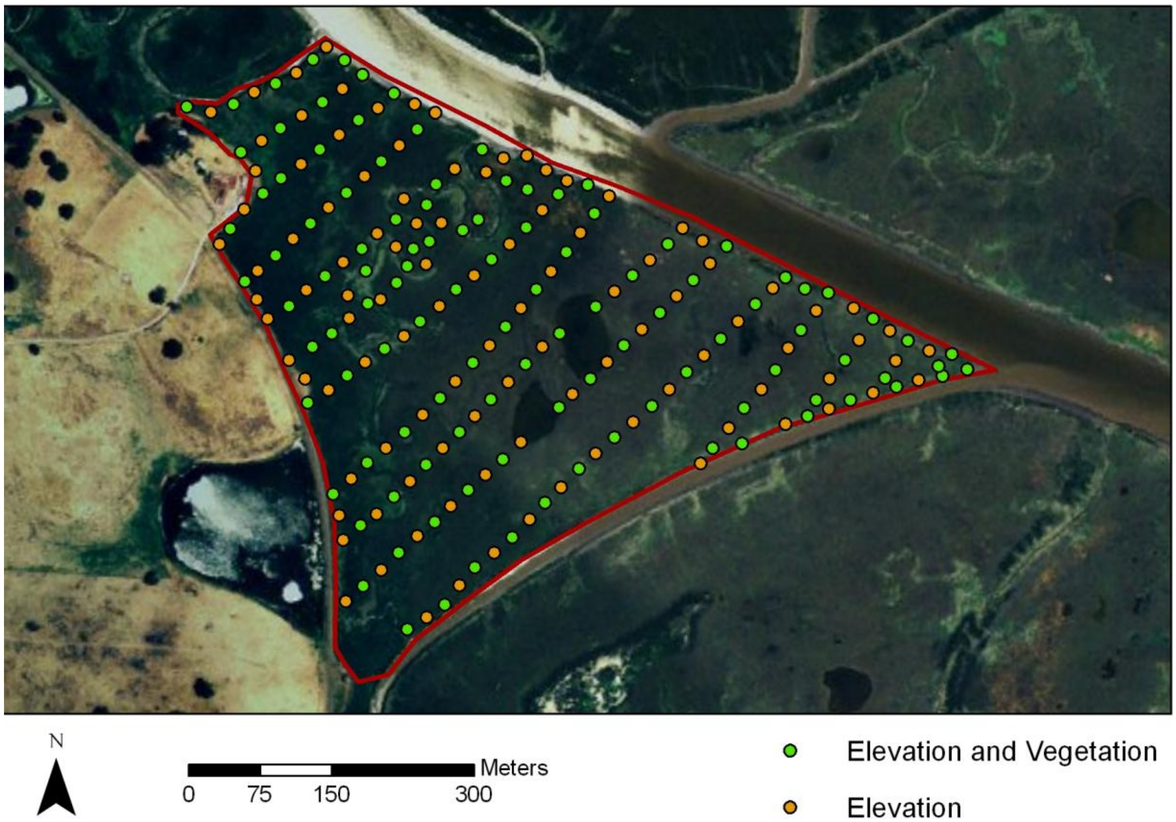

Figure I-1. Gambinini marsh with elevation and vegetation survey points taken in 2009.

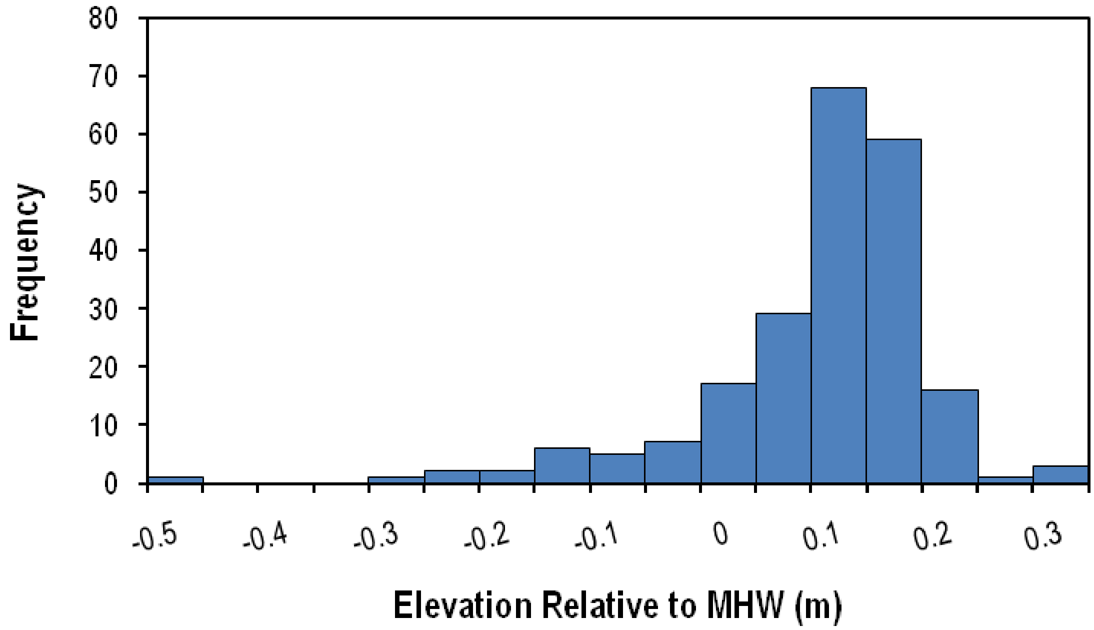

Figure I-2. Distribution of elevation samples relative to local mean high water (MHW) at Gambinini marsh.

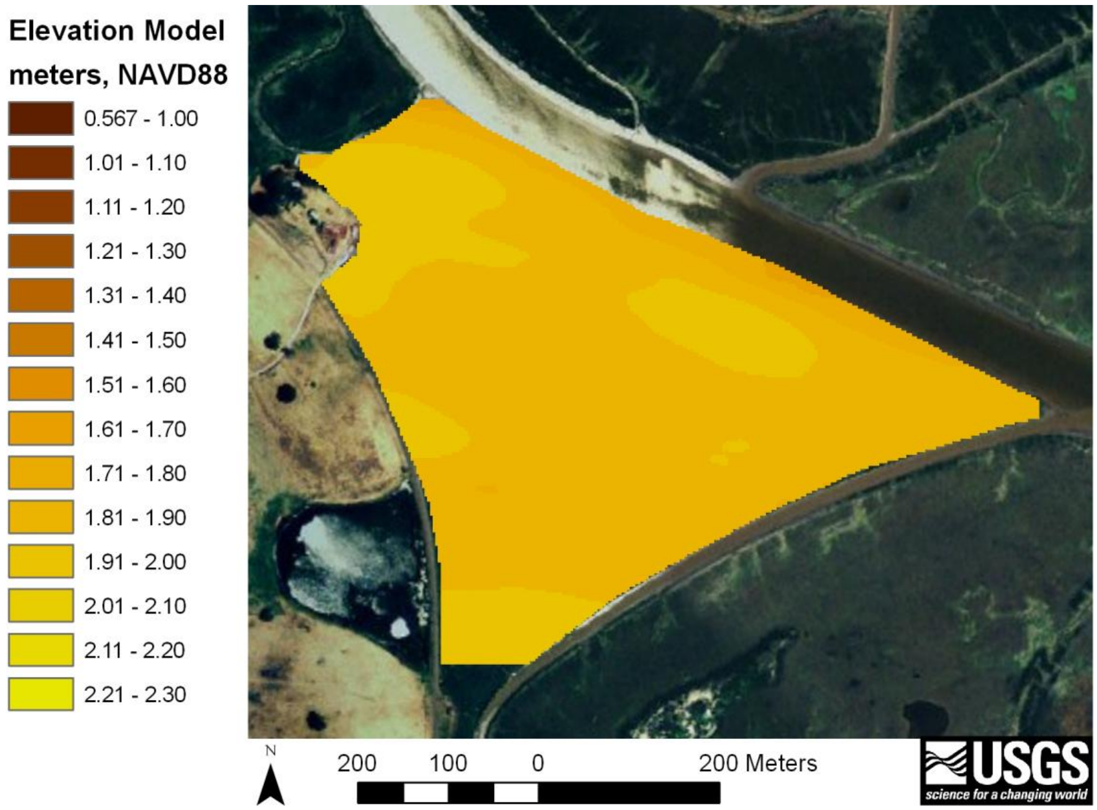

Figure I-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed at Gambinini concurrently with elevation surveys in October of 2009. A total of 110 locations (Fig. I-1) were measured for vegetation composition, height (cm), and percent cover (Table I-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, a stratification of vegetation species relative to MHW (Fig. I-4) was observed within this low slope marsh.

Table I-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Gambinini.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.06	0.10	27.83	9.58	40.46	11.82	87.50	23.70	109	99.09
Schoenoplectus spp.	-0.10	0.14	27.50	15.20	33.25	19.96	14.00	17.72	4	3.64
Grindelia stricta	-0.03	0.06	45.00	20.00	60.40	27.26	26.20	37.48	5	4.55
Jaumea carnosa	-0.03	-	12.00	-	17.00	-	75.00	-	1	0.91
Frankenia salina	0.11	0.09	25.00	2.08	30.57	5.97	28.29	22.60	7	6.36
Distichlis spicata	0.13	0.06	15.78	4.79	20.78	4.74	33.22	31.29	9	8.18
Lepidium latifolium	0.07	0.08	87.53	30.30	104.00	30.67	23.24	19.41	17	15.45

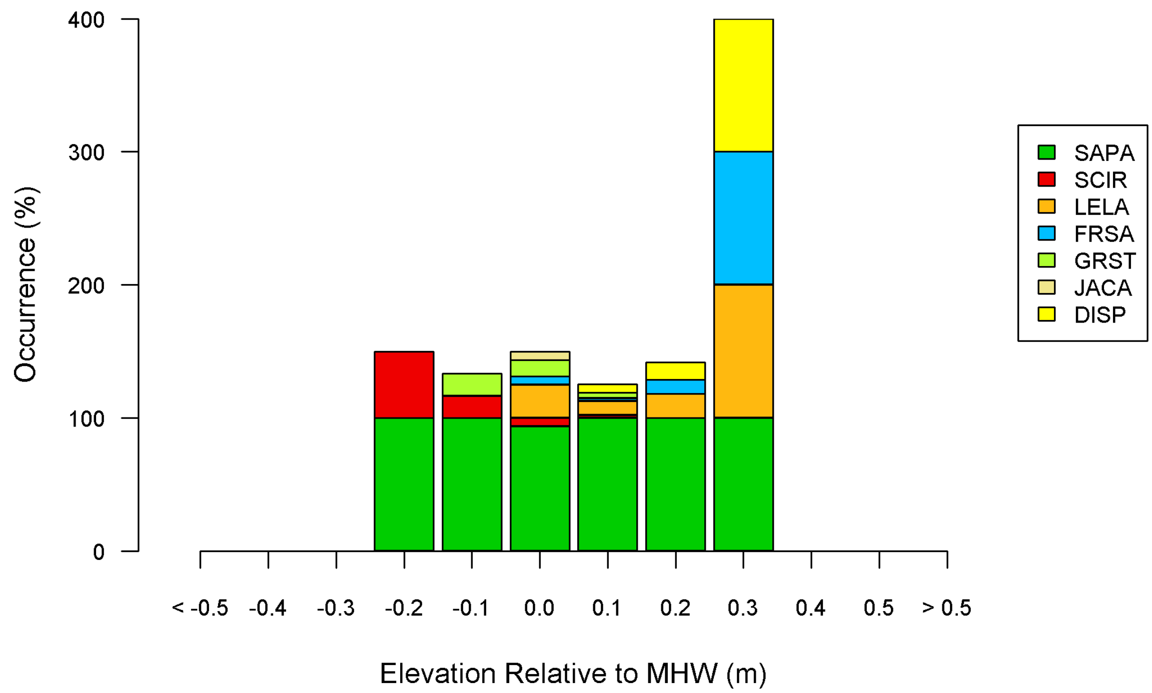

Figure I-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus* spp.*;* LELA = *Lepidium latifolium*; FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Water level monitoring

Site-specific water level was monitored between December 2009 and November 2010; data was unavailable for August 2010 due to equipment failure. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. We found MHW was at 1.80 m and mean higher high water (MHHW) at 1.96 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean elevation) was inundated most often in January 2010 (Fig. I-5). January recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in

January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform. Mean salinity during 2010 at Gambinini was 12.8 (SD = 8.2) PSS.

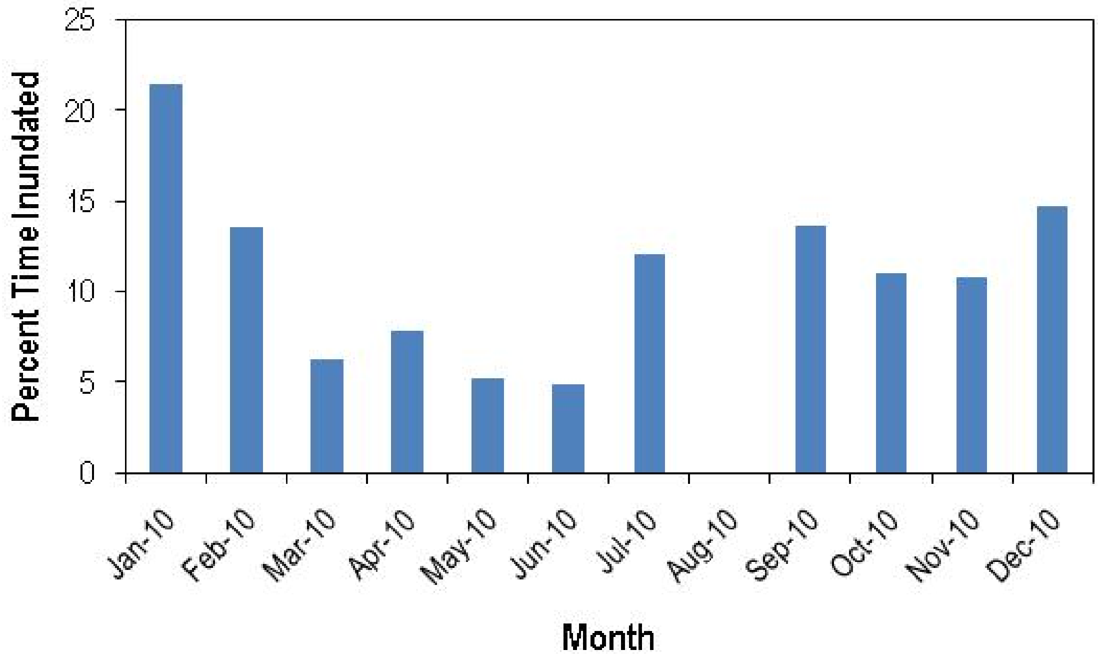

Figure I-5. Percent of time Gambinini was inundated monthly, based on the mean elevation of the marsh platform. Data were not available for August due to equipment failure.

Marsh elevation modeling

WARMER results indicate that Gambinini is unlikely to keep pace with local SLR through this century. Initial elevation was relatively high compared to other study sites, however, results show a gradual reduction in elevation relative to MHW through the century, with a more dramatic decline after 2080 (Fig. I-6). By 2080 the marsh is projected to be under mean sea level (MSL) and will function as a mudflat (Fig. I-7).

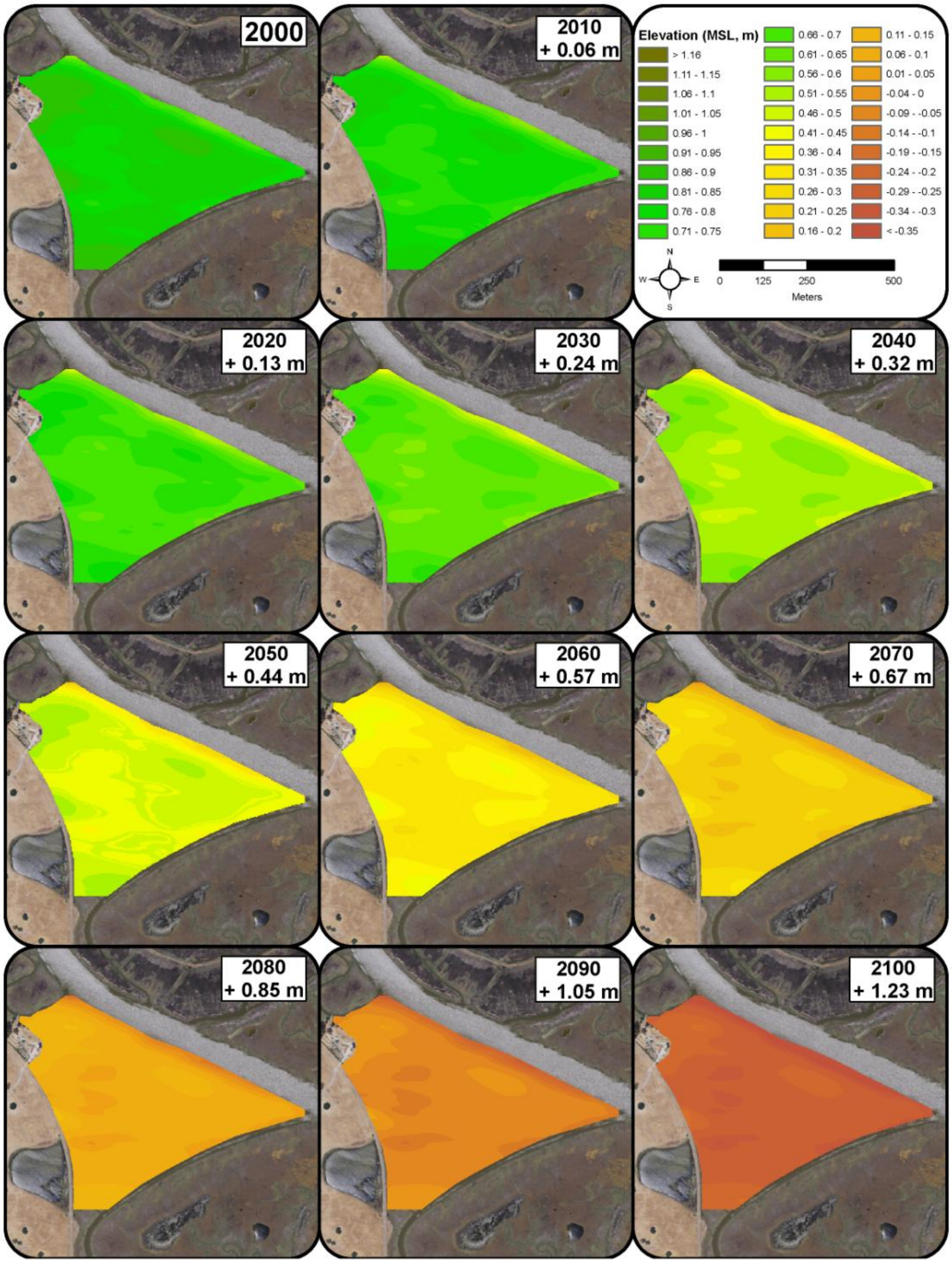

Figure I-6. WARMER results for Gambinini. WARMER accounts for changes in relative sea-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

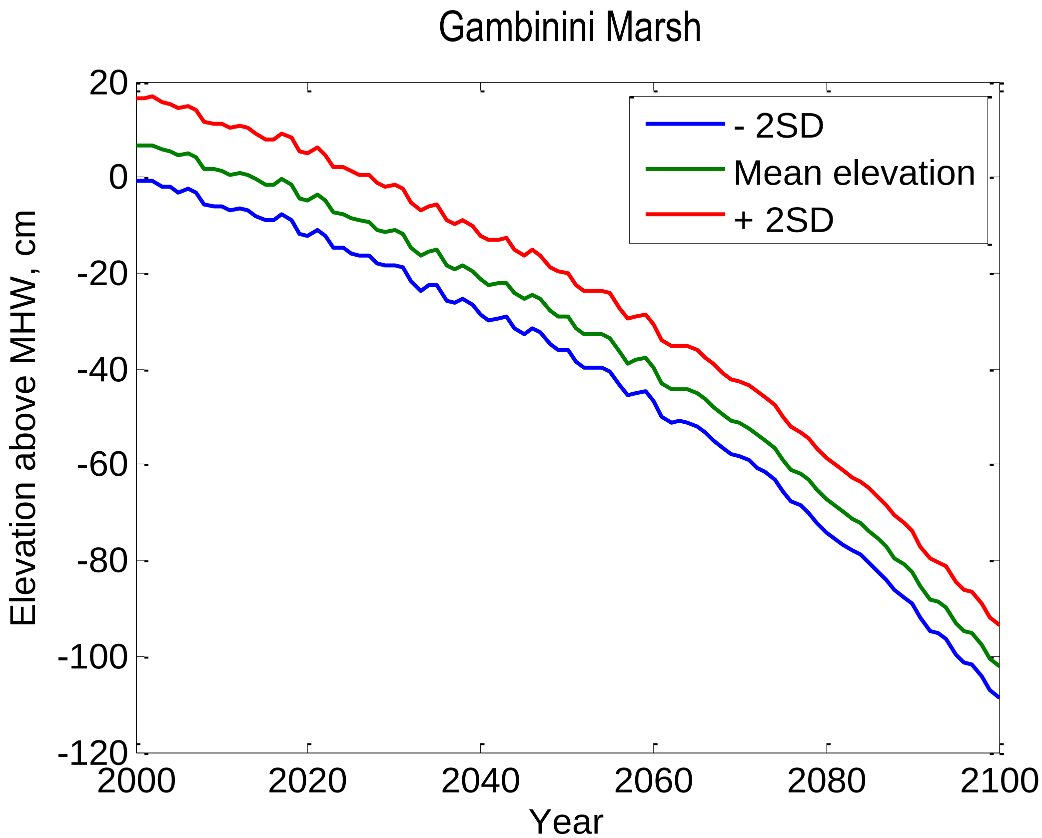

Figure I-7. Modeled scenarios of marsh elevation change for Gambinini. Elevation above MHW is plotted versus model year.

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities and used to interpret the WARMER SLR results (Figs. I-8 – I-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina spp.* Currently, Gambinini is primarily comprised of high and mid marsh plant communities. WARMER showed a steady decline in the amount of high marsh beginning in 2020 (+ 0.06 m SLR). By 2040 (+ 0.32 m SLR) all high marsh is projected to transition to mid marsh. By 2060 (+ 0.57 m SLR) most of Gambinini is projected to be low marsh and by 2080 (+ 0.85 m SLR) WARMER projects that the entire marsh will be below MSL and transition to a mudflat.

The WARMER model parameters for Gambinini were extrapolated using sediment core data from Petaluma Marsh, thus predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. In addition, quality control issues with the Petaluma sediment cores resulted in the removal of data that indicated high sedimentation rates. The Petaluma River is a major source of sediment to San Francisco Bay, thus it is likely that the inputs to WARMER are underestimating accretion potential. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentrations to characterize sediment deposition potential.

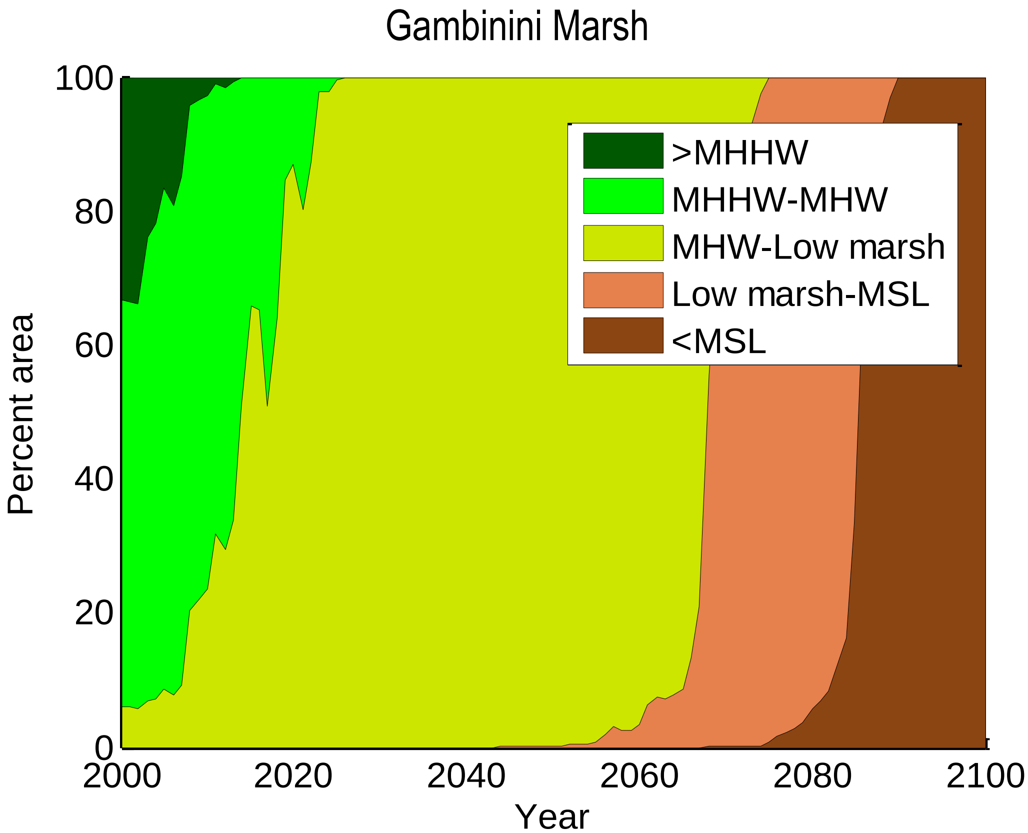

Figure I-8. Area of Gambinini within a given tidal range for the duration of the simulation period.

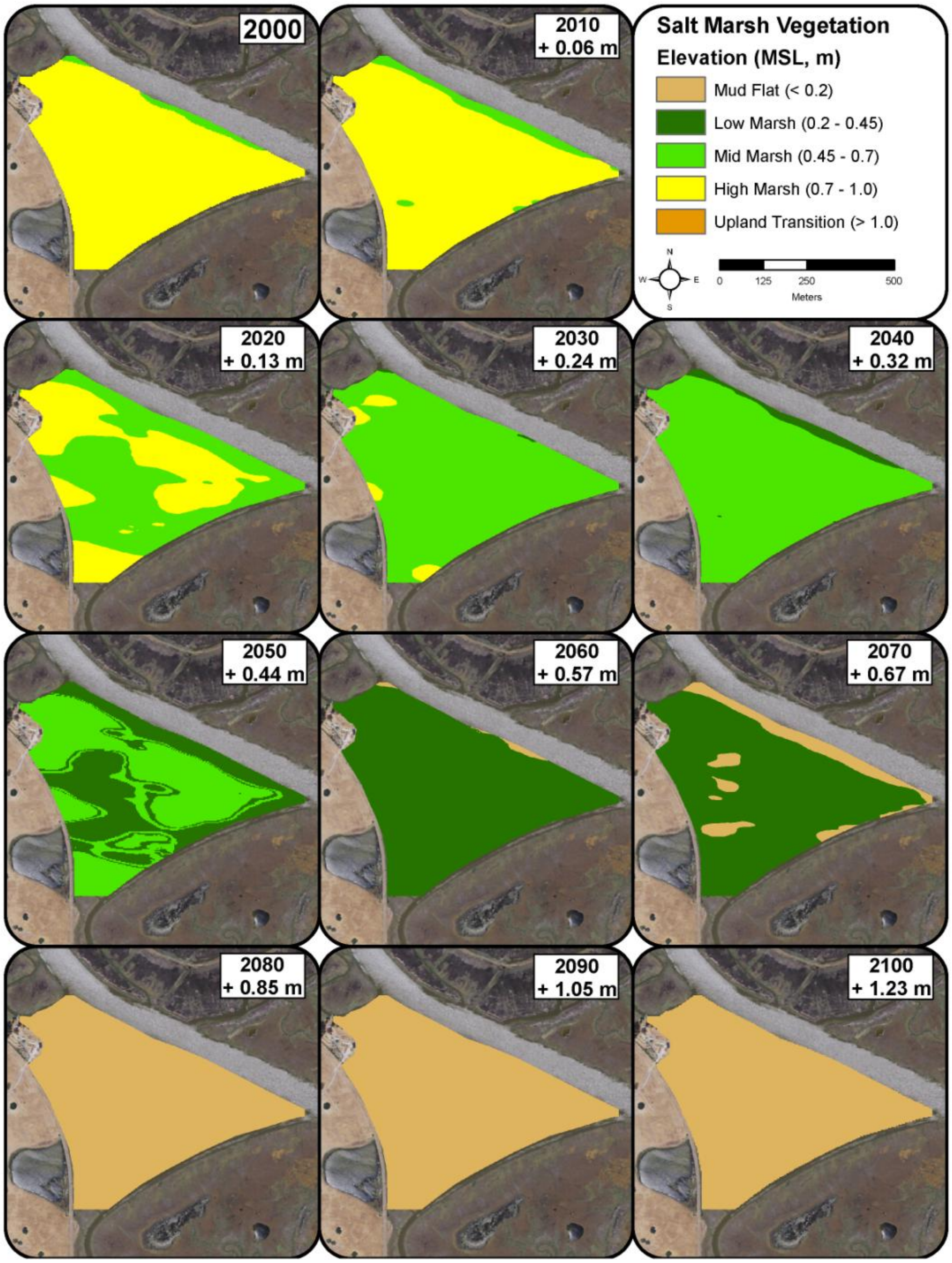

Figure I-9. Gambinini WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix J

Laumeister Marsh

Introduction

Located in south San Francisco Bay in Santa Clara county, Laumeister Marsh (hereafter Laumeister) is owned by the City of Palo Alto. It is managed by the U.S. Fish and Wildlife Service as part of Don Edwards National Wildlife Refuge which is the largest refuge in SFBE. Laumeister is recognized as an important stopover on the Pacific Flyway and is home for endangered species such as the California clapper rail (*Rallus longirostris obsoletus*).

The focus of this study was on 36.8 ha at Laumeister marsh. Elevation and vegetation surveys were done in 2009 - 2010 using an RTK GPS. To monitor tidal inundation and salinity, two water level loggers were deployed between 2009 - 2010.

Results

Elevation surveys

A total of 717 elevation measurements were taken at Laumeister (Fig. J-1). The elevation range was 1.15 - 2.20 m with a mean of 1.98 m (NAVD88). Over half (53%) of the survey points fell within 1.95 - 2.05 m, with a 0.1 m range. A majority (86%) of the survey points were located at elevations above mean high water (MHW; Fig J-2). Laumeister was the second highest marsh surveyed in this study. A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. J-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

Figure J-1. Laumeister Marsh with elevation and vegetation survey points taken in 2009 and 2010.

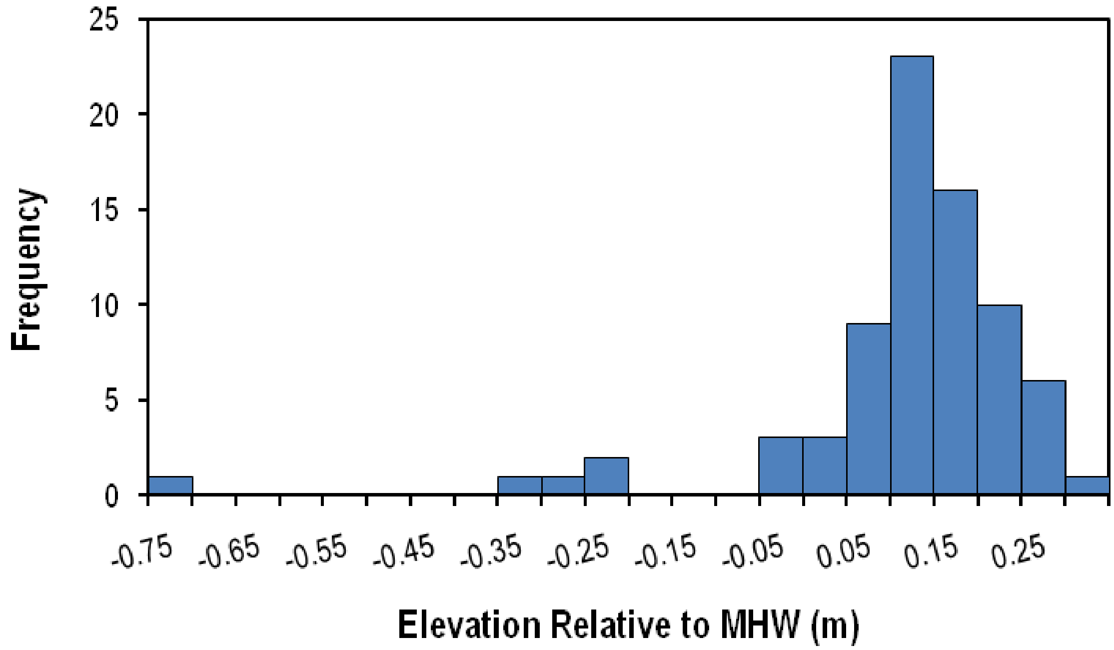

Figure J-2. Distribution of elevation samples relative to local mean high water (MHW) at Laumeister Marsh.

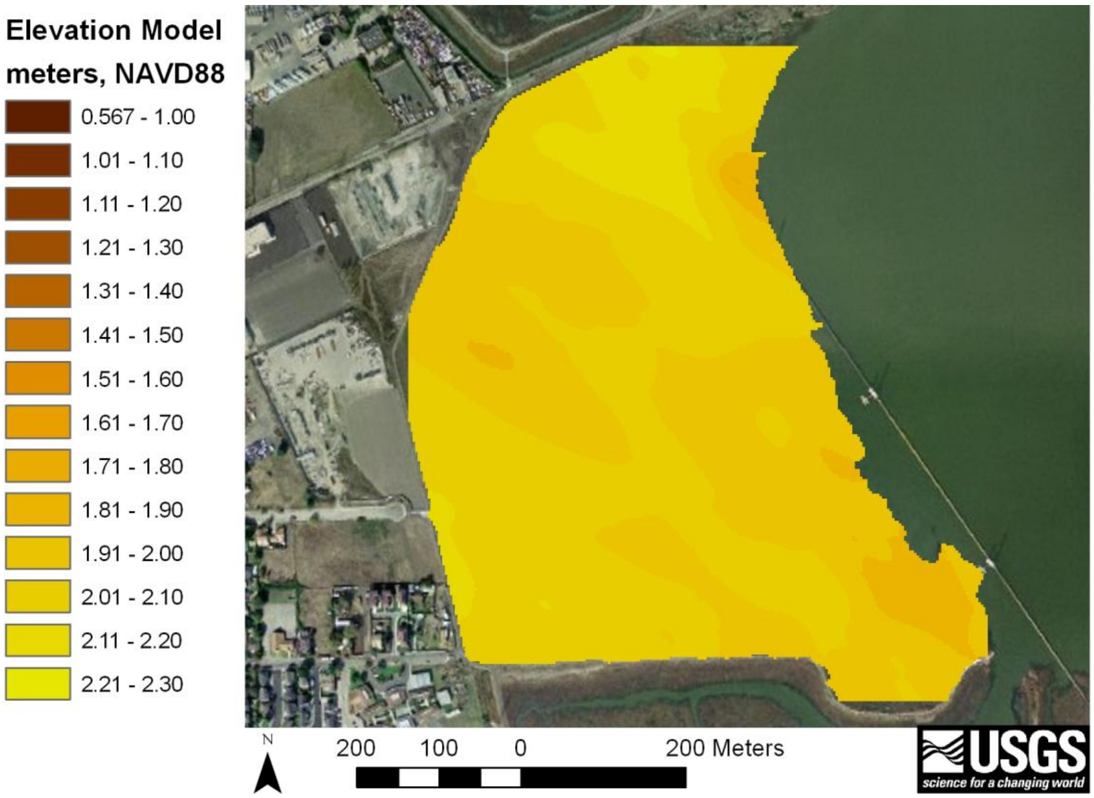

Figure J-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation was surveyed concurrently with elevation in 2010. A total of 72 locations (Fig. J-1) were surveyed for vegetation composition, height (cm), and percent cover (Table J-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, stratification of vegetation species relative to MHW (Fig. J-4) was observed within this low slope marsh.

Table J-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Laumeister.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.07	0.15	29.95	7.59	39.34	8.60	72.42	34.57	62	86.11
Spartina spp.	0.00	0.14	57.56	12.86	68.78	11.35	28.41	31.28	27	37.50
Grindelia stricta	0.08	0.21	64.20	12.97	72.20	14.76	27.10	31.09	20	27.78
Jaumea carnosa	0.08	0.07	14.67	4.04	21.33	2.89	55.00	37.75	3	4.17
Frankenia salina	0.25	-	30.00	-	33.00	-	30.00	-	1	1.39
Distichlis spicata	0.08	0.17	23.69	6.07	32.76	6.87	57.41	30.61	29	40.28
Lepidium latifolium	-0.08	0.46	28.50	7.85	44.00	6.73	46.25	44.98	4	5.56

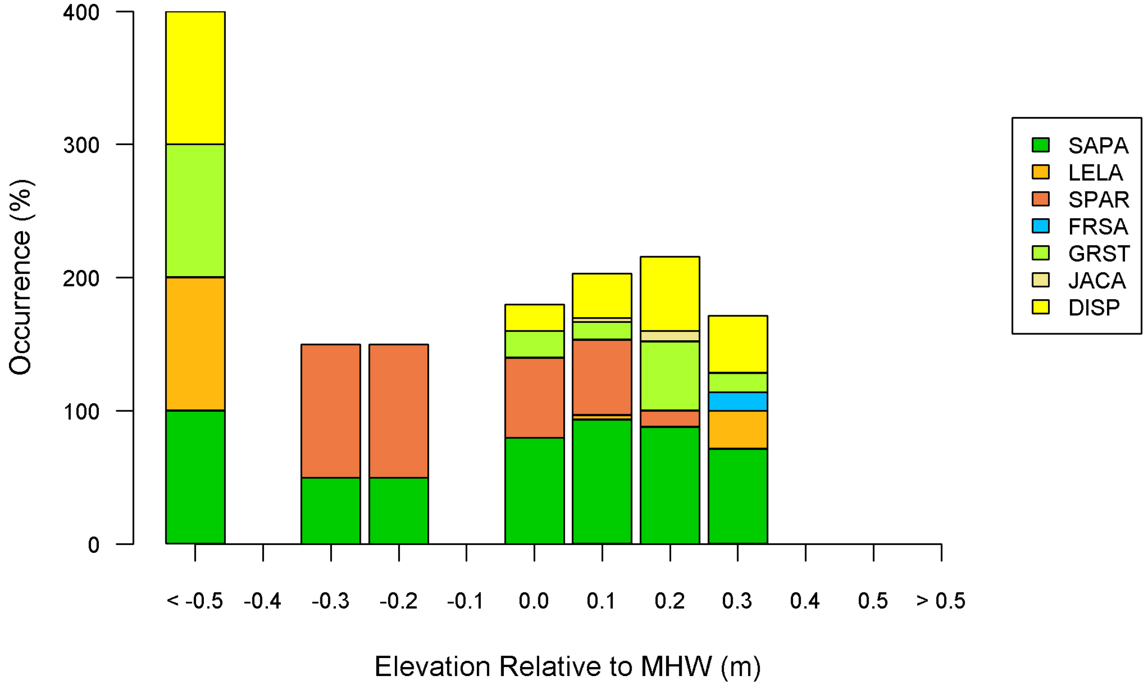

Figure J-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.; FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Water level monitoring

Site-specific water level was monitored for one year in December 2009 – May 2010. Water level was measured using two data loggers deployed at the mouth of a second order channel and in the marsh interior. Water levels throughout the year were recorded to evaluate seasonal patterns in tides. We found MHW was at 1.92 m and mean higher high water (MHHW) at 2.09 m for the site (NAVD88). The marsh platform (defined as mean elevation) was inundated most often from December 2009 through February 2010 (Fig. J-5). Those months recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform. Mean salinity during 2010 at Laumeister was 13.4 (SD = 7.9) PSS.

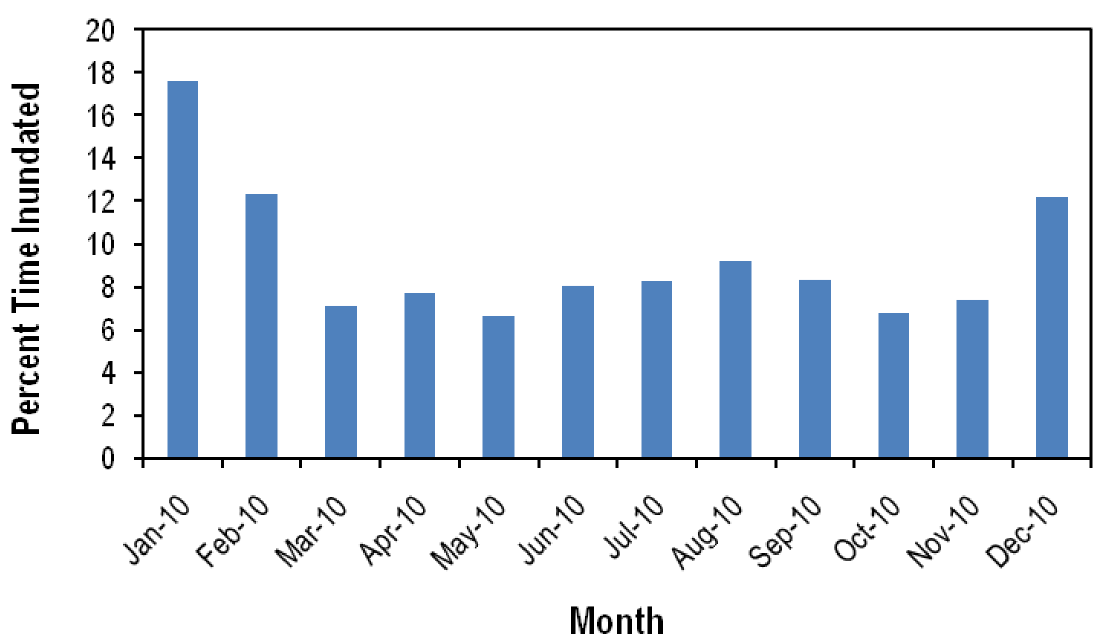

Figure J-5. Percent of time Laumeister was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

Laumeister had high initial elevation and accretion rates which allowed it sustain marsh elevation longer than other study sites. Despite this, WARMER results indicate that Laumeister will not keep pace with local SLR through this century. WARMER results show a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060; by 2050 the marsh is projected to be below MHW (Fig. J-6). By 2100, Laumeister is projected to remain ~ 0.4 m above mean sea level (MSL; Fig. J-7).

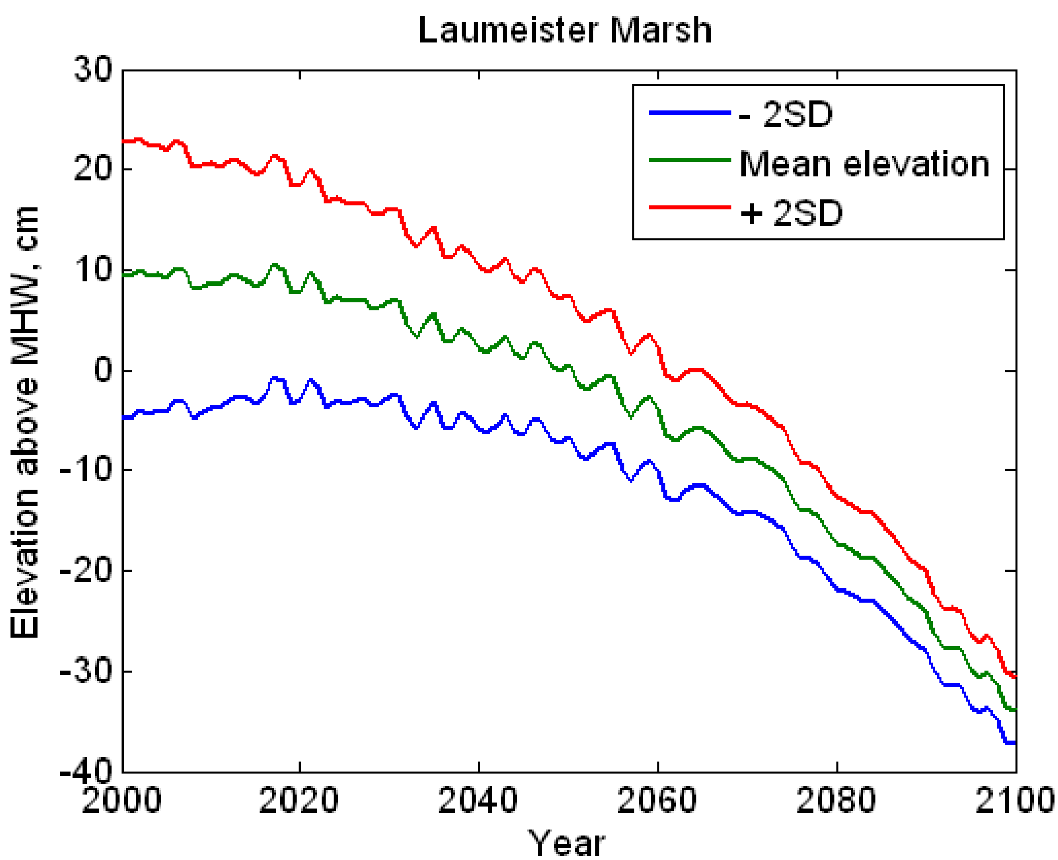

Figure J-6. WARMER scenarios of marsh elevation change for Laumeister. Elevation above MHW is plotted versus model year with two standard deviations (SD).

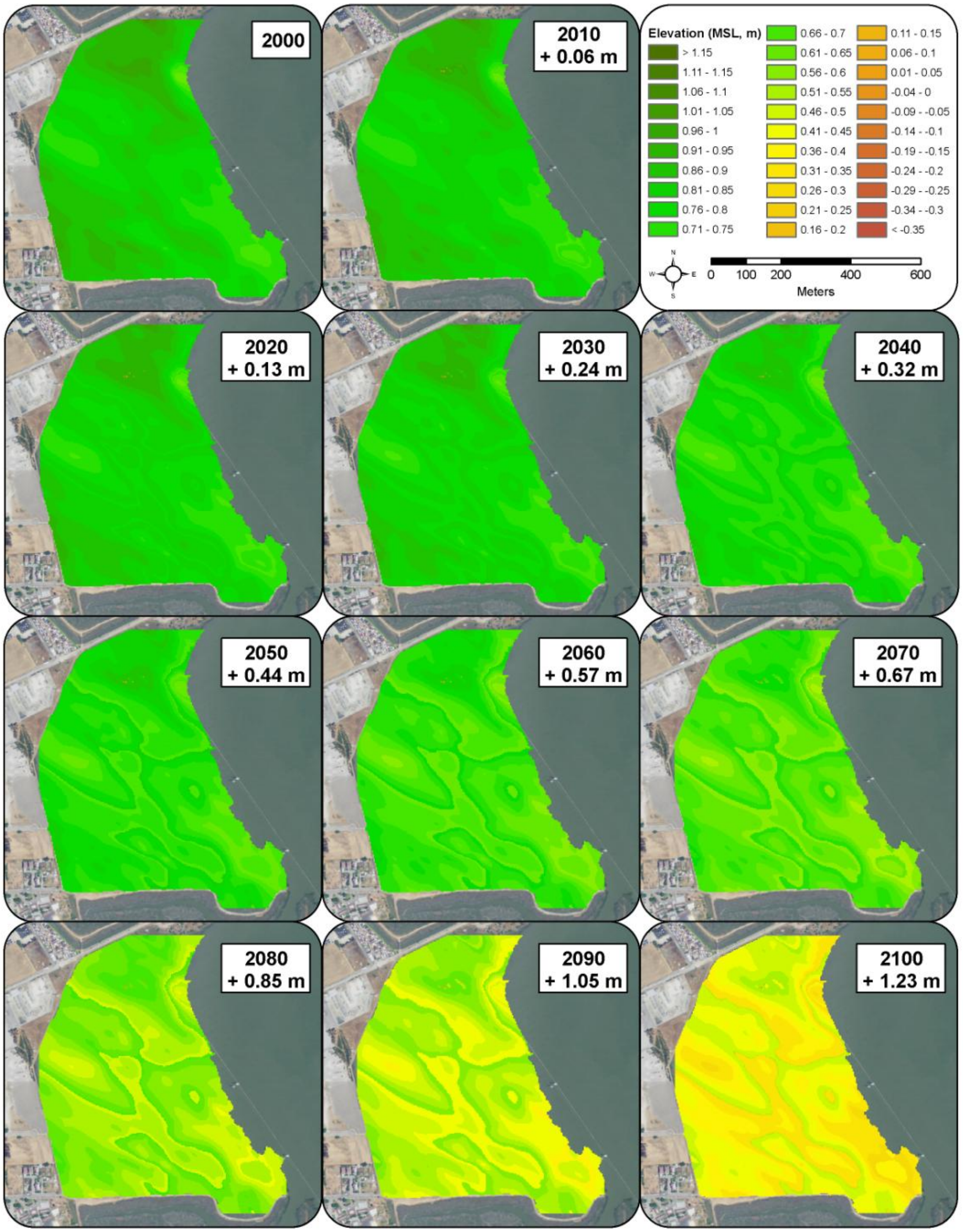

Figure J-7. WARMER results for Laumeister. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Thus, vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. J-8 – J-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently, Laumeister is primarily comprised of high marsh vegetation and low marsh dominated with *Spartina*. Model results show that high accretion rates, due in part to high suspended sediment concentrations in south San Francisco Bay, will sustain high marsh habitat through 2060 (+ 0.57 m SLR). Once the rate of sea-level rise increases in the second half of the century, Laumeister will begin to lose relative elevation and transition to predominantly mid marsh habitat by 2080 (+ 0.85 m SLR). By 2100, Laumeister transitions predominantly to low marsh habitat (+ 1.23 m SLR).

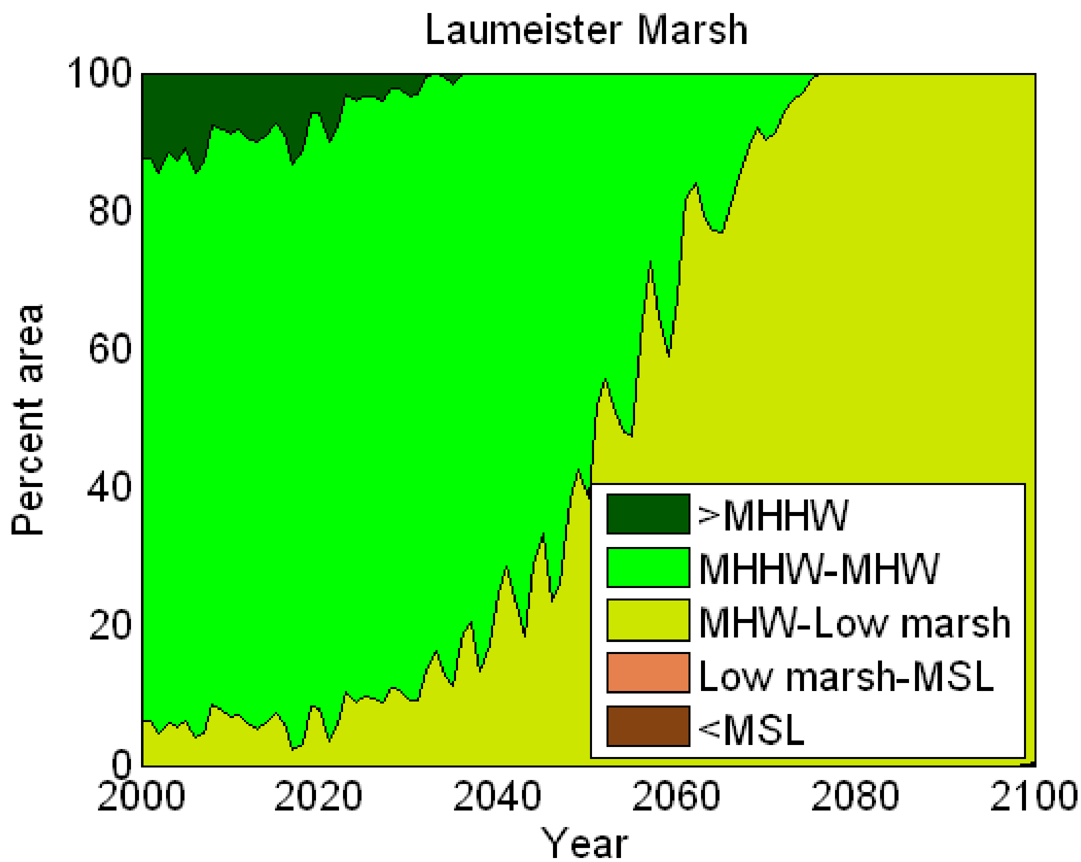

Figure J-8. Area of Laumeister within a given tidal range for the duration of the simulation period.

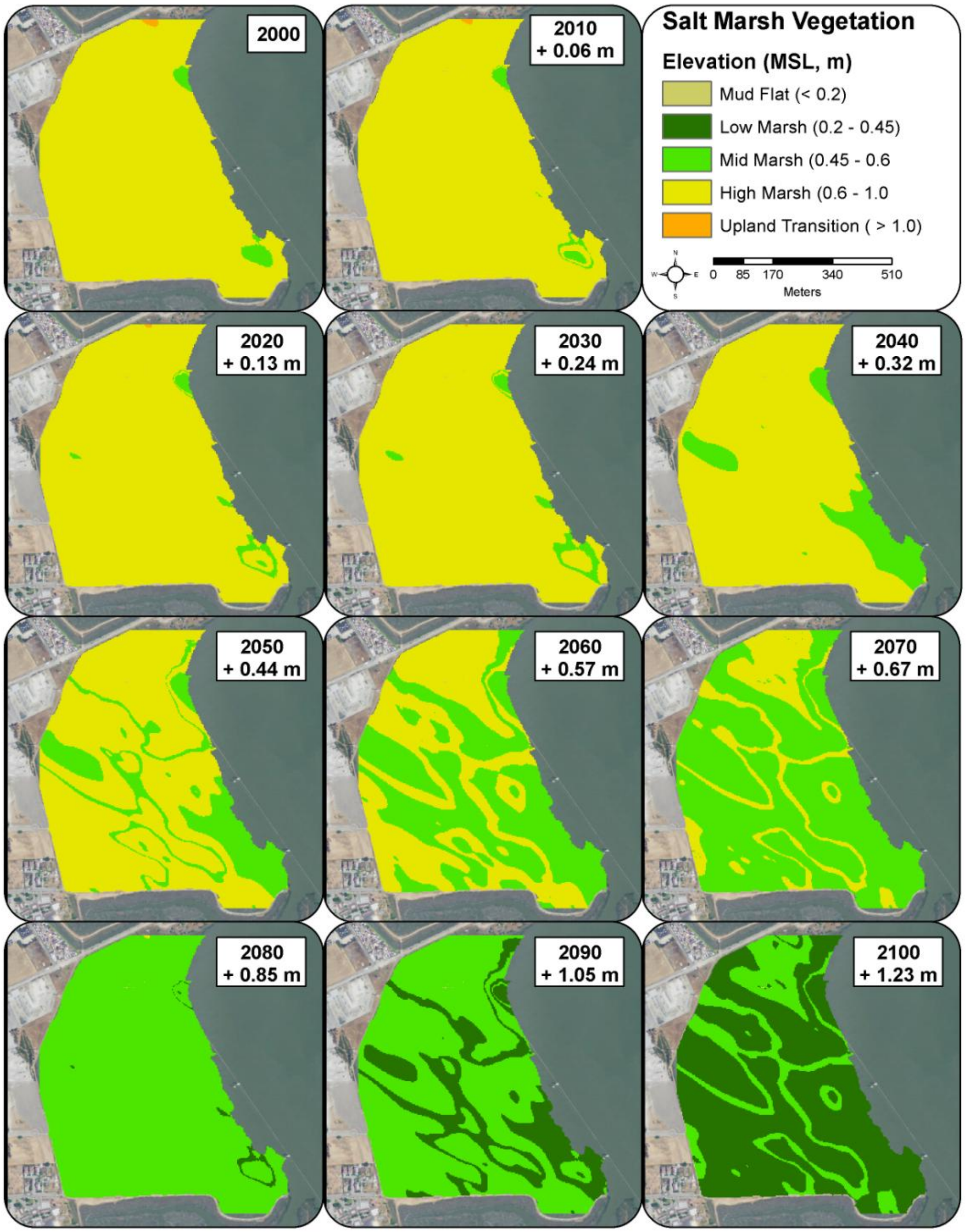

Figure J-9. Laumeister WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix K

Petaluma Marsh

Introduction

Petaluma Marsh (hereafter Petaluma) is located in Sonoma County on the Petaluma River and adjacent to Petaluma Slough. It is owned and managed by the California Department of Fish and Game. Petaluma is influenced by tidal flow from San Pablo Bay as well as freshwater flow from the Petaluma River. This site is part of the largest remaining natural tidal salt marsh in California and is recognized as an important habitat for many state listed species, such as the California black rail (*Laterallus jamaicensis*), and federally endangered species, such as salt marsh harvest mouse (*Reithrodontomys raviventris*).

This study focused on 80.6 ha of Petaluma marsh. Elevation and vegetation surveys were conducted in 2009 using an RTK GPS. To monitor tidal inundation and salinity, four water level loggers were deployed in 2009.

Results

Elevation surveys

A total of 655 elevation measurements were taken at Petaluma (Fig. K-1). The elevation range was 0.87 - 2.28 m with a mean of 1.82 m (NAVD88). Petaluma was one of the highest elevation marshes surveyed. Nearly three-fourths (74.8%) of the survey points were within 1.75 - 1.90 m, within a 0.15 m range (Fig. K-2). The majority (89%) of survey points were located at elevations above mean high water (MHW). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the Kriging method (Fig. K-3). This baseline elevation model was used as the initial state in the WARMER sea-level rise model; WARMER results were extrapolated across the elevation model.

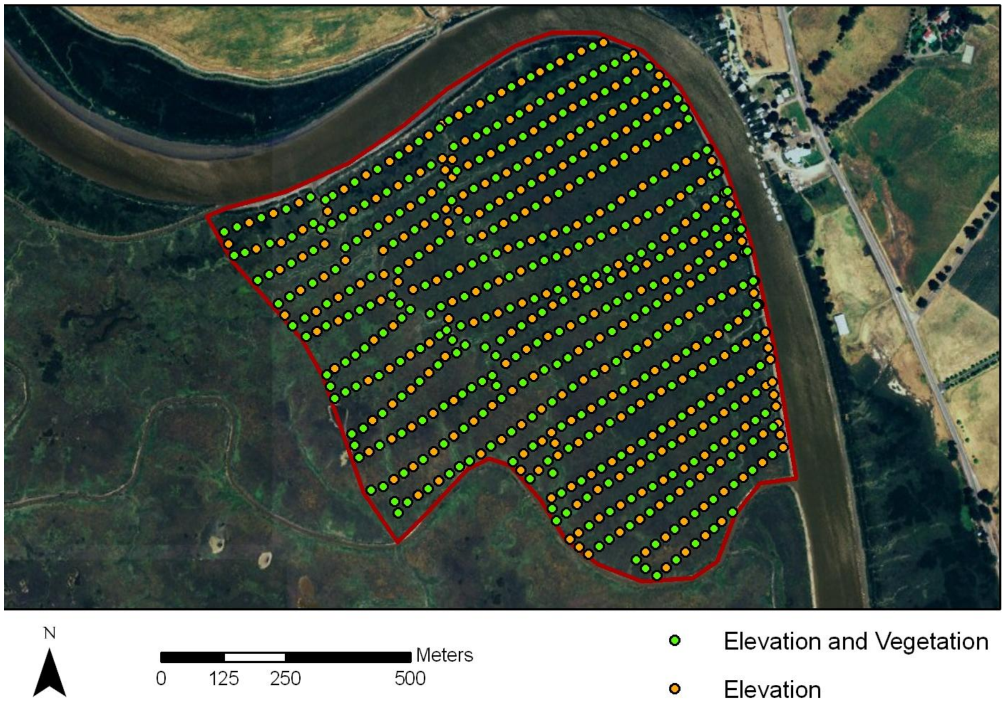

Figure K-1. Petaluma Marsh with elevation and vegetation survey points taken in 2009.

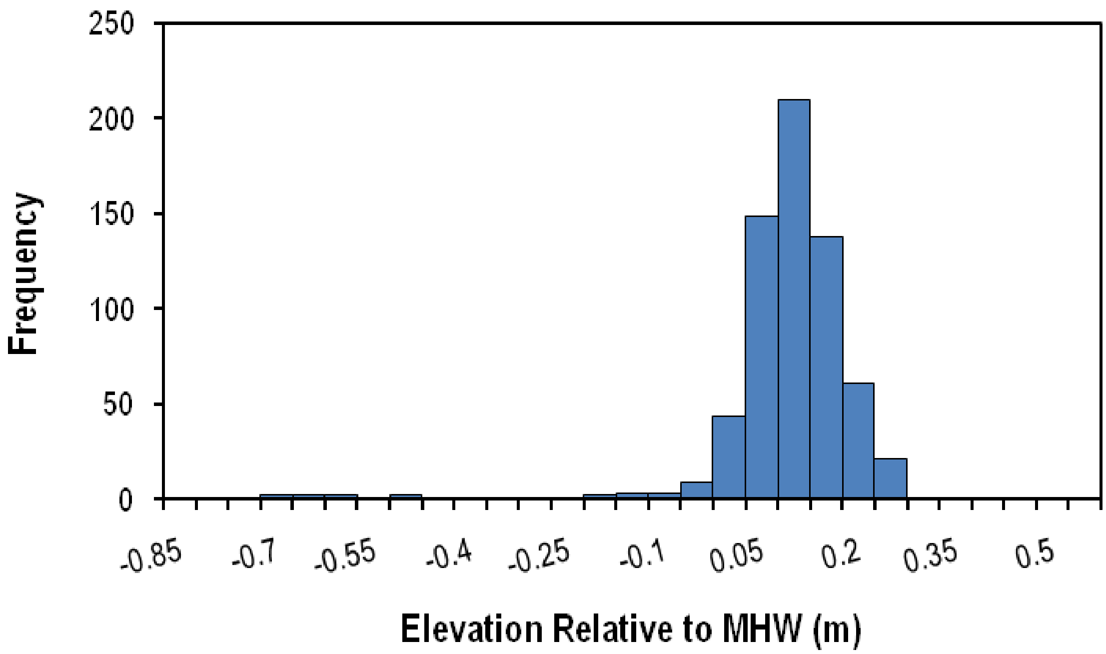

Figure K-2. Distribution of elevation samples relative to local mean high water (MHW) at Petaluma Marsh.

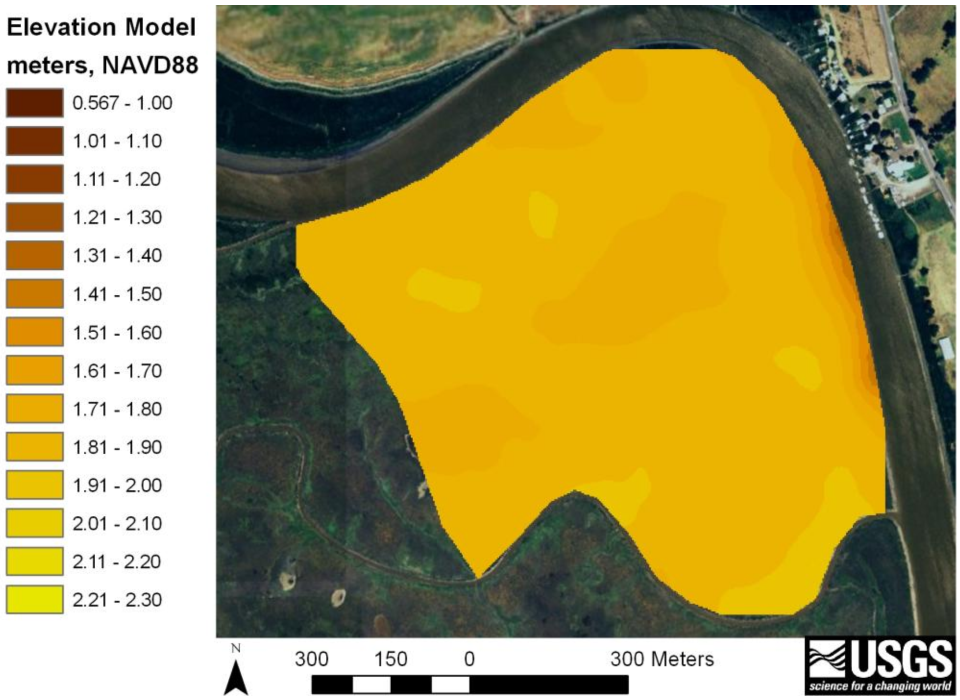

Figure K-3. Elevation model (3-m resolution) developed from ground RTK GPS elevation data.

Vegetation surveys

Vegetation and elevation surveys were done concurrently in October - November of 2009. A total of 357 locations (Fig. K-1) were measured for vegetation composition, height (cm), and percent cover (Table K-1). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, stratification of vegetation species relative to MHW (Fig. K-4) was observed within this low slope marsh.

Table K-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at Petaluma.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.08	0.07	39.82	10.98	49.22	11.30	84.53	24.69	345	96.91
Schoenoplectus spp.	-0.07	0.24	63.04	26.68	71.57	30.38	15.04	14.43	23	6.46
Grindelia stricta	0.11	0.07	66.22	21.25	75.67	24.71	25.06	18.94	18	5.06
Jaumea carnosa	0.06	0.05	16.97	5.32	20.40	6.51	21.05	21.95	62	17.42
Frankenia salina	0.11	0.06	31.20	8.16	35.80	8.50	47.02	33.15	46	12.92
Distichlis spicata	0.04	0.04	21.18	5.38	24.82	6.03	20.27	22.38	33	9.27
Lepidium latifolium	0.11	0.08	96.22	18.89	106.06	18.63	24.94	16.54	36	10.11
Baccharis pilurais	0.30	0.19	71.67	38.84	84.00	35.68	55.00	39.69	3	0.84

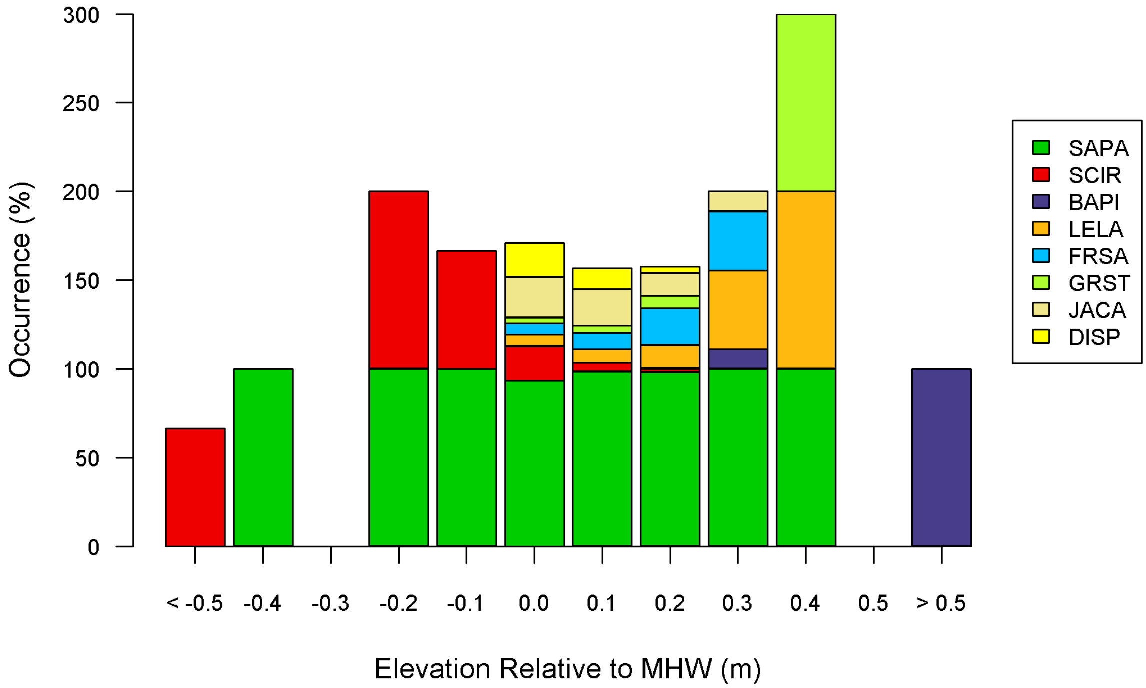

Figure K-4. Stratification of vegetation species was observed relative to MHW. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus* spp.*;* BAPI = Baccaris pilularis; LELA = *Lepidium latifolium*; FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*.

Water level monitoring

Site-specific water level was monitored for one year from December 2009 – May 2010. Water level was measured using four data loggers deployed at the mouth of a second order channels and in the marsh interior. Water levels throughout the year were recorded to evaluate seasonal patterns in tides. We found MHW was at 1.76 m and mean higher high water (MHHW) at 1.92 m for the site (NAVD88). The marsh platform (defined as mean elevation) was inundated most often from January 2010 through February 2010 (Fig. K-5). Those months recorded above average water levels due to several record breaking storms that brought low air pressure and substantial rainfall, resulting in higher than predicted tides. The cumulative rainfall in January 2010 was above average throughout the San Francisco bay area and daily rainfall records were broken in some locations (NOAA). This resulted in longer inundation periods of the marsh platform. Mean salinity during 2010 at Petaluma was 14.4 (SD = 8.3) PSS.

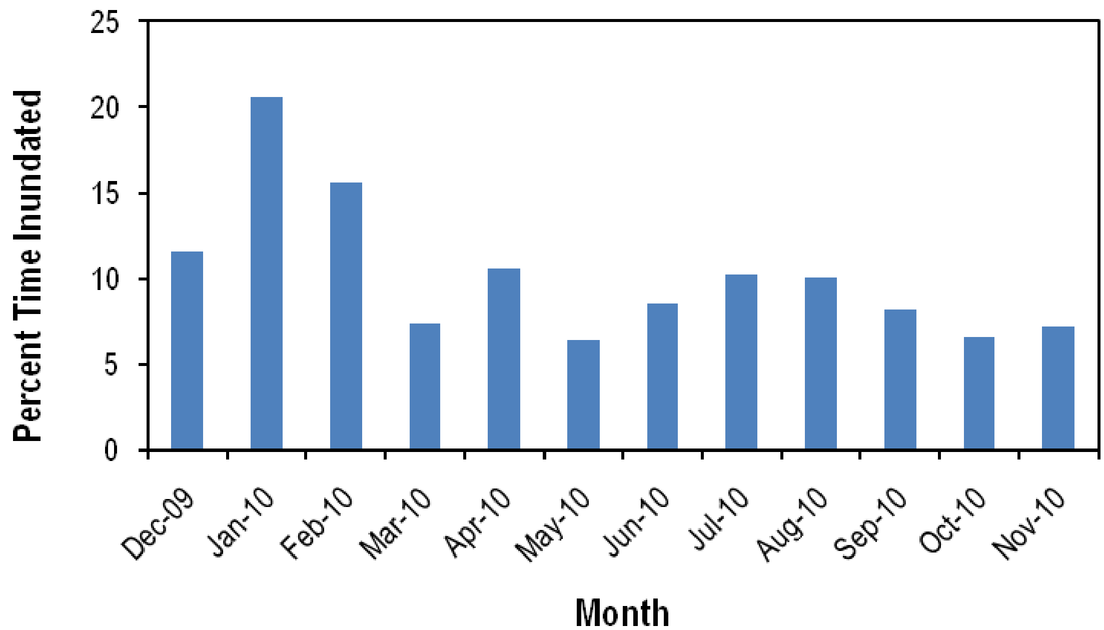

Figure K-5. Percent of time Petaluma Marsh was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER results indicate that Petaluma will not keep pace with local SLR through this century. WARMER results project a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060 (Fig K-6). By 2080 the marsh is projected to be under mean sea level (MSL) and will therefore transition to a mudflat (Fig. K-7).

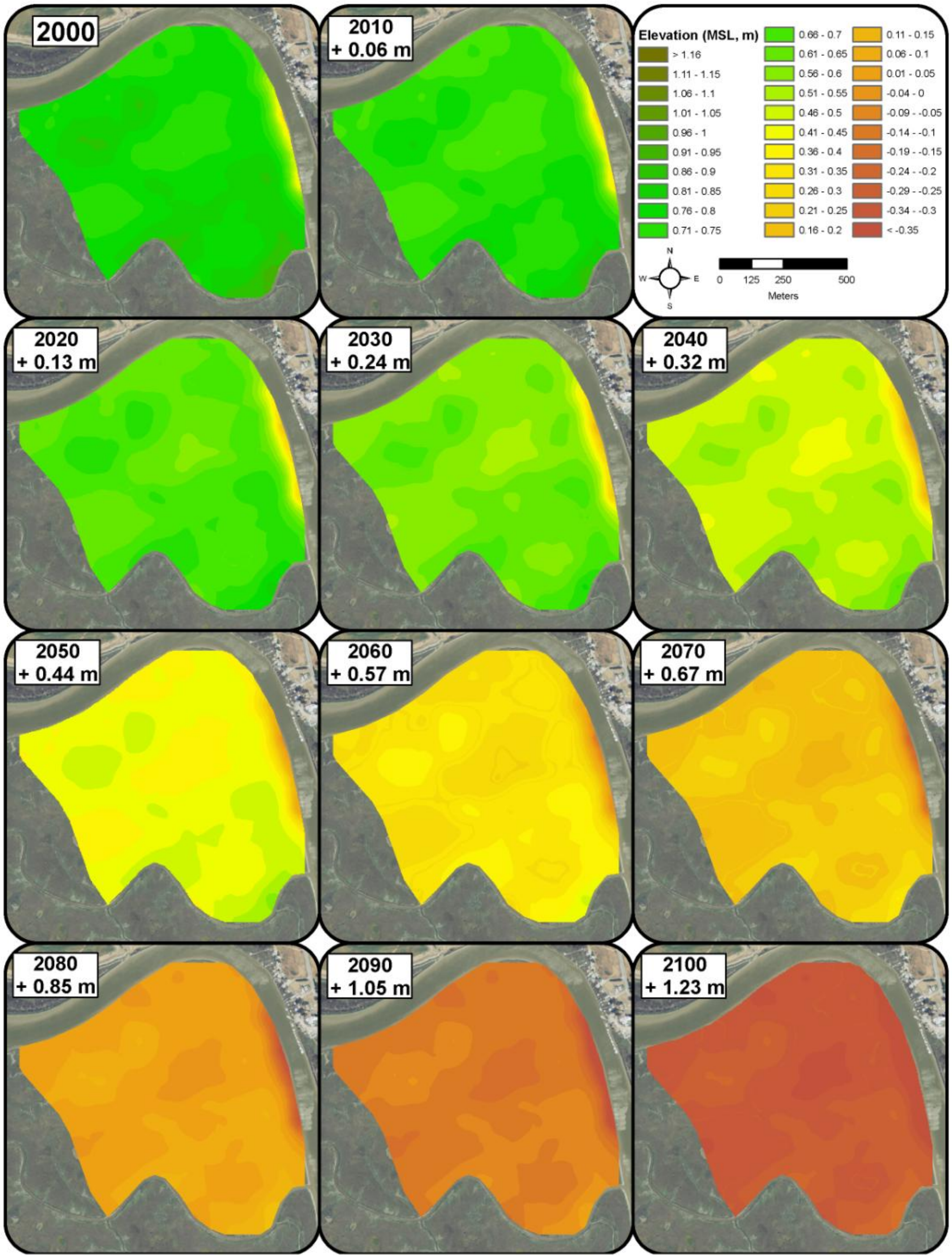

Figure K-6. WARMER results for Petaluma marsh. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity , compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

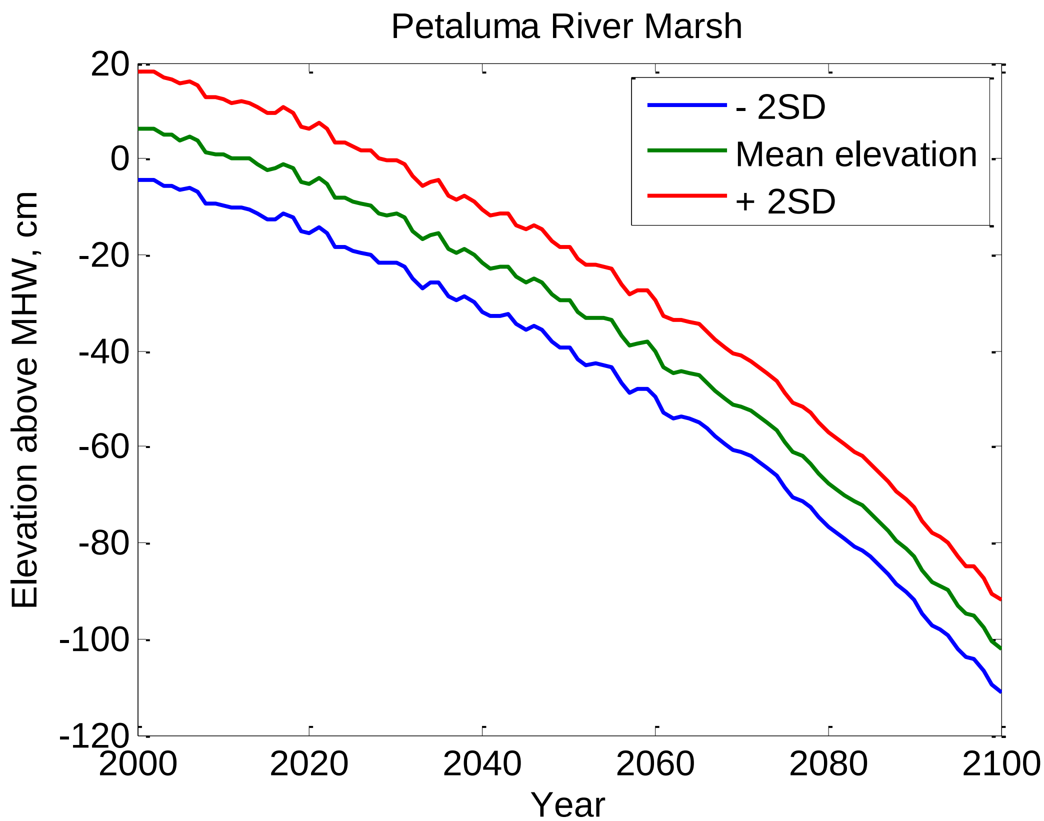

Figure K-6. WARMER scenarios for Petaluma marsh elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. K-8 – K-9). Upland transition (> 1.0 m MSL) is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina* spp. Currently, Petaluma is roughly 90% high marsh. However by 2030 (+ 0.24 m SLR) WARMER projects Petaluma to transition almost completely to mid marsh (Figs. K-9 – K-10). Petaluma is projected to transition to low marsh, dominated by *Spartina* spp. *and Schoenoplectus* spp.*,* by 2060 (+0.57 m SLR). By 2080 (+0.85 m SLR) the marsh will likely lose vegetation and become primarily mudflat.

Quality control issues with the Petaluma sediment cores resulted in the removal of data that indicated high sedimentation rates. The Petaluma River is a major source of sediment to San Francisco Bay; thus, it is likely that the inputs to WARMER are underestimating accretion potential.

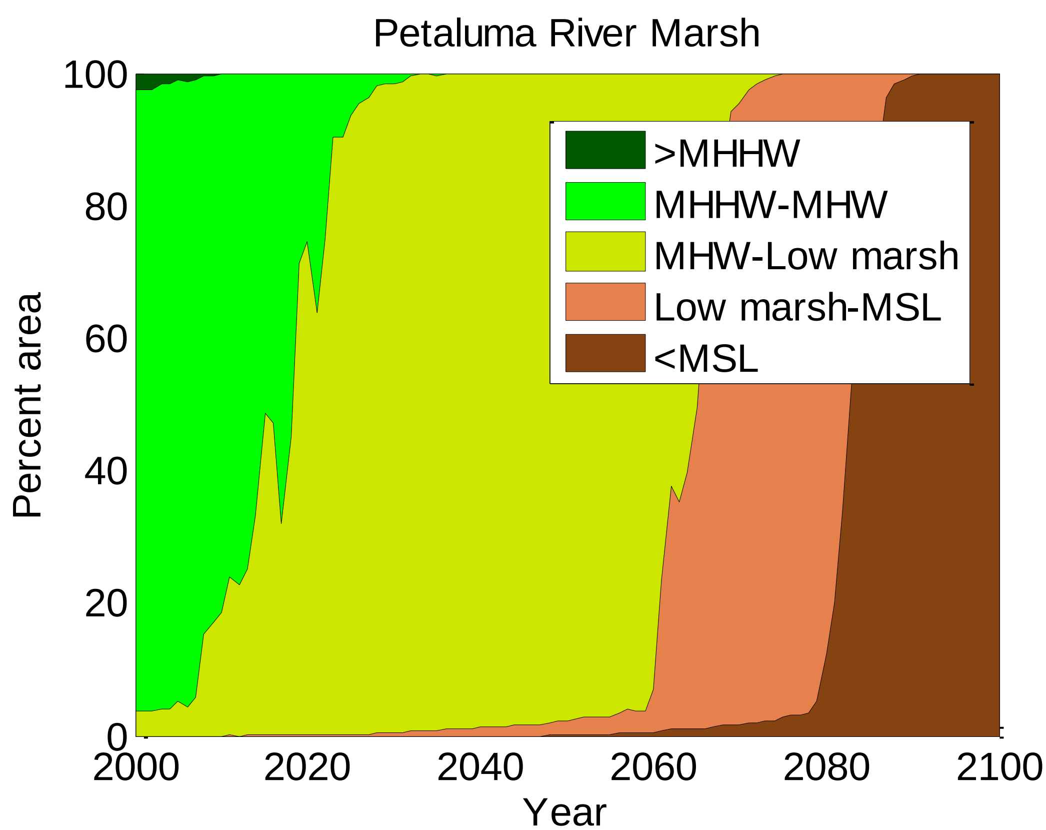

Figure K-8. Area of Petaluma within a given tidal range for the duration of the simulation period.

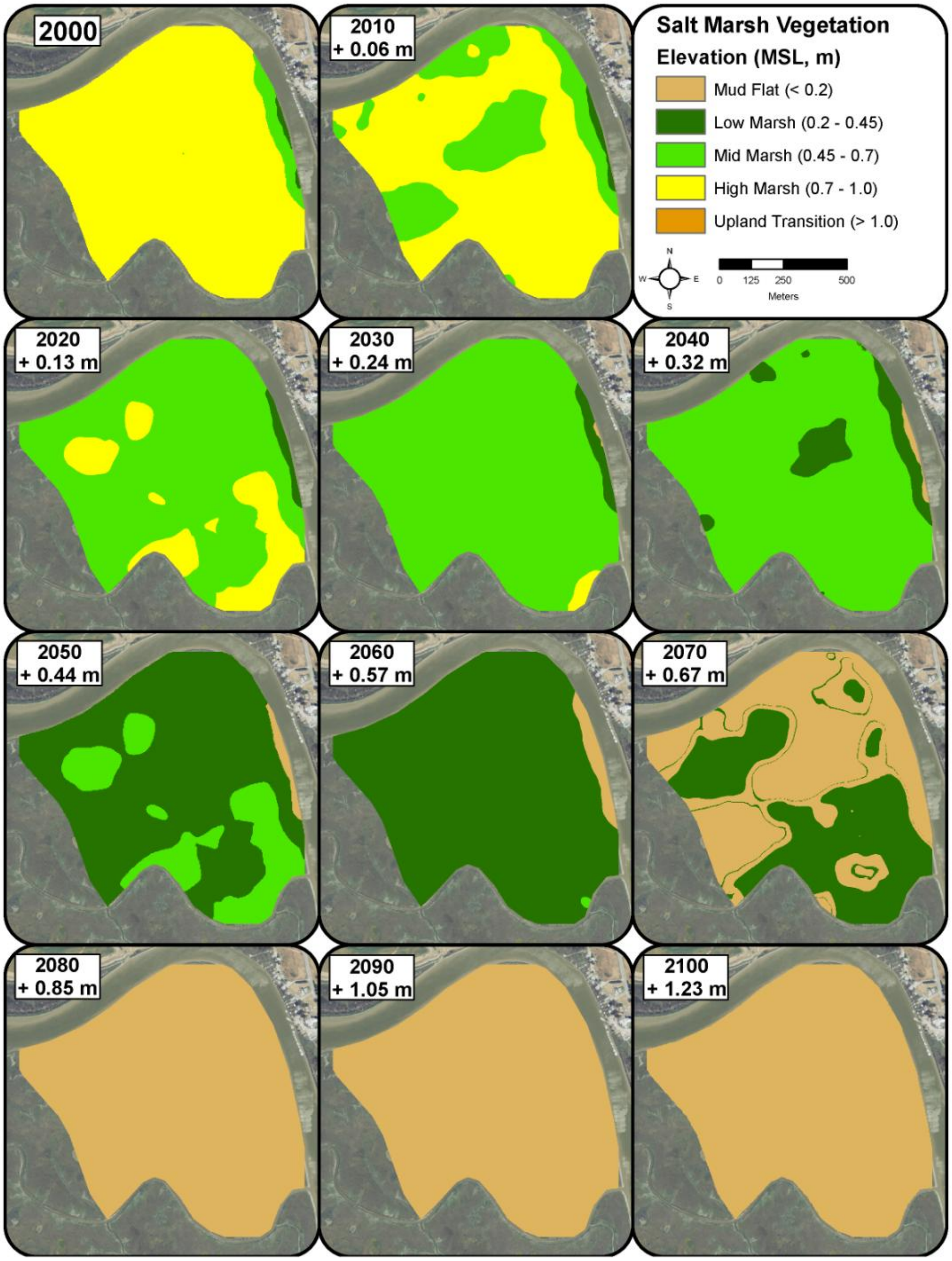

Figure K-9. Petaluma WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

Appendix L

San Pablo Bay Marsh

Introduction

San Pablo Bay National Wildlife Refuge marsh (hereafter San Pablo) is located on the north shore of San Pablo Bay in Sonoma, Solano, and Napa Counties. It is owned and managed by the U.S. Fish and Wildlife Service with adjacent lands owned and managed by California Fish and Game and Sonoma LandTrust. It is one of the largest areas of intact marsh in the San Francisco Bay estuary. San Pablo supports federally and state-listed species, such as the salt marsh harvest mouse (*Reithrodontomys raviventris*) and the California black rail (*Laterallus jamaicensis*). San Pablo is also an important stopover on the Pacific Flyway and provides critical migratory and wintering habitat for shorebirds. San Pablo is influenced both by the tides and freshwater input from Petaluma River, Sonoma Creek, and Napa River.

Due to the extent of San Pablo, we split data analysis into two sections; 962.6 ha on the northeast side and 449.5 ha on the northwest separated by Sonoma Creek. Elevation and vegetation surveys were conducted in 2008 - 2009 using an RTK GPS. To monitor tidal inundation and salinity water level loggers were deployed in 2009.

Results

Elevation

A total of 1,396 elevation measurements were taken at San Pablo (Fig. L-1, L-2). The elevation range was 0.56 - 3.11 m with a mean of 1.94 m (NAVD88). 58% of the survey points fell within 1.7 - 2.1 m. Over half (64%) of the survey points were located at elevations above mean high water (MHW; Fig. L-3). A 3-m resolution elevation model was developed in ArcGIS 9.3 (ESRI, Redlands, CA) Spatial Analyst using the

Kriging method (Figs. L-4 – L-5). This baseline elevation model was used as the initial state in the WARMER sea-level rise (SLR) model; WARMER results were extrapolated across the elevation model.

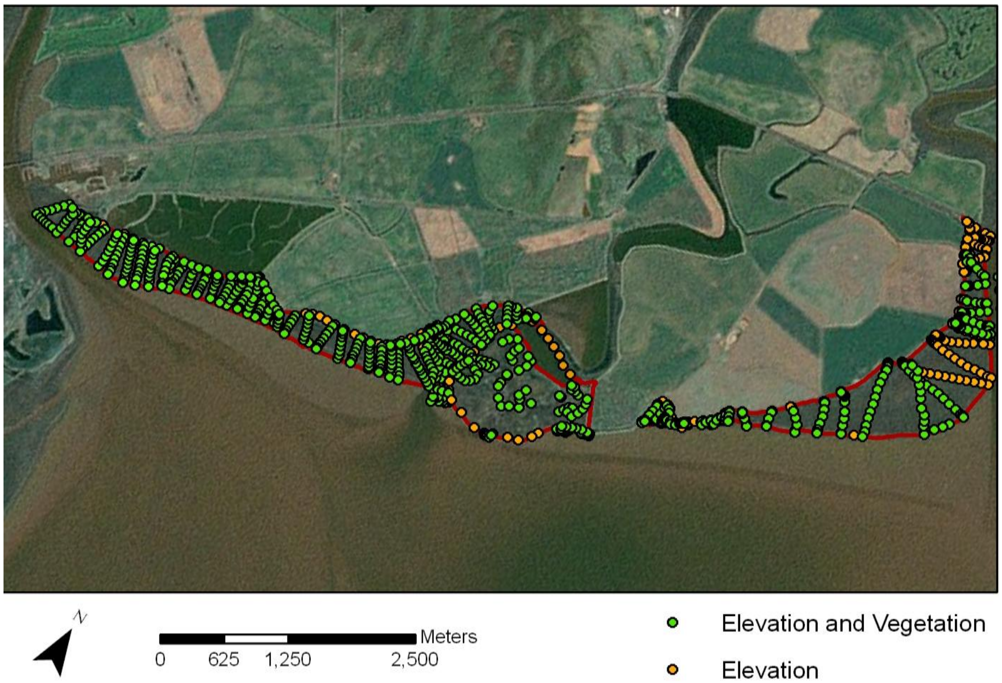

Figure L-1. Western portion of San Pablo with elevation and vegetation survey points taken in 2009.

Figure L-2. Eastern portion of San Pablo with elevation and vegetation survey points taken in 2008.

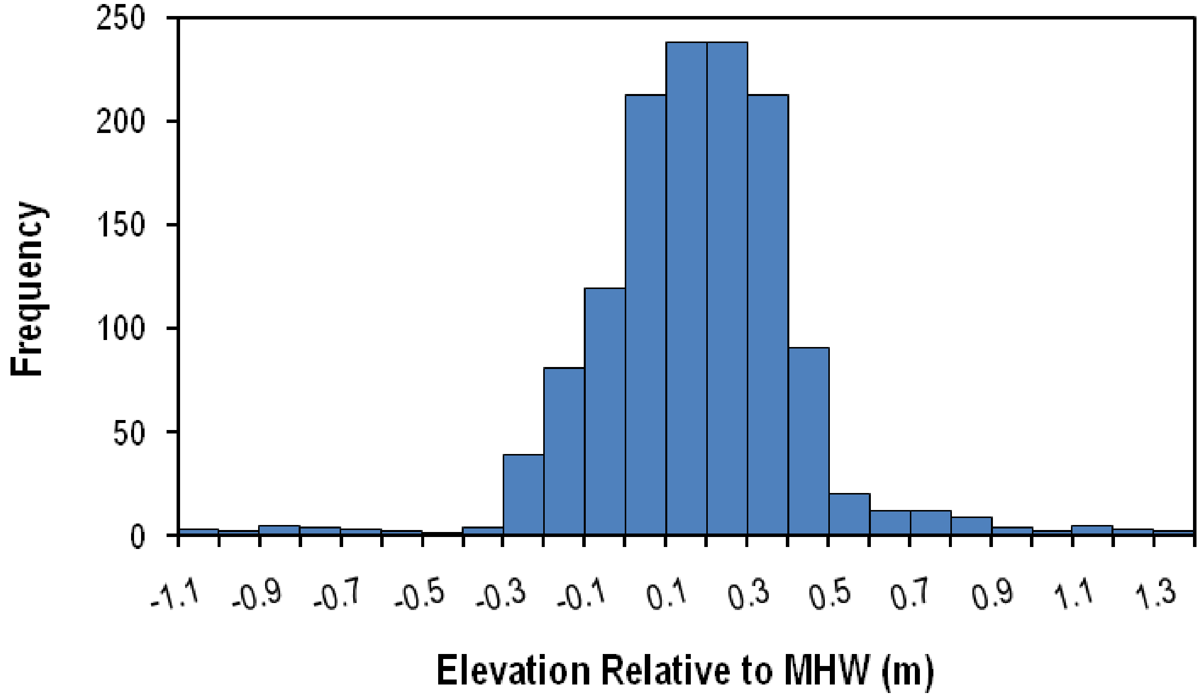

Figure L-3. Distribution of elevation relative to local mean high water (MHW) for all San Pablo data.

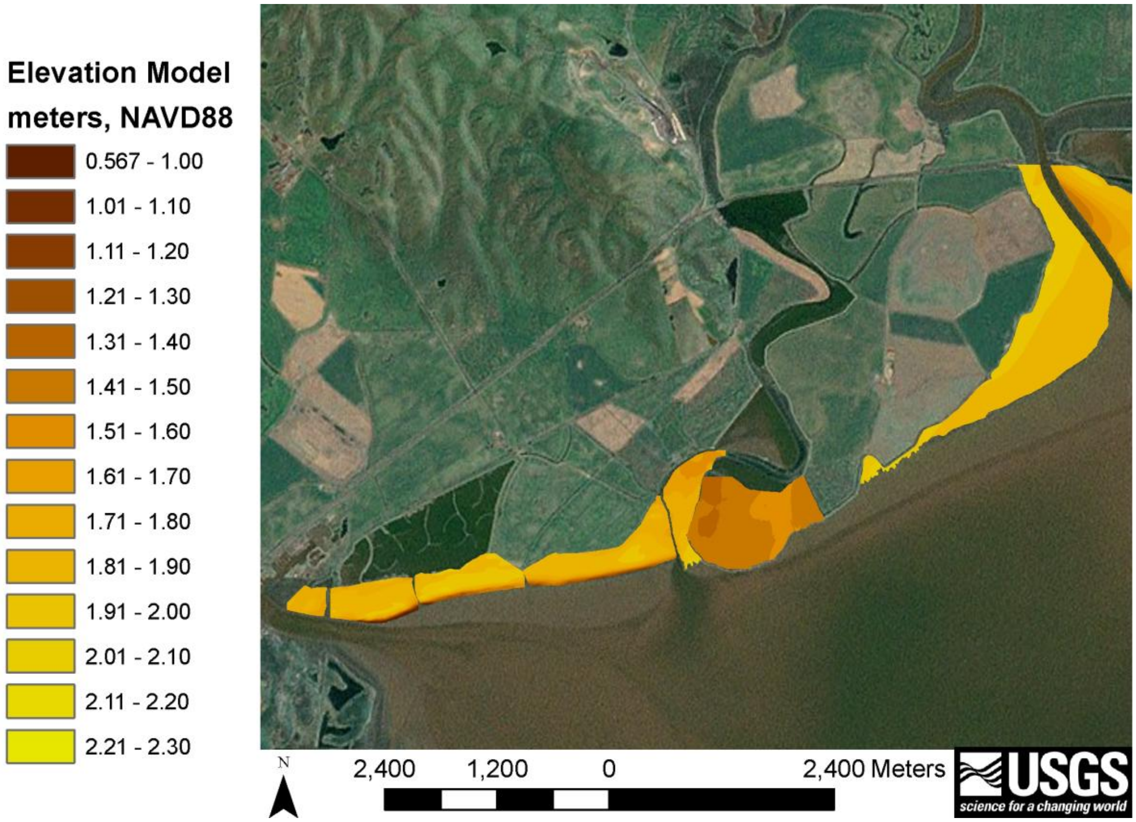

Figure L-4. Elevation model (3-m resolution) developed from ground RTK GPS elevation data for west San Pablo.

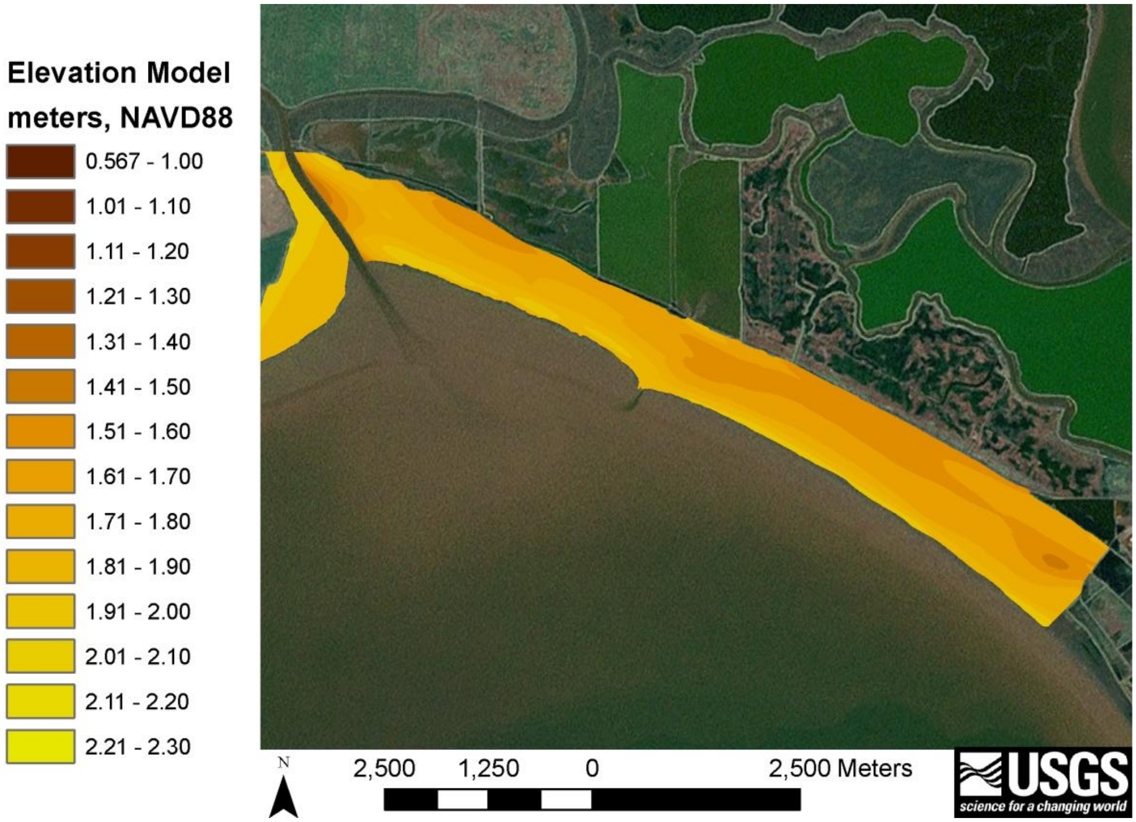

Figure L-5. Elevation model (3-m resolution) developed from ground RTK GPS elevation data for east San Pablo.

Vegetation

Vegetation was surveyed at San Pablo concurrently with elevation in the summer of 2008 and 2009. A total of 888 locations (Fig. L-1) were measured for vegetation composition, height (cm), and percent cover (Table L-1 – L-2). We did not distinguish between invasive and native *Spartina* spp. and *Schoenoplectus* spp. in the survey. Vegetation in marshes is sensitive to soil salinity, inundation patterns, and disturbance. Therefore, stratification of vegetation relative to MHW (Figs. L-6 – L-7) was observed within this low slope marsh.

Table L-1. Mean marsh elevation, average, and max height (cm), percent cover with standard deviations (SD), and presence by species at west San Pablo.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.08	0.19	44.41	12.49	52.82	13.56	76.43	33.73	579	84.90
Spartina spp.	-0.38	0.34	70.95	17.84	77.51	16.98	36.02	25.43	63	9.24
Schoenoplectus spp.	-0.21	0.19	31.08	33.15	32.42	34.75	15.58	23.36	12	1.76
Grindelia stricta	0.03	0.18	67.38	16.17	73.49	17.62	34.90	29.49	71	10.41
Jaumea carnosa	-0.06	0.21	16.45	8.26	20.00	9.86	57.24	34.31	33	4.84
Frankenia salina	0.17	0.27	20.92	10.53	25.50	11.77	40.47	32.05	76	11.14
Distichlis spicata	0.09	0.28	13.83	8.57	17.11	10.90	56.49	32.87	53	7.77
Lepidium latifolium	0.18	0.24	46.67	32.31	48.33	33.54	18.11	18.81	9	1.32
Atriplex triangularis	0.07	0.41	20.00	16.96	22.00	18.23	12.60	20.98	5	0.73
Baccharis pilurais	0.37	0.30	76.50	27.02	85.90	34.91	46.00	32.35	20	2.93

Table L-2. Mean marsh elevation, avg. and max height (cm), percent cover with standard deviations (SD), and presence by species at east San Pablo.

Species	***Elevation (MHW, m)***	***Elevation SD (MHW, m)***	***Avg. Height (cm)***	***Avg. Height SD (cm)***	***Max Height (cm)***	***Max Height SD (cm)***	***% Cover***	***% Cover SD***	***n***	***% Presence***
Sarcocornia pacifica	0.05	0.16	42.64	14.26	54.40	14.75	72.07	32.27	166	80.58
Spartina spp.	-0.16	0.25	66.13	17.44	74.38	16.26	21.94	17.25	16	7.77
Schoenoplectus spp.	0.13	0.14	90.00	14.14	107.50	10.61	15.00	7.07	2	0.97
Grindelia stricta	0.21	0.10	50.00	22.14	59.17	26.45	44.33	38.82	6	2.91
Frankenia salina	0.10	-	26.00	-	42.00	-	98.00	-	1	0.49
Lepidium latifolium	0.31	0.10	72.00	21.80	84.42	18.97	31.83	36.90	12	5.83
Baccharis pilurais	0.30	0.71	50.00	21.21	67.00	1.41	22.50	3.54	2	0.97

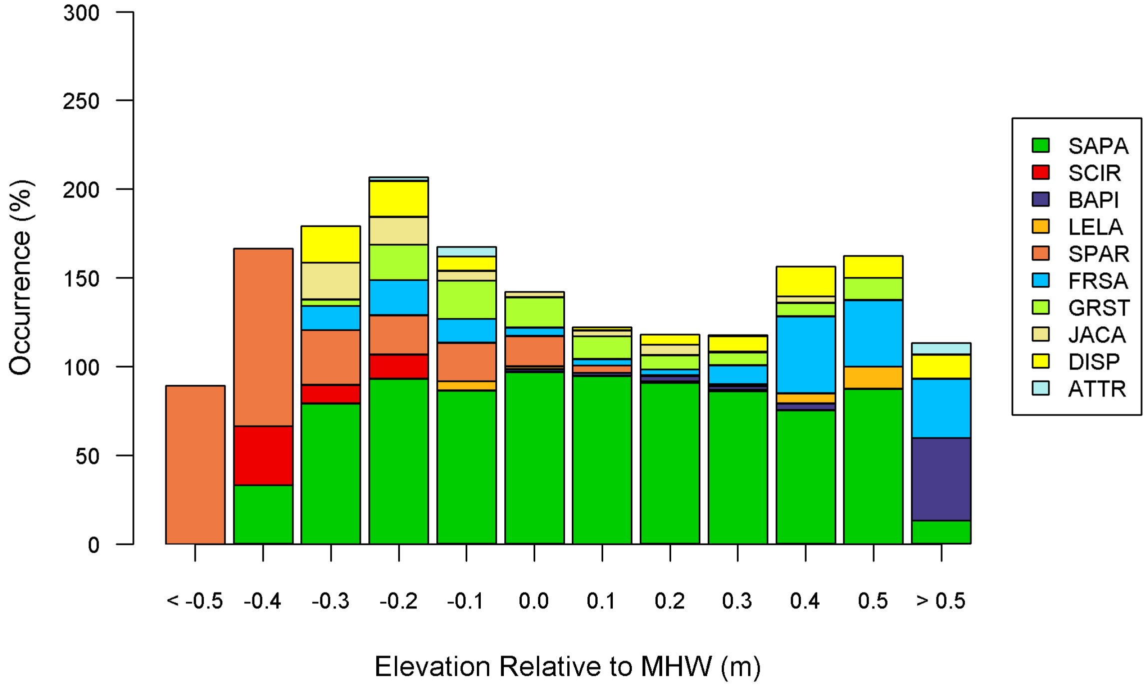

Figure L-6. Stratification of vegetation species was observed relative to MHW at west San Pablo. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus* spp.*;* BAPI: *Baccaris pilularis*; LELA = *Lepidium latifolium*; SPAR = *Spartina;* FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*; ATTR = *Atriplex triangularis.*

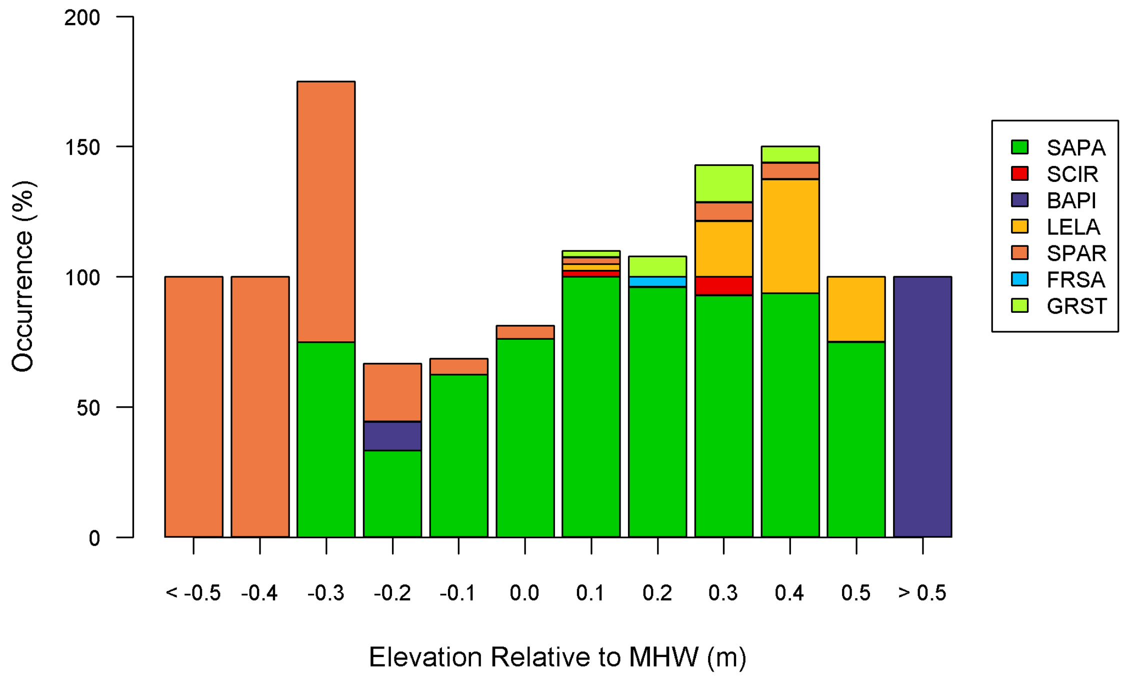

Figure L-7. Stratification of vegetation species was observed relative to MHW at east San Pablo. Species codes: SAPA = *Sarcocornia pacifica;* SCIR = *Schoenoplectus spp.;* BAPI = *Baccaris pilularis*; LELA = *Lepidium latifolium*; SPAR = *Spartina* spp.*;* FRSA = *Frankenia salina;* GRST = *Grindelia stricta;* JACA = *Jaumea carnosa*; DISP = *Distichlis spicata*; ATTR = *Atriplex triangularis.*

Water level monitoring

Site-specific water level was monitored for one year from December 2009 and May 2011. Water level was measured using four data loggers deployed at the mouth of second order channels and in the marsh interior. We found mean high water (MHW) at 1.68 m and mean higher high water (MHHW) at 1.85 m for the site (NAVD88). Water levels throughout the year were recorded to evaluate seasonal patterns in tides. The marsh platform (defined as mean marsh elevation) was inundated most often in January when the diurnal high tides were highest (Fig. L-8). Mean salinity during 2010 at San Pablo was 19.0 (SD = 5.9) PSS.

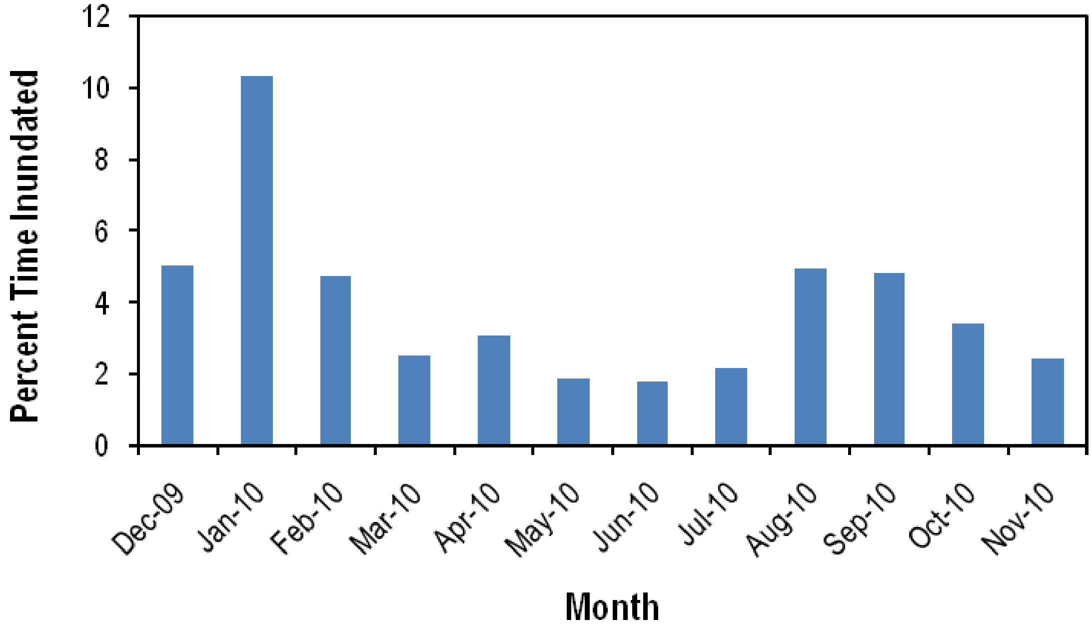

Figure L-8. Percent of time all of San Pablo was inundated monthly, based on the mean elevation of the marsh platform.

Marsh elevation modeling

WARMER results indicate that San Pablo will not keep pace with local SLR through this century. Results show a gradual reduction in elevation relative to MHW over time, with a more dramatic decline after 2060 (Figs. L-9 – L-10). By 2090 the marsh is projected to be under MSL, therefore transition to a mudflat (Fig. L-11).

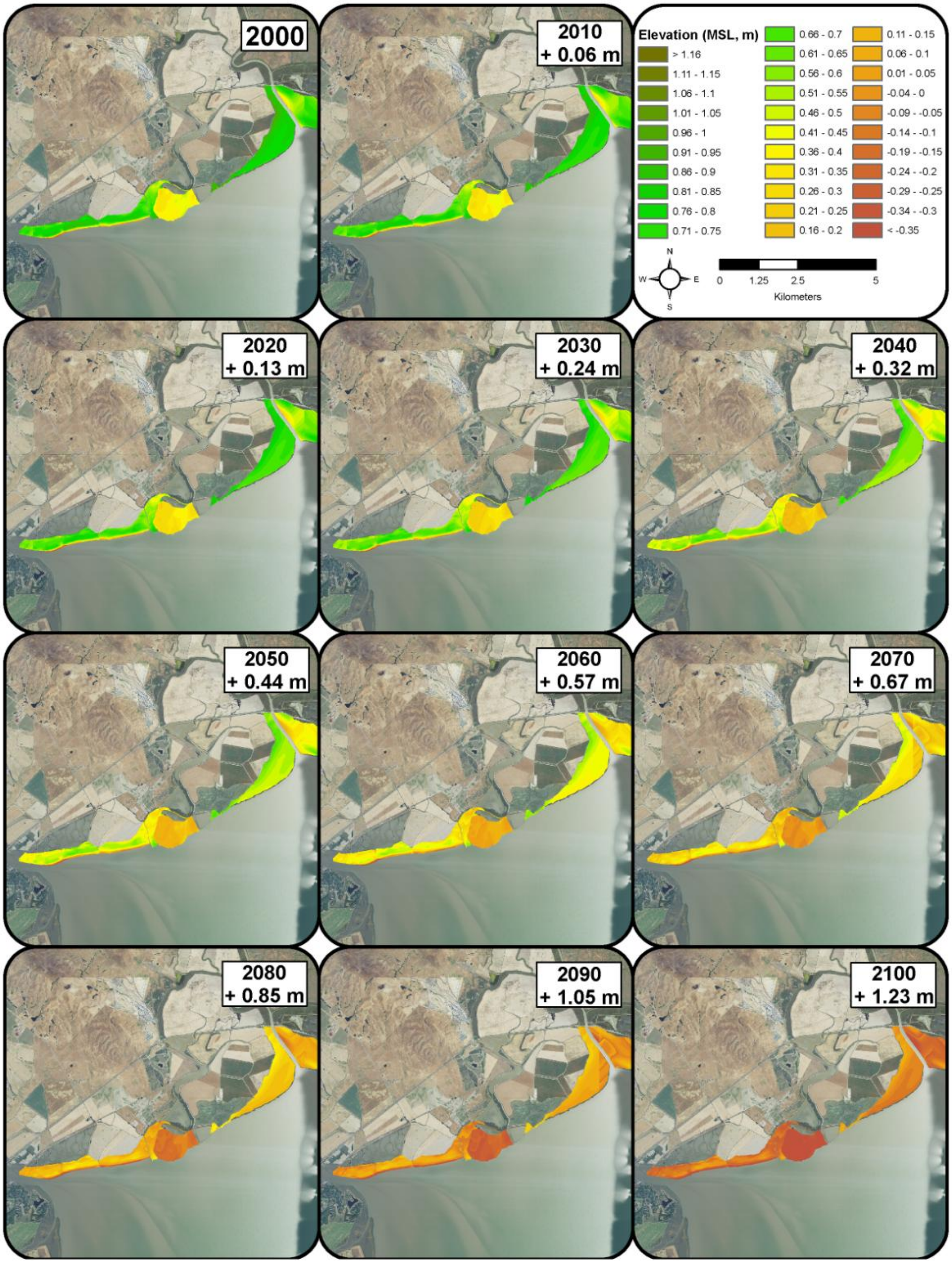

Figure L-9. WARMER results for west San Pablo. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

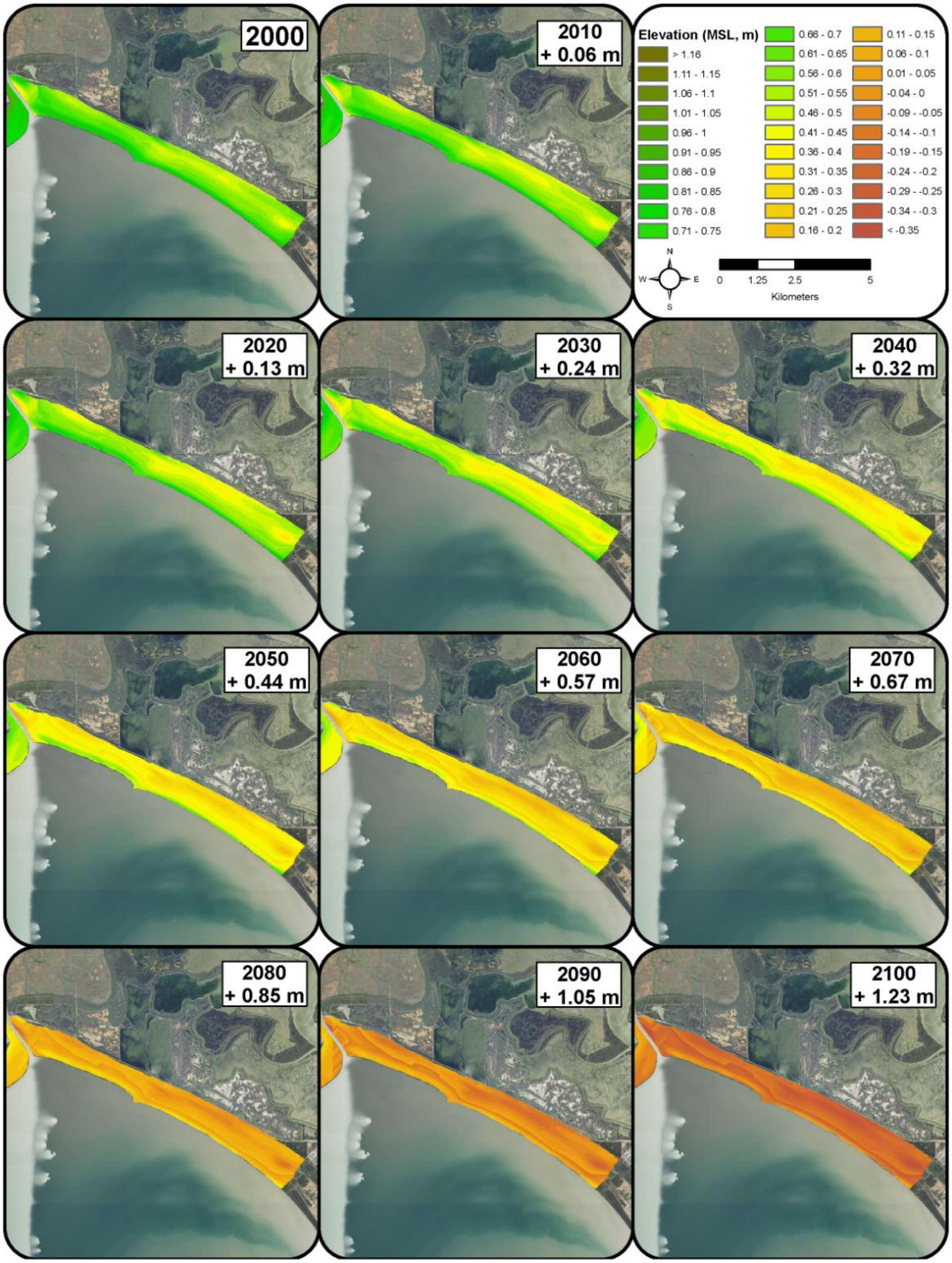

Figure L-10. WARMER results for east San Pablo. WARMER accounts for changes in relative seal-level, subsidence, inorganic sediment accumulation, above/below ground organic matter productivity, compaction, and decay. Non-linear sea-level rise projections for California were used (Cayan *et al.* 2009).

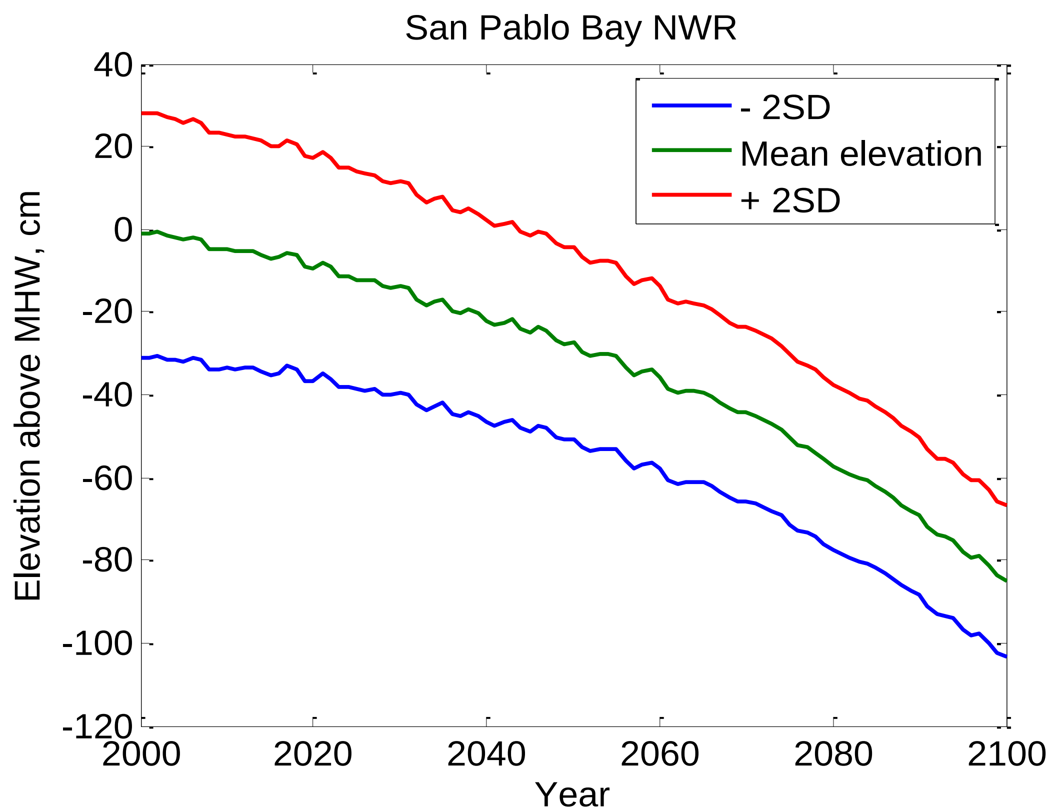

Figure L-11. WARMER scenarios for San Pablo elevation change. Elevation above MHW is plotted versus model year with two standard deviations (SD).

Elevation relative to the local tidal datum can be tied to vegetation observations (see methods). Vegetation data were categorized as mudflat, low, mid, high marsh, or upland transition plant communities (Table 4) and used to interpret the WARMER SLR results (Figs. L-12 – L-14). Upland transition (> 1.0 m MSL), is characterized by coyote bush (*Baccharis pilularis*). High marsh (0.7 – 1.0 m MSL) is characterized by *Frankenia salina* and *Jaumea carnosa*, while mid marsh (0.45 – 0.7 m MSL) is dominated by *Sarcocornia pacifica.* Low marsh (0.2 – 0.45 m MSL) is characterized by *Spartina* spp. or *Schoenoplectus* spp. in brackish areas. Mudflat habitat (< 0.2 m MSL) is unvegetated or sparsely covered with *Spartina spp.* Currently, west San Pablo is primarily mid and high marsh. High marsh is projected to increase from 2000 through 2020 (+ 0.13 m SLR). All high marsh vegetation is projected to be gone by 2040 (+ 0.32 m SLR). Mid marsh is dominate to 2060 (+ 0.57 m SLR), at which time it transitions to low marsh. A transition to mudflat is projected by 2080 (+ 0.85 m SLR).

East San Pablo is also primarily mid marsh habitat, with some high marsh vegetation bordering San Pablo Bay. All high marsh is projected to be mostly gone by 2020 (+ 0.13 m SLR), with mid marsh projected to be gone by 2050 (+ 0.44 m SLR). Low marsh dominates till 2070 (+ 0.67 m SLR) at which time east San Pablo begins to transition below MSL to a mudflat. All vegetation is gone by 2090 (+ 1.05 m SLR)

The WARMER model parameters for San Pablo Bay were extrapolated using sediment core data from China Camp marsh, thus predictions should be interpreted with caution as local sedimentation processes may be different between these marshes. To improve results, local site-specific sediment core data should be collected, along with suspended sediment concentrations to characterize sediment deposition potential.

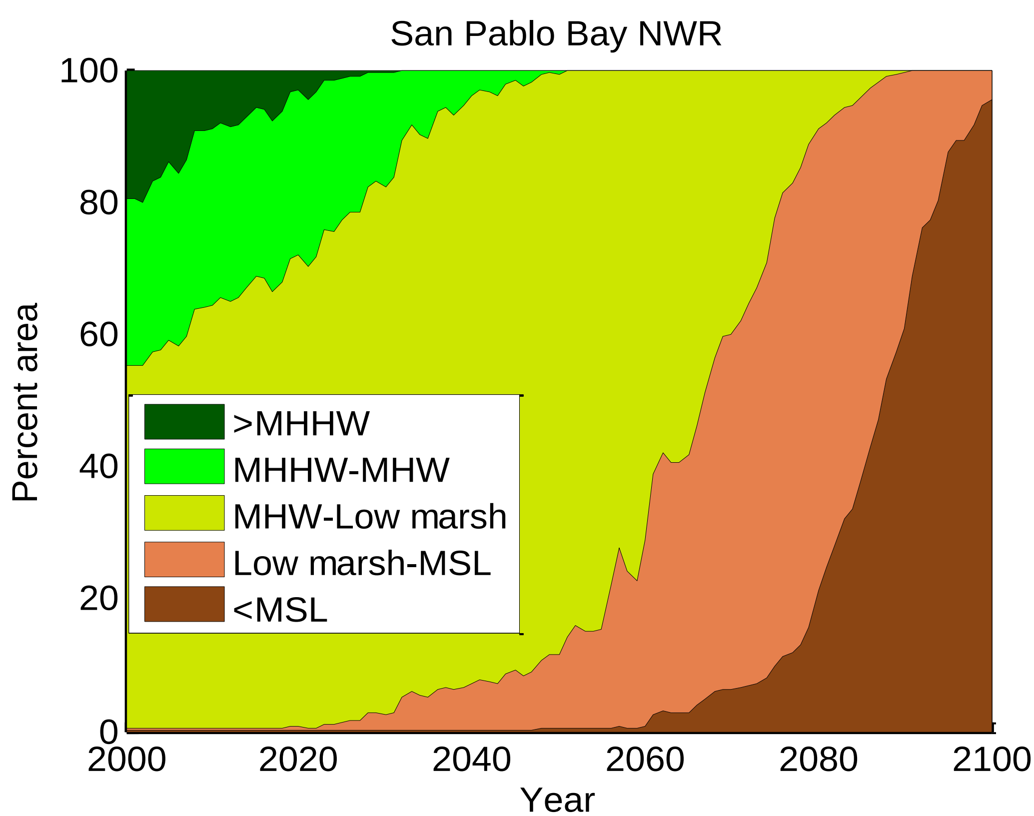

Figure L-12. Area of San Pablo within a given tidal range for the duration of the simulation period.

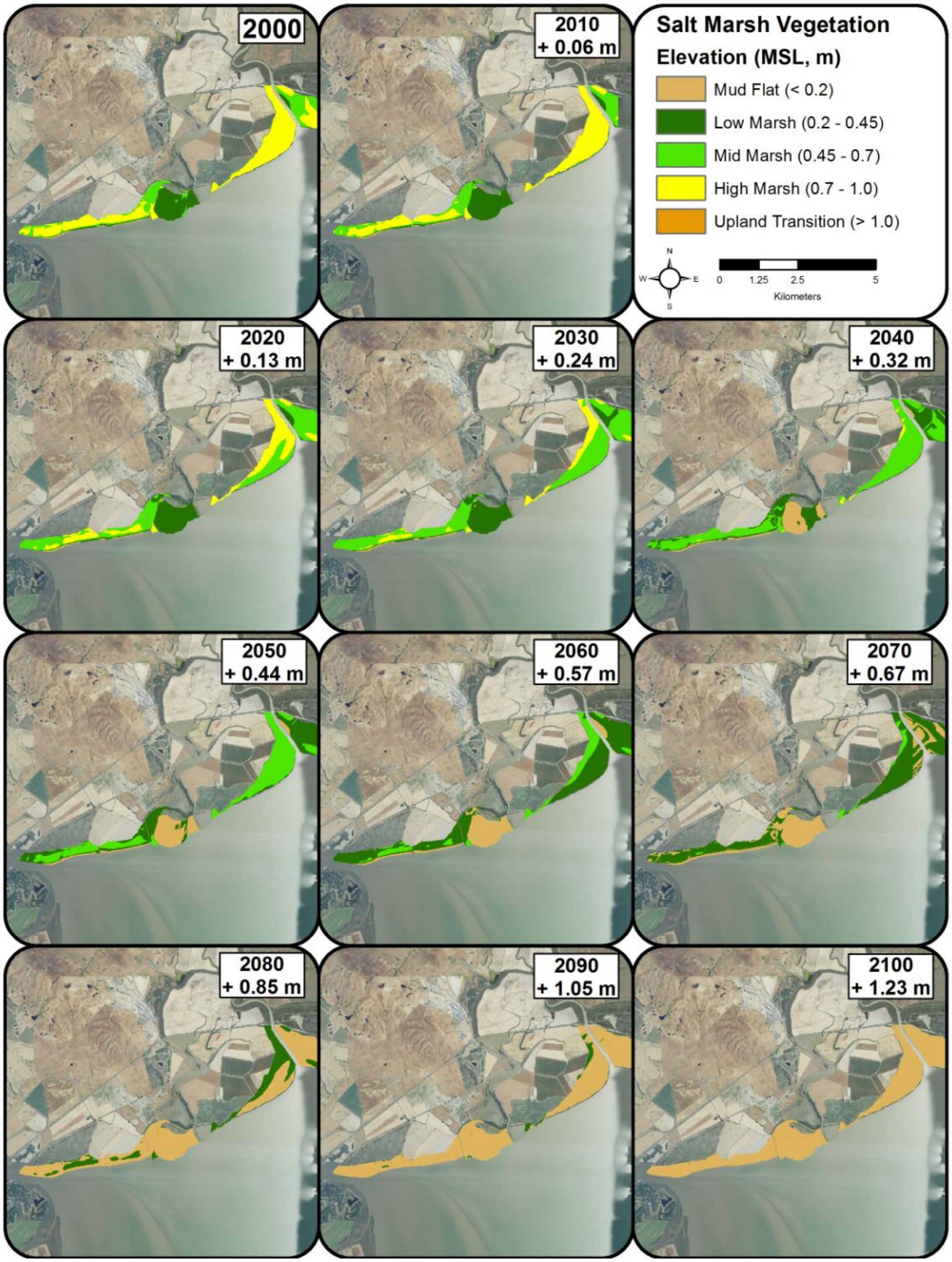

Figure L-13. West San Pablo WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.

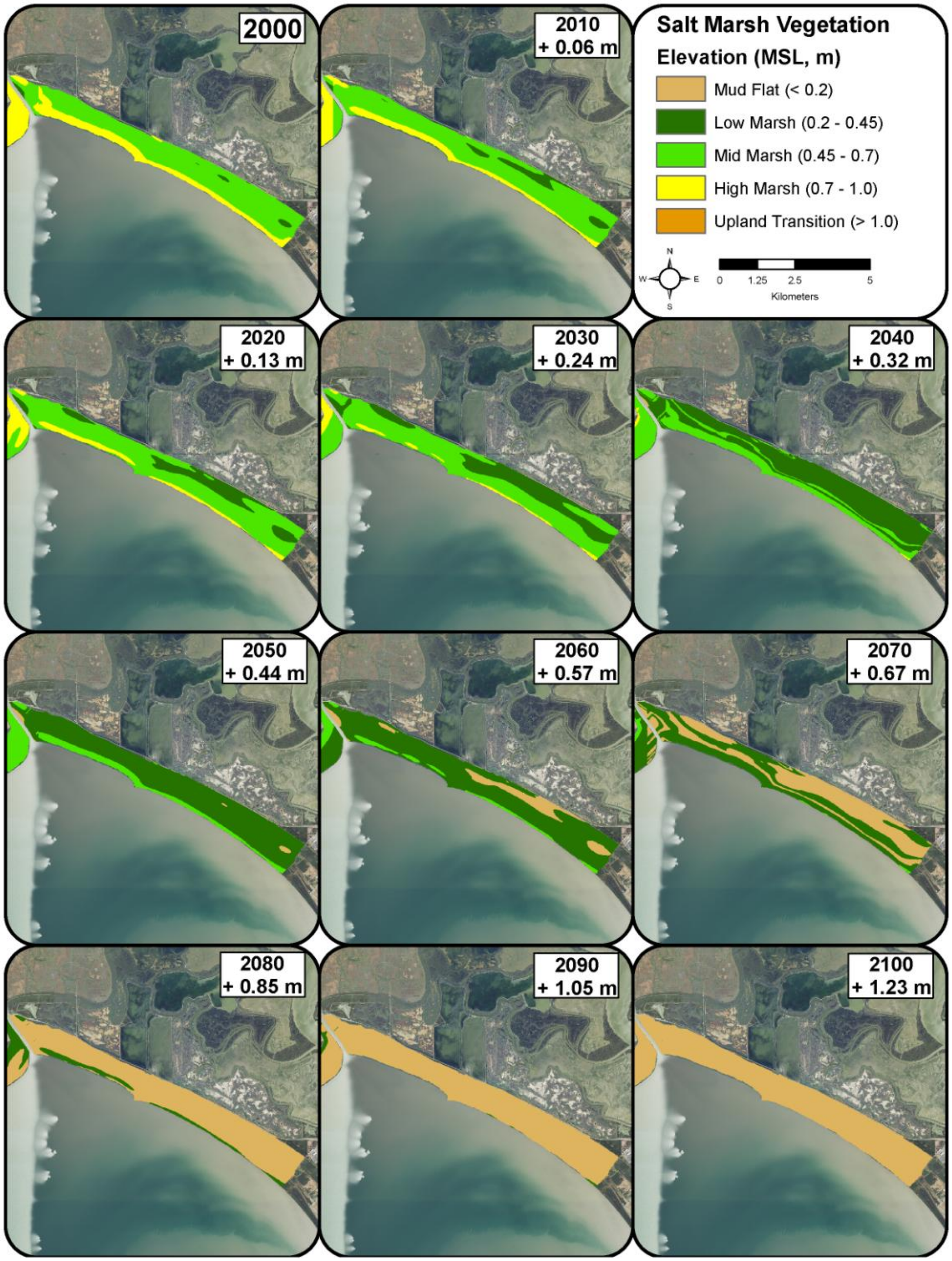

Figure L-14. East San Pablo WARMER results in terms of plant communities: mudflat, low, mid, or high marsh, or upland transition.