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Assessing Marsh response from sea-level rise applying local site conditions: Humboldt Bay Wetlands

USGS

Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay wetlands

U. S. Geological Survey, Western Ecological Research Center

Addendum - Data Summary Report
February 23, 2016

Prepared for the U. S. Fish and Wildlife Service, R8 Inventory and Monitoring Program

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Introduction:

Climate change threatens to affect the productivity and diversity of coastal ecosystems by altering nearshore physical and biological systems (IPCC, 2014). Effects on coastal environments include increased inundation from SLR and storms, salt water intrusion, erosion, shifting beach and mudflat profiles, changes in water temperature, and acidification (Scavia et al., 2002; Huppert et al., 2009). Recent estimates of global SLR by the year 2100 range from 75-190 cm (Vermeer and Rahmstorf, 2009) to 54-71 cm (Slangen et al., 2014). Due to tectonic uplift, the NRC projected SLR rates between 12 and 143 cm by 2110 for the California coastline north of Cape Mattole, including Humboldt Bay. Coastal ecosystems also face other pressures such as urban development, habitat fragmentation, altered hydrology, pollution, and introduction of non-native species (Gedan et al., 2009) that may exacerbate climate change effects on coastal productivity, biodiversity and accretion potential (Kirwan and Megonigal, 2013).

The broad goal of our research was to use site-specific data to develop local and regionally-applicable models that inform management of tidal wetlands within Humboldt Bay. Our overarching question was: how vulnerable are Humboldt Bay tidal marshes to different rates of SLR. This question was addressed with three broad objectives: (1) Assess past patterns in sedimentation to inform current SLR projections. This was accomplished by radioisotope dating of stratigraphic cores. (2) Measure baseline conditions in the tidal marshes. We characterized physical and biological properties at all study sites including topography, accretion rates, emergent vegetation, water level, salinity, and water temperature. These results are summarized in the main document, (3) Model tidal marsh elevation and habitat change under three SLR scenarios. We evaluated the degree of marsh habitat change under low, mid, and high SLR scenarios with the WARMER model (Swanson et al., 2014) for all study sites.

Methods:

Sediment coring and accretion rates

From 2013, we collected a total of 14 stratigraphic cores from three marshes in Humboldt Bay (Eureka Marsh, Jacoby Slough, and Mad River Slough) and analyzed 4 of those cores. We used a 1 m long Russian peat borer for all sediment recovery with multiple drives to capture sediment deeper than 1 m. We attempted to collect three or more sets of cores to characterize sediments from low, mid, and high elevation zones. We estimated marsh elevation zones in the field using observations of species composition, digital elevation maps, and by estimating the distance from open water or channels.

In order to establish a consistent datum to compare accretion across multiple cores, we analyzed several samples for radiocesium (^{137}Cs) activity as previously done for the San Francisco Bay area in Callaway et al. (2012). Peaks in atmospheric ^{137}Cs fallout are a byproduct of a peak in nuclear testing during 1963 C.E. For samples that had identifiable ^{137}Cs peaks, we calculated accretion rates by assuming that the bottom of the sample containing the peak represents 1963 C.E (Table 1).

Table 1. Results from 9 radiocarbon samples taken from 4 cores and submitted to the UC Irvine Keck Radiocarbon lab for analysis. ^{14}C ages as well as calibrated ages within the 2σ probability range are shown. These results were used to calculate long-term accretion rates given on the right side of the table. The mean probable age for each sample was used to calculate the number of years of accretion from the collection date to the sample.

Site	Core	Collection year (C.E.)	Depth (cm)	Material	^{14}C age (YBP)	2σ age range (YBP)			Median age (YBP)	Years of accretion	Accretion (mm yr^{-1})
Eureka	ERK13-01*	2013	73	organic	125	12	to	269	115	178	4.1
			130	organic	435	479	to	520	504	567	2.3
			272	marine	1760	828	to	1252	1039	1102	2.5
			389	marine	1740	798	to	1232	1019	1082	3.6
Jacoby	JCB13-01	2013	140	marine	735	1	to	270	119	182	7.7
			228	organic	675	564	to	673	655	718	3.2
Manila	MRL1	2013	23	organic	-3550	-13	to	-20	-17	46	4.9

3-01		198	organic	400	334	to	508	485	548	3.6
MRL1 3-03	2013	24	organic	-1990	-12	to	-32	-22	41	5.7

Vegetation zones

We used long-term (10 yr) NOAA tide data to assess inundation relationships with local elevation and thereby define the elevation limits of four intertidal habitat zones for evaluation of SLR impacts to marshes along the California coastline: low marsh, middle marsh, high marsh and transitional marsh. First, to determine region-specific relationships between elevation and inundation, we compiled data from all recorded high tides from 2004-2013 at the Charleston, Oregon NOAA tidal station (tidesandcurrents.noaa.gov). Using this time series, we determined the percentage of high tides that reached a given elevation. We defined low marsh as all elevations between the lowest vegetation plot and the elevation reached by 50% of all recorded high tides (low marsh flooded at least once daily, on average). We defined middle marsh as habitat flooded by 50-25% of all high tides (flooding once every 1-2 days, on average), and high marsh as elevations flooded by 3-25% of all high tides (flooding at least twice per month, but less than once every other day, on average). We defined transition zone marsh as habitat flooded by 0.14-3% of all high tides (flooding at least once annually, but no more than twice per month, on average). Mudflat occurred between local mean-lower low water (MLLW) and the lowest extent of emergent tidal marsh vegetation; subtidal habitat occurred below MLLW.

Using the regional NOAA data, we determined the z* ranges that corresponded to the four marsh zones as defined above. Finally, using MHHW and MTL estimates specific to each study site, we converted the regional z* ranges of each zone to local NAVD88 and MHHW ranges that corresponded with the defined habitat zones.

Tidal marsh ecosystem response modeling

We used WARMER, a 1-D cohort model of wetland accretion (Swanson et al., 2014), which is based on Callaway et al. (1996), to examine the effects of three SLR projections on future habitat composition at each study site. Each cohort in the model represents the total organic and inorganic matter added to the soil column each year. WARMER calculates annual elevation changes relative to MSL based on projected changes in relative sea level, subsidence, inorganic sediment accumulation, aboveground and belowground organic matter inputs, soil compaction, and organic matter decomposition for a representative marsh area (**Error! Reference source not found.**). Cohort density, a function of soil mineral, organic, and water content, is calculated at each time step to account for the decay of organic material and compaction of the soil column. The change in relative elevation is 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. In the model, the elevation of the marsh surface, *E*, at time *t* relative to local MSL is estimated as

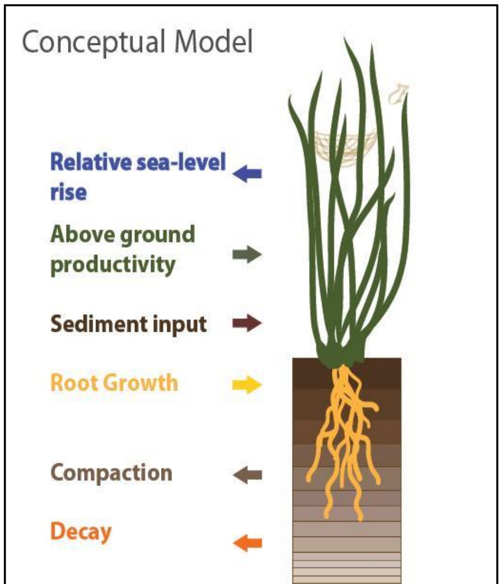

Figure 1. WARMER 1-D cohort conceptual model (Swanson et al., 2014).

$$E(t) = E(0) - SLR(t) + \sum_{i=0}^{t} V_i(t) \qquad \text{(Eq. 1)}$$

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 $V_i(t)$ is the volume per unit area, or height, at time *t*, of the cohort formed during year *i*.

We used WARMER to model decadal-scale changes in tidal wetland elevation at each site and summarized these data as changes in the spatial extent of the tidal marsh zones defined previously.

Model inputs

Sea-level rise scenario

In WARMER, we used the National Research Council's (2012) forecast for the Pacific coast which projects low, mid, and high SLR scenarios of 12, 63 and 142 cm by 2110. We used NRC's average annual SLR curve as the input function for the WARMER model. In the modeling exercises, we assumed that tide range remained constant through time, with only the position of MSL relative to land changing annually.

Inorganic matter

The annual sediment accretion rate is a function of inundation frequency and the mineral accumulation rates measured from 137Cs dating of soil cores sampled across each site. For each site, we developed a continuous model of water level from the major harmonic constituents of a nearby NOAA tide gauge. This allowed a more accurate characterization of the full tidal regime as our water loggers were located above MLLW. Following Swanson et al. (2014), we assumed that inundation frequency was directly related to sediment mass accumulation; this simplifying assumption does not account for the potential feedback between biomass and sediment deposition and holds suspended sediment concentration and settling velocity constant. Sediment accretion, *Ms,* at a given elevation, *z*, is equal to,

$$Ms(z)=S*f(z)$$

where *f(z)* is dimensionless inundation frequency as a function of elevation (*z*), and *S* is the annual sediment accumulation rate in g cm-2 y-1. We calibrated the amplitude of the logistic function to the sediment accumulation rates from the soil cores which were sampled across an elevation gradient at each study site. This method allowed us to estimate an annual accumulation rate (g cm^{-1} yr^{-1}) for each of our study sites (Figure 2).

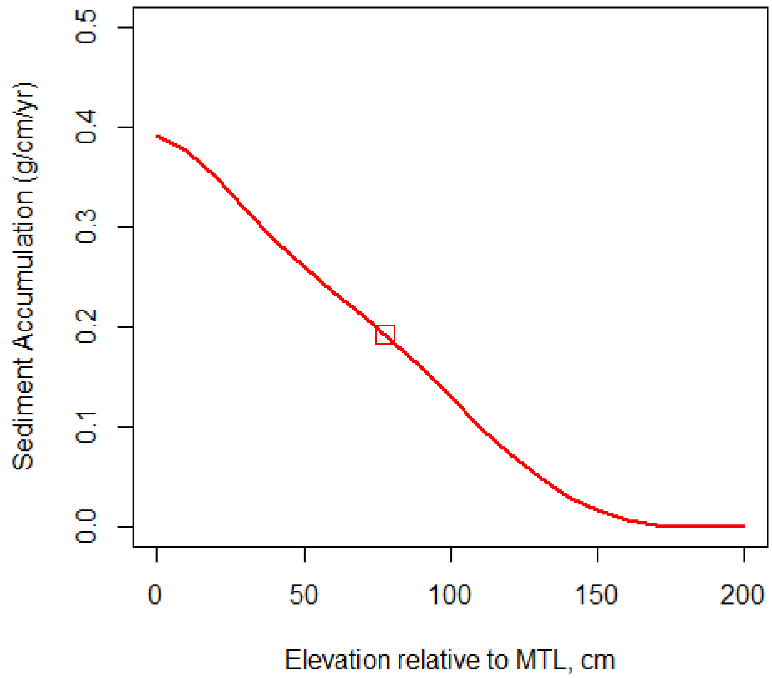

Figure 2. Estimated annual sediment accumulation curves (lines) and measured accumulation rates (points) for study sites across Humboldt Bay.

Organic matter

Overall we used a unimodal functional shape to describe the relationship between elevation and organic matter inputs to new soils, based on Atlantic coast work on *Spartina alterniflora* (Morris et al., 2002) and developed site-specific, asymmetric elevation-productivity relationships. We used Bezier curves to draw a unimodal parabola, anchored on the low elevation by the minimum elevation of vegetation from our surveys and at the high elevation by the maximum observed water level from a nearby NOAA tide gauge. We determined the elevation of peak productivity by analyzing the Normalized Difference Vegetation Index (NDVI; (NIR - Red)/(NIR + Red)) from 2011 NAIP imagery (4 spectral bands, 1 m resolution; Tucker, 1979) and our interpolated DEM. We then calibrated the amplitude of the unimodal function for the organic matter input rates (determined from sediment accumulation rates and the percent organic matter in the surface layer of the core) obtained from sediment cores across an elevation range at each site (Figure 3). To partition organic matter inputs between above and below ground fractions, we used a constant root-to-shoot ratio for organic matter production, determined from preliminary experimental data on flooding impacts to *Sarcocornia pacifica* growth in the San Francisco Bay estuary (Janousek et al., unpublished data). The mass of organic material generated below ground each year was distributed exponentially with depth and we set the coefficient of exponential decay, ***kdist***, equal to 1.0 (Deverel et al., 2008).

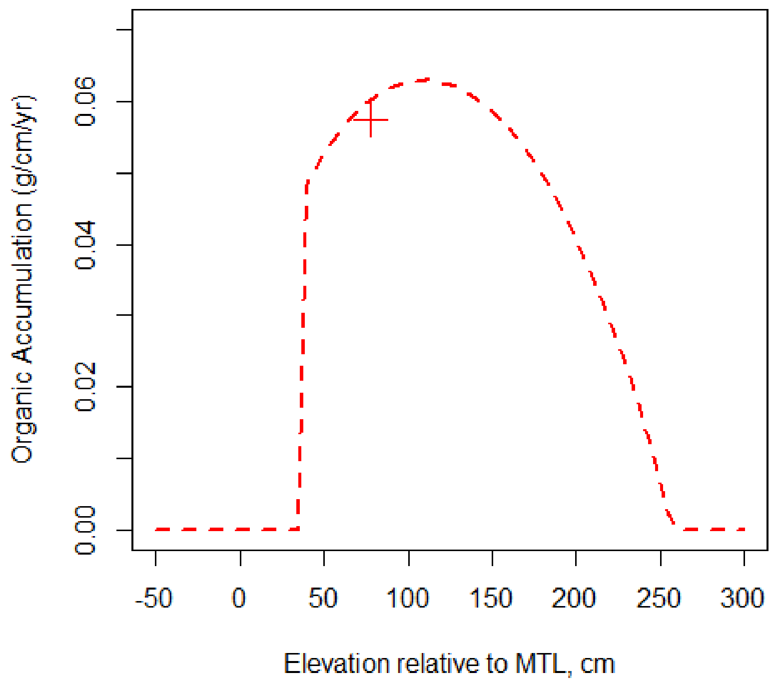

Figure 3. Calculated organic matter accumulation (lines) and measured accumulation rates (points) for study sites across Humboldt Bay. We used site-specific elevations the low marsh-mudflat boundary, maximum observed water level, and peak aboveground biomass to draw the curves. We calibrated the amplitude of the curve to measured accumulation rates from sediment cores.

Compaction and decomposition

Compaction and decomposition functions in the WARMER model followed Callaway et al. (1996). We determined sediment compaction using the difference in measured porosity between the top 5 cm and the bottom 5 cm of each sediment core. We estimated the rate of decrease, ***r***, in porosity of a given cohort as a function of the density of all of the material above that cohort:

$$r = 1 - \frac{p_b}{k_1 - p_b} \quad \text{(Eq. 4)}$$

where p_b is the density of the material above a cohort and k_1 was a calibration constant.

Following Swanson et al. (2014), we modeled decomposition as a three-stage process where the youngest organic material (less than one year old) decomposed at the fastest rate, organic matter one to two years old decayed at a moderate rate, and organic matter greater than two years old decayed at the slowest rate. Decomposition also decreased exponentially with depth. We determined the percentage of refractory (insoluble) organic material from the organic content measured in the sediment cores. We used constants to parameterize the compaction and decomposition functions from Deverel et al. (2008). Model parameters are provided in a table for each site (Table 2, Appendix Tables A2-G2).

Table 2. WARMER model parameters and soil core characteristics used for model calibration across study sites. Sediment accumulation rate is reported at the elevation of MSL.

Model parameter	Salmon Creek	Hookton Slough	White Slough	Eureka Marsh	Jacoby Marsh	Mad River Slough	Manila Marsh
Sediment accumulation rate ($g\ cm^{-2}\ yr^{-1}$)	0.396	0.396	0.398	0.382	0.391	0.392	0.392
Elevation of peak biomass (cm, MSL)	36.5	91.5	85.7	110	104.5	110	110
Minimum elevation of vegetation (cm, MSL)	-19.5	7.5	55.7	46	42.5	40	40
Max. aboveground organic accumulation ($g\ cm^{-2}\ yr^{-1}$)	0.071	0.0629	0.0613	0.0712	0.0628	0.0629	0.0629
Root-to-shoot ratio	0.458	0.458	0.458	0.458	0.458	0.458	0.458
Porosity at sediment surface (%)	89	89	89	89	89	89	89
Porosity at depth (%)	55	55	55	55	55	55	55
Refractory carbon (%)	25.8	25.8	25.8	25.8	25.8	25.8	25.8

Maximum astronomical tide (cm, MSL)	257	257	257	257	257	257	257
Historic sea-level rise ($mm\ yr^{-1}$)	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Organic matter density ($g\ cm^{-3}$)	1.14	1.14	1.14	1.14	1.14	1.14	1.14
Mineral density ($g\ cm^{-3}$)	2.61	2.61	2.61	2.61	2.61	2.61	2.61

Results

Across our study sites we found differences in soil characteristics, vegetation zonation, and modeling SLR into the future. Core results showed that the long term accretion rates are 3.5 mm yr^{-1} , while short term accretion rates ranged from 4.9 to 5.7 mm yr^{-1} with a mean of 5.3 mm yr^{-1} when averaging all cores analyzed throughout Humboldt Bay. Our modeling showed that most study sites maintained their elevation relative to sea level under the lowest SLR scenario with little change in habitat composition except for Hookton slough and White slough, with both sites changing from predominantly low marsh sites to mid marsh sites. However, under mid and high SLR rates, marsh vertical growth did not keep pace with SLR and habitat proportions at the sites shifted (middle marsh zones usually became low marsh or the site transitioned to intertidal mudflats). All study sites were highly vulnerable to a high SLR scenario, losing all vegetated habitat by 2110, with salmon creek even becoming partially subtidal habitat. However, the timing of habitat change varied across sites.

Site-Specific Results

Appendix A. WARMER results for Salmon Creek Marsh

Summary of results

- *Study site size*: 21.4 hectares
- *Location*: 40°40'49.413"N latitude, 124°13'19.945"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario, the site remains similar to current conditions while portions of mudflat habitat is reduced until gone by the year 2080 and becomes entirely composed of low marsh habitat. The mid SLR scenario is projected to result in a gradual shift in habitat composition with increasing proportions of mudflat habitat taking over low marsh habitat until 58% of the study area is mudflat by 2110. High SLR is projected to lead to a rapid transition in habitat zones. By 2090, the site becomes 99% non-vegetated mudflat and then begins to transition to subtidal habitat with 38% of the study area being subtidal by 2110.

Table A1. Vegetation zones for Salmon Creek. Zones were defined by degree of flooding by high tides.

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.702 to 0.390	1.720 to 1.400	2.622 to 2.310
High	3-25	0.390 to 0.018	1.400 to 1.018	2.310 to 1.938
Middle	25-50	0.018 to -0.195	1.018 to 0.800	1.938 to 1.725
Low	>50	-0.195 to -1.164	0.800 to -0.194	1.725 to 0.756

Table A2. Model input parameters for Salmon Creek. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate (g/cm²/yr)	0.396	Core Calibration
Elevation of Peak Biomass (cm, MSL)	36.5	NDVI from NAIP
Minimum Elevation of Vegetation (cm, MSL)	-19.5	Field Surveys
Max. Aboveground Organic Accumulation (g/cm²/yr)	0.0710	Core Calibration
Root:Shoot	0.458	Marsh Organs
Porosity Surface (%)	89	Core
Porosity Depth (%)	55	Core
Refractory Carbon (%)	25.8	Core
Maximum Astronomical Tide (cm, MSL)	257	North Spit Tide Gauge (NOAA,9418767)
Historic Sea-Level Rise (mm/yr)	4.7	North Spit Tide Gauge (NOAA,9418767)
Organic Matter Density (g/cm³)	1.14	DeLaune 1983
Mineral Density (g/cm³)	2.61	DeLaune 1983

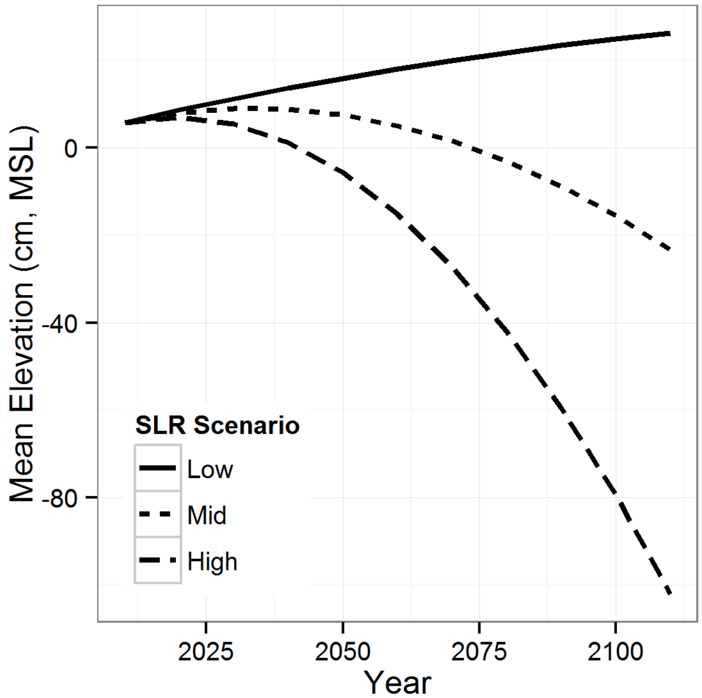

Figure A1. WARMER model projections for the change in average marsh elevation (relative to MSL) at Salmon Creek from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

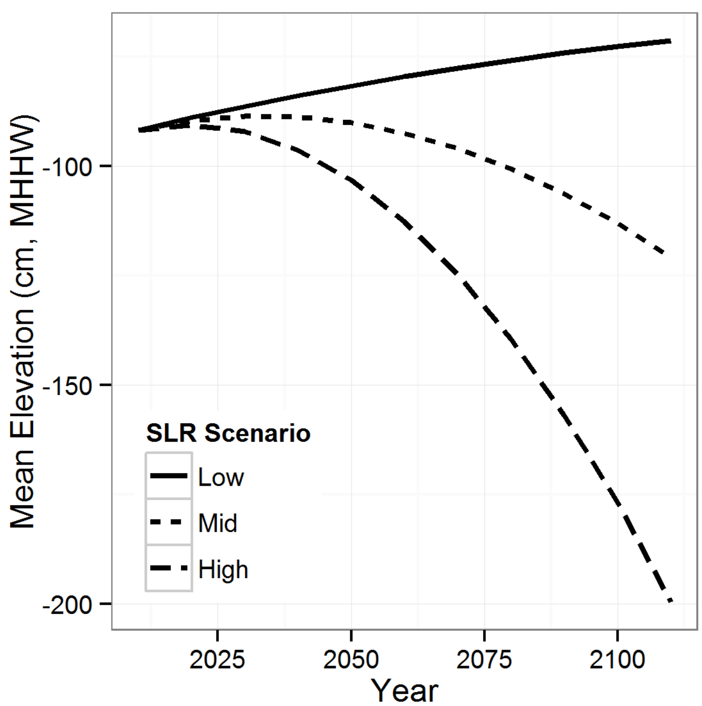

Figure A2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Salmon Creek from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

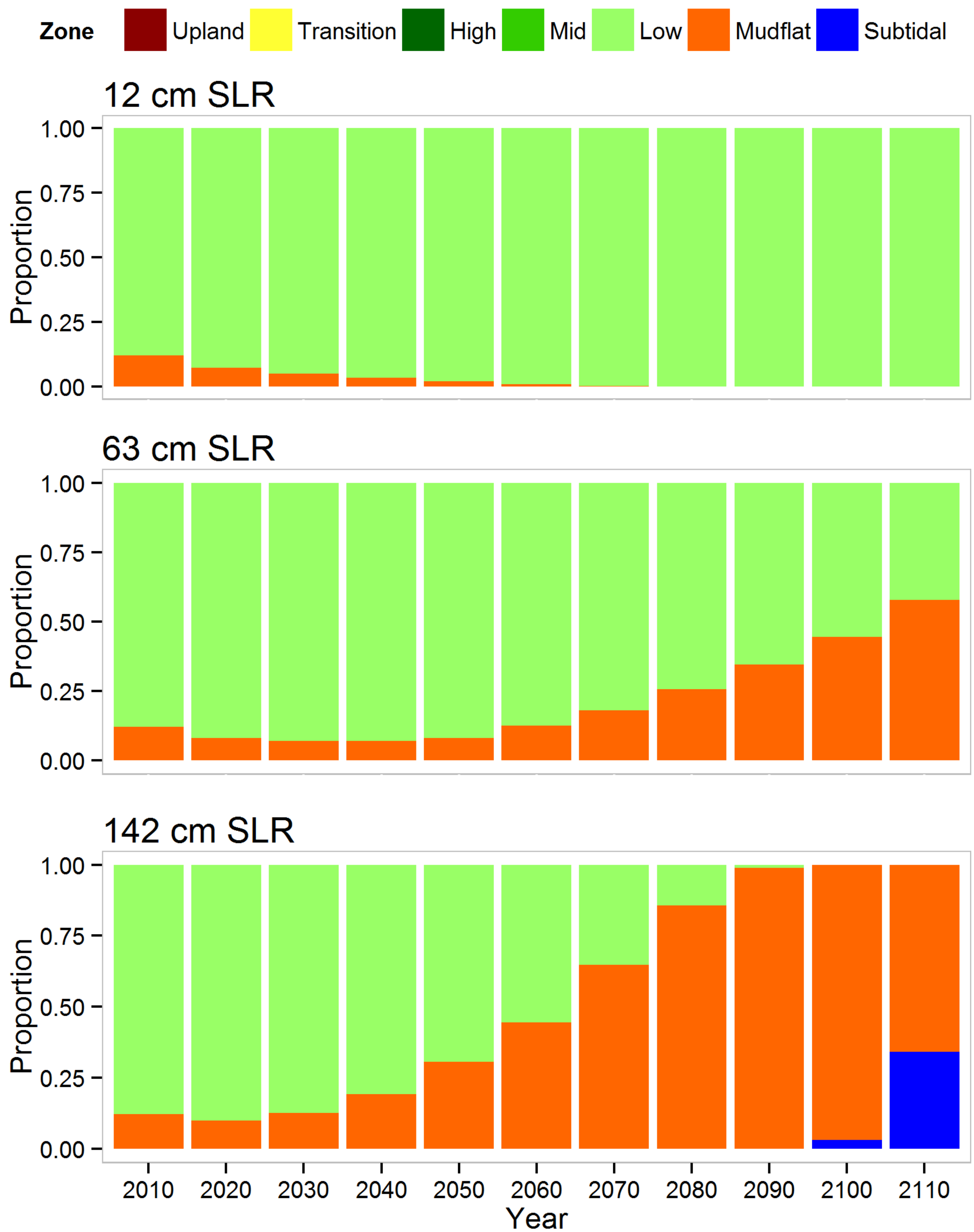

Figure A3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Salmon Creek under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table A3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0
Mid	0	0	0	0	0	0	0	0	0
Low	88	98	100	88	92	42	88	69	0
Mudflat	12	2	0	12	8	58	12	31	66
Subtidal	0	0	0	0	0	0	0	0	34

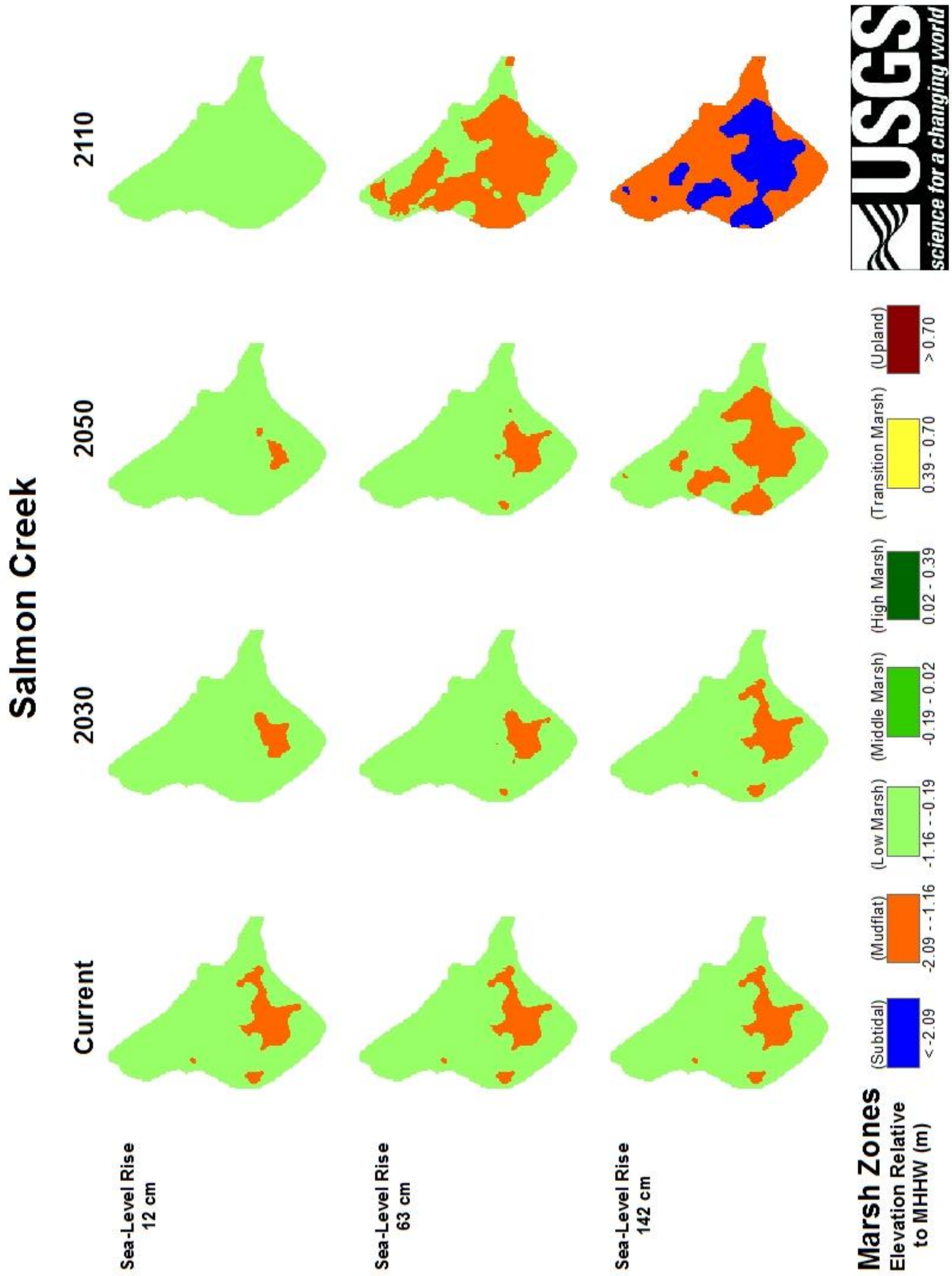

Figure A4. Projected habitat distribution at Salmon Creek for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

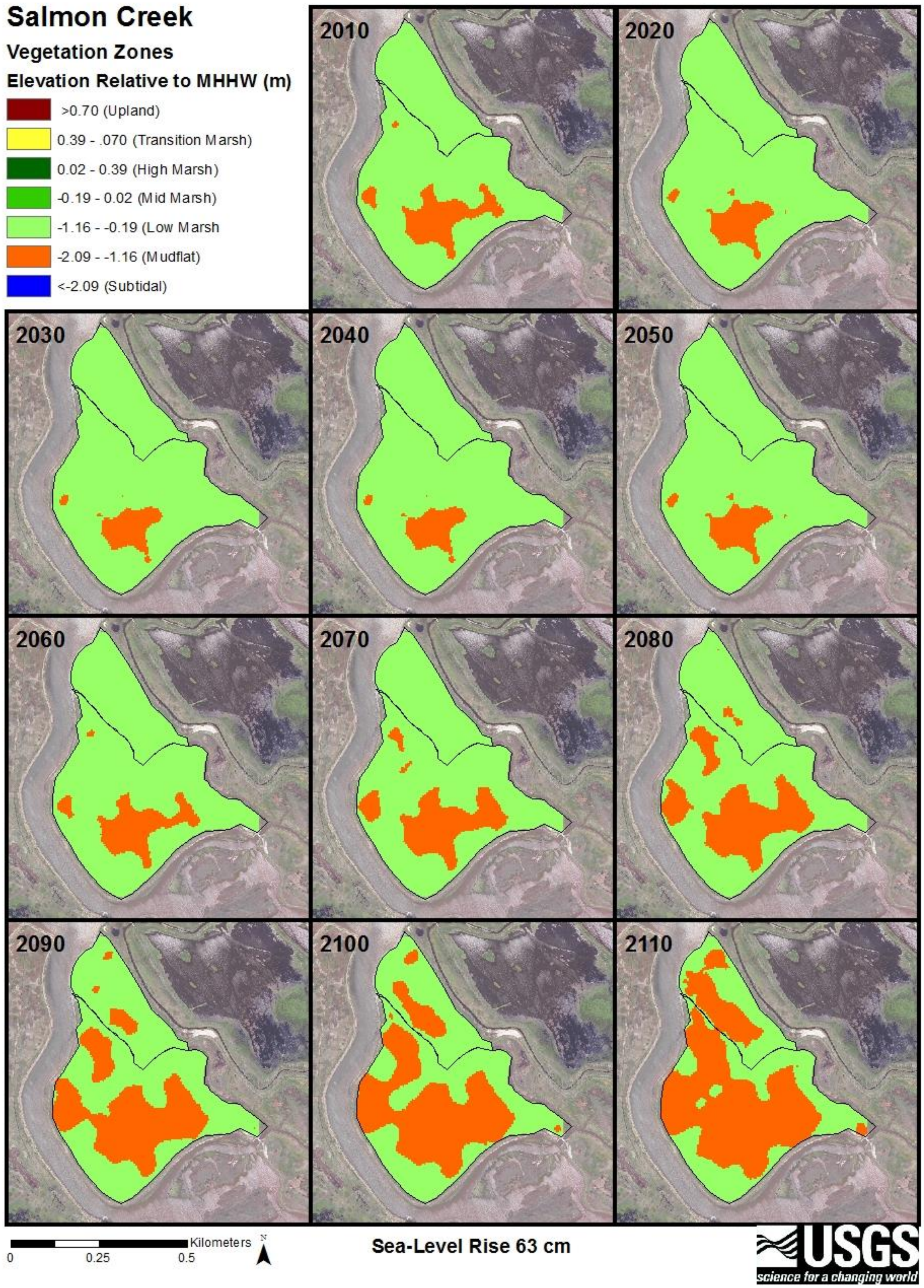

Figure A5. Projected changes in Salmon Creek habitat zones under the mid NRC sea-level rise scenario (63 cm).

Appendix B. WARMER results for Hookton Slough Marsh

Summary of results

- *Study site size*: 3.2 hectares
- *Location*: 40°40'41.752"N latitude, 124°13'4.347"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario, the site remains similar to current conditions while mid marsh gradually increases and low marsh gradually decreases through the coming century. The mid SLR scenario is projected to result in a shift in habitat composition with mid marsh decreasing and disappearing by 2070 while low marsh increases to comprise 100% of the study area. High SLR is projected to lead to a rapid decrease of mid marsh which disappears by 2050. The study area then consists of 100% low marsh before beginning to transition to mudflat in 2090 and becoming 100% mudflat by 2110.

Table B1. Vegetation zones for Hookton Slough. Zones were defined by degree of flooding by high tides.

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.702 to 0.390	1.720 to 1.400	2.622 to 2.310
High	3-25	0.390 to 0.018	1.400 to 1.018	2.310 to 1.938
Middle	25-50	0.018 to -0.195	1.018 to 0.800	1.938 to 1.725
Low	>50	-0.195 to -1.164	0.800 to -0.194	1.725 to 0.756

Table B2. Model input parameters for Hookton Slough. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate ($g/cm^2/yr$)	0.396	Core Calibration
Elevation of Peak Biomass (cm, MSL)	91.5	NDVI from NAIP
Minimum Elevation of Vegetation (cm, MSL)	7.5	Field Surveys
Max. Aboveground Organic Accumulation ($g/cm^2/yr$)	0.0629	Core Calibration
Root:Shoot	0.458	Marsh Organs
Porosity Surface (%)	89	Core
Porosity Depth (%)	55	Core
Refractory Carbon (%)	25.8	Core
Maximum Astronomical Tide (cm, MSL)	257	North Spit Tide Gauge (NOAA,9418767)
Historic Sea-Level Rise (mm/yr)	4.7	North Spit Tide Gauge (NOAA,9418767)
Organic Matter Density (g/cm^3)	1.14	DeLaune 1983
Mineral Density (g/cm^3)	2.61	DeLaune 1983

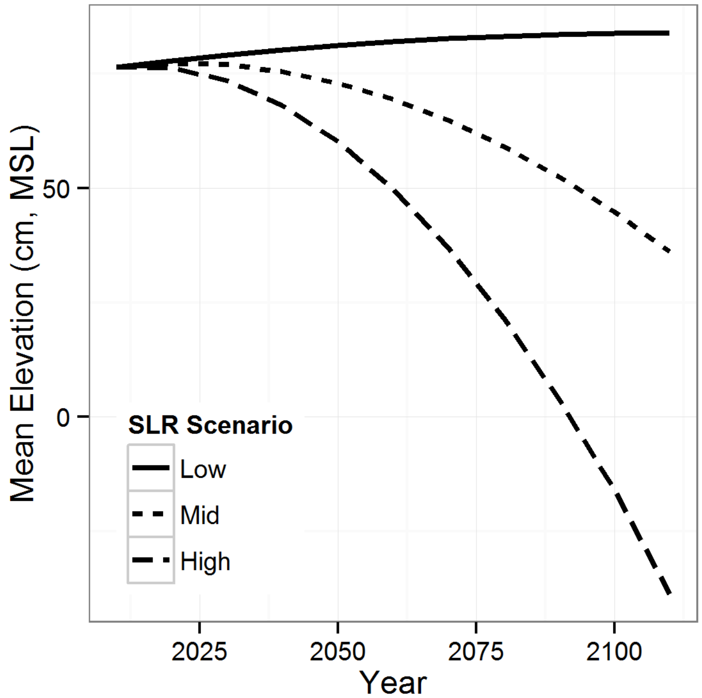

Figure B1. WARMER model projections for the change in average marsh elevation (relative to MSL) at Hookton Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

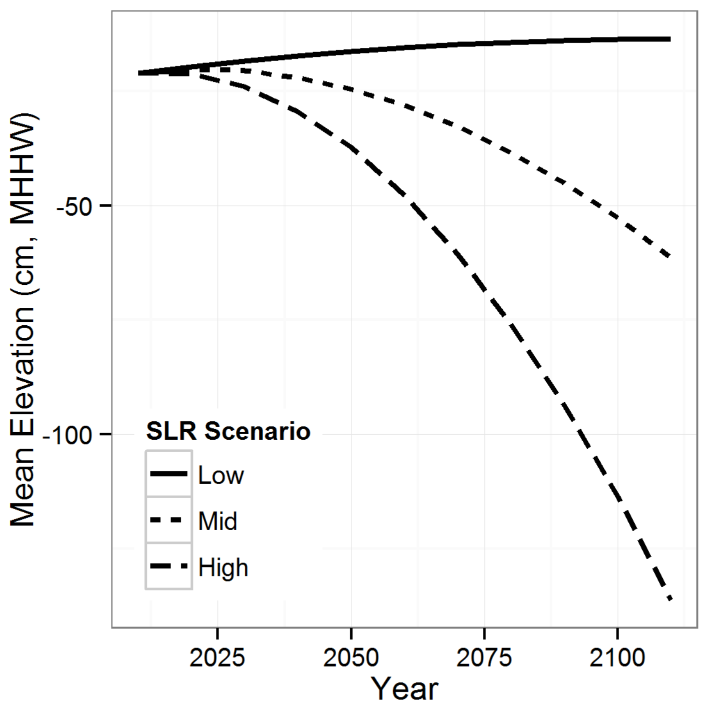

Figure B2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Hookton Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

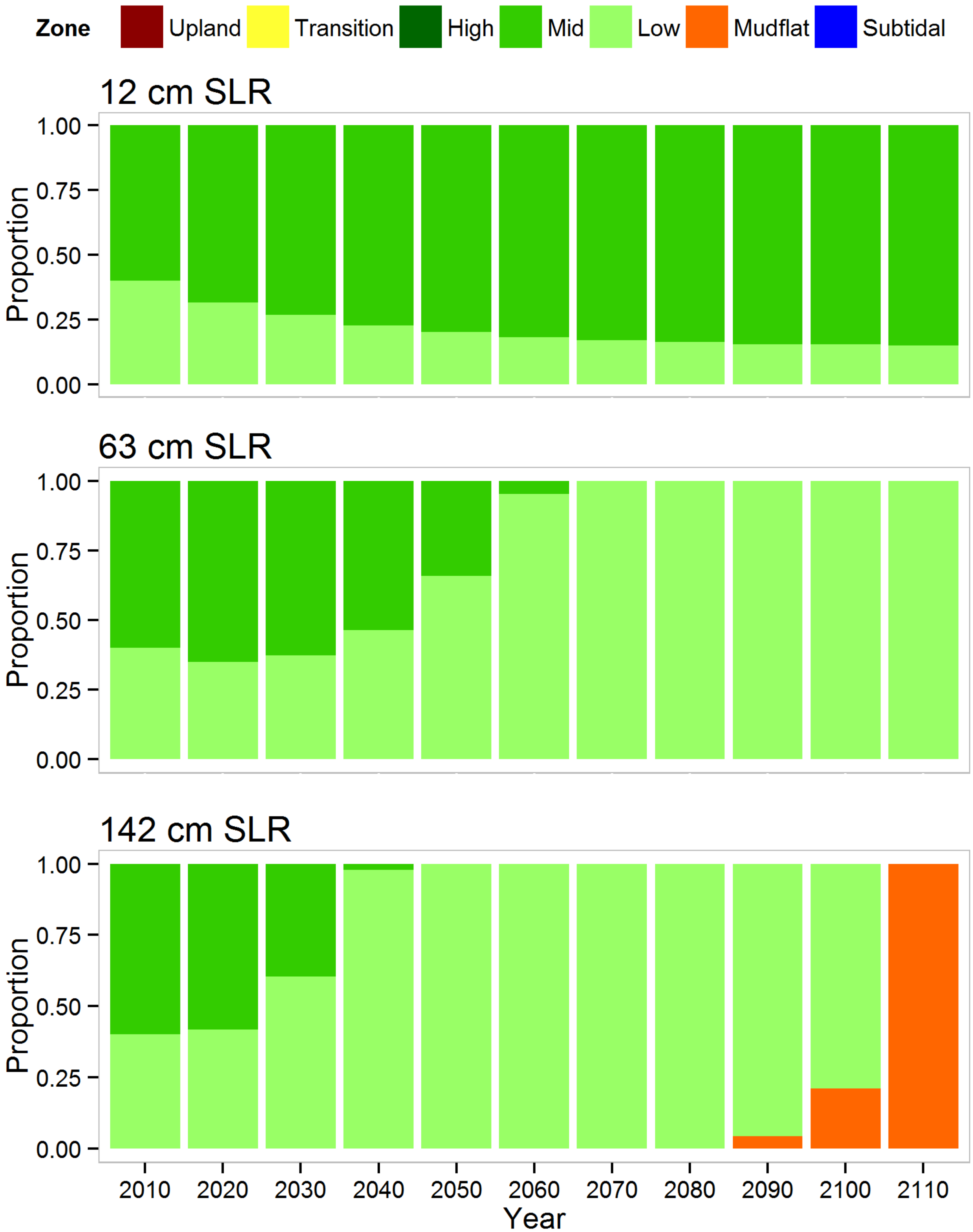

Figure B3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Hookton Slough under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table B3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0
Mid	60	80	85	60	34	0	60	0	0
Low	40	20	15	40	66	100	40	100	0
Mudflat	0	0	0	0	0	0	0	0	100

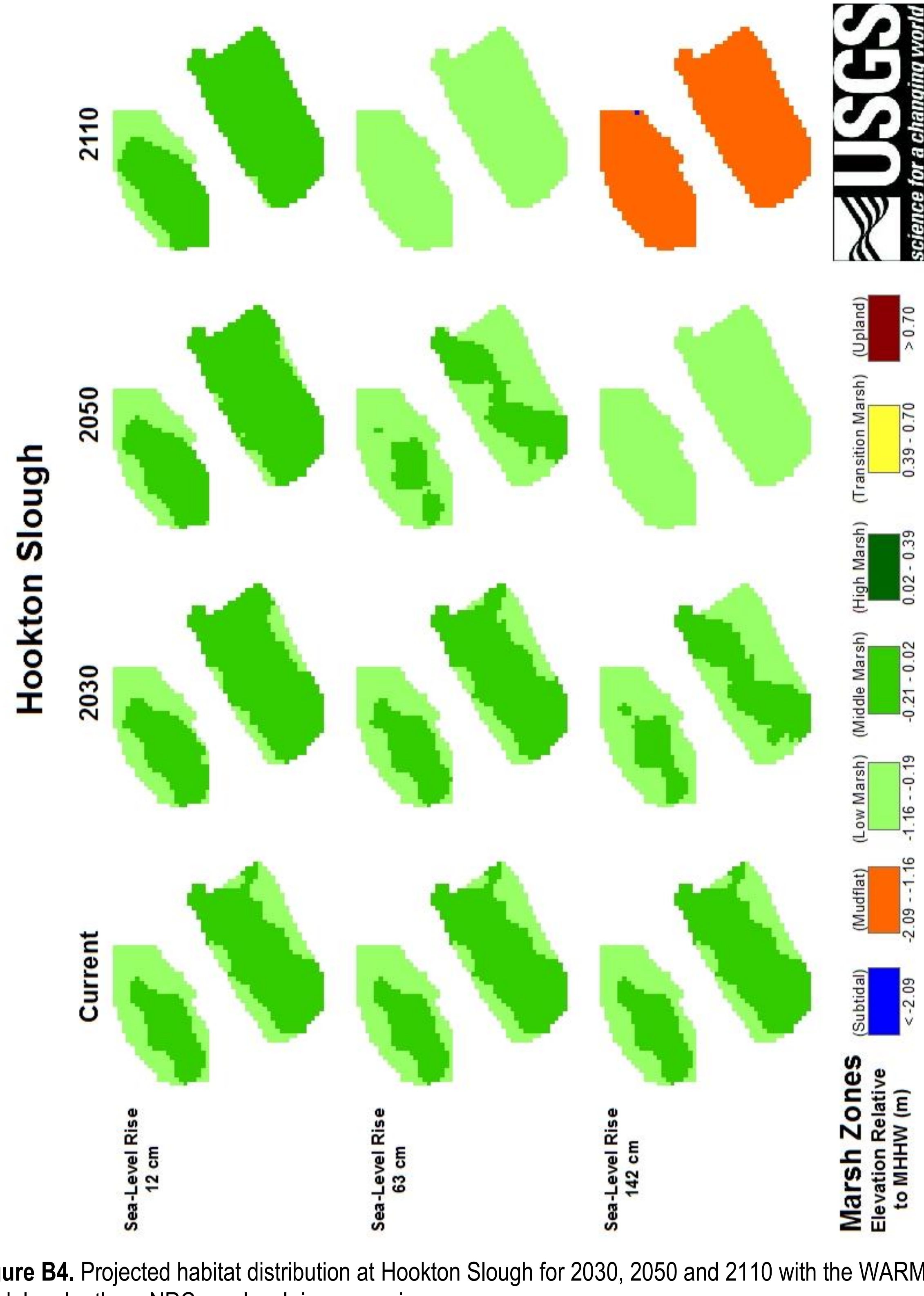

Figure B4. Projected habitat distribution at Hookton Slough for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

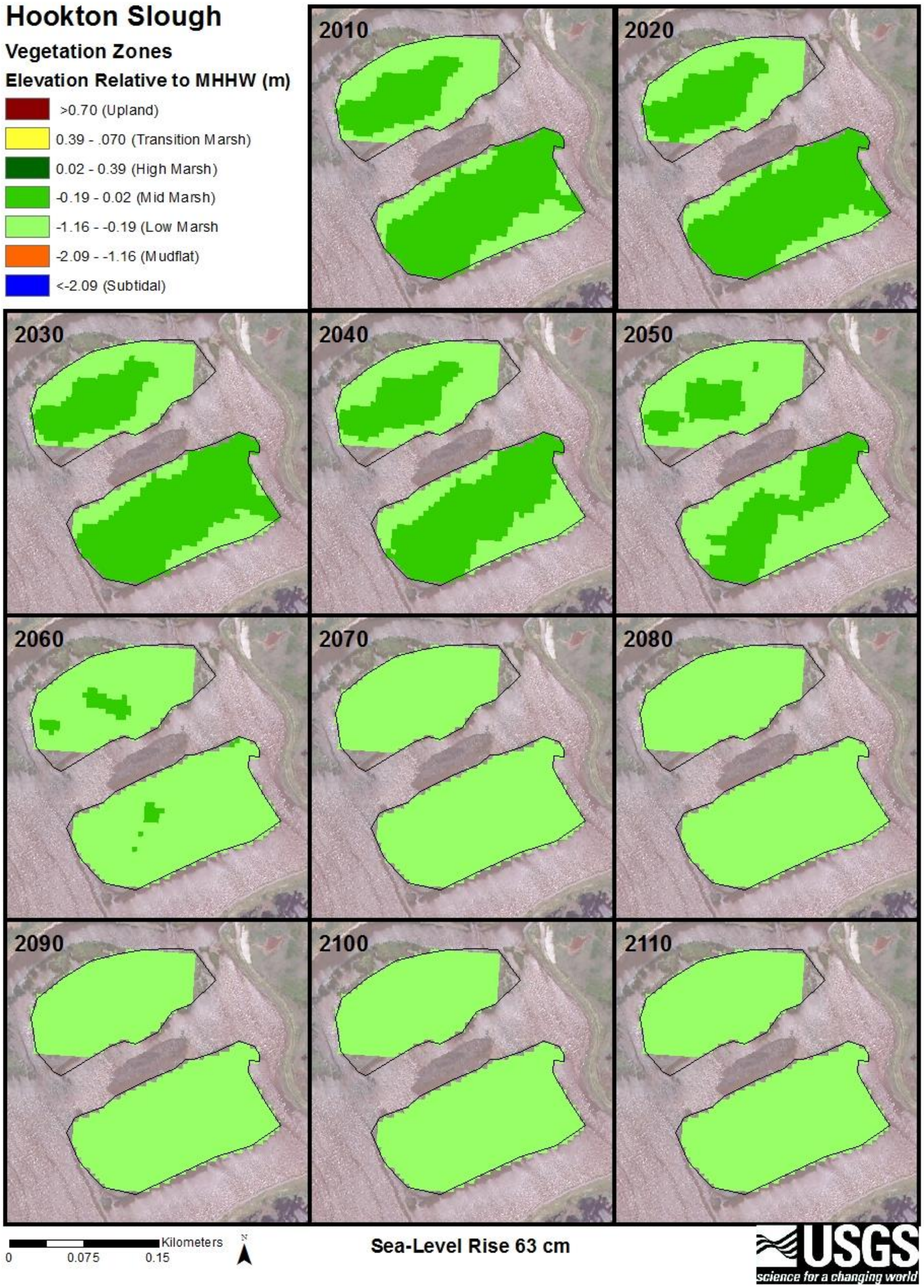

Figure B5. Projected changes in Hookton Slough zones under the mid NRC sea-level rise scenario (63 cm).

Appendix C. WARMER results for White Slough Marsh

Summary of results

- *Study site size*: 3.9 hectares
- *Location*: 40°42'13.338"N latitude, 124°12'56.041"W longitude.
- *Sea-level rise marsh response modeling*: White Slough marsh modeling results are very similar to Hookton marsh modeling results. Under the NRC's low SLR scenario, the site remains similar to current conditions while mid marsh gradually increases and low marsh gradually decreases through the coming century. The mid SLR scenario is projected to result in a shift in habitat composition with mid marsh decreasing and disappearing by 2070 while low marsh increases to comprise 100% of the study area. High SLR is projected to lead to a rapid decrease of mid marsh which disappears by 2050. The study area then consists of 100% low marsh before beginning to transition to mudflat in 2090 and becoming 100% mudflat by 2110.

Table C1. Vegetation zones for White Slough. Zones were defined by degree of flooding by high tides.

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.702 to 0.390	1.720 to 1.400	2.622 to 2.310
High	3-25	0.390 to 0.018	1.400 to 1.018	2.310 to 1.938
Middle	25-50	0.018 to -0.195	1.018 to 0.800	1.938 to 1.725
Low	>50	-0.195 to -1.164	0.800 to -0.194	1.725 to 0.756

Table C2. Model input parameters for White Slough. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate ($g/cm^2/yr$)	0.398	Core Calibration
Elevation of Peak Biomass (cm, MSL)	85.7	NDVI from NAIP
Minimum Elevation of Vegetation (cm, MSL)	55.7	Field Surveys
Max. Aboveground Organic Accumulation ($g/cm^2/yr$)	0.0613	Core Calibration
Root:Shoot	0.458	Marsh Organs
Porosity Surface (%)	89	Core
Porosity Depth (%)	55	Core
Refractory Carbon (%)	25.8	Core
Maximum Astronomical Tide (cm, MSL)	257	North Spit Tide Gauge (NOAA,9418767)
Historic Sea-Level Rise (mm/yr)	4.7	North Spit Tide Gauge (NOAA,9418767)
Organic Matter Density (g/cm^3)	1.14	DeLaune 1983
Mineral Density (g/cm^3)	2.61	DeLaune 1983

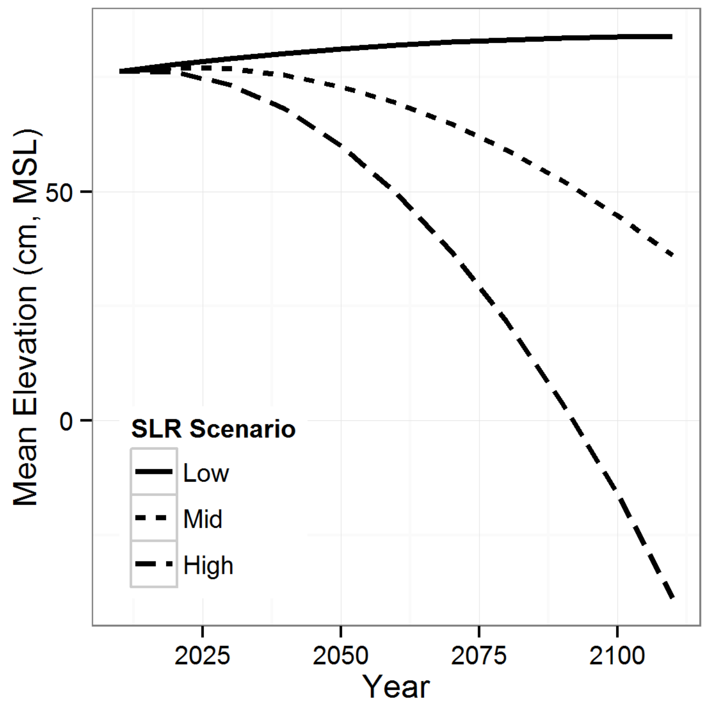

Figure C1. WARMER model projections for the change in average marsh elevation (relative to MSL) at White Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

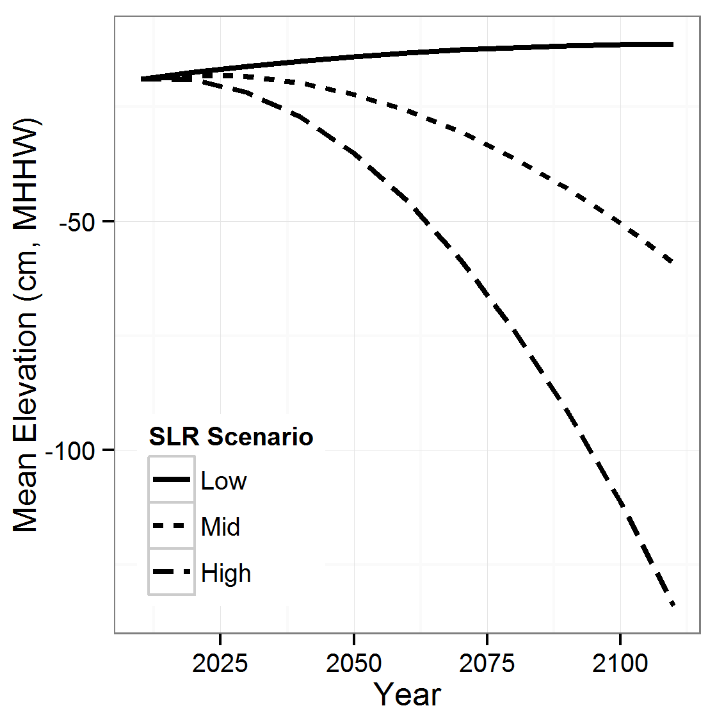

Figure C2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at White Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

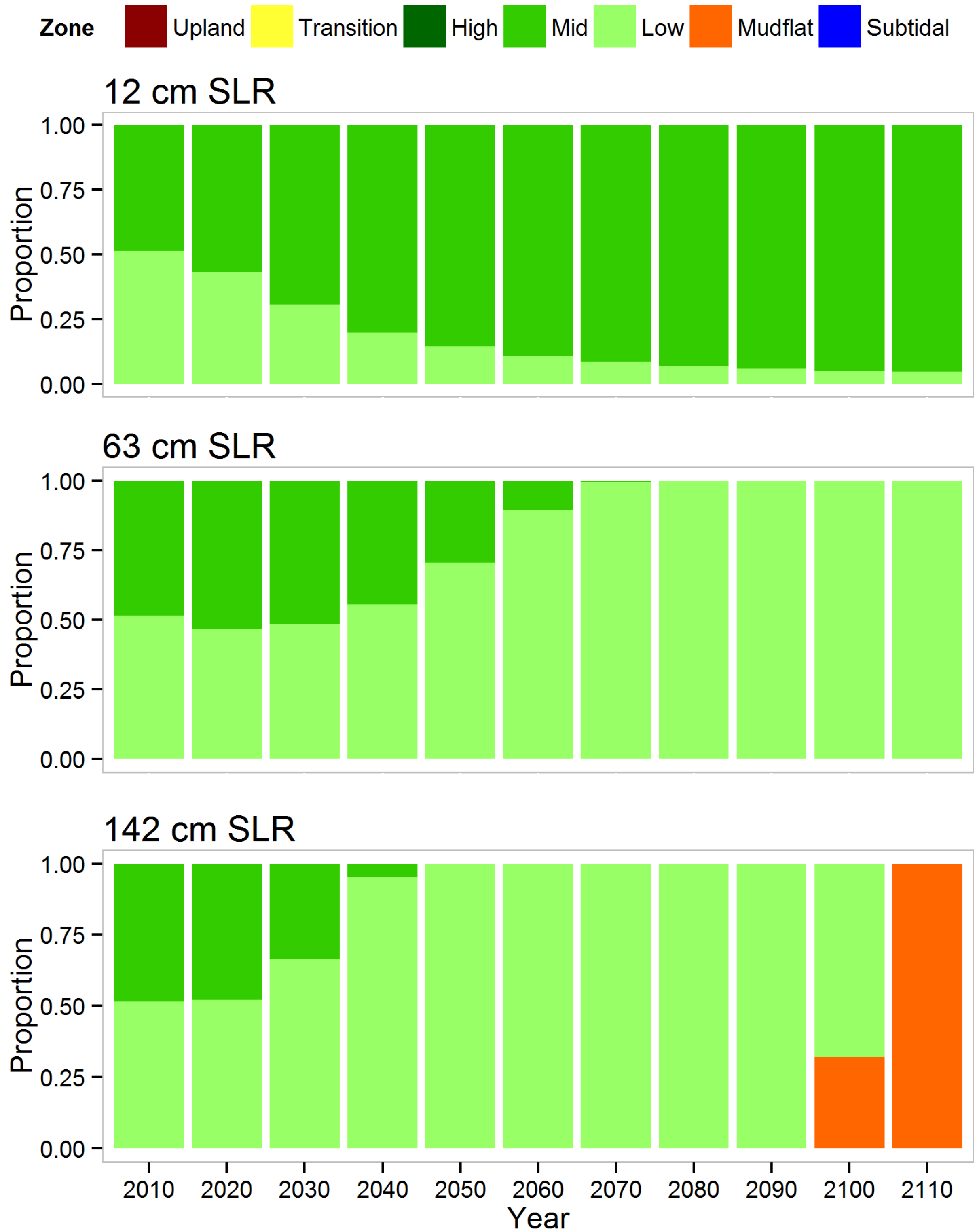

Figure C3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at White Slough under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table C3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0
Mid	49	85	95	49	29	0	49	1	0
Low	51	15	5	51	71	100	51	99	0
Mudflat	0	0	0	0	0	0	0	0	100

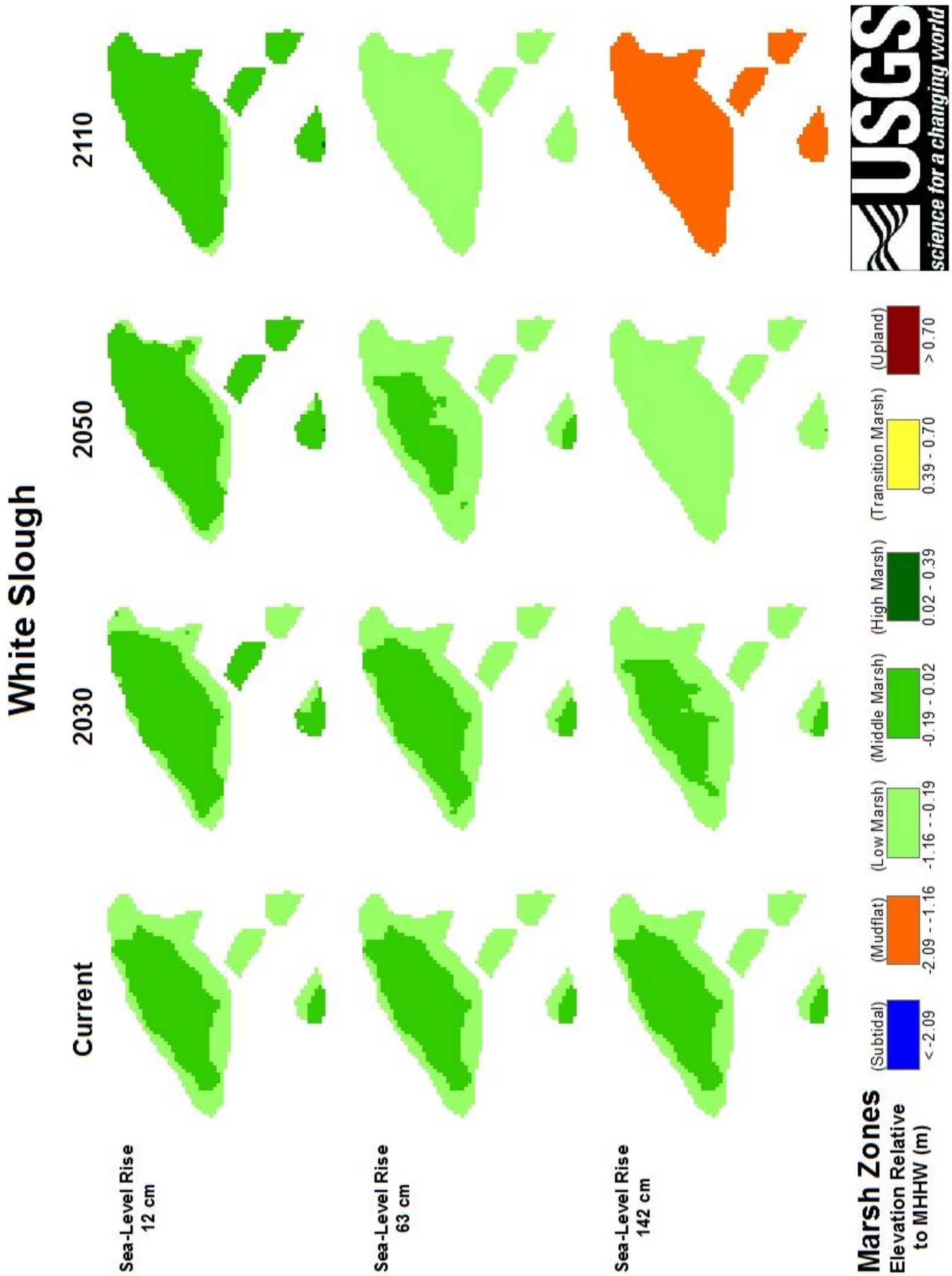

Figure C4. Projected habitat distribution at White Slough for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

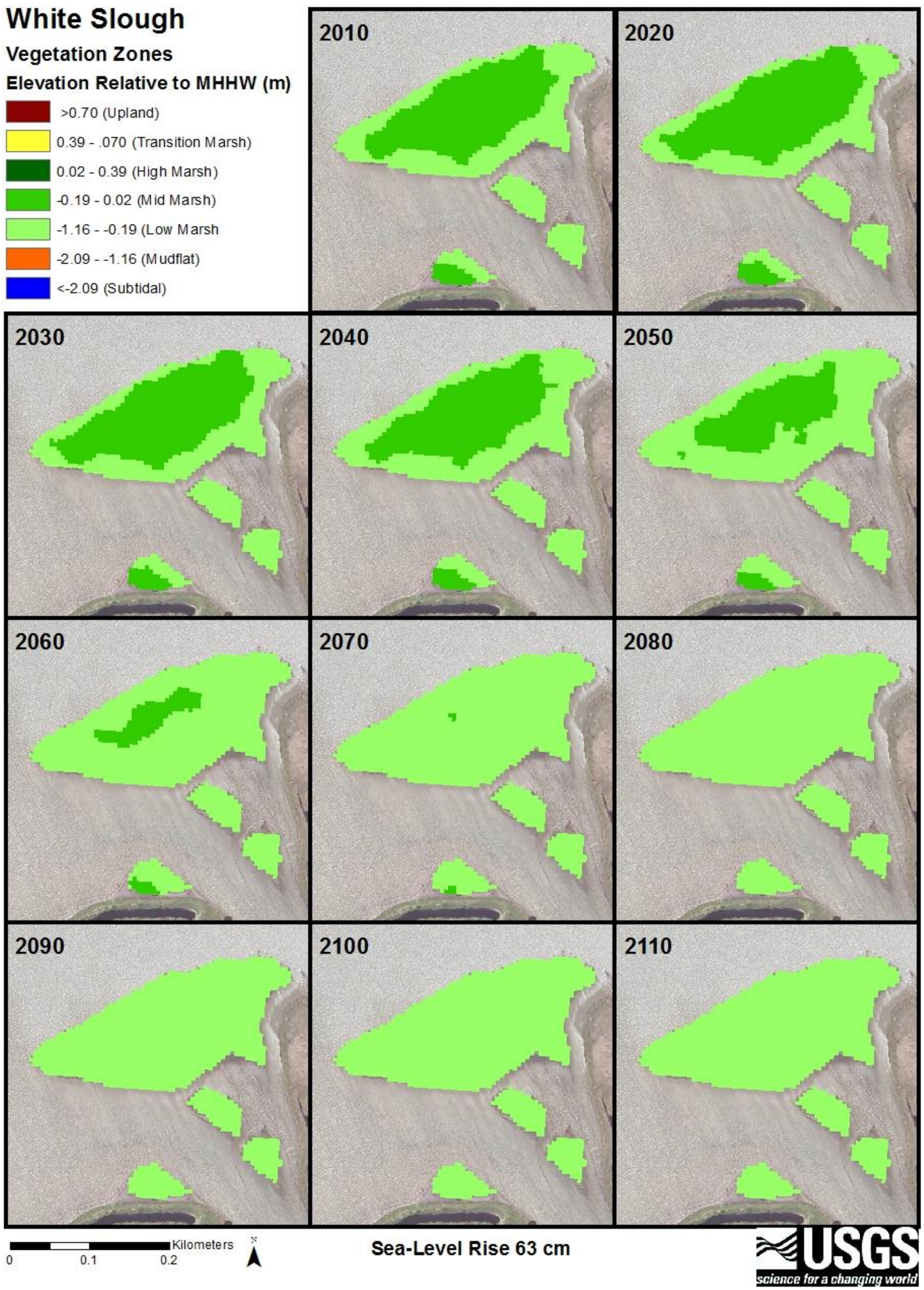

Figure C5. Projected changes in White Slough habitat zones under the mid NRC sea-level rise scenario (63 cm).

Appendix D. WARMER results for Eureka Marsh

Summary of results

- *Study site size*: 33.2 hectares
- *Location*: 40°48'19.483"N latitude, 124°7'55.383"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario, the site remains similar to current conditions and is composed predominantly of mid and low marsh with a small portion of mudflat. The mid SLR scenario is projected to result in a decrease of mid marsh until its disappearance in 2070, as well as a decrease of low marsh habitat until its disappearance in 2010. Mudflat habitat gradually increases under this scenario until the entire study area is mudflat by 2010. High SLR is projected to lead to a rapid transition in habitat zones with the disappearance of mid marsh by 2050 and low marsh by 2070. The site becomes 100% non-vegetated mudflat by 2070 and remains that way through 2010.

Table D1. Vegetation zones for Eureka Marsh. Zones were defined by degree of flooding by high tides.

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.758 to 0.421	1.720 to 1.400	2.763 to 2.426
High	3-25	0.421 to 0.019	1.400 to 1.018	2.426 to 2.024
Middle	25-50	0.019 to -0.211	1.018 to 0.800	2.024 to 1.794
Low	>50	-0.211 to -0.503	0.800 to 0.523	1.794 to 1.502

Table D2. Model input parameters for Eureka Marsh. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate (g/cm²/yr)	0.382	Core Calibration
Elevation of Peak Biomass (cm, MSL)	110	NDVI from NAIP
Minimum Elevation of Vegetation (cm, MSL)	46	Field Surveys
Max. Aboveground Organic Accumulation (g/cm²/yr)	0.0712	Core Calibration
Root:Shoot	0.458	Marsh Organs
Porosity Surface (%)	89	Core
Porosity Depth (%)	55	Core
Refractory Carbon (%)	25.8	Core
Maximum Astronomical Tide (cm, MSL)	257	North Spit Tide Gauge (NOAA,9418767)
Historic Sea-Level Rise (mm/yr)	4.7	North Spit Tide Gauge (NOAA,9418767)
Organic Matter Density (g/cm³)	1.14	DeLaune 1983
Mineral Density (g/cm³)	2.61	DeLaune 1983

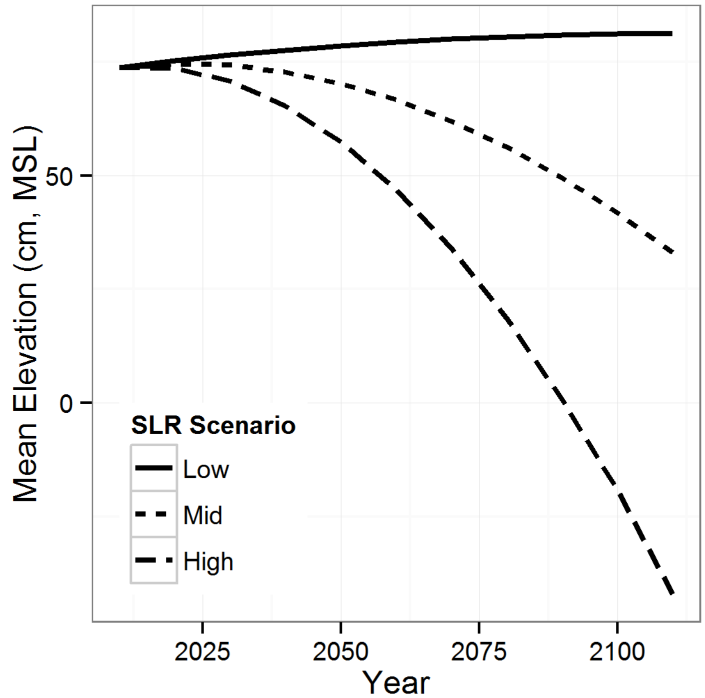

Figure D1. WARMER model projections for the change in average marsh elevation (relative to MSL) at Eureka Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

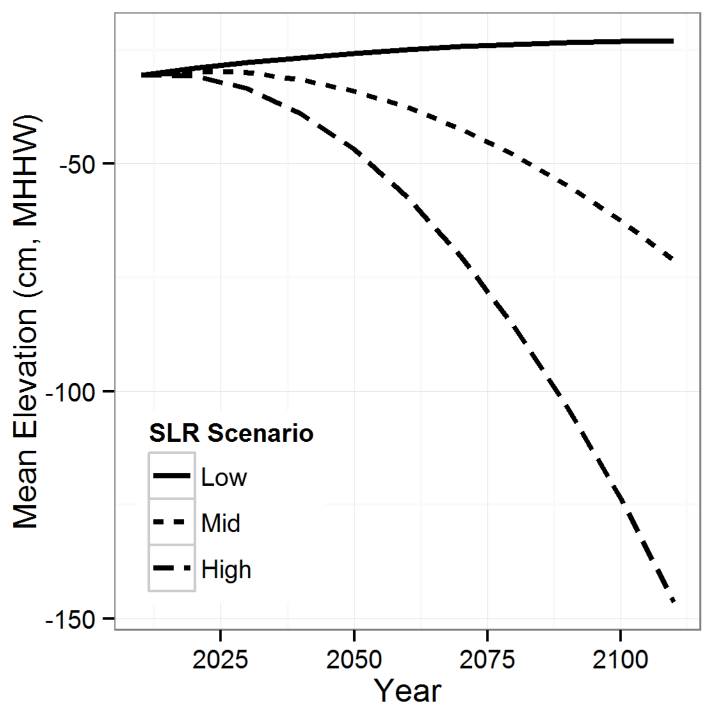

Figure D2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Eureka Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

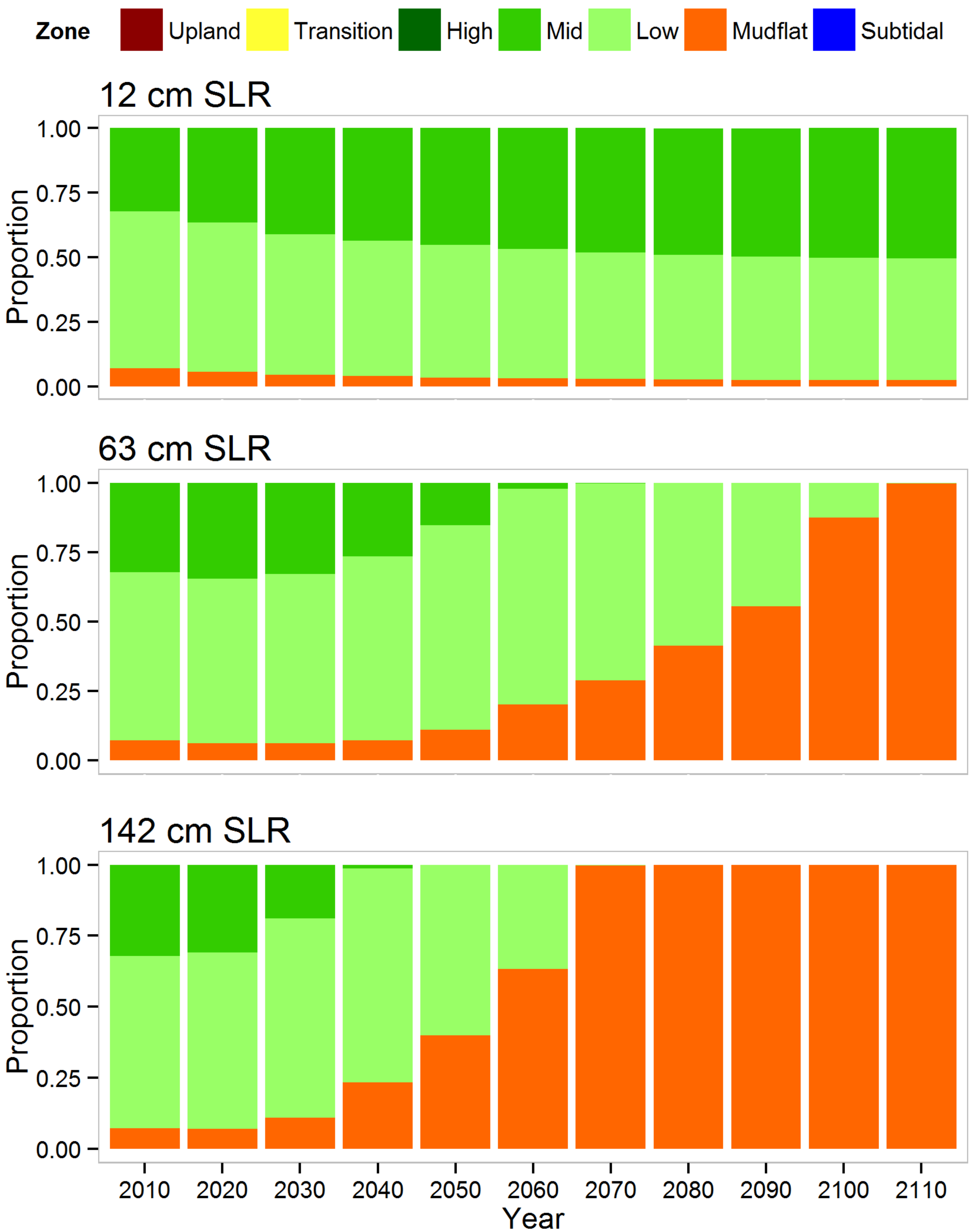

Figure D3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Eureka Marsh under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table D3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	0	0	0	0	0	0	0	0	0
Mid	32	45	50	32	15	0	32	0	0
Low	61	51	47	61	74	0	61	60	0
Mudflat	7	4	3	7	11	100	7	40	100

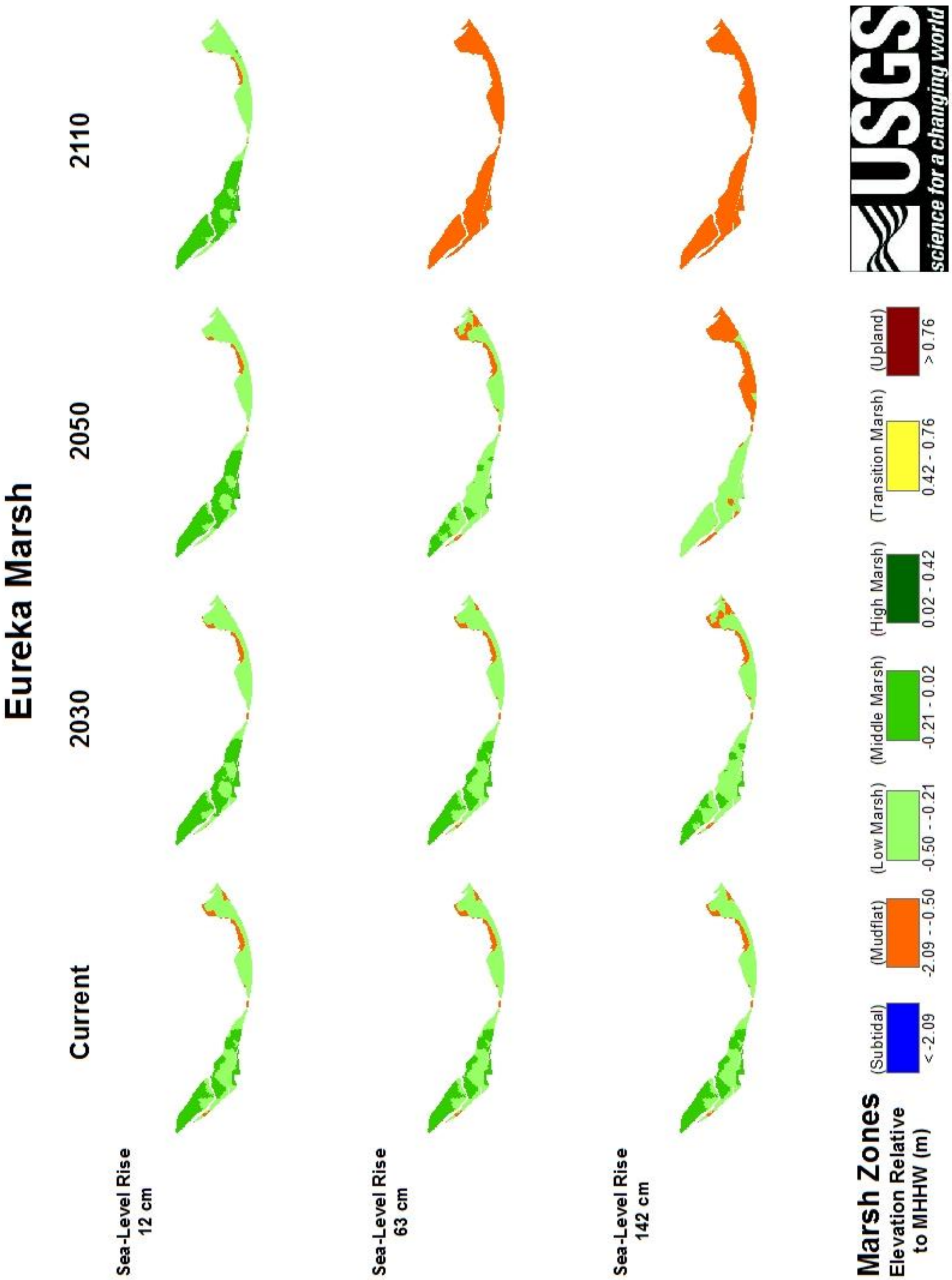

Figure D4. Projected habitat distribution at Eureka Marsh for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

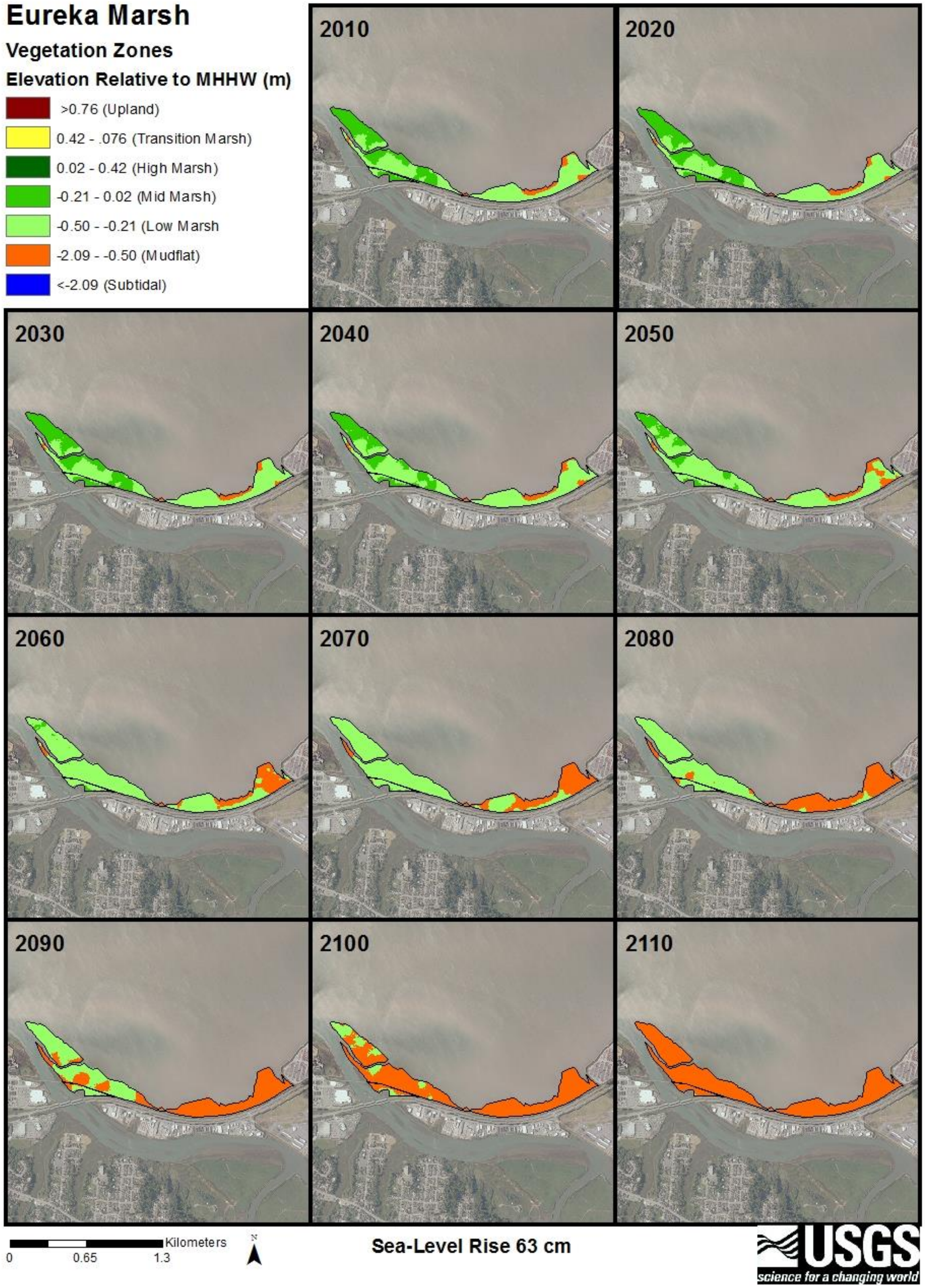

Figure D5. Projected changes in Eureka Marsh habitat zones under the mid NRC sea-level rise scenario (63 cm).

Appendix E. WARMER results for Jacoby Marsh

Summary of results

- *Study site size*: 30.5 hectares
- *Location*: 40°50'31.775"N latitude, 124°5'5.171"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario, the site remains similar to current conditions and is composed predominantly of mid and high marsh with a small portion of low marsh. The mid SLR scenario is projected to result in a gradual shift in habitat composition with high marsh lost by 2080 and mid marsh lost by 2100. By 2110, the site is projected to be comprised of mostly low marsh with some mudflat habitat. High SLR is projected to lead to a rapid transition in habitat zones. By 2090, the site becomes 100% non-vegetated mudflat

Table E1. Vegetation zones for Jacoby Marsh. Zones were defined by degree of flooding by high tide

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.758 to 0.421	1.720 to 1.400	2.763 to 2.426
High	3-25	0.421 to 0.019	1.400 to 1.018	2.426 to 2.024
Middle	25-50	0.019 to -0.211	1.018 to 0.800	2.024 to 1.794
Low	>50	-0.211 to -0.503	0.800 to 0.523	1.794 to 1.502

Table E2. Model input parameters for Jacoby Marsh. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model Parameter	Value	Source
Sediment Accumulation Rate ($g/cm^2/yr$)	0.391	Core Calibration
Elevation of Peak Biomass (cm, MSL)	104.5	NDVI from NAIP
Minimum Elevation of Vegetation (cm, MSL)	42.5	Field Surveys
Max. Aboveground Organic Accumulation ($g/cm^2/yr$)	0.0628	Core Calibration
Root:Shoot	0.458	Marsh Organs
Porosity Surface (%)	89	Core
Porosity Depth (%)	55	Core
Refractory Carbon (%)	25.8	Core
Maximum Astronomical Tide (cm, MSL)	257	North Spit Tide Gauge (NOAA,9418767)
Historic Sea-Level Rise (mm/yr)	4.7	North Spit Tide Gauge (NOAA,9418767)
Organic Matter Density (g/cm^3)	1.14	DeLaune 1983
Mineral Density (g/cm^3)	2.61	DeLaune 1983

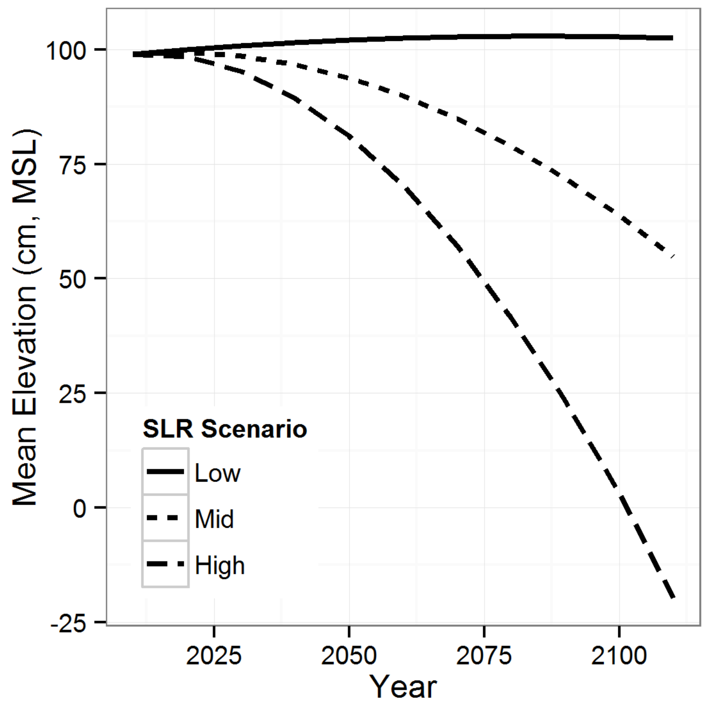

Figure E1. WARMER model projections for the change in average marsh elevation (relative to MSL) at Jacoby Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

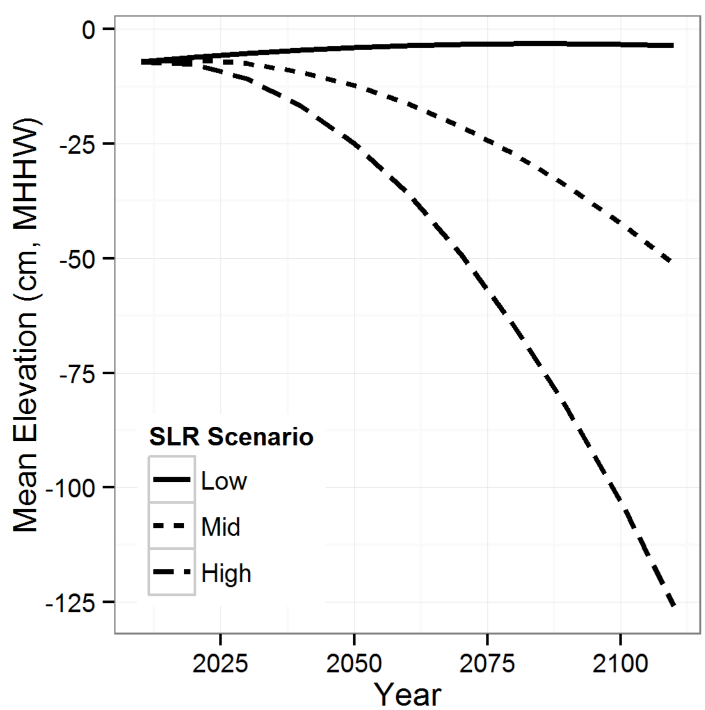

Figure E2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Jacoby Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

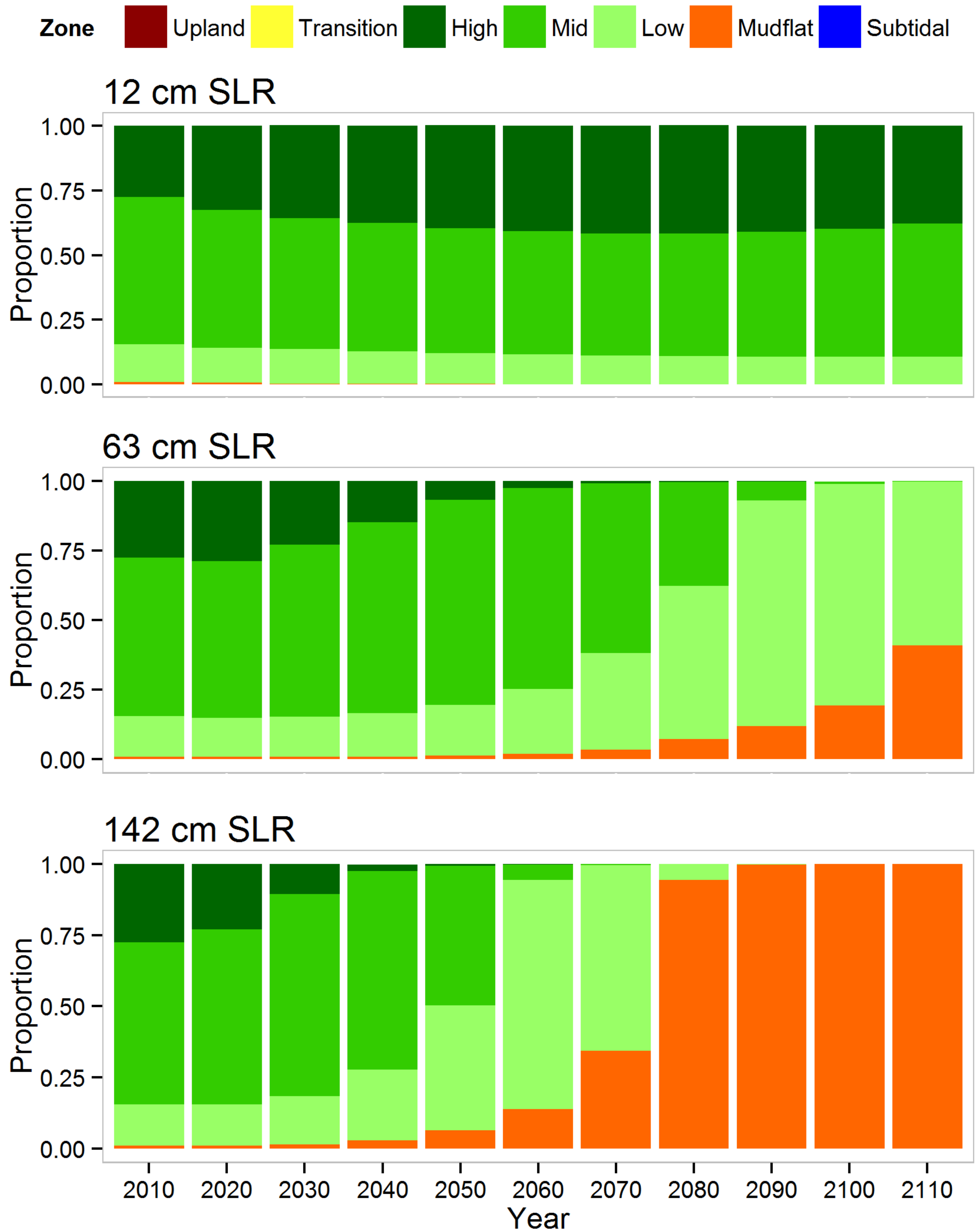

Figure E3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Jacoby Marsh under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table E3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	27	40	38	21	7	0	27	1	0
Mid	57	48	51	77	74	0	57	49	0
Low	15	12	11	2	18	59	15	44	0
Mudflat	1	0	0	0	1	41	1	6	100

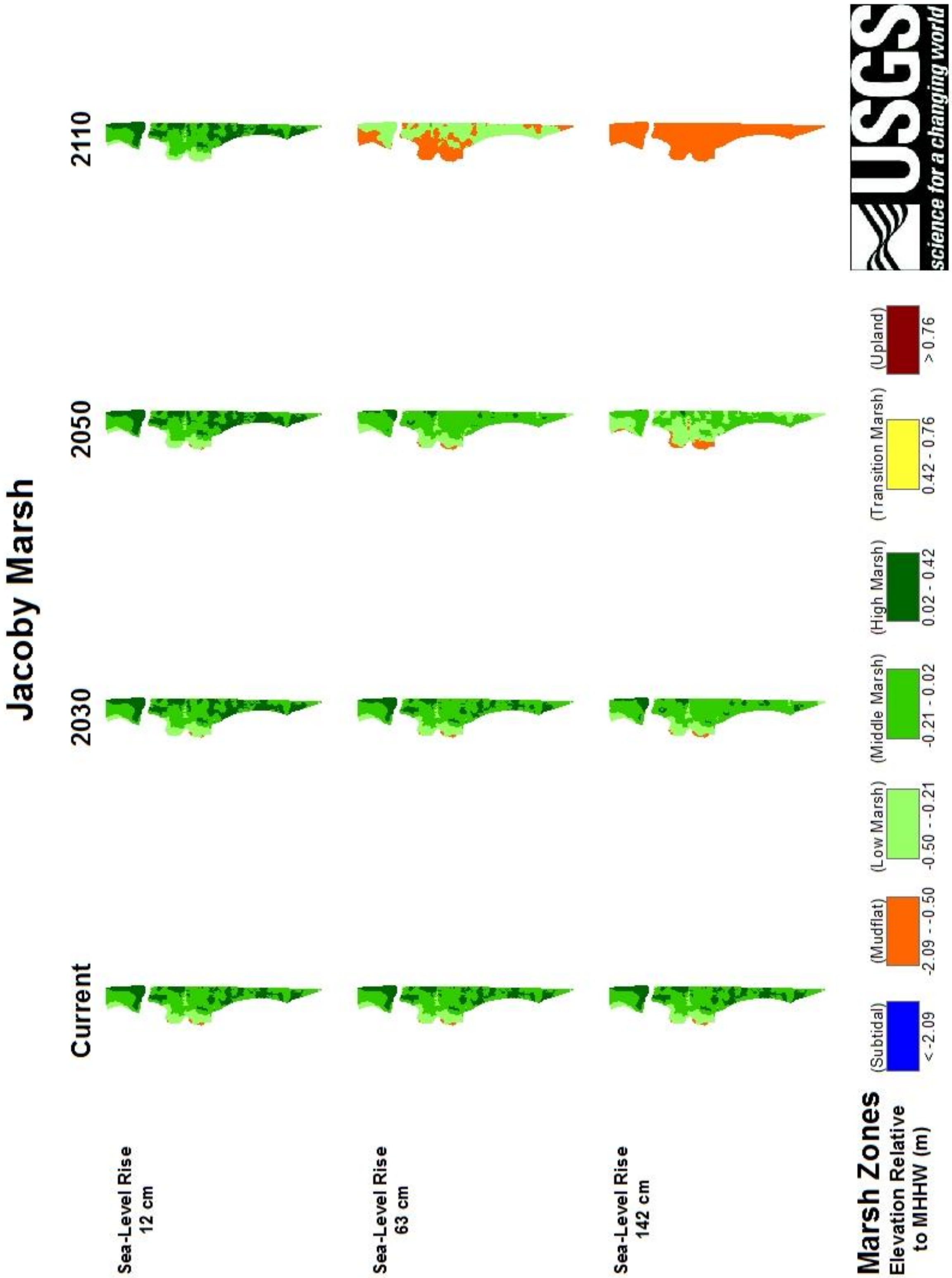

Figure E4. Projected habitat distribution at Jacoby Marsh for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

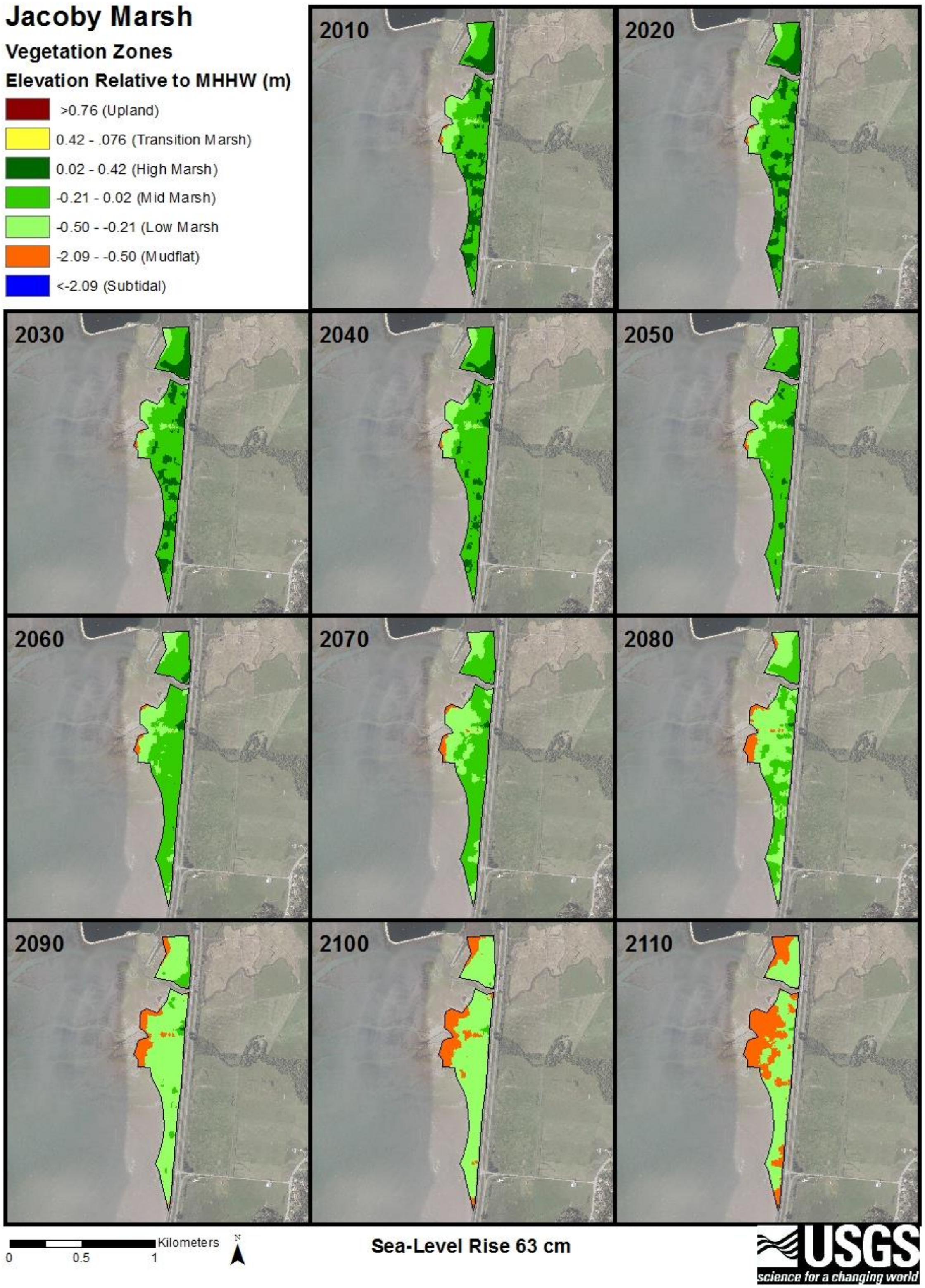

Figure E5. Projected changes in Jacoby Marsh habitat zones under the mid NRC sea-level rise scenario (63 cm).

Appendix F. WARMER results for Mad River Slough Marsh

Summary of results

- *Study site size*: 38.3 hectares
- *Location*: 40°41'19.61"N latitude, 124°12'36.08"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario, the site remains composed of high and mid marsh through the coming century. The mid SLR scenario is projected to result in a gradual shift in habitat composition with high marsh lost by 2080 and mid marsh lost by 2100. By 2110, the site is projected to be comprised of mostly low marsh with some mudflat habitat. High SLR is projected to lead to a rapid transition in habitat zones. By 2090, the site becomes 100% non-vegetated mudflat

Table F1. Mean percent cover of dominant plant species by marsh zone at Mad River Slough. Zones were defined by degree of flooding by high tides.

[JunBal = *Juncus balticus*; SarPac = *Sarcocornia pacifica*; DisSpi = *Distichlis spicata*; PotAns = *Potentilla anserina*; JauCar = *Jaumea carnosa*; TriCon = *Triglochin concinna*; TriMar = *Triglochin maritima.]*

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.758 to 0.421	1.720 to 1.400	2.763 to 2.426	2	JunBal (50), SarPac (50), DisSpi (3), PotAns (3)
High	3-25	0.421 to 0.019	1.400 to 1.018	2.426 to 2.024	119	DisSpi (47), SarPac (27), JauCar (16), TriCon (15)
Middle	25-50	0.019 to -0.211	1.018 to 0.800	2.024 to 1.794	44	DisSpi (45), SarPac (29), JauCar (25), TriCon (12)
Low	>50	-0.211 to -0.503	0.800 to 0.523	1.794 to 1.502	8	SarPac (68), DiSpi (31), JauCar (13), TriMar (1)

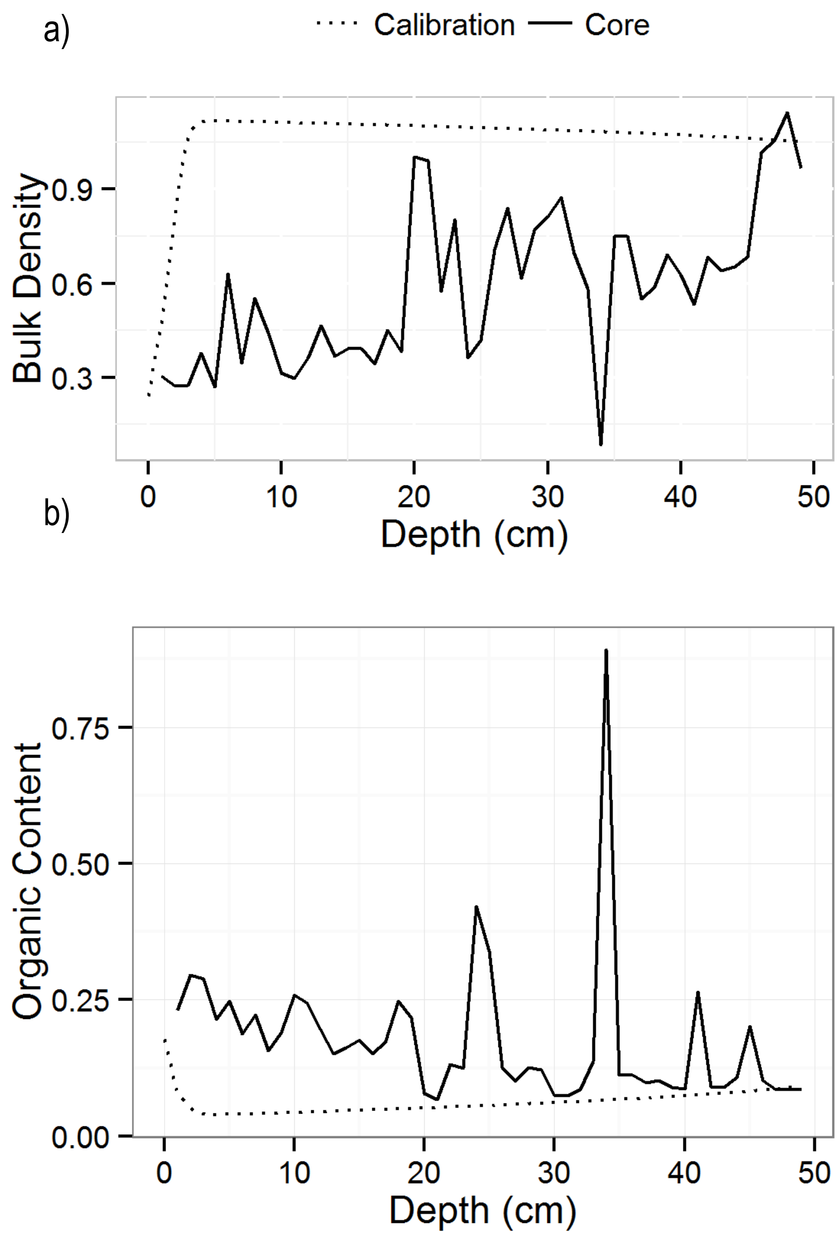

Figure F1. Deep sediment core calibration of the WARMER model using depth profiles of (a) bulk density (g cm^{-3}) and (b) organic matter content (%).

Table F2. Model input parameters for Mad River Slough. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model parameter	Value	Source
Sediment accumulation rate (g cm^{-2} yr^{-1})	0.392	Core calibration
Elevation of peak biomass (cm, MSL)	110	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	40	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0629	Core calibration
Root-to-shoot ratio	0.458	C. Janousek, unpub data
Porosity at sediment surface (%)	89	Core
Porosity at depth (%)	55	Core
Refractory carbon (%)	25.8	Core
Maximum astronomical tide (cm, MSL)	257	North Spit tide gauge (NOAA,9418767)
Historic sea-level rise (mm yr^{-1})	4.7	North Spit tide gauge (NOAA,9418767)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

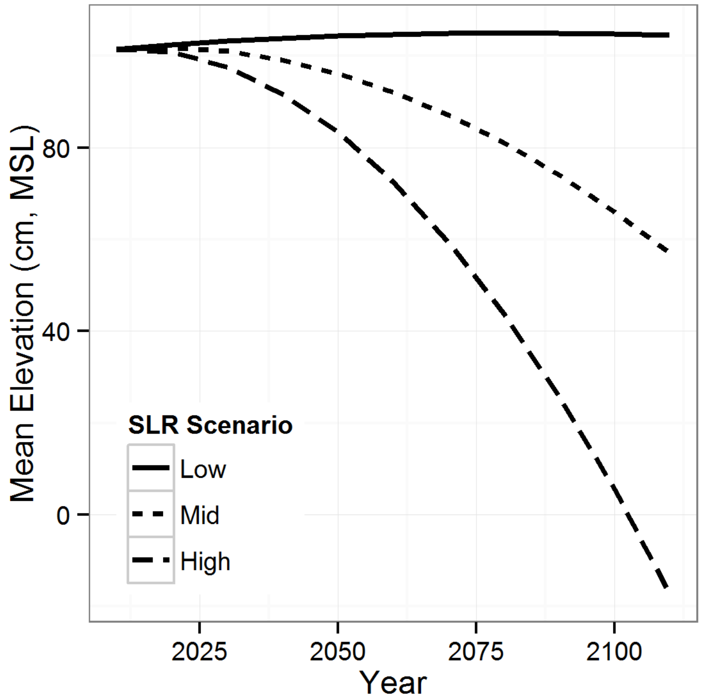

Figure F2. WARMER model projections for the change in average marsh elevation (relative to MSL) at Mad River Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

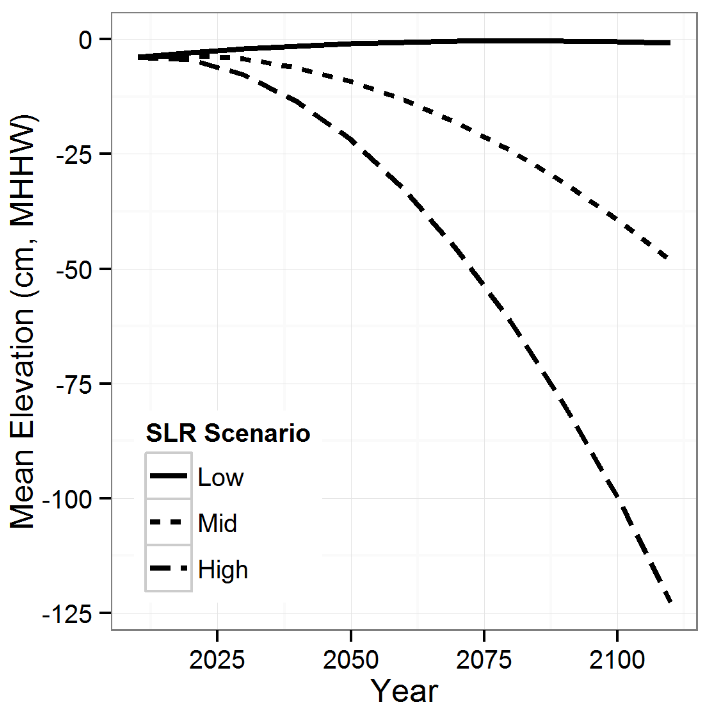

Figure F3. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Mad River Slough from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

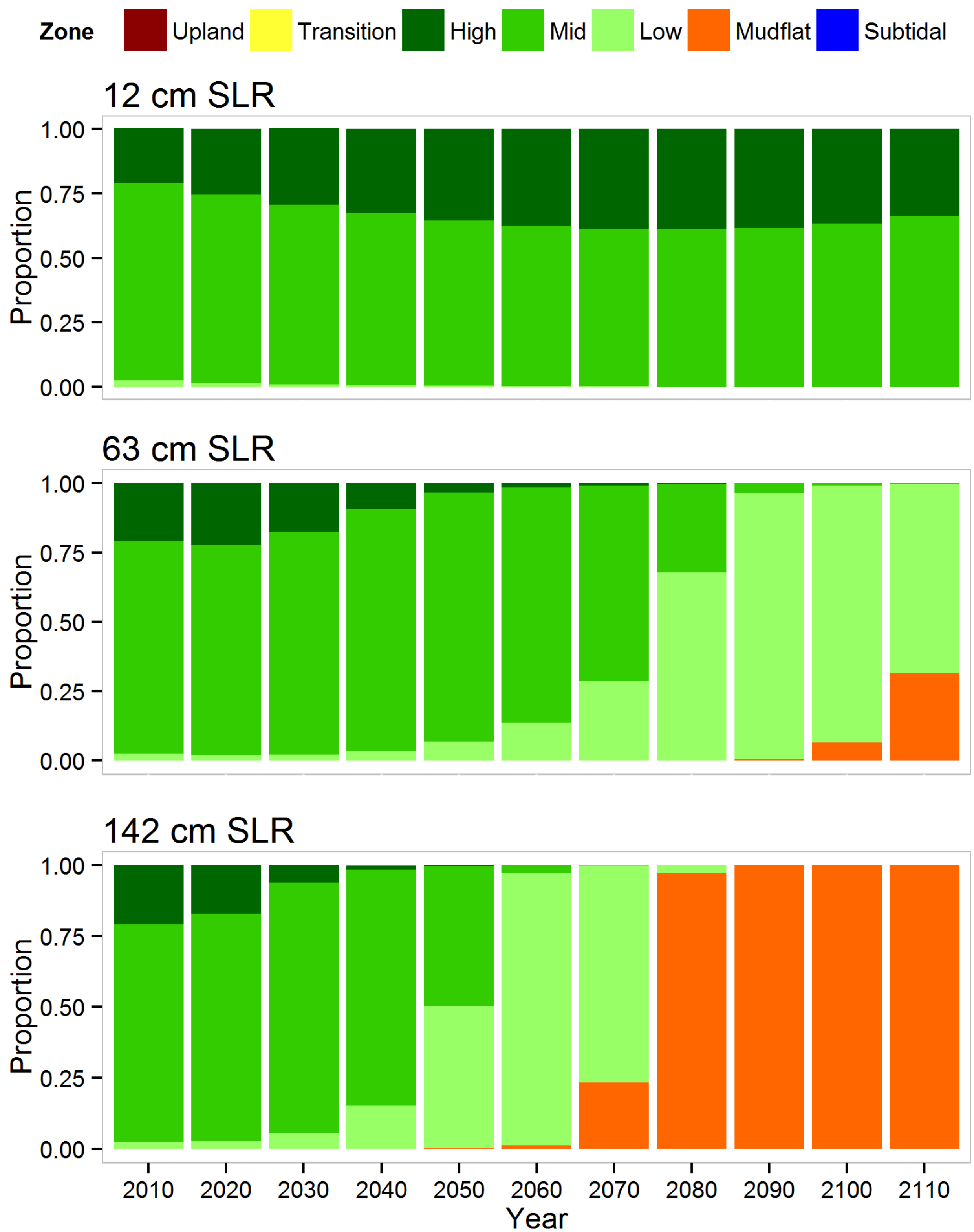

Figure F4. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Mad River Slough under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table F3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	21	36	34	21	3	0	21	1	0
Mid	77	64	66	77	90	0	77	49	0
Low	2	0	0	2	7	68	2	50	0
Mudflat	0	0	0	0	0	32	0	0	100

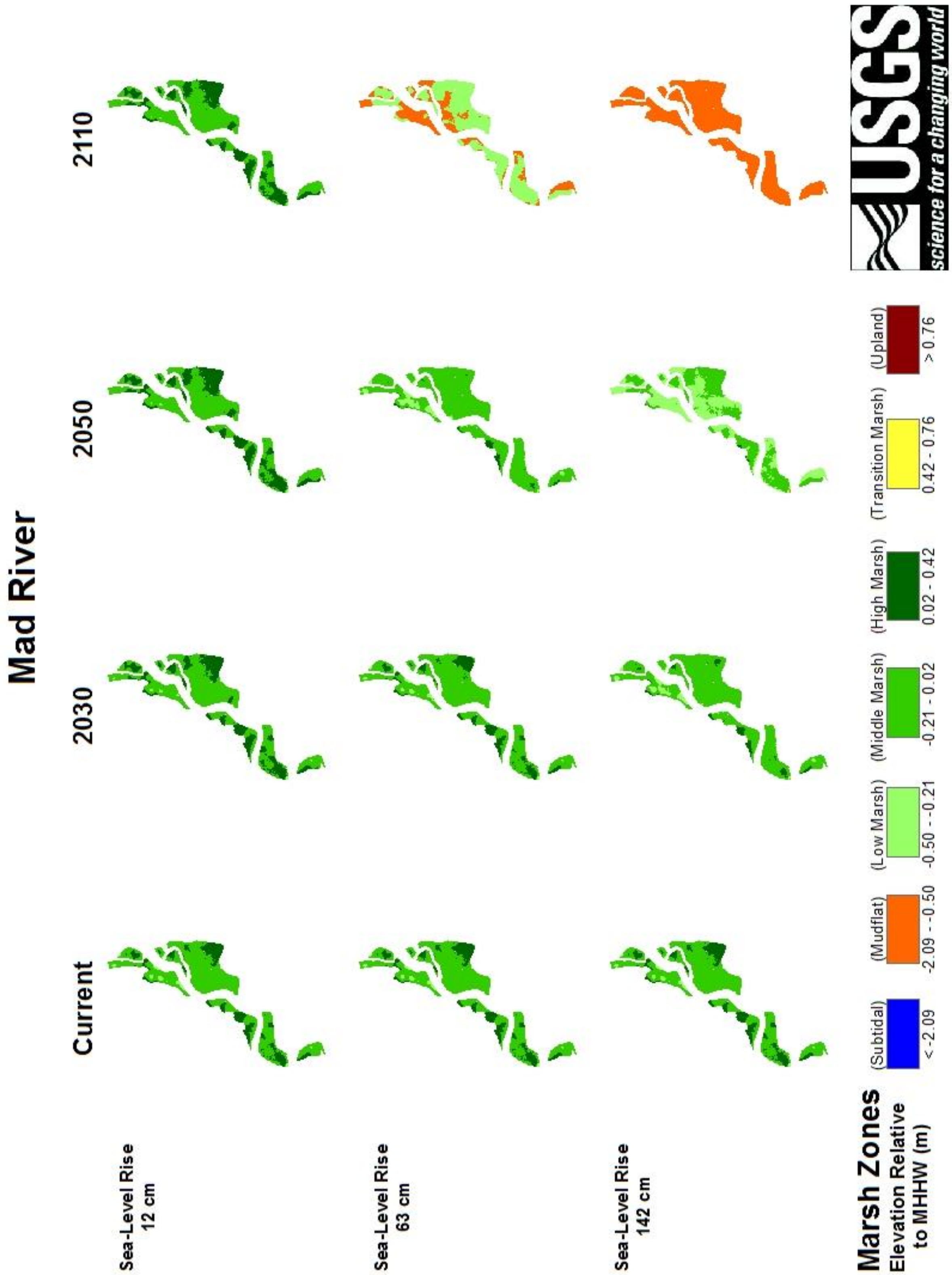

Figure F5. Projected habitat distribution at Mad River Slough for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

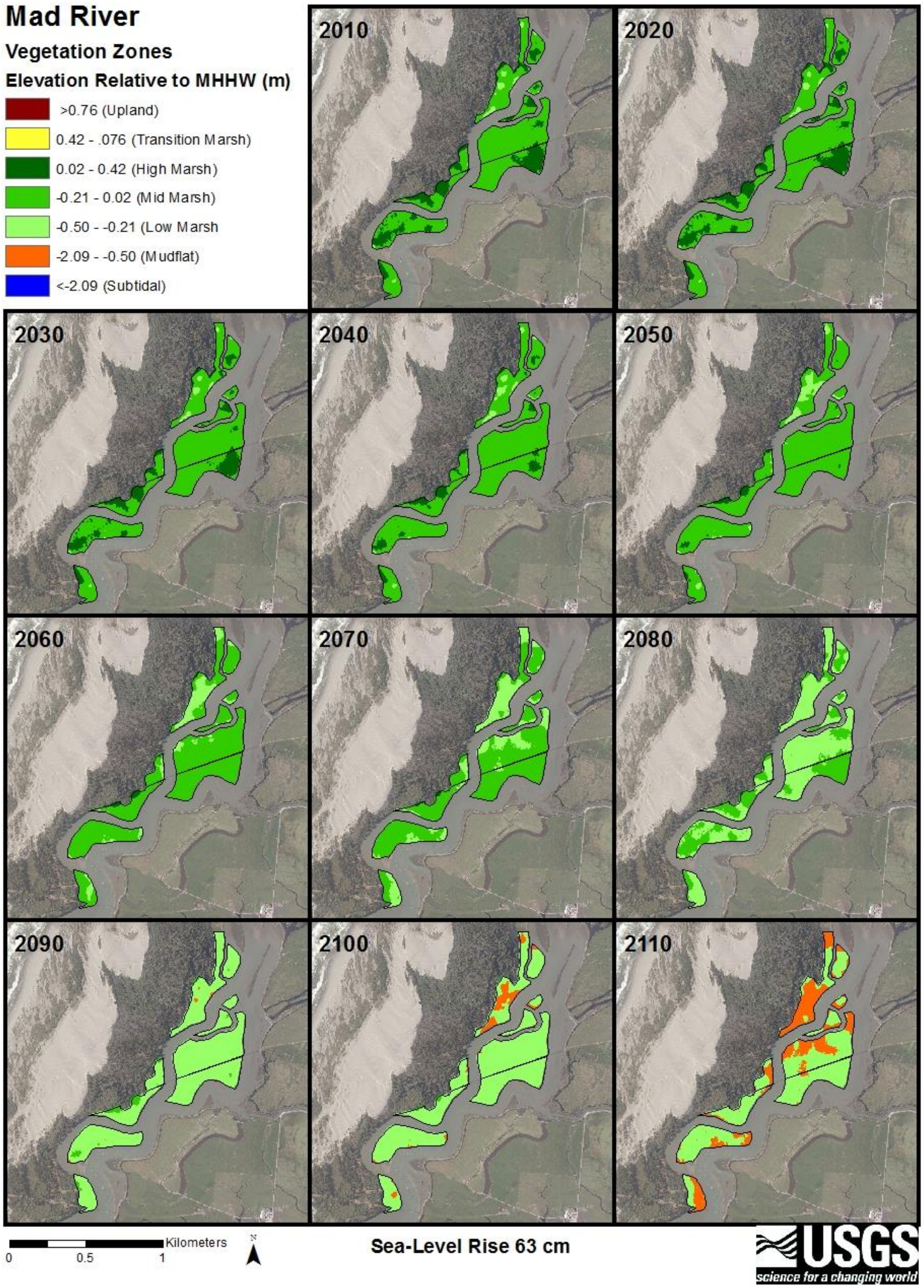

Figure F6. Projected changes in Mad River habitat zones under the mid NRC sea-level rise scenario (63 cm).

Appendix G. WARMER results for Manila Marsh

Summary of results

- *Study site size*: 38 hectares
- *Location*: 40°51'40.22"N latitude, 124°9'8.947"W longitude.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR scenario the site remains similar to current conditions and is composed predominantly of low marsh. The mid SLR scenario is projected to result in a gradual shift in habitat composition with mudflat increasing through the century until 98% of the study area is mudflat habiata by 2110. High SLR is projected to lead to a rapid transition in habitat zones. By 2090, the site becomes 100% non-vegetated mudflat

Table G1. Vegetation zones for Manila Marsh. Zones were defined by degree of flooding by high tides.

Marsh zone	% high tides reaching zone	MHHW range (m)	z* range	NAVD88 range (m)
Transition	0.14-3	0.758 to 0.421	1.720 to 1.400	2.763 to 2.426
High	3-25	0.421 to 0.019	1.400 to 1.018	2.426 to 2.024
Middle	25-50	0.019 to -0.211	1.018 to 0.800	2.024 to 1.794
Low	>50	-0.211 to -0.503	0.800 to 0.523	1.794 to 1.502

Table G2. Model input parameters for Manila Marsh. Sediment accumulation rate is reported at the elevation of MSL. NDVI is the Normalized Difference Vegetation Index and NAIP is the National Agriculture Inventory Program.

Model parameter	Value	Source
Sediment accumulation rate (g cm^{-2} yr^{-1})	0.392	Core calibration
Elevation of peak biomass (cm, MSL)	110	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	40	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0629	Core calibration
Root-to-shoot ratio	0.458	C. Janousek, unpub data
Porosity at sediment surface (%)	89	Core
Porosity at depth (%)	55	Core
Refractory carbon (%)	25.8	Core
Maximum astronomical tide (cm, MSL)	257	North Spit tide gauge (NOAA,9418767)
Historic sea-level rise (mm yr^{-1})	4.7	North Spit tide gauge (NOAA,9418767)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

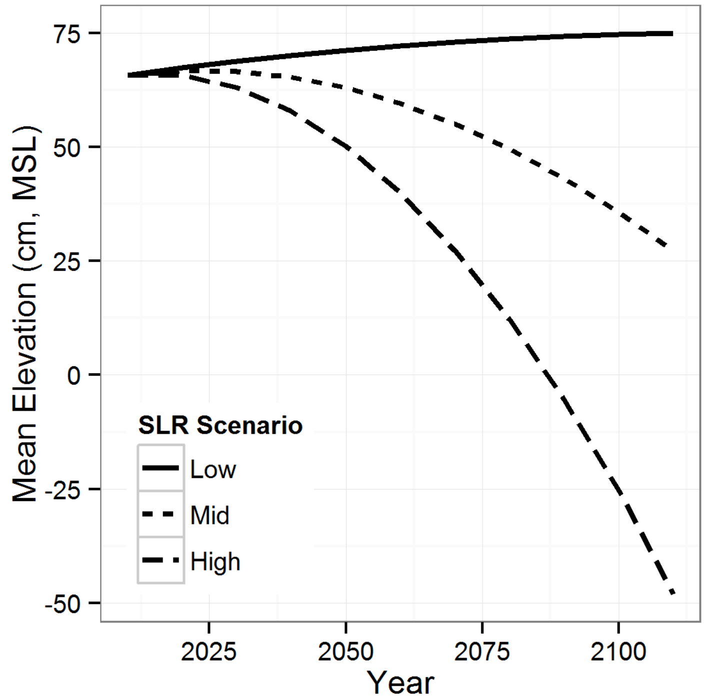

Figure G1. WARMER model projections for the change in average marsh elevation (relative to MSL) at Manila Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

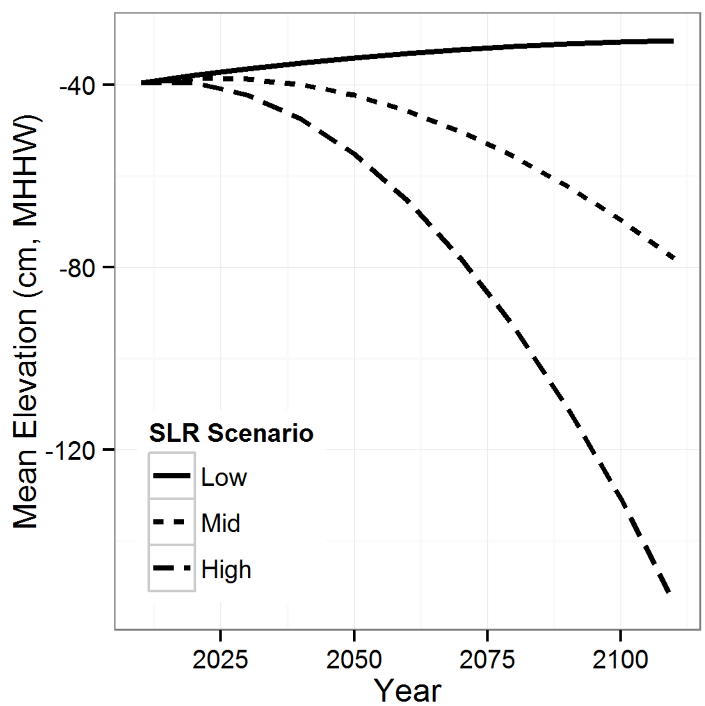

Figure G2. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Manila Marsh from 2010 to 2110 under low, mid, and high NRC sea-level rise scenarios.

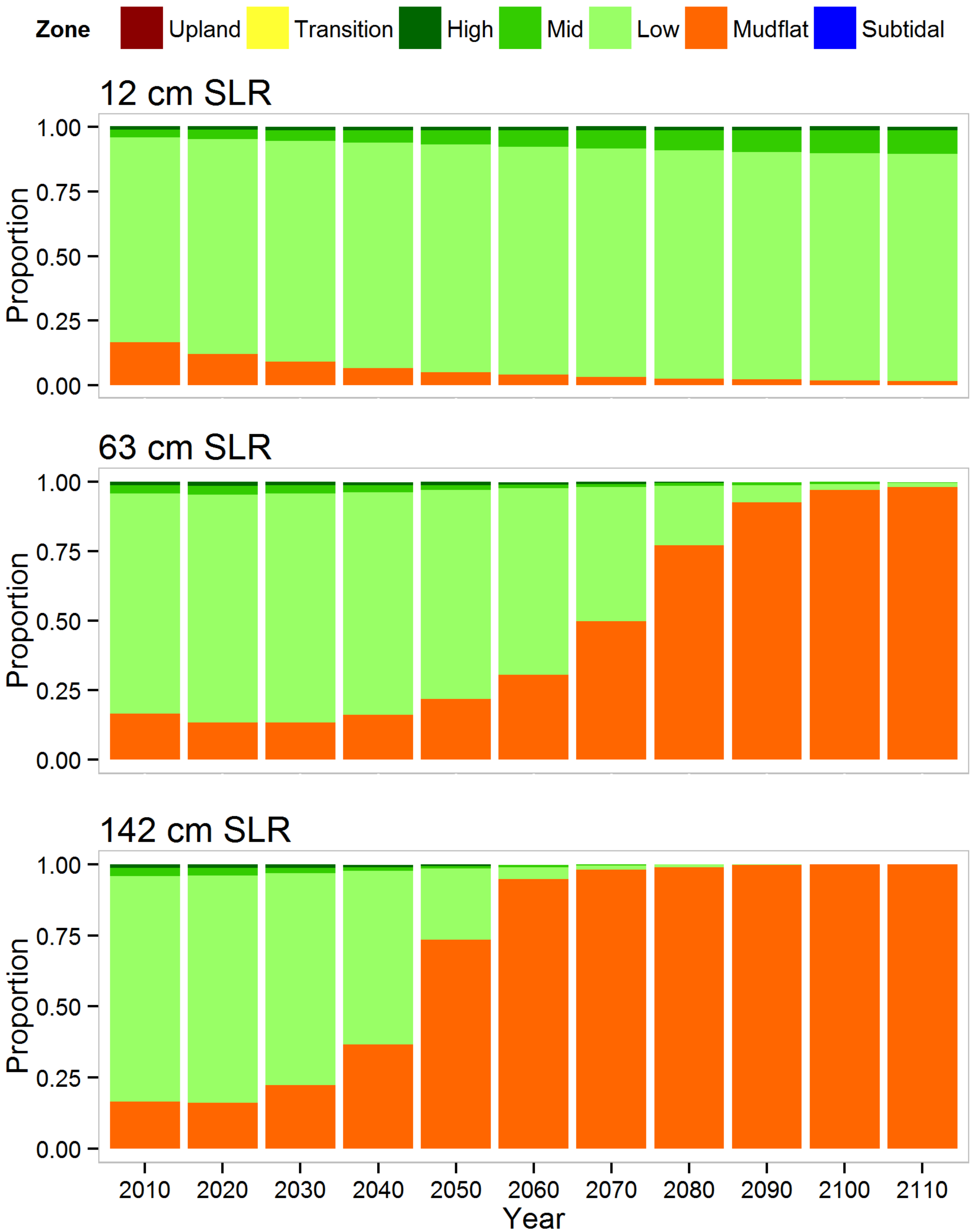

Figure G3. WARMER projections for change in the relative proportion of upland; transitional, high, mid and low marsh; and mudflat habitat at Manila Marsh under the NRC's low (44 cm), mid (93 cm), and high (166 cm) sea-level rise scenarios from 2010 to 2110.

Table G3. Model projections for change in the percentage of marsh elevation zones for three NRC sea-level rise scenarios between 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
Habitat	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	0	0	0	0	0	0	0	0
High	1	1	1	1	1	0	1	1	0
Mid	3	6	9	3	2	0	3	1	0
Low	79	88	88	79	75	2	79	25	0
Mudflat	17	5	2	17	22	98	17	73	100

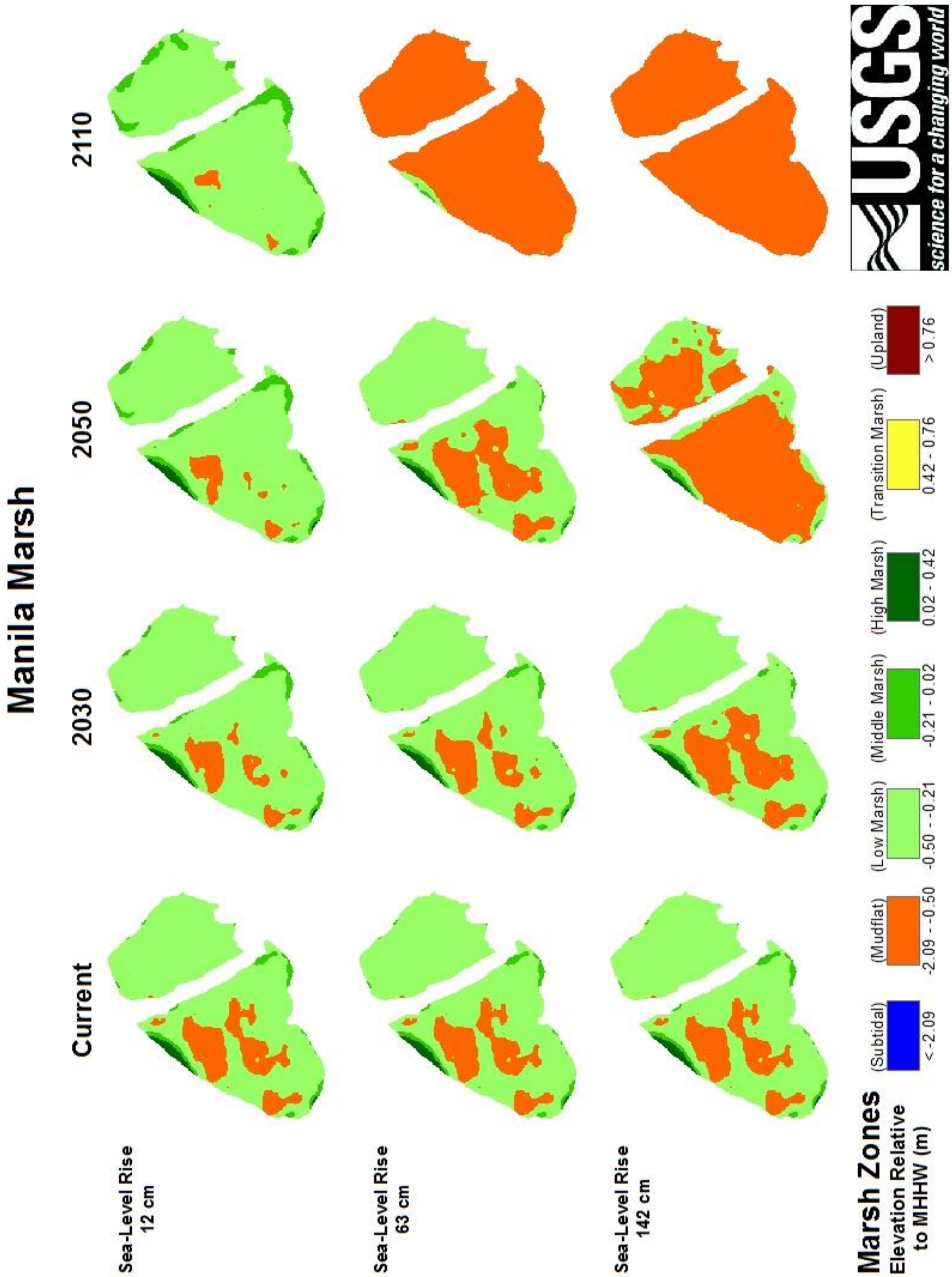

Figure G4. Projected habitat distribution at Manila Marsh for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

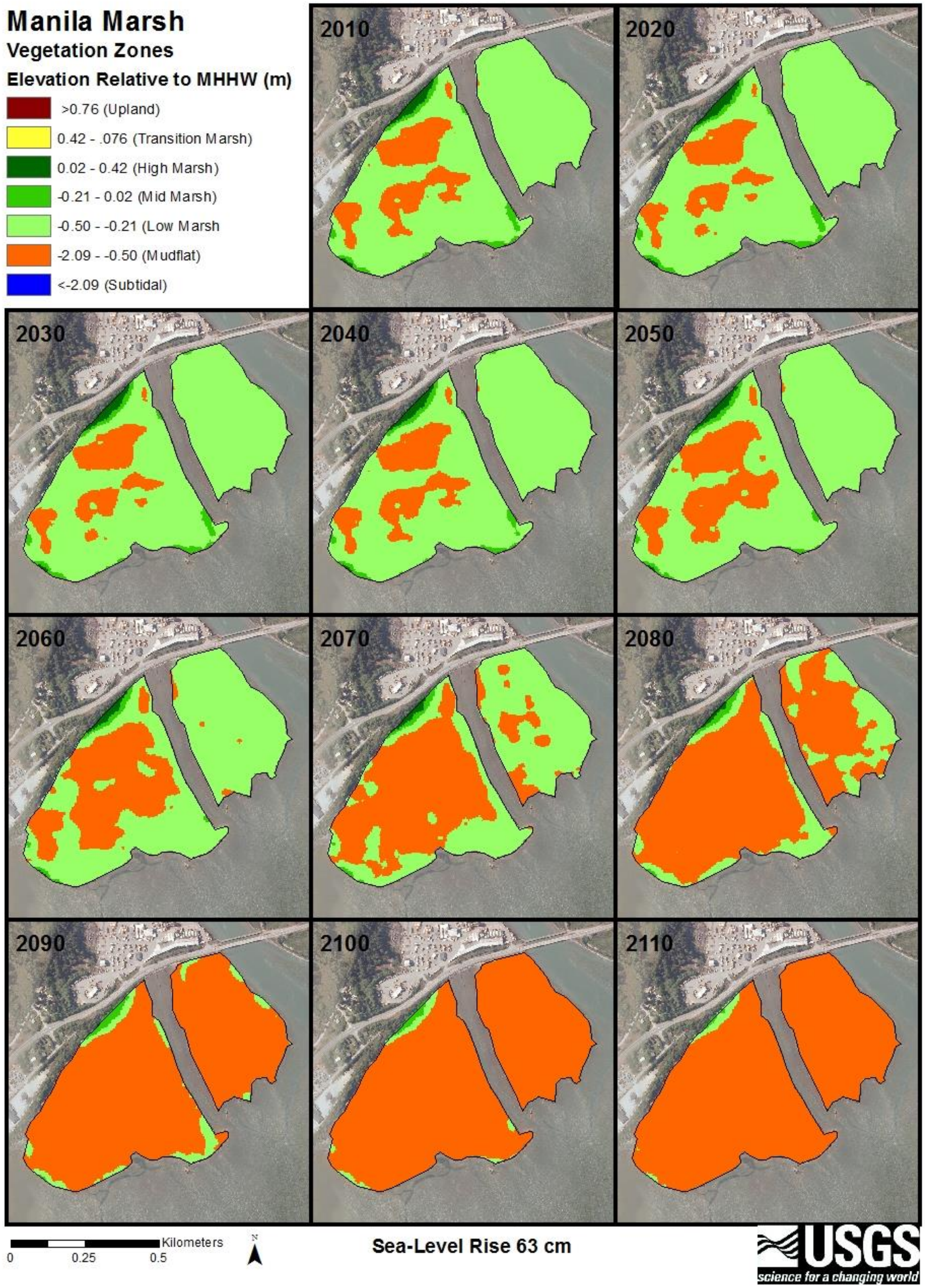

Figure G5. Projected changes in Manila Marsh habitat zones under the mid NRC sea-level rise scenario (63 cm).