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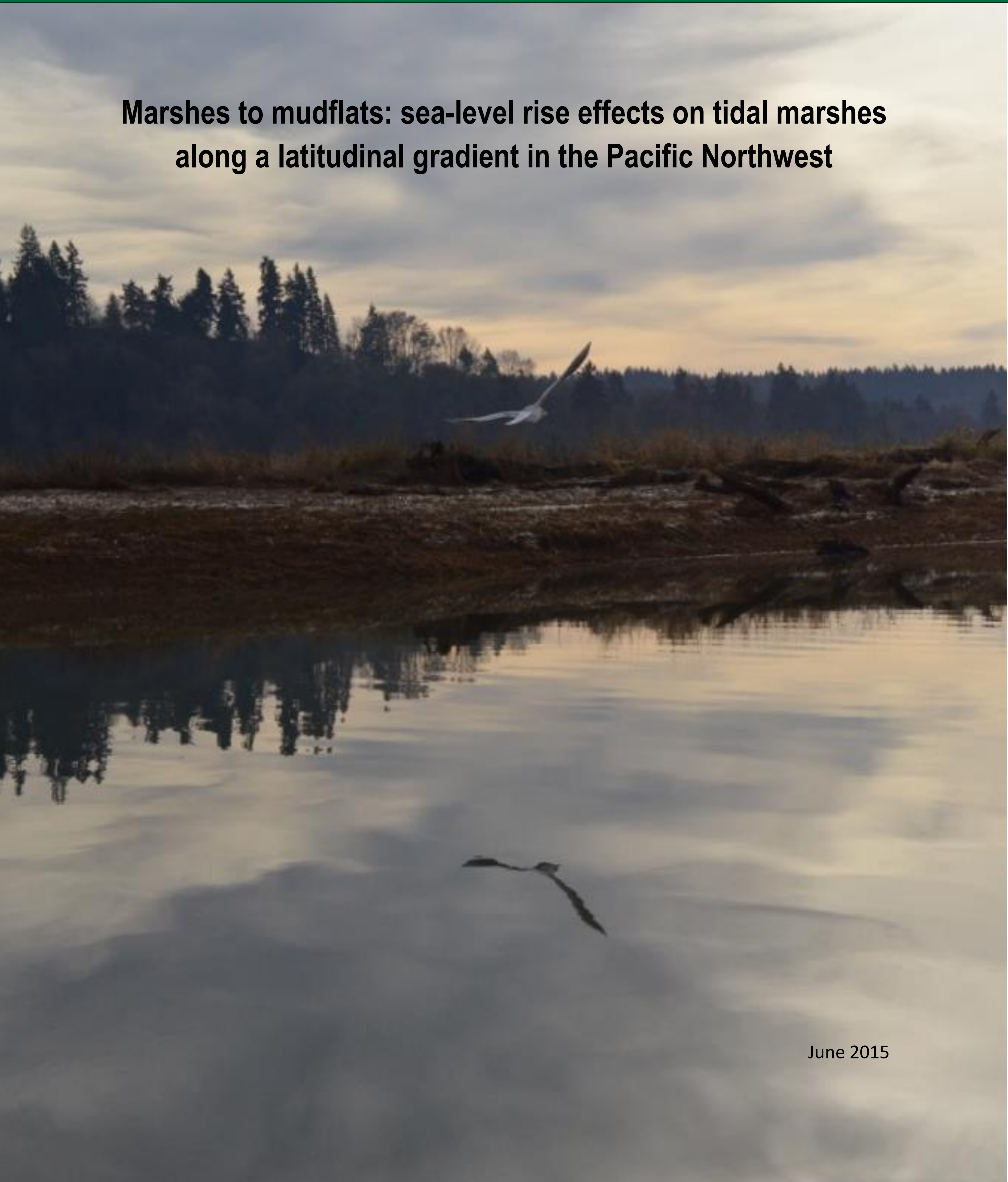
Marshes to mudflats: sea-level rise effects on tidal marshes along a latitudinal gradient in the Pacific Northwest



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Section 2: Public Summary

In the Pacific Northwest, coastal wetlands support a wealth of ecosystem services including habitat provision for wildlife and fisheries and flood protection. The tidal marshes, mudflats, and shallow bays of coastal estuaries link marine, freshwater and terrestrial habitats and provide economic and recreational benefits to local communities. Climate change effects such as sea-level rise are currently altering these habitats, but we know little about how these areas will change over the next 50-100 years. Our study examined the effects of sea-level rise on nine tidal marshes in Washington and Oregon, with the goal of providing scientific data to support future coastal planning and conservation. We compiled physical and biological data, including coastal topography, tidal inundation, vegetation structure, and current and historic sediment accretion rates to assess and model how sea-level rise may alter these ecosystems in the future. Multiple factors, including initial elevation, marsh productivity, sediment availability, and rates of sea-level rise affected marsh persistence. Under a low sea-level rise scenario, all marshes remained vegetated with little change in the present configuration of marsh plant communities or gradually increased proportions of mid, high, or transition marsh vegetation zones. However at most sites, mid sea-level rise projections led to loss of middle and high marsh and gain of low marsh habitat. Under a high sea-level rise scenario, marshes at most sites eventually converted to intertidal mudflats. Two sites (Grays Harbor, and Willapa) appeared to have the most resilience to a high sea-level rise rate, persisting as low marsh until at least 2110. Our main model finding is that most tidal marsh study sites have resiliency to sea-level rise over the next 50-70 years, but that sea-level rise will eventually outpace marsh accretion and drown most high and mid marsh habitats by 2110.

Section 3: Technical Summary

Coastal land managers are faced with many challenges and uncertainties in planning adaptive strategies for conserving estuarine habitats under future climate change scenarios. Projected climate change effects on coastal environments include sea-level rise (SLR), changes in freshwater delivery, salt water intrusion, erosion, shifting mudflat profiles, and changing water temperature and ocean acidity. Climate change research is often conducted on isolated ecosystems where interactions among adjacent habitats are not fully considered. However, nearshore habitats such as shallow bays, mudflats and tidal marshes are intricately-linked transitional ecotones between the marine and terrestrial environment. These habitats are particularly sensitive to climate change due to potential shifts in coastal inundation, salinity, storms and other environmental factors. Assessment of coastal climate change vulnerability requires integration of physical and ecological response models to project changes to tidal marsh ecosystems and habitats. Using a detailed approach that links baseline data to mechanistic modeling, we assessed the vulnerability of tidal marsh habitats at nine sites along the Pacific Northwest coastline. Our overarching questions were: (1) how do tidal marsh site characteristics vary across estuaries, and (2) does tidal marsh susceptibility to SLR vary along a latitudinal gradient and between estuaries? We addressed these questions with three specific objectives: (1) measure topographical and ecological characteristics (e.g., elevation, tidal range, vegetation composition) for tidal marsh and intertidal mudflats, (2) model SLR vulnerability of these habitats, and (3) examine spatial variability of these projected changes along the latitudinal gradient of the Washington and Oregon coasts. Our data show differences in baseline topography, vegetation, soil characteristics, salinity and tidal datums among sites. Vulnerability to SLR was dependent on projections of future SLR rates, initial elevation, sediment accretion potential, and site productivity. Low SLR had little impact or a positive impact (increase proportions of mid and high marsh zones) on the spatial extent or composition of future tidal marshes. However, mid to high SLR scenarios changed the composition of tidal marshes (high and middle marsh zones usually became low marsh) or resulted in loss of vegetated marsh areas to intertidal mudflats. Sites responded differentially in terms of the timing and extent of habitat change over the coming century. Our research products include site-specific baseline data for managers and scientists, habitat vulnerability assessments at a local scale, and a region-wide comparison of tidal marsh vulnerability to SLR. Our findings are timely for managers and policy makers who need to develop future adaptation plans for estuarine habitats to sustain coastal wetland ecosystem functions and services such as fish and wildlife habitat provision and flood protection.

Section 4: Purpose and Objectives

Climate change threatens the persistence and diversity of coastal ecosystems by altering 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, and changes in water temperature and acidification (Scavia et al. 2002; Huppert et al. 2009; National Research Council 2012). Recent estimates of global SLR by the year 2100 range from 57-110 cm (Jevrejeva et al. 2012) to 75-190 cm (Vermeer and Rahmstorf 2009) and 54-71 cm (Slangen et al. 2014). In the Pacific Northwest, SLR rates are projected to be between 12-143 cm (National Research Council 2012). Along the Pacific coast of the United States local variation in SLR rates are affected by global scale ice sheet dynamics, North American glacial rebound, regional tectonics, local freshwater flow and ocean circulation patterns (National Research Council 2012). Coastal ecosystems also face other non-climate stressors including continued urbanization and land use change, habitat fragmentation, altered hydrology, pollution, and introduction of non-native species (Gedan et al. 2009). These other stressors may exacerbate climate change effects on coastal ecosystem persistence, productivity and biodiversity (Kirwan and Megonigal 2013).

Projections of future global climate conditions and SLR provide insufficient information on local ecosystem change which is needed to inform management. To obtain reliable estimates of impacts at smaller spatial scales (often the most relevant to on the ground management decisions) it is necessary to collect fine-scale information on environmental conditions to help inform ecosystem management and identify habitats most vulnerable to climate impacts (Figure 1). To understand climate impacts to coastal ecosystems from the site to regional scale, we established the Coastal Ecosystem Response to Climate

Change (CERCC) program. To assess the scope of physical and biological climate change impacts to this region we established a network of sites along the full latitudinal gradient of the Pacific Northwest coastline, providing insight into how variation in tide range, SLR, water temperature and salinity, and other climate variables impact the vulnerability of these critical coastal habitats. Nine sites were distributed in Washington and Oregon tidal marshes from Puget Sound to southern Oregon. The CERCC program also includes seven sites along the California coast that are not included in this report but can be found in a companion USGS report (Figure 2). The program is led by the U.S. Geological Survey, Western Ecological Research Center with co-leads at Oregon State University, the University of California, Los Angeles, and local and regional management agencies.

Regional and local understanding of SLR impacts will be essential in developing comprehensive vulnerability assessments for key management concerns and the development of climate adaptation strategies. Our research is relevant to several ongoing federal research priorities. For instance, our work addresses the priority goals established in "*Rising to the Urgent Challenge*" developed by the U.S. Fish & Wildlife Service to establish their strategic climate change plan and assist managers with development of adaptation and planning strategies (USFWS 2010). In addition, our research helps meet one of the priority objectives in the Department of the Interior's *National Fish, Wildlife & Plants Climate Adaptation Strategy* (2012) developed as a collaborative effort mandated by Congress (PI Thorne, Coastal development team member). Our data provides information needed to increase preparedness of resource managers (e.g., U.S. Fish & Wildlife Service, National Park Service, NOAA NERR, state wildlife agencies) who address restoration and management of lands and species. This research is a key priority topic for the North Pacific and California Landscape Conservation Cooperatives in their strategic plans. In addition, the CERCC program addresses the USGS Science Strategy which includes anticipating ecosystem change and assessing consequences of climate change and its effects.

At the state level, Washington and Oregon have highlighted coastal ecosystems as important areas susceptible to climate change and have prioritized research to assist in adaptation planning for resource management and ecosystem services. The information emerging from our CERCC network will provide local managers and decision makers with the information they need to address endangered and threatened species management, wetland conservation, anadromous fish and migratory bird management, habitat conservation and recovery plans while making informed decisions on habitat resiliency and land acquisition planning that effectively considers the effects of climate change. Our CERCC network is a research model that can be potentially transferred to other coastal regions throughout the US.

The overarching goal of our research was to use site-specific data to develop local and regionally-applicable climate change models that inform management of tidal wetlands along the Pacific Northwest coast. Our questions were: (1) how do tidal marsh site characteristics vary across estuaries, and (2) does tidal marsh susceptibility to SLR vary along a latitudinal gradient and between estuaries? We addressed these questions with three specific objectives: (1) measure topographical and ecological characteristics (e.g., elevation, tidal range, vegetation composition) for tidal marsh and intertidal mudflats, (2) model SLR vulnerability of these habitats, and (3) examine spatial variability of these projected changes along the latitudinal gradient of the Washington and Oregon coasts.

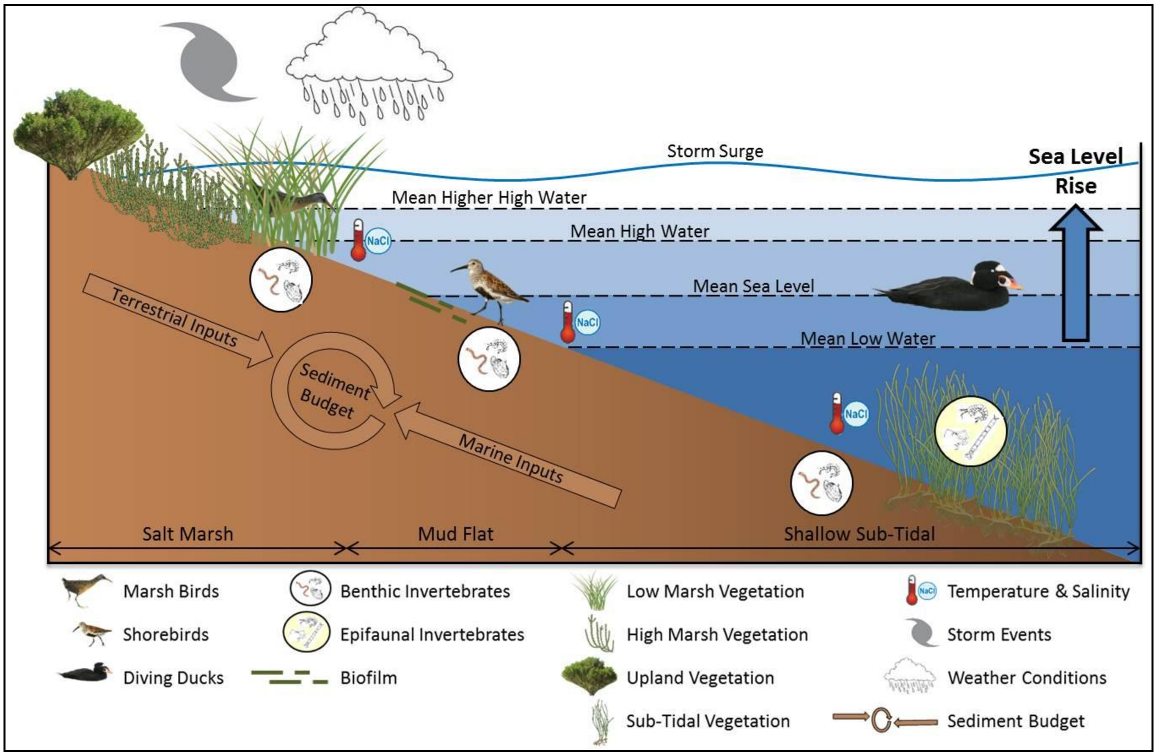

Figure 1. Conceptual model of linkages among physical and biological processes along the coast to assess climate-induced changes.

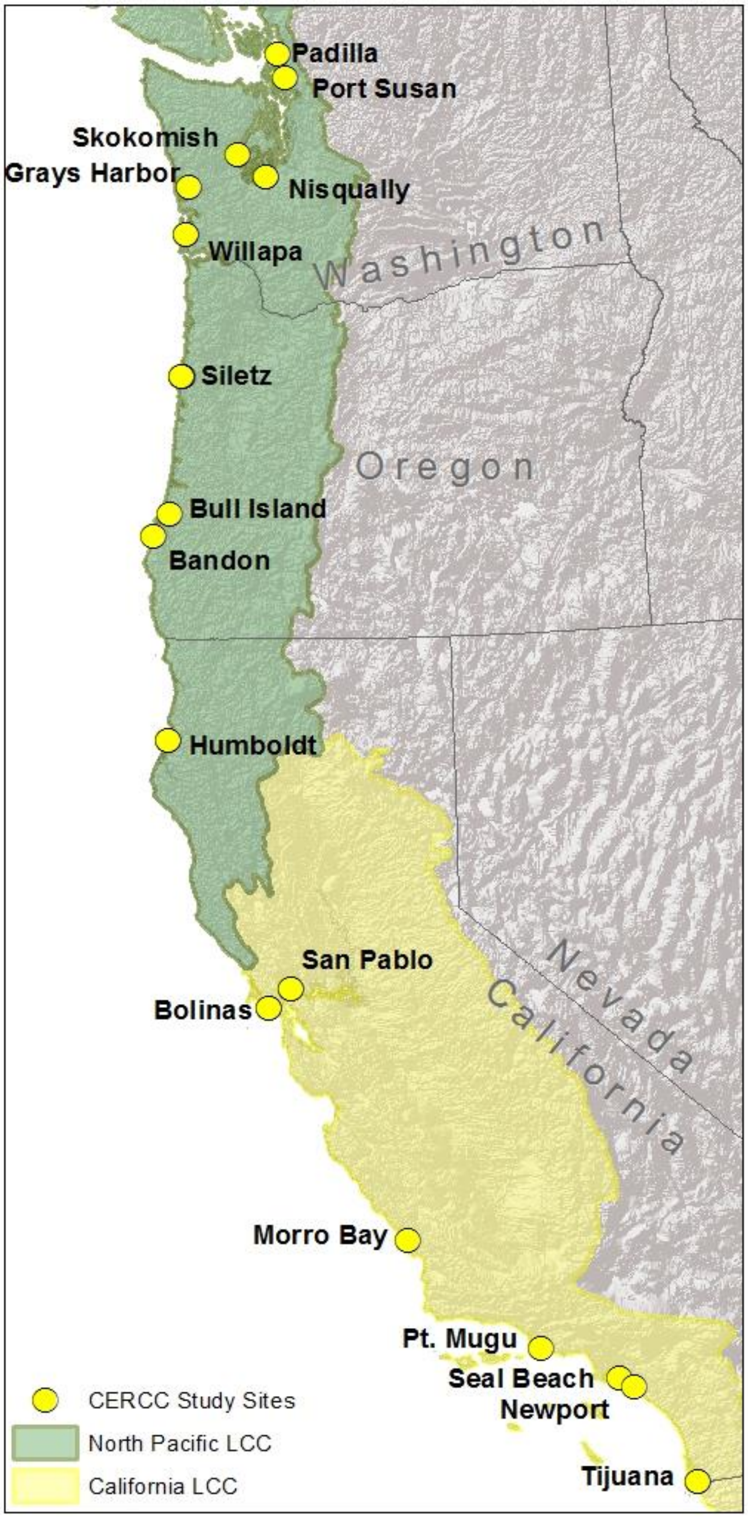

Figure 2. The seventeen project study sites that make up the CERCC network are located within the boundaries of the North Pacific and California Landscape Conservation Cooperatives (LCCs).

Section 5: Organization and Approach

5.1 Study areas

The research was conducted at nine tidal marshes in coastal estuaries spanning the Washington and Oregon coastlines from Padilla Bay in northern Washington to Bandon marsh located at the mouth of the Coquille River in southern Oregon (Figure 3). These sites are managed by local NGOs (non-governmental organization), Native American tribes and federal or state agencies. The sites were located in Padilla National Estuarine Research Reserve (hereafter Padilla), Port Susan Bay Preserve (hereafter Port Susan), Skokomish Estuary within lands of the Skokomish Indian Tribe (hereafter Skokomish), Nisqually National Wildlife Refuge in southern Puget Sound (hereafter Nisqually), Grays Harbor National Wildlife Refuge (hereafter Grays Harbor), Tartlatt Slough within Willapa Bay National Wildlife Refuge (hereafter Willapa), Siletz National Wildlife Refuge (hereafter Siletz), Bull Island within South Slough National Estuarine Research Reserve in Coos Bay (hereafter Bull Island), and Bandon National Wildlife Refuge on the Coquille Estuary (hereafter Bandon). Each study site comprised a portion of the tidal marsh and adjacent nearshore habitat. Although the entire Washington and Oregon coasts have a temperate climate, the sites spanned a broad range of hydrologic and oceanographic conditions. Overall tidal range decreased from northern Washington to southern Oregon.

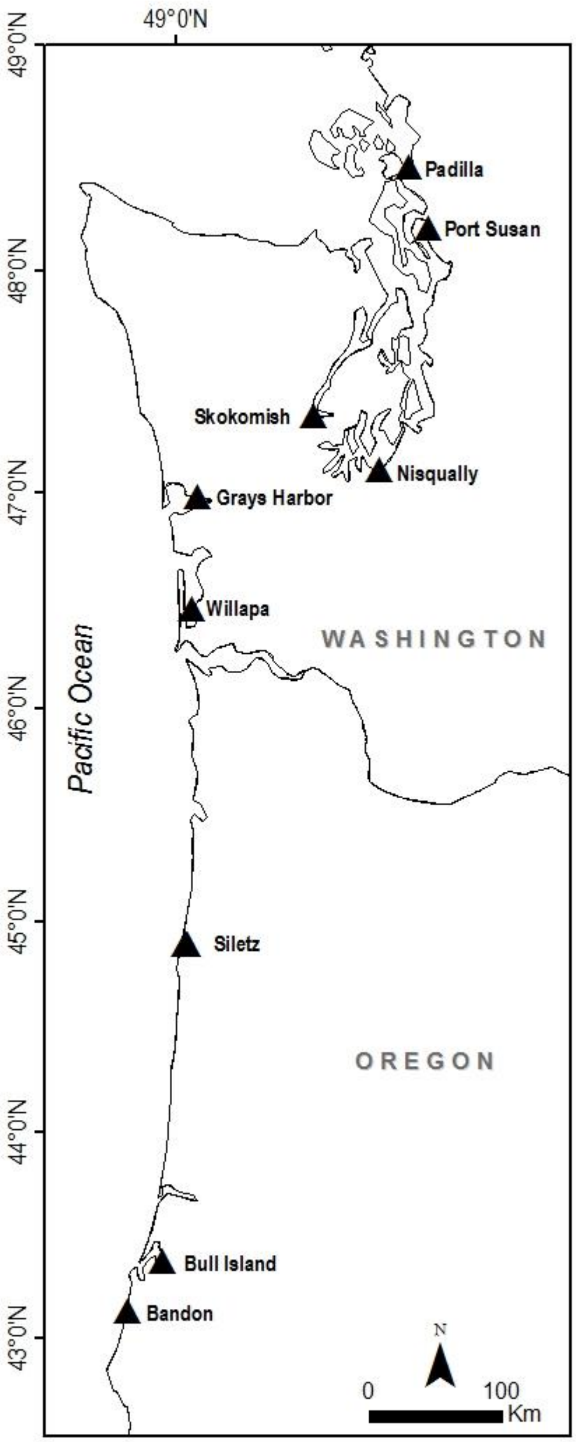

Figure 3. Pacific Northwest study sites in the Coastal Ecosystem Response to Climate Change (CERCC) network were located along a latitudinal and tidal gradient.

5.2 Elevation surveys

Figure 4. A USGS technician collects elevation data using a RTK GPS at Bandon National Wildlife Refuge.

To assess the current topography of tidal marsh study sites we conducted survey-grade global positioning system (GPS) surveys between 2009 and 2014 using a Leica RX1200 Real Time Kinematic (RTK) rover (±1 cm horizontal, ±2 cm vertical accuracy; Leica Geosystems Inc., Norcross, GA; Figure 4). At sites with RTK GPS network coverage (Padilla, Port Susan, Nisqually, Siletz, Bull Island, and Bandon), rover positions were received in real time from the Leica Smartnet system via a CDMA modem (www.lecia-geosystems.com). At sites without network coverage (Skokomish, Grays Harbor, and Willapa), rover positions were received in real time from a Leica GS10 antenna base station via radio link. At sites where we used the base station, we adjusted all elevation measurements using an OPUS correction (www.ngs.noaa.gov/OPUS). We used the WGS84 ellipsoid model for vertical and horizontal positioning and referenced positions to a local National Geodetic Survey (NGS) benchmark or a benchmark established by a surveyor (Figure 4). Average measured vertical errors at benchmarks were 1-9 cm throughout the study, comparable to the stated error of the GPS.

To measure topographic variation at each site, we surveyed marsh surface elevation along transects perpendicular to the major tidal sediment source, with a survey point taken every 12.5 m; 50 m separated transect lines (Appendix Figs. A1 – I1). We used the Geoid09 model to calculate orthometric heights from ellipsoid measurements (m, NAVD88; North American Vertical Datum of 1988) and projected all points to NAD83 UTM zone 10 using Leica GeoOffice v7.0.1 (Leica Geosystems Inc, Norcross, GA).

Table 1. National Geodetic Survey benchmarks used as references in elevation survey with associated measured error (published elevation – average measured elevation). Sites are ordered from north to south.

Site	Benchmark PID	Latitude (N)	Longitude (W)	Average error (m)	Survey methodology
Padilla	NERR*	48° 29' 36"	122° 28' 56"	0.02	Network
Port Susan	TR2700	48° 14' 21"	122° 20' 52"	-0.01	Network
Skokomish	SY1268	47° 19' 26"	123° 07' 33"	0.02	Base station
Nisqually	SY0739	47° 07' 02"	122° 39' 58"	-0.01	Network
Grays Harbor	AC5450	46° 58' 15"	123° 56' 13"	0.03	Base station
Willapa	SD0349	46° 22' 14"	124° 01' 36"	0.08	Base station
Siletz	QE1413	44° 53' 54"	124° 00' 29"	0.04	Network
Bull Island	AA5128	43° 08' 36"	124° 24' 59"	-0.09	Network
Bandon	AA5128	43° 08' 36"	124° 24' 59"	0.07	Network

* Benchmarks installed and surveyed by Skagit County, WA

5.3 Elevation modeling

In ArcGIS 10.2.1 Spatial Analyst (ESRI 2013, Redlands, CA), we created a digital elevation model (DEM) for each site using the survey elevation data points. We processed the elevation point data with exponential ordinary kriging methods (5 x 5 m cell size) while adjusting model parameters to minimize the root-mean-square (RMS) error to create the best model fit for the DEM (Table 2). We used elevation models as the baseline conditions for subsequent analyses including tidal inundation patterns, SLR response modeling, and mapping of sites by specific elevation (flooding) zones.

In this report we present elevation data as both local orthometric heights (NAVD88) and local mean higher high water (MHHW) based on computation of site-specific MHHW from water level data (described below). For comparison of results among sites with different tidal ranges, we also standardized elevations to local tide range, using the z* metric where z* = (z-MTL)/(MHHW-MTL) as described in Swanson et al.

(2014). The lowest extent of tidal marsh generally occurs at approximately z* = 0.0 (mean tide level, MTL) while z* = 1.0 (local MHHW) is approximately equal to the mid-high marsh boundary

Table 2. Root mean square error (RMS, m) for the digital elevation models (DEM) of each site. Sites are ordered from north to south.

Site	RMS (m)
Padilla	0.108
Port Susan	0.073
Skokomish	0.146
Nisqually	0.080
Grays Harbor	0.074
Willapa	0.108
Siletz	0.081
Bull Island	0.115
Bandon	0.156

5.4 Vegetation surveys

We conducted vegetation surveys concurrently with elevation surveys at every fourth elevation point (~25% of the elevation points) (Figure 5). We visually assessed percent cover of all plant species within a 0.25 m^2 quadrat, and recorded the average and maximum height (measured to the nearest centimeter) of each species. Total plant cover in a plot could exceed 100% due to vegetation layering. Vascular plant nomenclature generally follows Baldwin et al. (2012) and Cook et al. (2013).

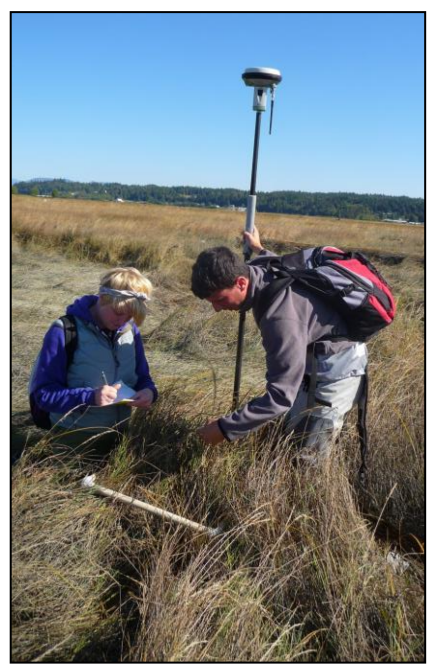

Figure 5. USGS technicians collecting vegetation data at Port Susan

5.5 Vegetation zones

To consistently delineate habitat elevation zones for analyses and mapping across all study sites we used long-term National Oceanic and Atmospheric Administration (NOAA) tide gauges and local vegetation data to determine patterns of flooding extent and vegetation limits with elevation across the Pacific Northwest. We defined subtidal habitat as all vegetated or unvegetated areas below local mean lower low water (MLLW), which is the average of the lower low water height of each tidal day. Intertidal mudflat comprised the zone between MLLW and the lowest measured extent of tidal marsh vegetation at each site (typically roughly at mean tide level, MTL). Higher in the intertidal, we defined four vegetated marsh zones based on long-term inundation data (low marsh, middle marsh, high marsh and transitional marsh).

To delineate elevation zones within vegetated tidal marsh we compiled high tide data from 2004-2013 at three NOAA tidal stations along the US west coast: Charleston, OR, Toke Pt., Willapa Bay, WA, and Seattle, WA (tidesandcurrents.noaa.gov) to assess average inundation frequency in the upper intertidal. Using these time series, we determined the percentage of high tides during the 10 year period that reached a given elevation (z*). We defined low marsh as the range of elevations from the lowest extent of vegetation at a site to the elevation reached by at least one daily high tide on average. Middle marsh comprised habitat flooded by 50-25% of all high tides (inundated between once daily and once every 2 days), and high marsh included 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 (inundated at least once annually, but no more than twice per month, on average). We computed z* values for the boundaries between zones (subtidal, mudflat, low marsh, mid marsh, high marsh, transition marsh, and upland) from tidal data at each long-term NOAA station.

At each site in the study, we used the z* values calculated from a nearby NOAA station (e.g., Bandon was paired with Charleston NOAA records) and the local tidal datums to determine the local NAVD88 and MHHW elevations that corresponded with each z* value defining zone boundaries. We used Charleston data for all Oregon sites, Toke Point for outer coast Washington sites and Seattle for all sites in Puget Sound.

5.6 Water monitoring

To determine inundation patterns and calculate site-specific tidal datums, we deployed water level data loggers (Model 3001, Solinst Canada Ltd., Georgetown, Ontario, Canada and Model U-20-001-01-Ti, Onset Computer Corp., Bourne, MA, USA) at all sites over the study period (Figure 6). Each site had one or two loggers (n = 16; Table 3). We placed loggers at the mouth and upper reaches of second-order tidal channels to capture high tides and determine seasonal inundation patterns. Water loggers collected water level readings every six minutes starting on the date of deployment and continuing to the present. We used data from the lowest elevation logger at each site to develop local hydrographs and inundation rates. We surveyed loggers with RTK GPS at the time of deployment and at each data download that occurred quarterly, to correct for any vertical movement. We corrected all raw water level data with local time series of barometric pressure. For Solinst loggers, we deployed independent barometric loggers (Model 3001, Solinst Canada Ltd., Georgetown, Ontario, Canada); for Hobo water level loggers, we used barometric pressure from local airports (distance < 10 miles).

Figure 6. Water level logger deployed in secondary tidal marsh channel.

To determine tidal channel salinities, we deployed one conductivity logger at each site next to the lower elevation water level logger (Odyssey conductivity/temperature logger, Dataflow Systems Pty Limited, Christchurch, New Zealand). We converted specific conductance values obtained with the Odyssey loggers to practical salinity units using the equation from UNESCO (1983).

We used water level data to estimate local tidal datums for all sites using procedures outlined in the NOAA Tidal Datums Handbook (NOAA 2003). We only calculated local MHW and MHHW because the loggers were positioned in the intertidal, which is relatively high in the tidal frame, and therefore did not capture MLW or MLLW and could not be used to compute these lower datums. We estimated mean tide level (MTL) for each site by using NOAA's VDATUM 3.4 software (vdatum.noaa.gov), except at Bandon where we used MTL directly from historic NOAA data. Many results in this report are reported relative to local MHHW calculated from local water data.

Table 3. Water level monitoring occurred at all study sites. Manufacturer information, number of loggers currently deployed, date of deployment and source of barometric pressure data for compensation varied across sites. Sites are ordered from north to south.

Site	Water level logger manufacturer	Number of water level loggers deployed	Date of deployment	Compensation method
Padilla	Hobo	2	Oct-12	Bellingham International Airport
Port Susan	Solinst	1	Apr-11	Arlington Municipal Airport
Skokomish	Hobo	2	Sep-12	Sanderson Airport
Grays Harbor	Hobo	2	Sep-12	Bowerman Airport
Nisqually	Solinst	1	Feb-10	barologger
Willapa Bay	Hobo	2	Sep-12	Astoria Regional Airport
Siletz	Hobo	2	Jan-14	barologger
Bull Island	Hobo	2	Aug-12	Southwest Oregon Regional Airport
Bandon	Hobo	2	Aug-12	Southwest Oregon Regional Airport

5.7 Bathymetry

We performed bathymetric surveys using a shallow-water echo-sounding system (Takekawa et al. 2010, Brand et al. 2012) comprised of an acoustic profiler (Reson, Inc.; Slangerup, Denmark, Navisound 210), Leica Viva RTK GPS, and laptop computer mounted on a shallow-draft, portable flat-bottom boat (Figure 7). The RTK GPS enabled high resolution elevations of the water surface. The rover positions were received from the Leica Smartnet system (www.lecia-geosystems.com) or base station and referenced to the same bench mark used in the elevation surveys (Table 1). We mounted a variable frequency transducer on the front of the boat and connected it to the sounder; the sounder worked in areas of >10 cm of water. We recorded twenty depth readings and one GPS location each second along transects spaced 100 m apart perpendicular to the nearby salt marsh. We calibrated the system before use with a bar-check plate and adjusted the sound velocity for salinity and temperature differences. The bar-check plate was suspended below the transducer at a known depth that was verified against the transducer readings.

Figure 7. A USGS technician conducting bathymetric surveys

5.8 Bathymetry modeling

We synthesized the bathymetry data to create a digital elevation model (DEM) of the nearshore regions at Port Susan, Skokomish, Nisqually, Grays Harbor, Willapa, and Bull Island using ArcGIS 10.2.1 Spatial Analyst (ESRI 2013, Redlands, CA) with exponential ordinary kriging methods (5 x 5 m cell size). We removed portions of bathymetry data that overlapped with elevation surveys conducted on the tidal marsh. In this report we present elevation data as local orthometric heights (NAVD88). At Padilla we mapped the nearshore area using the methodologies outlined in the Sections 5.2 and 5.3 as the dense eelgrass beds would have increased the error in acoustic measurements.

5.9 Deep sediment coring

To parameterize accretion for SLR models, we measured historic rates of mineral and organic matter accumulation at each site by collecting deep soil cores with a Russian peat borer (Figure 8). At each site, we obtained cores in each of three vegetation zones: low, medium, and high marsh. Coring locations were determined by RTK GPS elevation and tidal inundation data. Sediment cores were 50 cm deep and 5 cm in diameter. In the lab, we cut cores into 1 cm sections to process for bulk density, porosity, and organic matter composition using loss on ignition in a muffle furnace at 550ºC for 8 hr (Heiri et al. 2001).

Figure 8. A sediment core taken at a CERRC study site

We used Cesium-137 (^{137}Cs) isotope dating techniques to determine accumulation rates in deep soil cores. Atmospheric nuclear testing prior to 1964 resulted in the spread of ^{137}Cs across the globe creating a reliable marker horizon in soils (Ritchie and McHenry 1990). We used a gamma spectrometer at the Oregon State University Radiation Center to detect ^{137}Cs activity, measured in picocuries (pCi), in 1 cm core samples for 24 hr. We standardized the ^{137}Cs activity of each sample to its mass. The depth of the ^{137}Cs peak activity indicated the 1964 marker horizon, which we used to determine average soil accretion rates over the last half century.

5.10 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 SLR projections across each study site. Each cohort in the model represents the total organic and inorganic matter added to the soil column each year. WARMER calculates 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 for a representative marsh area (Figure 9). Each cohort provides the mass of inorganic and organic matter accumulated at the surface in a single year as well as any subsequent belowground organic matter productivity (root growth) minus decay. Cohort density, a function of mineral, organic, and water content, is calculated at each time step to account for the decay of organic material and auto-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 over the unit area model domain.

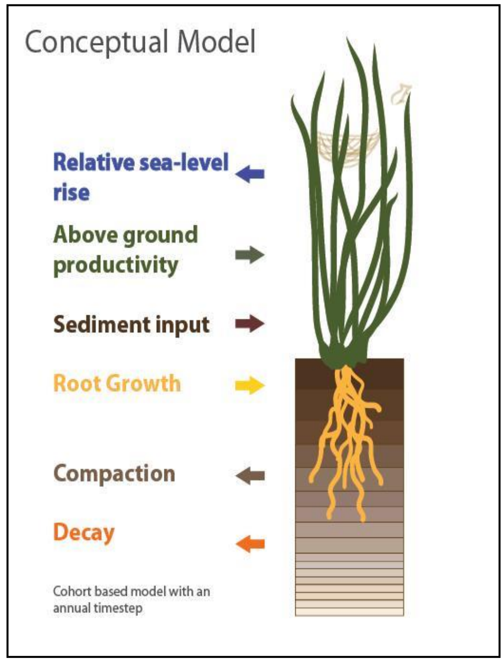

Figure 9. WARMER 1-D conceptual model that shows the input variable for the modeling approach (from Swanson et al. 2014).

The elevation of the marsh surface, *E*, at time *t* relative to local MSL is estimated as

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

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*. The total volume of an individual cohort is estimated as the sum of the mass of pore space water, sediment, and organic matter, divided by the cohort bulk density for each annual time step. Elevation is adjusted relative to sea level rise after each year of organic and inorganic input, compaction, and decomposition. We parameterized WARMER from the elevation, vegetation, and water level data collected at each site. We evaluated model outputs between 2010 and 2110 using marsh elevation zones defined above.

Model inputs

Sea-level rise scenarios

In WARMER, we incorporated a recent forecast for the Pacific coast which projects low, mid, and high SLR scenarios of 12, 64 and 142 cm by 2110, respectively (NRC 2012). We used the average annual SLR curve as the input function for the WARMER model. We assumed the difference between the maximum tidal height and minimum tidal height (tide range) remained constant through time, with only MSL changing annually.

Inorganic matter

The annual sediment accretion rate is a function of inundation frequency and the mineral accumulation rates measured from ^{137}Cs 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, M_s, at a given elevation, z, is equal to,

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

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} (Figures 10-11).

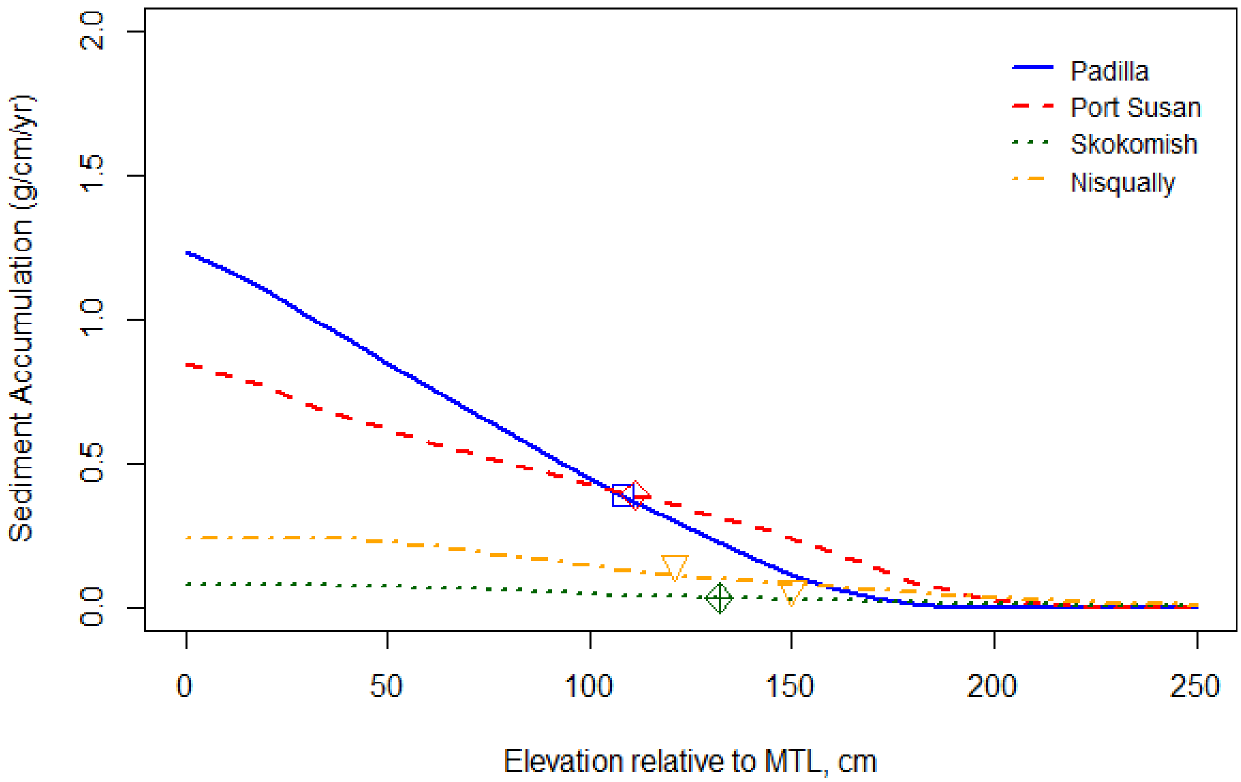

Figure 10. Calculated annual sediment accumulation curves (lines) and measured accumulation rates (points) for study sites in Puget Sound, WA. Padilla values area based on core data from Port Susan.

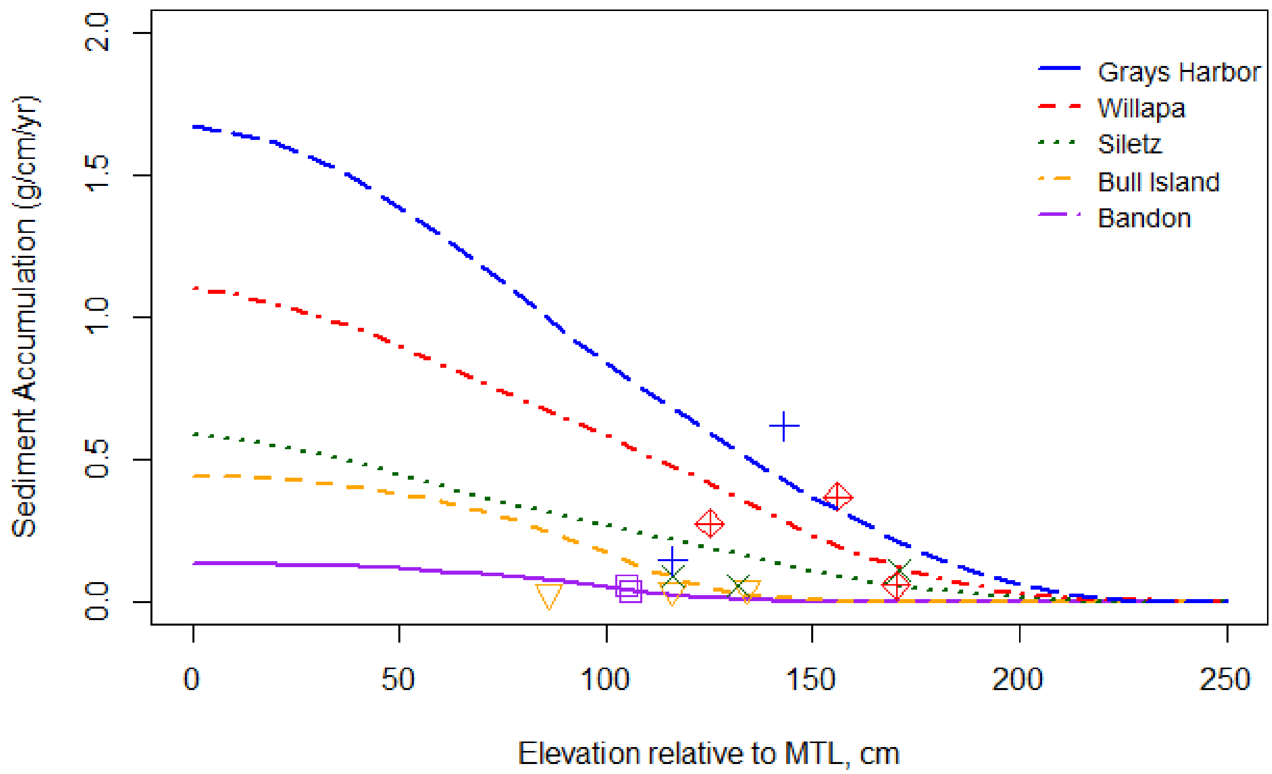

Figure 11. Calculated annual sediment accumulation curves (lines) and measured accumulation rates (points) for sites along the outer Pacific coast in Washington and Oregon.

Organic matter

We used a unimodal functional shape to describe the relationship between elevation and organic matter (Morris et al. 2002), based on Atlantic coast work on *Spartina alterniflora.* Given that Pacific Northwest tidal marshes are dominated by other plant species, we developed site-specific, asymmetric unimodal relationships to characterize elevation-productivity relationships. We used Bezier curves to draw a unimodal parabola, anchored on the low elevation by MTL 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 to 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 (Figures 12-13). The curves were truncated to zero below the lowest observed marsh elevation for each site from our vegetation surveys, reflecting the observed transition to unvegetated mudflat. The root-to-shoot ratio for each site was set to 1.95, the mean value from an inundation experiment conducted at Siletz in 2014 for *Juncus balticus* and *Carex lyngbyei,* two common high and low marsh species in the Pacific Northwest (C. Janousek et al., unpublished results). 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),

$$root\_prod = kdist * rs * om(x) * e^{-kdist*d} \qquad \text{(Eq. 8)}$$

where *rs* is the calibrated root-to-shoot ratio, *d* is cohort depth, *om(x)* is the functional relationship between elevation (cm, MSL) and aboveground productivity calculated above.

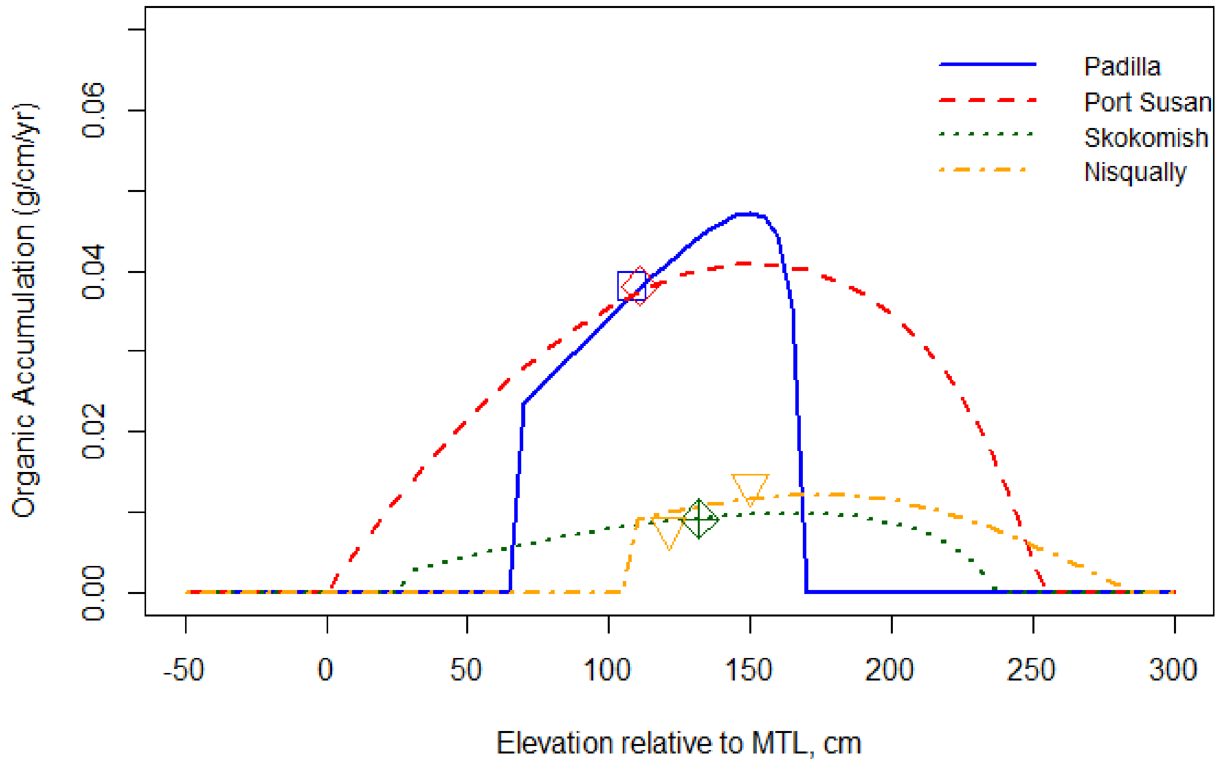

Figure 12. Calculated organic matter accumulation (lines) and measured accumulation rates (points) across the Puget Sound study sites. Site specific elevations of minimum vegetation, maximum observed water level, and peak aboveground biomass were used to draw the curves. The amplitude of the curve was calibrated to measured accumulation rates from sediment cores.

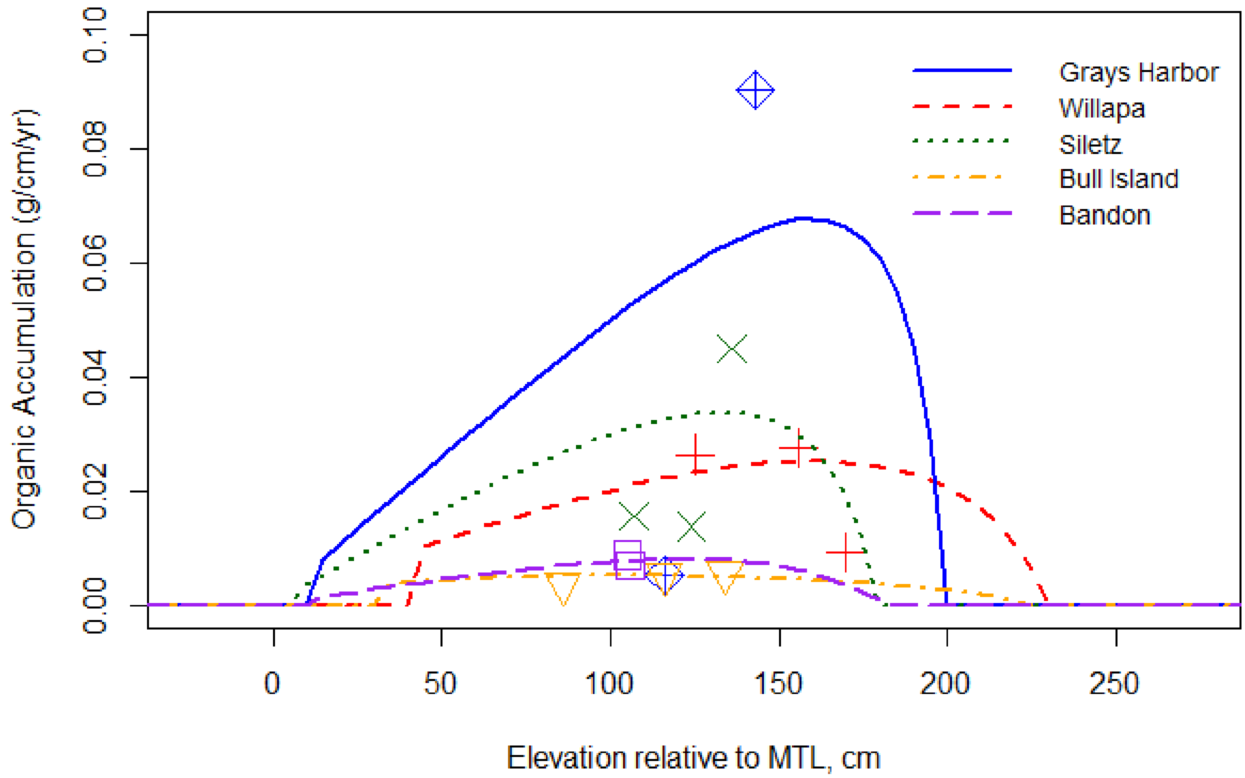

Figure 13. Calculated organic matter accumulation (lines) and measured accumulation rates (points) for sites along the outer Pacific coast. Site specific elevations of minimum vegetation, maximum observed water level, and peak aboveground biomass were used to draw the curves. The amplitude of the curve was calibrated to measured accumulation rates from sediment cores.

Compaction and decomposition

Compaction and decomposition functions of WARMER followed Callaway et al. (1996). We determined sediment compaction by estimating a rate of decrease in porosity from 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:

$$r = 1 - \frac{p_b}{k_1 - p_b} \qquad \text{(Eq. 9)}$$

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-tiered 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 decomposition functions from Deverel et al. (2008). The decomposition rate was defined as,

$$decmp_i = m_i e^{-kdec_i * d} \quad \text{(Eq. 10)}$$

where *i* is related to the age class 1, 2 or 3. *kdec* was set to 1.31, 0.57, or 0.1 respective of each age class, *m* was set to 0.92, 0.37, 0.16, depending on age class, and *d* is cohort depth.

Implementation

For each site, we ran WARMER at 37 initial elevations (every 10 cm from 0 to 360 cm, NAVD88). A two hundred year spin-up period for each model run was used to build an initial soil core. A constant rate of sea-level rise was chosen that the modeled elevation after 200 years was equal to the initial elevation. After the spin-up period, sea-level rose according to the scenario (+12, 63, or 142 cm by 2110). Linear interpolation was used to project model results every 10 years onto the continuous DEM developed from the RTK surveys.

Model parameters are provided in a table for each site within the appendices (Appendix Tables A4-I4).

Section 6: Project Results

6.1 Tidal wetland elevations

Local DEMs spanned approximately 1.5 m of vertical relief at most of the study sites, with the majority of elevation points occurring across a 1.0 m band centered approximately at MHHW (Table 4, Figure 14). Individual sites varied significantly in median elevation relative to MHHW, with the highest median elevation occurring at Grays Harbor and Padilla and the lowest at Port Susan (Figures 14-17). Relative to MHHW, all sites had significantly different mean elevation except for pair-wise comparisons between Padilla, Grays Harbor and Siletz, as well as Nisqually and Bull Island (one-way ANOVA, Tukey pairwise comparison, $F = 496.4$, $P < 0.01$; Figure 15).

Overall the topographic range was large at most sites, demonstrating that a range of habitat types were present (Figures 18). Siletz, however, had a relatively more constrained elevation profile because it mostly consisted of high tidal marsh. All sites had significantly different topographic profiles (36 pair-wise Kolmogorov-Smirnov tests; all $P < 0.03$; Figure 16).

We used long-term patterns of regional flooding extent and local DEMs to delineate habitats or vegetation zones. Padilla and Siletz were comprised mostly of high and middle tidal marsh vegetation communities. Nisqually and Willapa were also mainly comprised of high and middle tidal marsh, but had low marsh adjacent to deeper water. Skokomish, Grays Harbor, and Bandon were comprised mostly of middle marsh, with patches of high marsh occurring toward the inland edges of each site and low marsh present immediately adjacent to open water. Port Susan and Bull Island were comprised of mainly low marsh (Figure 18). See appendices for detailed site specific results.

Table 4. Metadata for each study site includes: area of study site (hectares); number of RTK GPS elevation points used in digital elevation models (DEM) interpolation; mean, maximum, minimum, and elevation range (all in meters, NAVD88). Sites are ordered from north to south.

Site	Area (ha)	Elevation data points (n)	Mean elevation (m)	Maximum elevation (m)	Minimum elevation (m)	Elevation range (m)
Padilla	5.2	76	2.47	2.79	2.22	0.57
Port Susan	51.5	897	2.23	3.46	1.28	2.18
Skokomish	28.8	605	2.66	4.08	1.48	2.60
Nisqually	59.9	1072	2.77	3.16	2.26	0.90
Grays Harbor	67.8	1192	2.42	2.58	1.45	1.13
Willapa	74.8	1230	2.42	3.23	1.72	1.51
Siletz	69.2	1196	2.3.5	2.75	1.74	1.01
Bull Island	97.2	1605	2.04	2.58	1.45	1.13
Bandon	96.7	1710	2.03	3.01	1.38	1.63

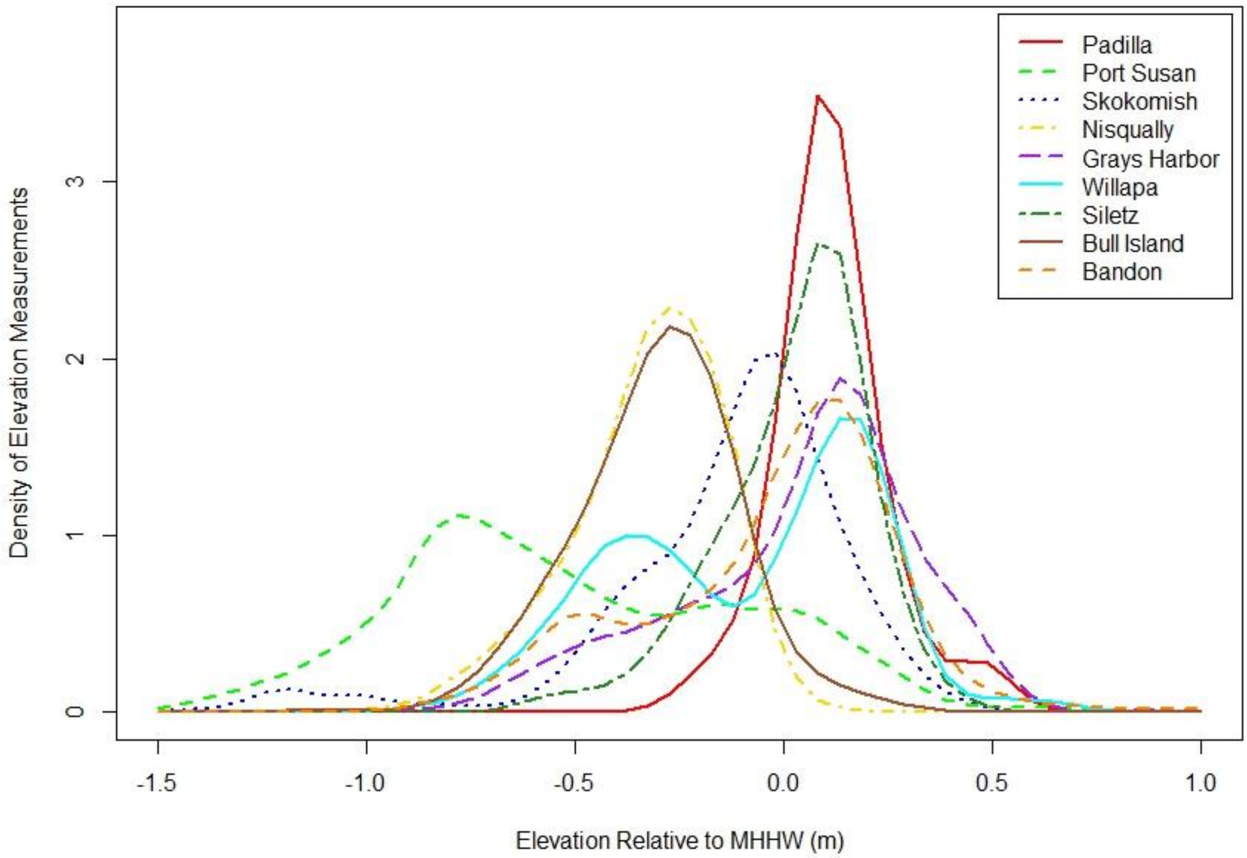

Figure 14. Density of elevation measurements relative to mean higher high water (MHHW) showing variability across sites.

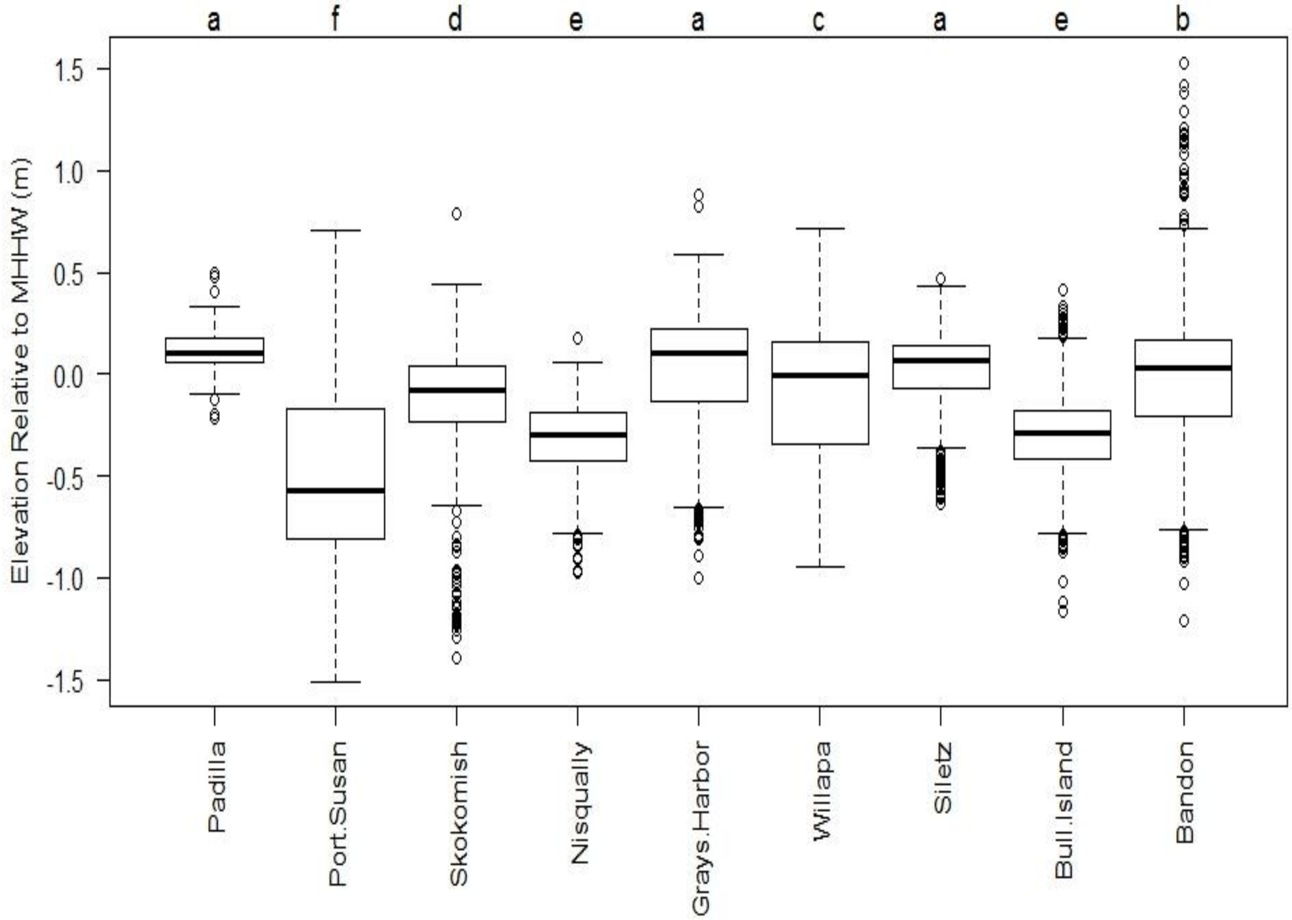

Figure 15. Distribution of elevation data points across all nine study sites from north to south (m, relative to MHHW).The black horizontal bars show the median elevation, boxes indicate the interquartile range, upper and lower whiskers encompass points no greater than 1.5 times the length of the box, and open circles indicate outliers. Letters above the plot represents significant differences in mean elevation.

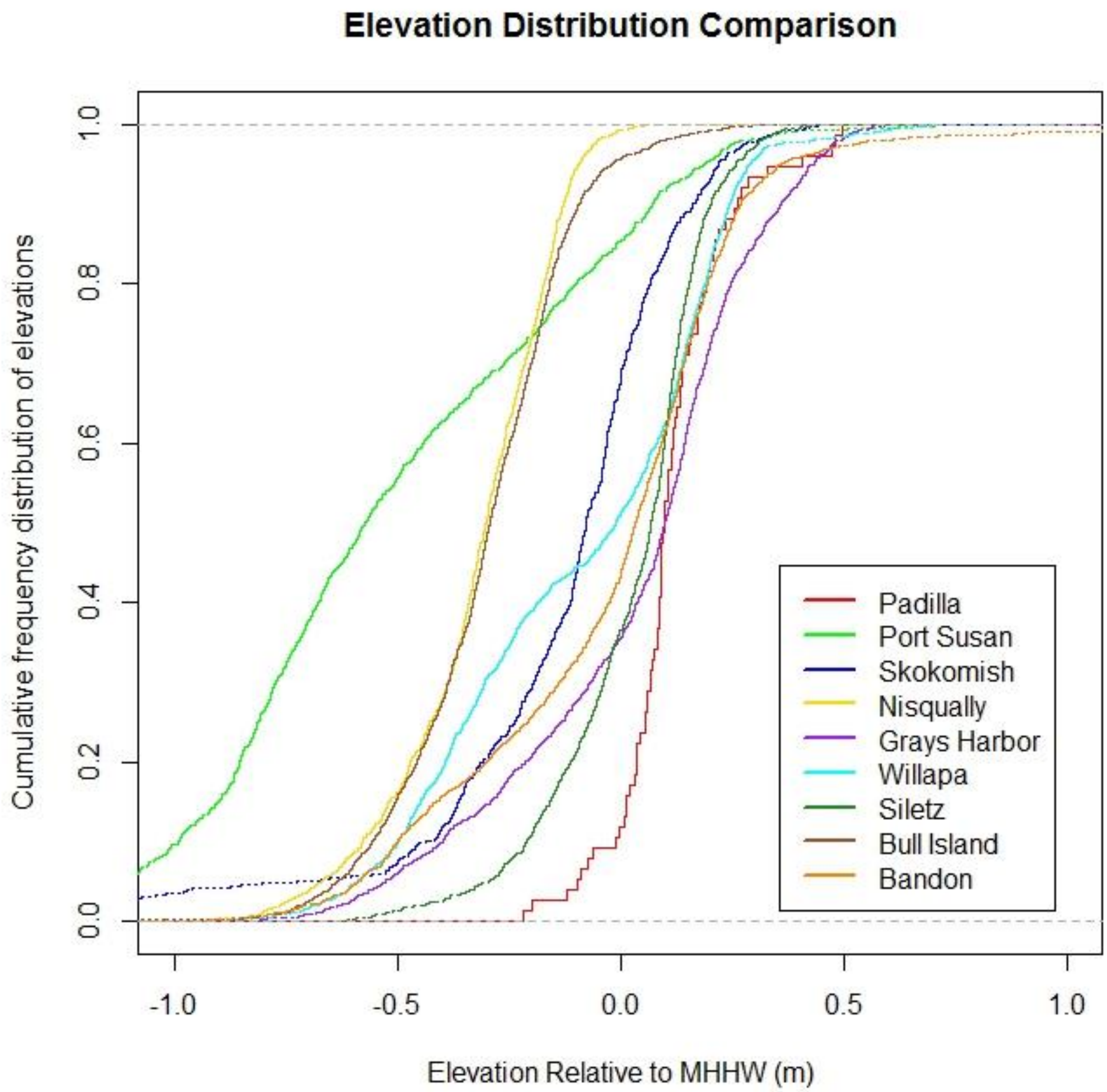

Figure 16. Cumulative frequency distribution of elevation data points relative to mean higher high water (MHHW) across the nine study sites. More steeply sloping curves indicate sites with more pronounced marsh platforms and less steeply sloping curves indicate marshes with more gradual changes in elevation.

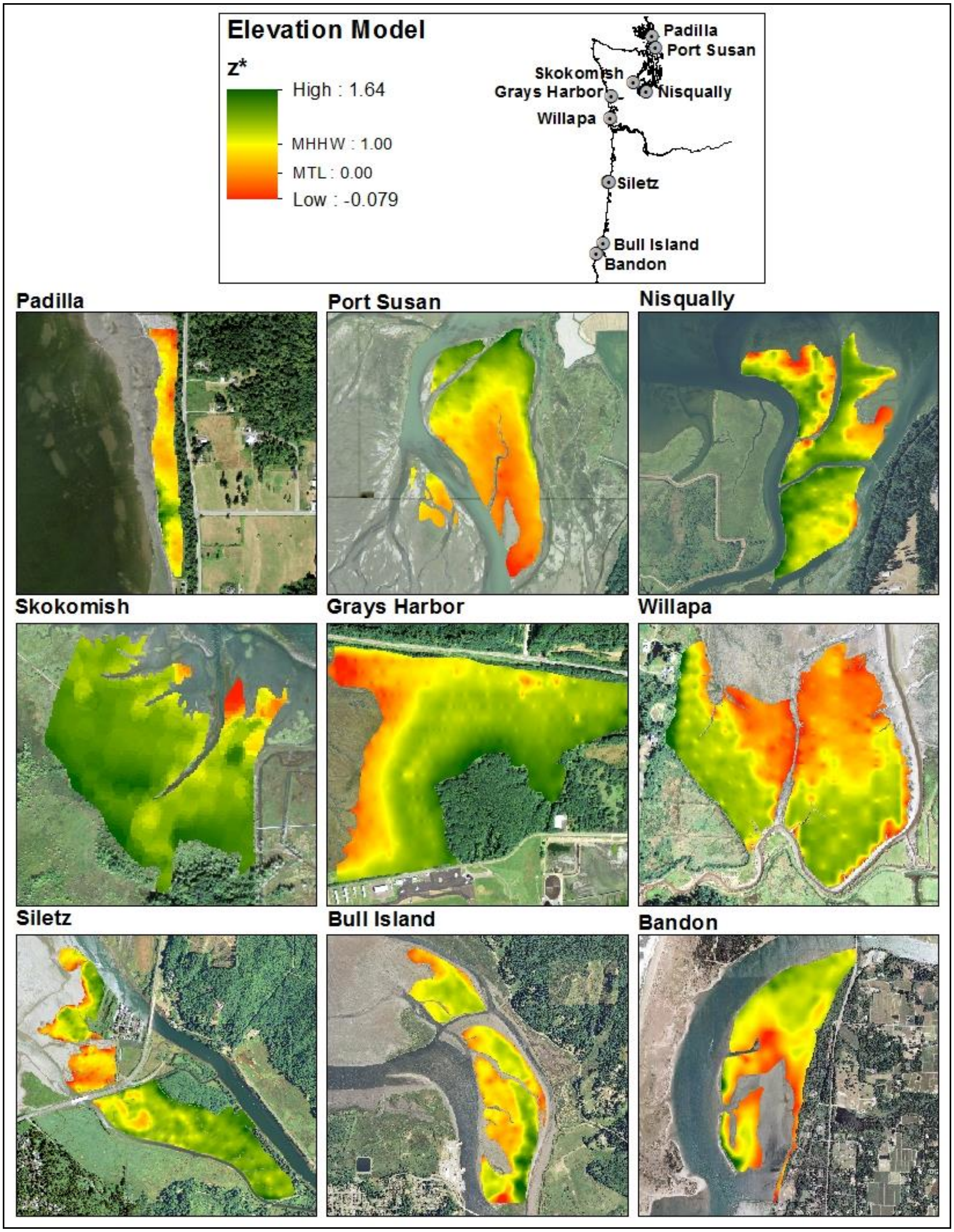

Figure 17. Digital elevations models (DEMs) presented in a standardized elevation (z*) across the nine study sites in the Washington and Oregon CERCC network show that many of the sites have elevation gradients from high to low elevations.

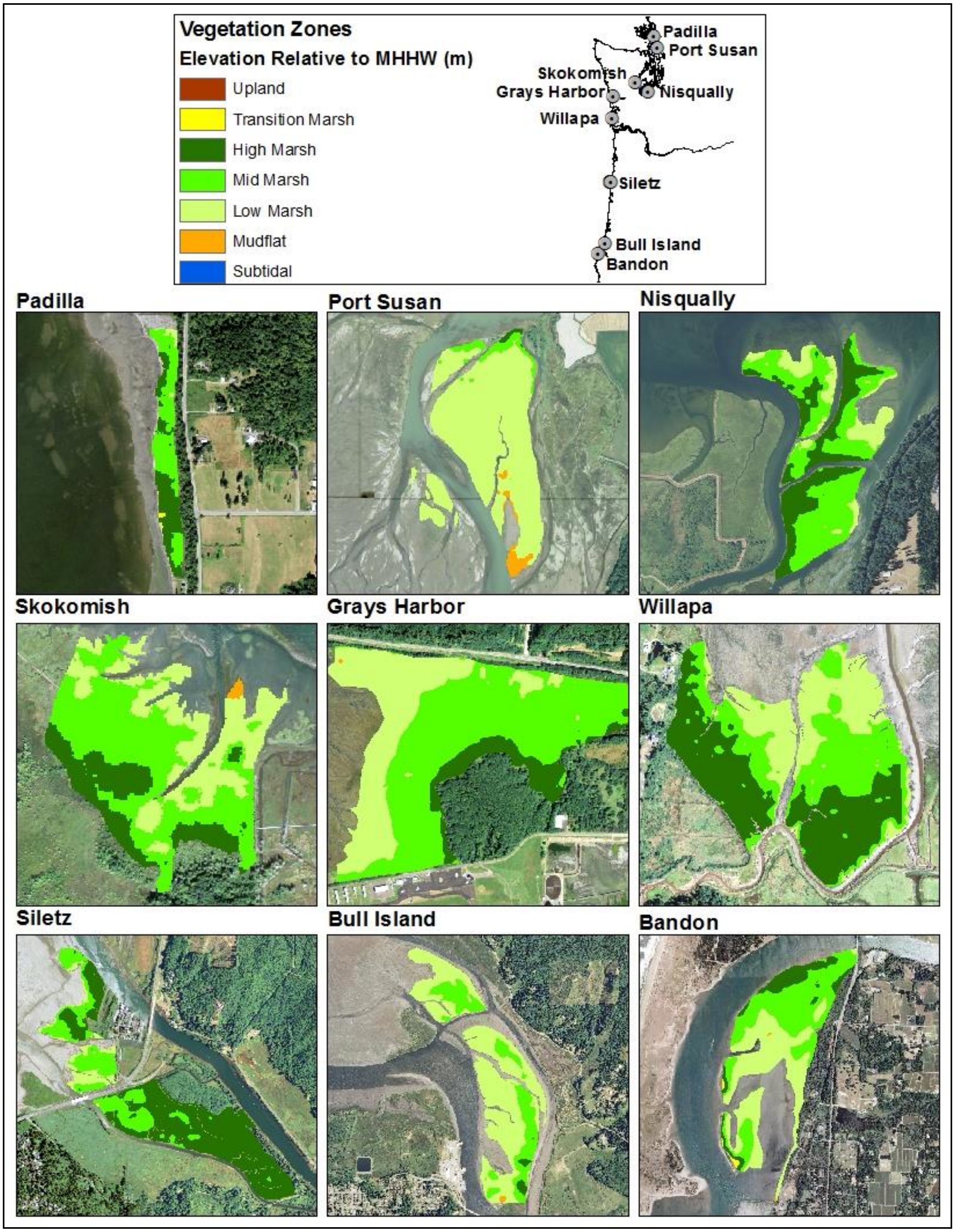

Figure 18. Distribution of tidal marsh vegetation zones across the nine study sites in the Washington and Oregon CERCC network illustrates that most sites have all the identified vegetation zones. Vegetation zones were defined by tidal flooding extent.

6.2 Bathymetry

We collected bathymetry data in the adjacent nearshore habitat at all sites (except for Siletz) for a total of 984.4 hectares surveyed (Figure 19, Table 5). We found large variation bathymetry among sites with areas ranging from large shallow mudflats to deep narrow channel systems. Elevation of the adjacent nearshore habitat ranged from -49.7 to +2.68 m. The average bathymetric range was 2.2 m for all study sites except Skokomish, which had a large measured range due to inclusion of offshore areas of Puget Sound. See appendices for detailed site specific results.

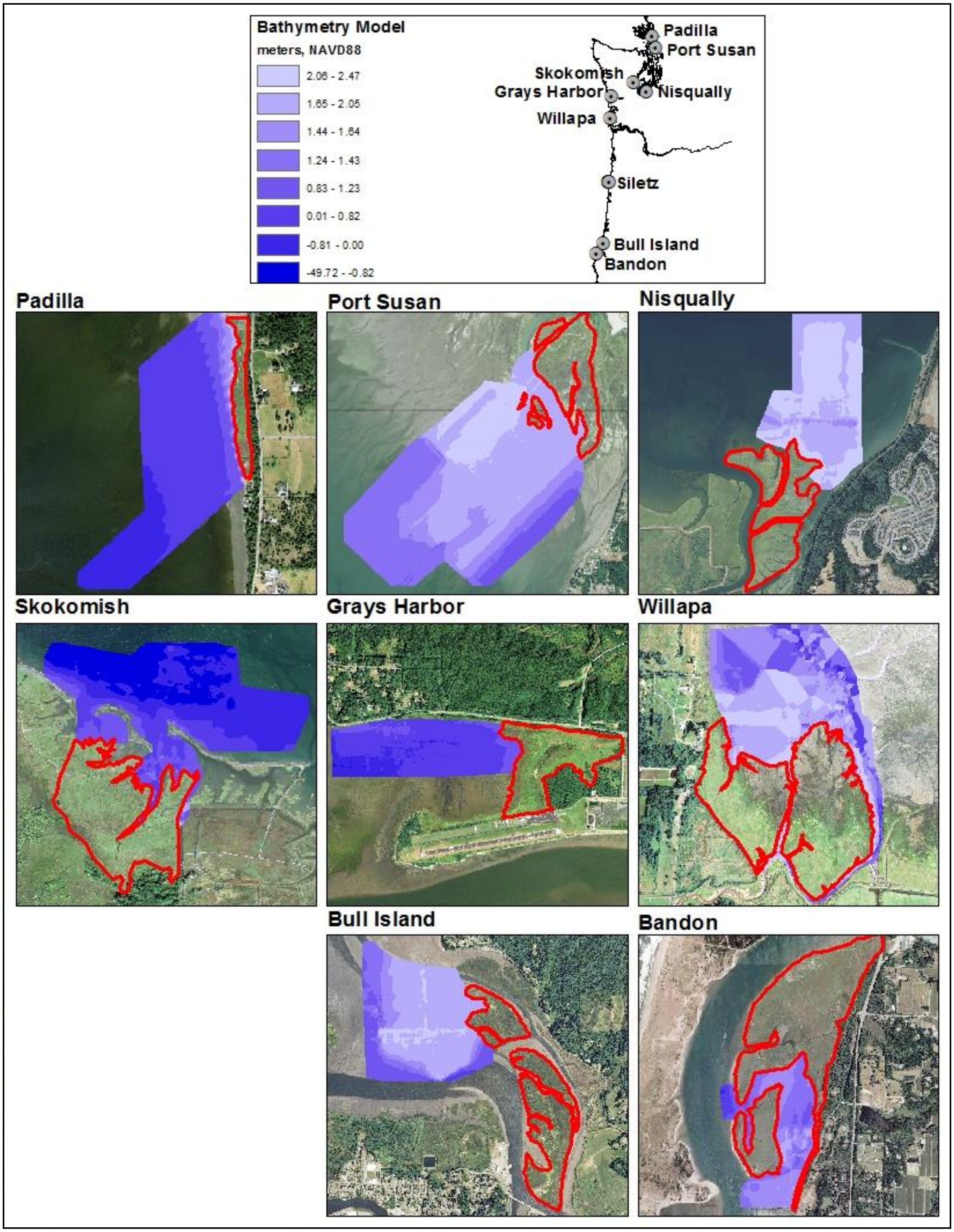

Figure 19. Bathymetry coverage across the eight study sites shows that nearshore mudflat habitats have shallow ranges at most sites. Bathymetric data were not collected at Siletz.

Table 5. Area (hectares) and maximum and minimum elevations (meters; NAVD88) of nearshore habitat for each site. Sites are ordered from north to south. Bathymetry surveys were not conducted at Siletz.

Site	Area (ha)	Mean elevation (m)	Maximum elevation (m)	Minimum elevation (m)	Elevation range (m)
Padilla	50.6	0.38	2.47	-0.7	3.17
Port Susan	319.1	1.67	2.46	1.01	1.45
Skokomish	59.3	-2.17	2.18	-49.73	51.91
Nisqually	124.9	2.04	2.58	1.4	1.18
Grays Harbor	117.3	0.39	1.35	-1.41	2.76
Willapa	84.1	1.68	2.68	-0.51	3.19
Bull Island	182.3	1.65	2.29	0.59	1.7
Bandon	46.8	1.38	1.78	-0.28	2.06

6.3 Sediment characteristics

We found substantial variation in net accretion rates across the study sites (Table 6). Among cores taken from mid-elevation marsh habitat, Grays Harbor and Willapa had the highest net accretion rates (8.7 and 8.9 mm yr^{-1} respectively), while Bandon and Skokomish had the lowest net accretion rates (2.5 and 1.7 mm yr^{-1}, respectively). Organic matter content and bulk density in the upper 20 cm of cores varied across elevation zones and across all study sites (Table 7). Siletz and Skokomish had the highest mean organic matter content across the elevation gradient, while Grays Harbor and Port Susan had the lowest organic matter content. Sediment bulk density was highest at Port Susan and Nisqually, and lowest at Grays Harbor and Bull Island. See appendices for detailed site specific results.

Table 6. Net accretion rates (mm yr^{-1}) from soil cores sampled at low, mid, and high elevation marsh zones across the study sites (n=1). A subset of the cores have not yet been dated, and therefore have no accretion rate value (NA). Padilla was not cored. Sites are ordered from north to south.

	Marsh elevation zone		
Site	**Low**	**Mid**	**High**
Port Susan	NA	7.3	NA
Skokomish	NA	1.7	NA
Nisqually	3.7	3.3	NA
Grays Harbor	NA	8.7	NA
Willapa	6.5	8.9	6.1
Siletz	4.9	3.7	2.1
Bull Island	3.3	3.3	3.5
Bandon	NA	2.5	2.5

Table 7. Average sediment organic matter content and bulk density from the top 20 cm of cores at low, mid, high marsh locations across the study sites (n=1). Analysis on a subset of the cores has not yet been completed (NA). Sites are ordered from north to south.

	Organic matter (%)			Bulk density (g cm^{-3})		
Site	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Port Susan	NA	7.1	11.3	NA	0.51	0.60
Skokomish	NA	26.0	20.0	NA	0.16	0.20
Nisqually	5.4	19.8	10.3	0.42	0.24	0.40
Grays Harbor	NA	7.9	NA	NA	0.11	NA
Willapa	10.6	7.8	15.1	0.40	0.28	0.11
Siletz	21.7	21.2	18.4	0.23	0.33	0.31
Bull Island	14.8	16.9	18.8	0.10	0.16	0.17
Bandon	7.3	18.0	12.1	0.33	0.20	0.28

6.4 Water monitoring

Water level loggers deployed within marsh channels recorded variation in water levels and salinity throughout the study duration. Loggers often did not capture lower portions of the tidal curve because of their location in tidal marsh channels which frequently drain at lower tides. From peak water levels, we calculated site-specific tidal datums (MHW and MHHW), and information on the highest observed water level (HOWL) during the time series (Table 8). Our site specific tidal datum calculations generally closely matched tidal datums computed at nearby NOAA stations (tidesandcurrents.noaa.gov). Differences likely reflect site-specific tidal and bathymetric conditions in local estuarine hydrology.

Table 8. Tidal datums (m, NAVD88) calculated from water level loggers deployed at each site, except as noted. HOWL = highest observed water level, MHHW = mean higher high water, MHW = mean high water, MTL = mean tide level. Sites are ordered from north to south.

Site	Time series length	HOWL	MHHW	MHW	MTL
Padilla	NA	NA	2.37*	2.13*	1.36*
Port Susan	2 yr 10 mo	3.86	2.71	2.47	1.33*
Skokomish	2 yr 2 mo	3.80	2.76	2.48	1.22*
Nisqually	3 yr 7 mo	4.94	3.11	2.82	1.23*
Grays Harbor	1 yr	3.27	2.39	2.17	1.27
Willapa	NA	NA	2.24*	2.01*	0.76*
Siletz	1 yr**	NA	2.32**	2.11**	1.13*
Bull Island	2 yr 2 mo	3.10	2.33	2.12	1.09*
Bandon	1 yr 6 mo	2.96	2.04	1.84	1.11***

* Values estimated from VDATUM model. ** Values are from Brophy et al. (2011). *** Value from NOAA historic station at Bandon.

We collected salinity data at all sites, however, due to equipment recalls and failure we do not have salinity data for the duration of the study. We report weekly maximum salinities since many of our salinity loggers were not submerged during the entire tidal cycle at all sites, except for Grays Harbor due to recalled loggers and loggers being washed away during storm events. We observed a high level of variation in salinity between and within sites (Figure 20). Siletz experienced the greatest variation in salinity during the study period, ranging from 0.8 to 32 ppt. Willapa was the freshest system, ranging from 12-15 ppt and had very little temporal variation. The largest variation in salinity at most sites occurred from September through December. All sites had salinity below 35 ppt throughout most of the year; however the highest salinities were measured in August. See appendices for detailed site specific results.

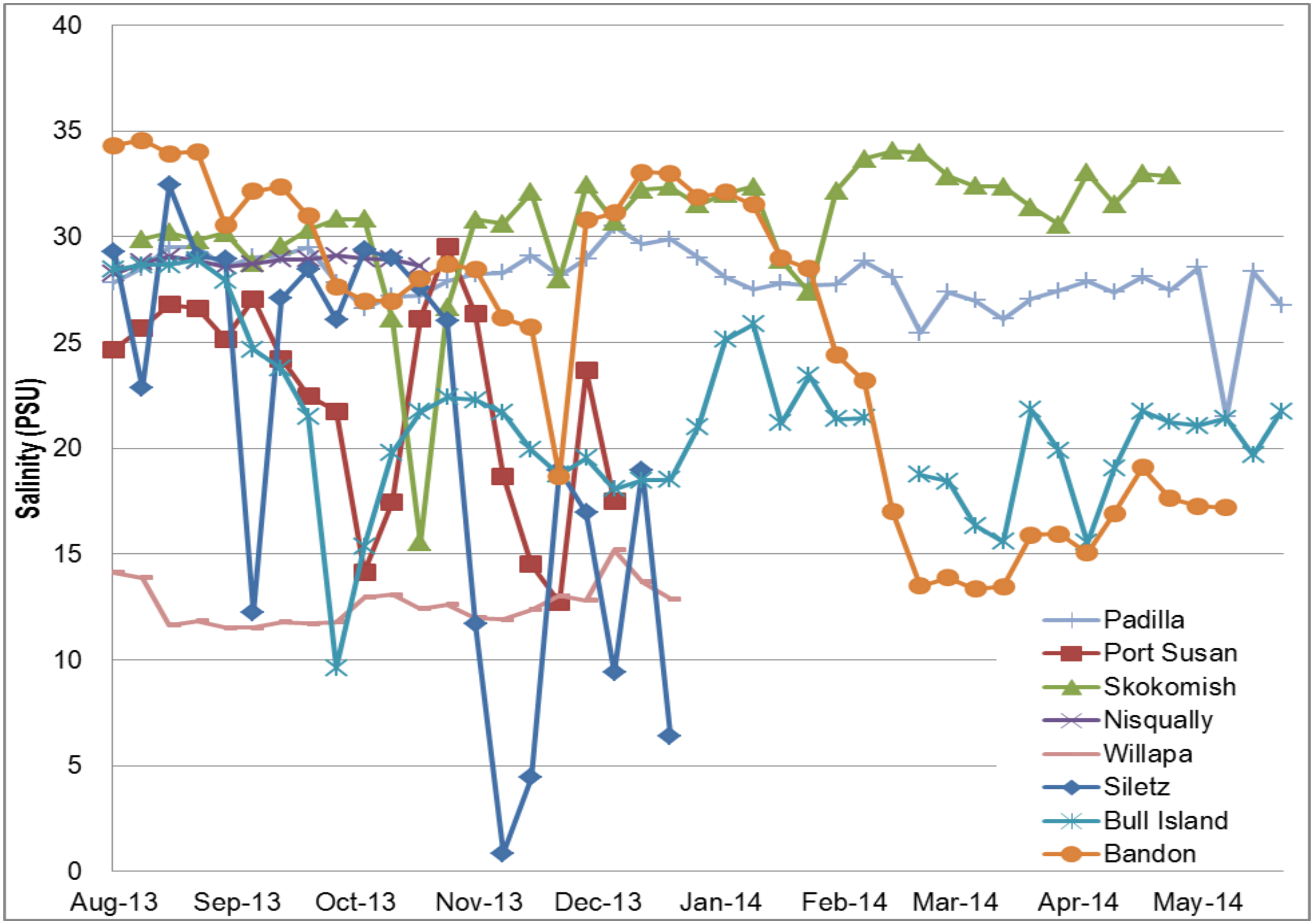

Figure 20. Weekly maximum salinity at eight study sites between August 2013 and May 2014.

6.5 Vegetation

We located 69 tidal wetland species in 2,154 vegetation plots across the nine estuaries in the study Table 9, Appendix Tables A1–I1). Common species included *Carex lyngbyei, Sarcocornia perennis, Distichlis spicata, Deschampsia cespitosa, Juncus balticus* and *Potentilla anserina*. The frequency of several common species varied markedly across the sites (Figure 21). *Distichlis spicata* dominated the flora at five of the nine sites, but was relatively uncommon at Port Susan and Grays Harbor. *Deschampsia cespitosa*, a middle to high marsh tussock-forming species was frequent at the three Oregon sites and at Willapa but much less common in Puget Sound marshes. The high marsh rush, *Juncus balticus*, was most frequent at Siletz and absent or rare at Willapa and Padilla. *Carex lyngbyei* occurrence was variable regionally, ranging from >75% frequency at Bull Island to near absence at Padilla (it did not occur in any surveyed plots, but a few plants were observed at the upland margin of the site in late 2014). See appendices for detailed site specific results.

Table 9. Number of vegetation plots sampled and total site plant species richness at the nine study sites in the Pacific Northwest. Sites are ordered from north to south.

Site	Plots sampled	Total plant richness
Padilla, WA	19	15
Port Susan, WA	210	29
Skokomish, WA	128	21
Nisqually, WA	245	29
Grays Harbor, WA	271	21
Willapa, WA	276	19
Siletz, OR	126	31
Bull Island, OR	380	18
Bandon, OR	372	43

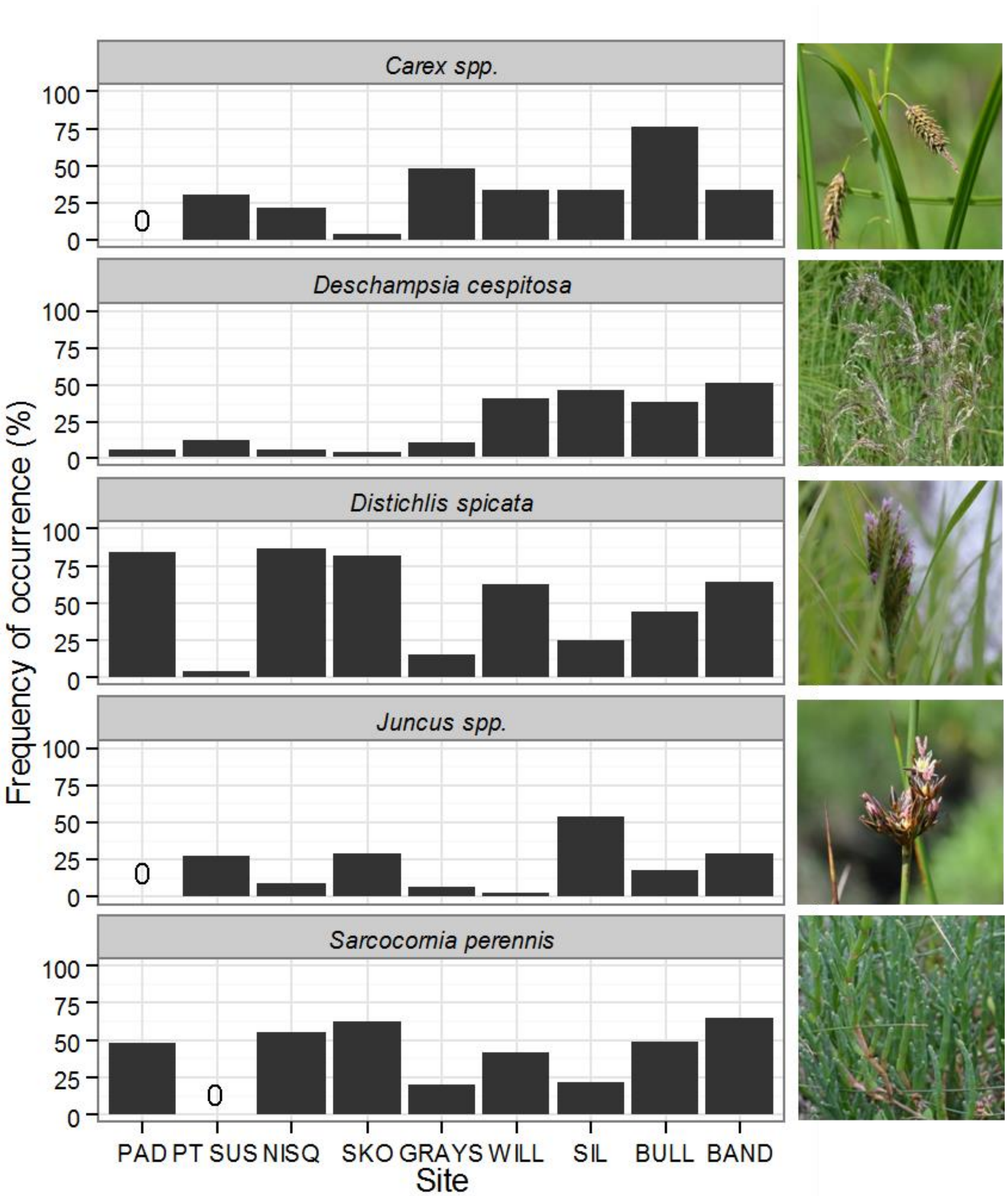

Figure 21. Differences in the frequency of occurrence of five common Pacific Northwest tidal wetland species across sites in Oregon and Washington. PAD = Padilla; PT SUS = Port Susan; NISQ = Nisqually; SKO = Skokomish; GRAYS = Grays Harbor; WILL = Willapa; SIL = Siletz; BULL = Bull Island; BAND = Bandon. *Carex* spp. was comprised of *C. lyngbyei*, except at Grays Harbor, where some plants were probably *C. obnupta*. *Juncus* spp. was comprised of *J. balticus* at all sites, except for Skokomish, where a mixture of *J. balticus* and *J. gerardii* was present. All photos by C. Janousek.

We delineated marsh zones using long-term NOAA tidal data combined with our site-specific elevation and water level data and examined plant abundance in these major zones across the sites. At many sites, plant composition tended to vary by zone, but not necessarily in consistent ways across the region (Tables A2-I2). For instance, at Bandon, *Sarcocornia perennis* was the most abundant high marsh species (with *Deschampsia cespitosa* most abundant in middle and low marsh), while *S. perennis* was the most abundant plant in low marsh at Grays Harbor (*Carex* spp. dominated in mid-marsh and *Potentilla anserina* dominated high marsh). Vertical zonation of plant assemblages was less pronounced at other sites, including Nisqually where *Distichlis spicata* had the highest mean cover in all three major marsh zones.

Low marsh habitat was common at Bull Island, Willapa, Nisqually, and Port Susan. Common species in this zone included *Sarcocornia perennis*, *Distichlis spicata*, *Carex lyngbyei*, and *Triglochin maritima*. Middle tidal marsh was present at all of the sites and particularly common at Skokomish. Common species included all of the aforementioned taxa and *Deschampsia cespitosa*, *Juncus balticus* and *Agrostis stolonifera*. High marsh was only common at Bandon, Siletz, Willapa, Grays Harbor and Padilla. Common high marsh species included many species found in other zones, but also included *Potentilla anserine* and *Atriplex prostrata*. Transition zone habitat (defined as wetland flooding at least once per year but no more than once per month) was limited at most of our study sites. Zonation of individual species per site are illustrated in the respective appendices (Figures B4-I4).

Our data suggest that most Pacific Northwest vegetation communities are dominated by native species. The major exception is creeping bentgrass (*Agrostis stolonifera*) a likely nonnative, which can be locally common at many sites in the region. At Siletz, *A. stolonifera* was the most frequently occurring taxon (found in 84% of all surveyed plots) and had a mean cover of 59% across the site. Despite this high abundance, Siletz still supported relatively high native plant diversity. *Agrostis stolonifera* was relatively uncommon at Willapa, Nisqually, Skokomish and Padilla. *Atriplex prostrata* another nonnative, occurred commonly across sites in the region, but never attained >6% cover at any site. Marsh vegetation at Bull Island in Coos Bay was among the least invaded (it had only one non-native species, *A. stolonifera*, at 6% mean cover). Willapa Bay was also relatively un-invaded, having only three non-native species in relatively low abundance: *A. stolonifera* (3% mean cover), *A. prostrata* (0.2%) and *Cotula coronopifolia* (0.1%).

Aside from *A. stolonifera* and *A. prostrata*, most non-native species occurred only infrequently at the sites we studied. Other non-native species included brass buttons (*Cotula coronopifolia*), curly dock (*Rumex crispus*), trefoil (*Lotus corniculatus*), reed canary grass (*Phalaris arundinacea*), thistles (*Cirsium arvense* and *C. vulgare*), tall fescue (*Schedonorus arundinaceus*), and velvet grass (*Holcus lanatus*). Small patches of non-native *Spartina* hybrid and *Phragmites australis* were observed in Grays Harbor in late 2014, but were not found in any surveyed plots during 2012. Plant richness varied by site in the Pacific Northwest (

Table 9). For instance, at the Oregon sites, more than twice as many vascular plants were located at Bandon than at Bull Island in nearby Coos Bay despite similar sample sizes. At the plot level, Bandon, Siletz, Nisqually and Skokomish had the highest plant richness (Figure 22). Each of these sites are relatively heavily impacted by freshwater flow (Nisqually and Skokomish are located next to major river deltas) suggesting the role of freshwater in affecting overall richness. Padilla and Grays Harbor were the least diverse sites at the plot level, averaging less than three species per plot.

Relatively high evenness among common species and the presence of many rarer taxa both appear to contribute to the high diversity of Pacific Northwest tidal wetland plant assemblages. Unlike many California marshes, Pacific Northwest marshes support several dominant species. For instance, at Bandon, nine species occurred in at least 20% of plots at the site (Appendix Table I1). Similarly, Nisqually and Siletz had eight species occurring in at least 20% of plots. However, rarer taxa also contribute to the high richness of Pacific Northwest marshes. At Bandon, there were 30 taxa that occurred in less than 5% of the plots. See appendices for detailed site specific results.

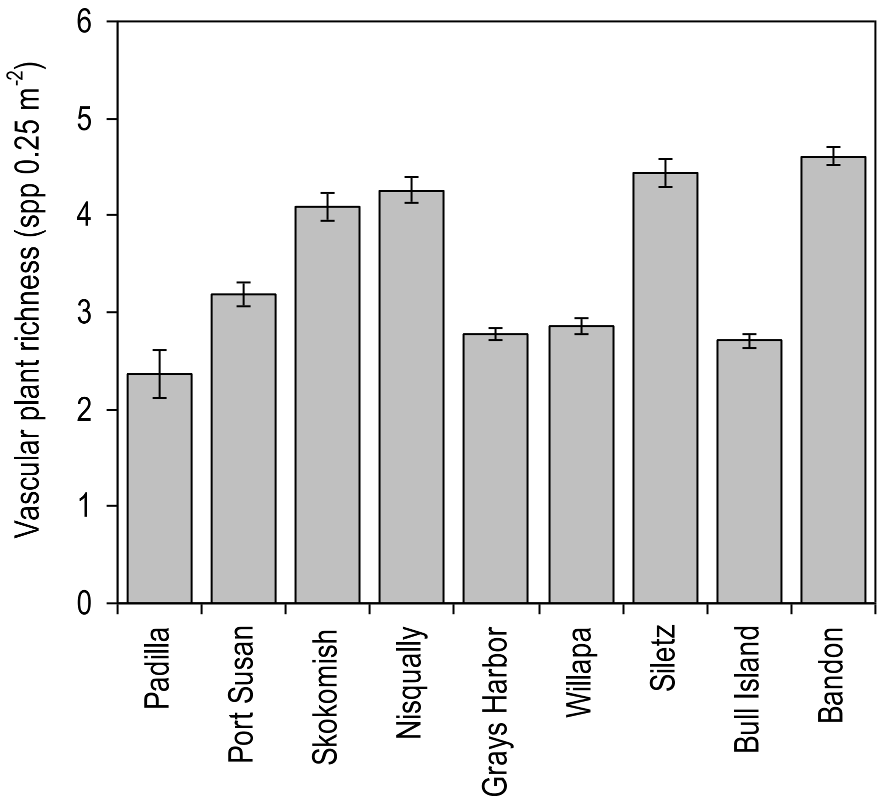

Figure 22. Mean (±SE) vascular plant richness (species per 0.25 m^2) in vegetation plots at the nine sites. Sites are ordered from north to south.

6.6 WARMER SLR modeling

Application of the WARMER model to our site-specific DEMs under three SLR scenarios showed changes in mean marsh elevation at all sites by the year 2110 (Figure 23). The SLR projections used in the models had a large effect on final site elevation by 2110. Padilla, Port Susan, Skokomish, Nisqually, Grays Harbor, Willapa, Siletz, Bull Island and Bandon persisted as tidal marsh with similar vegetation composition under the NRC's low (+12 cm/100yr) SLR rate, with mean elevation increasing or remaining unchanged over the coming century, demonstrating tidal marsh resiliency to low SLR rates (Figure 24). However there was a decline in mean site elevation under middle (+63 cm/100 yr) and high (+142 cm/100 yr) SLR scenarios, with acceleration of marsh loss between 2050 and 2110. Projected mean marsh elevation at Skokomish and Bandon remained unchanged under low SLR scenarios, but mean site elevation declined under mid and high SLR scenarios. Bandon was the only site to have mean elevation below MTL in 2110 under the high SLR scenario. Mean site elevation at all other sites was above local MTL. See appendices for detailed site specific results.

WARMER results also showed state changes in vegetation zones and their spatial distribution (Figure 25; Appendix Figures A10–I10, A11–I11) under mid SLR scenarios for most sites. For instance at Willapa, which has a relatively high proportion of high marsh presently, habitat composition was projected to remain relatively similar to present conditions until 2050. By 2090, however, virtually all high marsh was projected to transition to middle and low marsh vegetation zones. Projected changes at Nisqually were similar to Willapa. A mixture of high, mid and low marsh remains until 2090, but the site is modeled to be 86% low marsh by 2110.

At Grays Harbor, we projected that elevation would increase throughout the coming century under the mid SLR scenario. High marsh habitat expands between 2010 and 2080, with 72 percent of the marsh comprising of high marsh habitat in 2110. The entire site was projected to remain vegetated throughout the modeled period, which is similar to Padilla, Nisqually, Willapa, Siletz, and Bull Island. In contrast, Port Susan, Skokomish, and Bandon begin to transition to unvegetated mudflat toward the end of 2110.

Under the NRC's high SLR scenario, all of our study sites in Washington and Oregon are projected to undergo substantial changes in elevation profiles over the coming century, which are expected to result in changes to tidal marsh plant community composition and available habitat (Figure 26). At all of the study sites except Grays Harbor, Willapa, and Siletz, high marsh is essentially lost between about 2040 and 2060. These sites lose high marsh by 2080-2090. WARMER projections suggest that all sites will lose all mid marsh by 2110 except Grays Harbor. The WARMER projections suggest that under high SLR scenarios, Grays Harbor and Willapa will be mainly comprised of low marsh by 2110; the rest of the sites are comprised largely of unvegetated mudflat (Figure 26). See appendices for detailed site specific results.

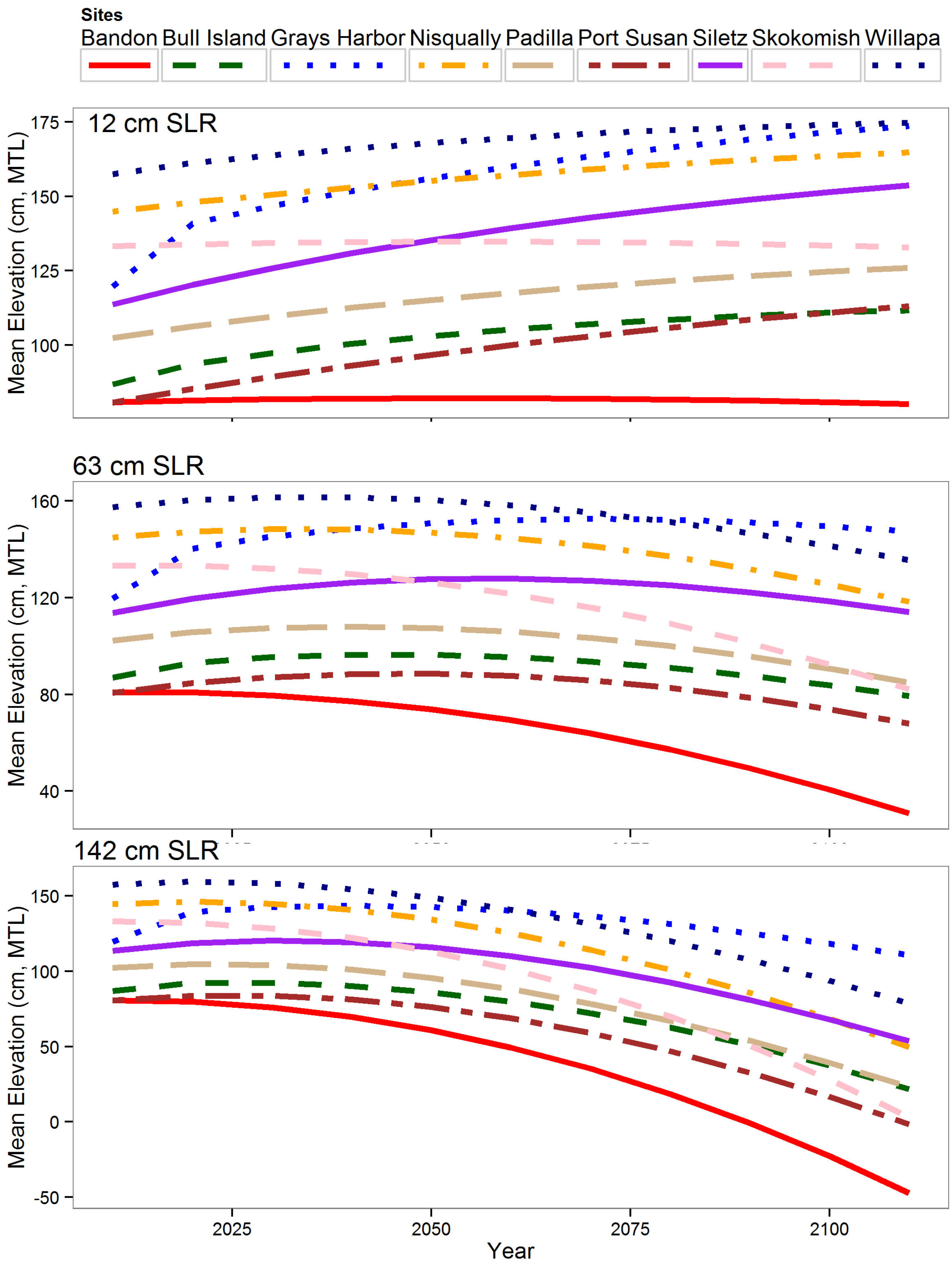

Figure 23. Projected changes in mean site elevation to 2110 using the WARMER model. Low, mid and high SLR scenarios are +12 cm, +63 cm, and +142 cm by the year 2110, respectively.

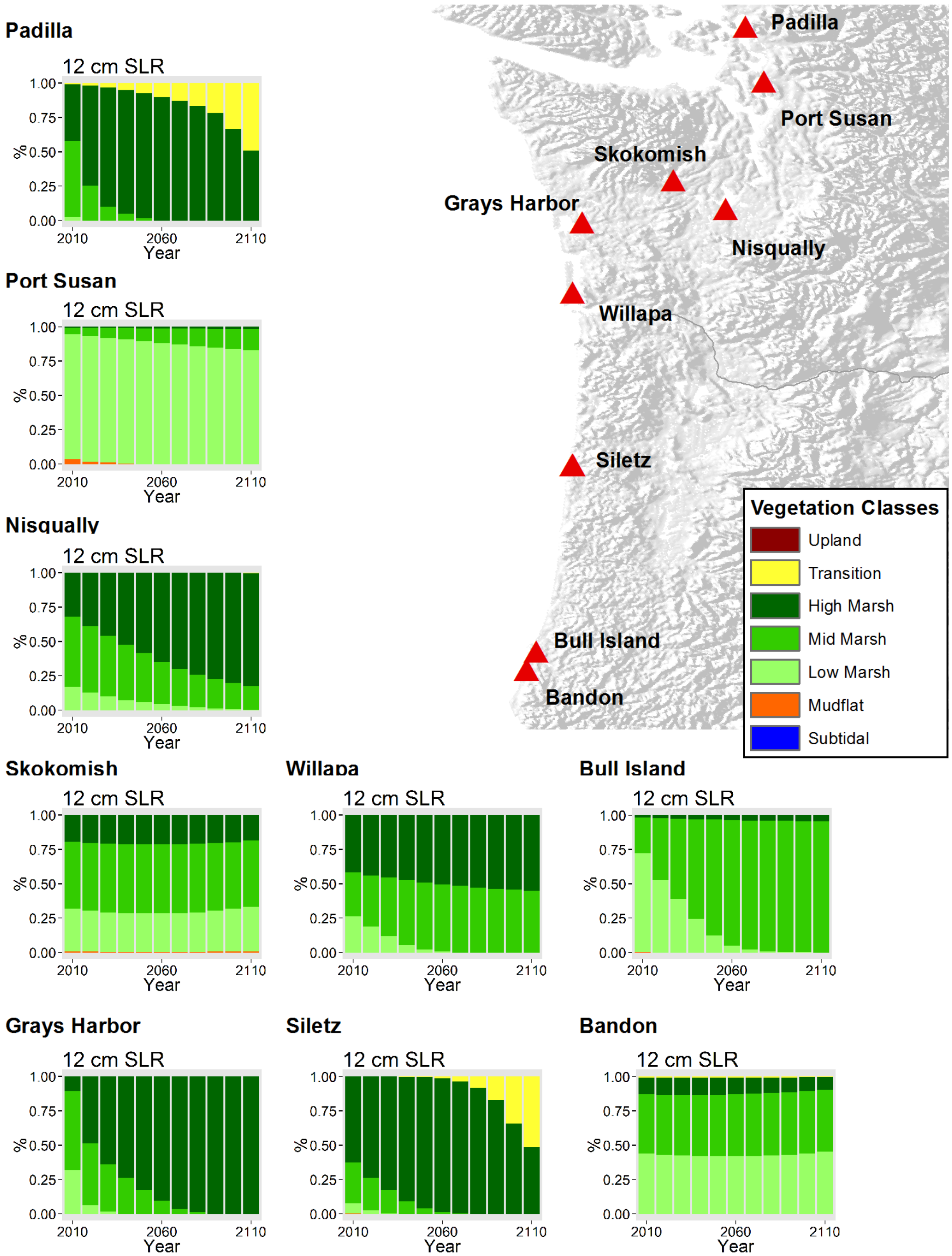

Figure 24. Projected changes to the relative abundance of marsh vegetation zones under the NRC's low SLR scenario (+12 cm by 2110). All marsh vegetation composition remains unchanged or shows increases in proportions of mid, high and transition marsh vegetation zones. We assumed no marsh transgression upslope at all sites. Site specific results are located in the Appendix.

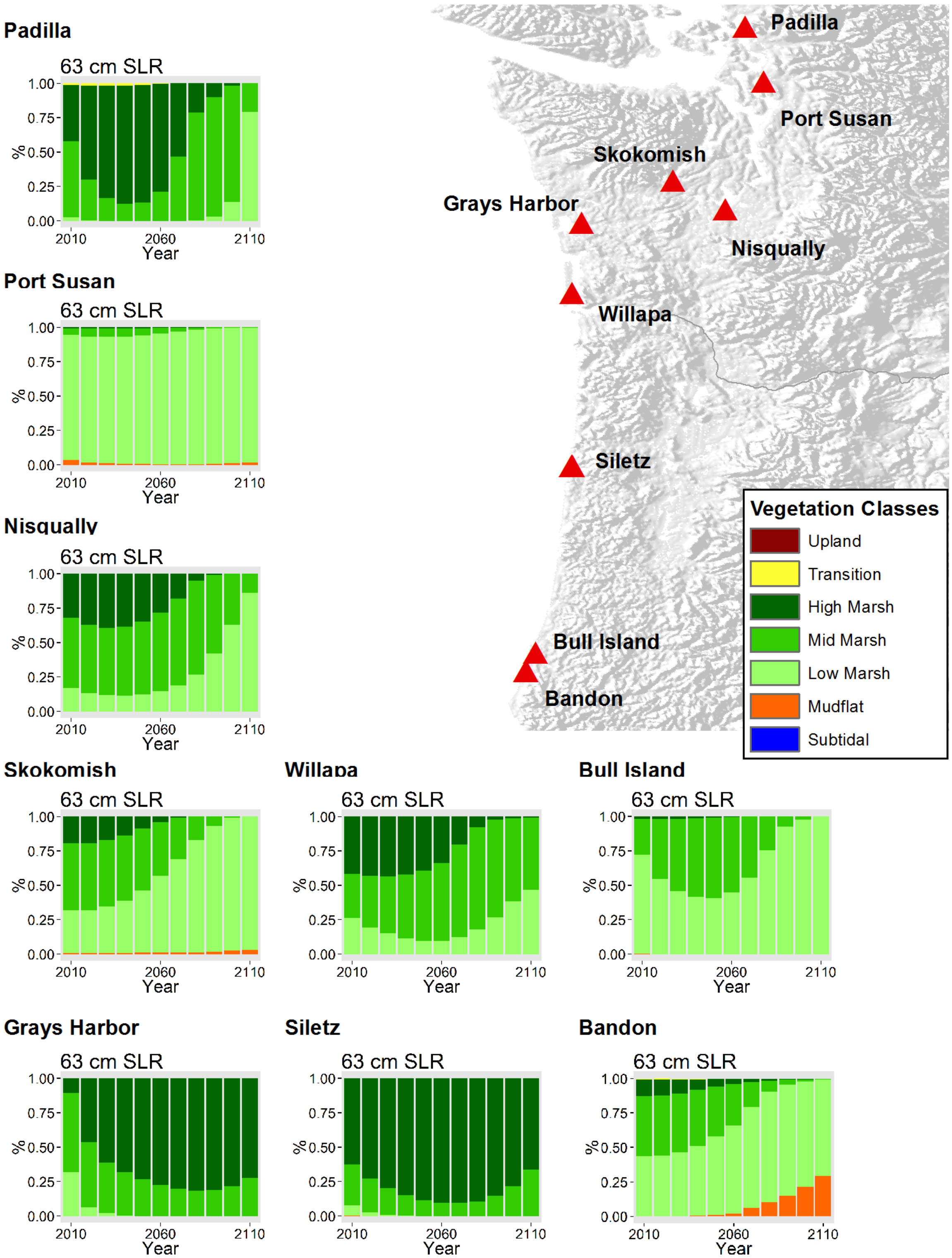

Figure 25. Projected changes to the relative abundance of marsh vegetation zones under the NRC's mid SLR scenario (+63 cm by 2110). Majority of marsh vegetation composition shows gradual decreases in proportions of mid and high marsh vegetation zones. We assumed no marsh transgression upslope at all sites. Site specific results are located in the Appendix.

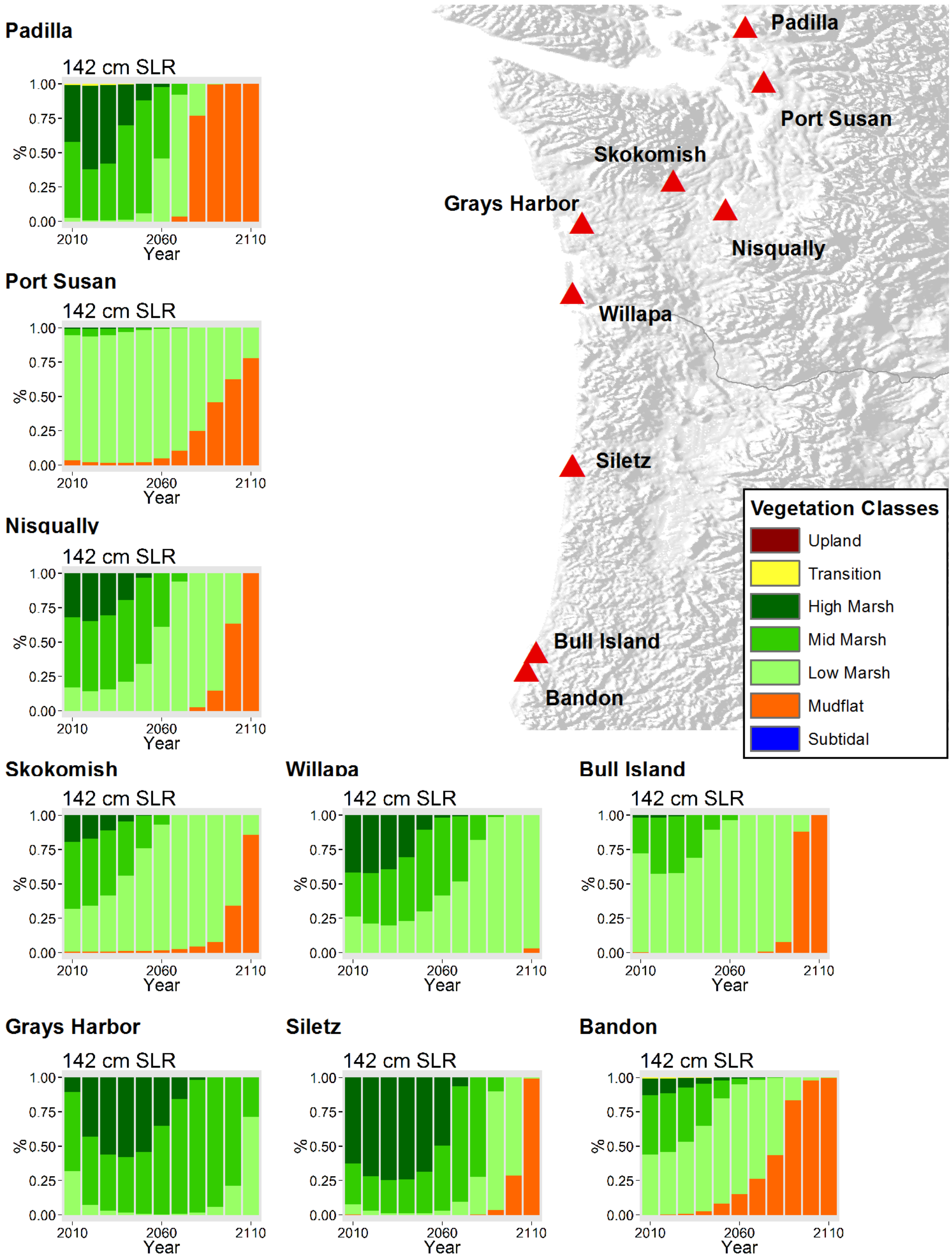

Figure 26. Projected changes to the relative abundance of marsh vegetation zones under the NRC's high SLR scenario (+142 cm by 2110). All marsh vegetation is presumed to be lost once the area transitions to mudflat. We assumed no marsh transgression upslope at all sites. Site specific results are located in the Appendix.

Section 7: Analysis and Findings

Our SLR modeling results suggests that Pacific Northwest tidal marshes are at risk of transitioning to unvegetated mudflat under the NRC's mid and high SLR scenarios, however there is substantial variation in vulnerability across sites (Figure 24 - 26). At all sites under mid and high SLR rates, most high and mid marsh habitat will not persist within current marsh areas, suggesting a change in vegetation communities across estuaries. Low marsh persists at a few sites under the highest SLR scenario (mainly at Willapa and Grays Harbor). Differences in initial starting marsh elevation and net accretion rates resulted in different model projections. Sites with high net accretion rates and initial elevations, such as Willapa, were projected to maintain low marsh over the next century regardless of the SLR rate. Alternatively, sites with low net accretion rates, such as Nisqually and Skokomish, are projected to transition to unvegetated tidal flats.

Under low and mid SLR scenarios, model projections of marsh elevation are more optimistic, with most sites maintaining elevation profiles similar to their current conditions (Figure 24, 25). Some sites are projected to remain vegetated, but transition to low marsh. The likelihood of these lower SLR scenarios being realized, however, is diminishing as new data from the Arctic and Antarctic suggest that previous research may have underestimated the rate of polar ice sheet melting and its contributions to global SLR (e.g., Enderlin et al. 2014, McMillian et al. 2014). Projections of global SLR that incorporate these new findings have not yet been produced for the Pacific coast.

A sufficient sediment supply for accretion is critical for the maintenance of tidal marshes under accelerating SLR. Modifications to estuaries that reduce sediment supply can inhibit the potential for marsh accretion. For example, upstream dams can severely limit the amount of suspended sediment that is available for marsh accretion in estuaries (Weston 2014). High measured accretion rates at Port Susan may be attributed to the undammed Stillaguamish River, especially when compared to the dammed Nisqually River. Both sites are within Puget Sound and have similar plant communities, however the model projections for each site are very different. Similarly, land use practices (e.g., extensive logging) near southern Willapa Bay may be responsible for the elevated net accretion rates observed. A better understanding of the effects of both proximate (net accretion rates, sediment supply) and land use changes on projections of future tidal marsh elevation is important for developing management plans for accelerating SLR.

To inform management decision making we conducted a preliminary analysis to discern which model parameters have the greatest influence on elevation change (Table 10). A boosted regression tree analysis used model parameters across each site to explain variance in elevation change after 100 modeled years. The results showed that the total amount of SLR is the primary driving force in marsh sustainability. In addition, the results demonstrated that not only is the magnitude of SLR over the next century important, but the acceleration of SLR in the latter half of the century is also critical for understanding marsh sustainability. SLR, initial elevation, and inorganic sediment accumulation are all dominant factors which determine tidal marsh sustainability.

Initial tidal marsh elevation (0 to 360 cm in 10 cm increments) had the second greatest relative impact on final elevation model output. For example, the higher the starting elevation, the greater of the likelihood that the tidal marsh would keep pace with SLR. Together, organic matter accumulation rates (maximum) and inorganic sediment accumulation (at 0 cm MSL) explained about 23% of variance in the final model output, with inorganic matter accumulation rates having a greater impact on final elevation than organic sediment contributions. SLR, initial elevation, sediment accumulation, and organic matter input accounted for 95% of the influence in projected elevation change. Tidal range, refractory carbon, and soil porosity (the difference between porosity at the top and bottom of the soil cores) had a negligible influence on model results, together accounting for 5% of the variance. The factors which resource managers may have the ability to manage (initial elevation and sediment accumulation rate) accounted for ~50% of the total variance.

Table 10. Relative influence of major model parameters in elevation change by 2110. We calculated variable importance using a boosted regression tree model with elevation change after 100 years of sea-level rise across 37 initial elevations, 3 sea-level rise scenarios, and the 9 study sites.

Variable	Relative influence (%)
Sea-level rise by 2110	40
Initial elevation (relative to MTL)	32
Sediment accumulation rate	17
Organic matter accumulation rate	6
Porosity	4
Tidal range	0.2
Refractory carbon	0.1

Section 8: Conclusions and Recommendations

In this study, we used intensive local sampling at a series of sites along the Washington and Oregon coasts to model local and regional differences in tidal marsh vulnerability to SLR. We documented site-specific differences in elevation, vegetation composition, mineral and organic matter accretion, and water level and salinity characteristics. Using deep core data we found that Pacific Northwest tidal marshes had variable historic accretion rates, which also varied between high and low marsh zones. Integrating the elevation, vegetation, and accretion data into elevation modeling (WARMER) under the NRC's SLR scenarios, we determined that tidal marsh persistence is likely to vary between estuaries and is dependent on the SLR scenarios.

Under low SLR rates, tidal marsh persisted at all sites, but mid and high SLR rates threatened the persistence of vegetated marsh at most of the sites over the coming century (Figure 24). The timing and degree of projected impacts varied among sites. Under mid SLR projections, all sites lost high marsh habitat by 2110, and most became entirely low marsh habitat (Figure 25). Under mid SLR scenarios, Bull Island and Siletz in Oregon were the most vulnerable areas in the study, with loss of all vegetated marsh habitat by 2110. However, all other study sites also became relatively lower in elevation, tending to transition to low marsh habitat over the next 50-100 years.

Changes in tidal marsh composition with SLR may impact a variety of wetland-dependent organisms. For instance, changes in relative elevation across these marshes are expected to result in changes in plant community composition because of existing patterns of plant zonation along inundation gradients. Loss of mid and high marsh habitat across the region could have negative impacts on terrestrial wildlife that use less frequently inundated tidal marsh for cover, foraging and nesting. For example, common marsh inhabitants such as passerines and rails will probably lose mid-high marsh nesting and foraging habitats. However, corresponding gains in low marsh and mudflat may increase habitat available for marine algae (Janousek and Folger 2012), estuarine fish, shellfish species, and foraging areas for migratory shorebirds, and waterfowl.

Future sediment supply and marsh productivity are likely to be key determinants of future tidal marsh persistence in the Pacific Northwest. In over half of our study sites, the high SLR scenario resulted in transition from tidal marsh to mudflat habitat, suggesting that historic rates of net accretion are less than what is needed to keep pace with increasing sea level. Our preliminary findings suggest that Washington and Oregon tidal marsh persistence over the coming century is threatened if mid and high projections of coastal SLR are realized. However, more data are needed on these important ecosystems to fully determine their vulnerability to SLR, including understanding of variation in contemporary accretion rates within estuaries, elevation-productivity relationships for dominant vegetation species, and how surrounding land use practices may impede or allow the migration of wetlands upslope. In addition, integrating marsh transgression processes into modeling can help identify areas where marsh migration upslope could occur which could prevent total hectares loss of marshes.

To promote habitat persistence (especially in transitional, high, and mid marsh habitat), it may be necessary to take one or more proactive management steps to ensure habitat persistence. For instance, protecting and restoring habitat adjacent to current tidal marshes may ensure that marshes are able to migrate into upland areas. Management of watershed practices may help downstream marshes obtain adequate sediment supply. More exploration of options for management actions for marsh elevation augmentation and adaptation is needed.

This project was successful in evaluating SLR vulnerability across a range of estuary types in the Pacific Northwest. Our results inform both local and regional perspectives on potential tidal marsh vulnerability to SLR. We successfully partnered with local and regional resource managers to help provide information to inform their climate change planning process. Recommended next steps for this research program include:

- Incorporation of marsh migration processes into coastal modeling
- Additional research on processes inherent in marsh accretion potential, including organic matter contributions and suspended sediment availability
- Understanding changes in marsh function due to SLR including vegetation responses to inundation
- Assessment of suspended sediment delivery to river dominated estuaries and how this contributes to tidal marsh accretion seasonally and with storms
- Linking of intertidal mudflat processes with tidal marsh accretion rates
- Model expansion to other nearshore habitat types
- Better assessment of migratory bird use of these habitats and how that may change in the future
- Development of vulnerability assessments for key management resources

- Integration of site-specific results with landscape scale sea-level rise modeling to assess estuary wide impacts

Success of a regional project such as the CERCC network requires local manager and stakeholder engagement. Tidal marsh SLR response results were translated into vegetation zones to make the information more accessible to managers and their decision making processes. This project was successful in SLR modeling for tidal marsh ecosystems, however better integration with adjacent habitats (e.g., mudflats, uplands) would improve the scope of the results to the broader estuarine environment. Additionally, while our project was successful in projecting changes to habitat types (marsh vegetation zones), we did not address one of our stated project objectives – to link those changes directly to bird ecology.

Section 9: Outreach

Comprehensive physical and ecological response models were developed at a local scale relevant to land managers, while also enabling a broader regional perspective. Our results will be available in final report form (e.g., U.S. Geological Survey OFR) to the USGS CSCs, North Pacific LCC, FWS NWRs, NOAA NERR, Washington State Parks, Oregon State Parks, and other interested land managers. Our study complements regional climate change programs including the California LCC, FWS I&M, and NOAA NERR climate change programs, as well as ongoing wetland restoration projects at Nisqually, Port Susan, and Willapa Bay.

We conducted three science delivery workshops in the Pacific Northwest within the North West Climate Science Center (NWCSC) region funded by the North Pacific Landscape Conservation Cooperative (LCC, Table 11). Our workshop objectives were to: (1) disseminate site-specific baseline data and modeling results, reveal coast-wide trends, and identify data gaps; (2) identify how local climate science results may be incorporated into habitat conservation, planning, and adaptation strategies; and (3) develop a coast wide climate change science needs assessment to inform the California and North Pacific LCCs. A total of 40 individuals from state, federal, local, NGO's, and Tribes attended the workshops. A final report outlining workshop findings will be compiled and provided to the NWCSC and NPLCC in FY16. Workshop information can be viewed on the Climate Commons webpage (http://climate.calcommons.org/article/SLR-workshops).

These workshops allowed the establishment of a dialog and built partnerships between project scientists and land managers. The establishment of this dialog has led to fruitful relationships between partners and improved management understanding about climate change impacts to their estuary. These modeling results have management implications at the region level, for example, they are being used by R1 USFWS Refuges to identifying areas for future planning and prioritization processes, identifying science needs and restoration efforts.

In Willapa Bay, eight stakeholder groups attended the workshop because of their shared interest in the natural resources of the estuary, which include migratory birds, eelgrass, recreation opportunities, the local shellfish industry, and fisheries. In particular the results at Willapa Bay NWR were more optimistic than other estuaries and showed that a portion of the refuge would persist with SLR to 2110. At the workshop participants identified that an important next step would be to expand science information and modeling to include other refuge parcels and adjacent habitat types (e.g., eelgrass beds, mudflats, and beaches) to see if vulnerability to SLR varied across these key resources which would help inform management actions.

A workshop was held at the Nisqually NWR and was attended by fourteen participants representing eight stakeholder groups which included: USFWS, Nisqually River Foundation, Washington

DNR, Nisqually Reach Nature Center, Nisqually Natural Resources, Pierce County Surface Water Management, and the Makah Fisheries Management. At this workshop we presented sea-level rise response models for tidal marsh parcels within Nisqually NWR and Grays Harbor NWR. The attendees of this workshop were interested in learning about the current conditions of the area and future scenarios of habitats, specifically tidal marsh habitat, eelgrass, salmon populations, sedimentation, and the overall connectivity of the estuary. Our modeling results helped inform their management concern about accretion rates and sedimentation availability within the refuge. Discussions occurred about what management techniques could be used to increase local marsh accretion to keep pace with SLR and prevent the loss of important habitats. Another key topic was concerns about the connectivity of the estuary and the need to identify areas for future marsh migration and the I5 corridor barrier.

The tidal marsh in Siletz Bay have not been the focus of much previous research and therefore was a key information gap for the USFWS of the Oregon Coast National Refuge complex. This research provided local managers with important baseline data on marsh elevation, flooding regime, and vegetation distributions, as well as projections of future elevation and vegetation changes under SLR scenarios. During the science delivery workshops representatives from USFWS, OR Habitat Join Venture, US EPA, Oregon Department of Fish & Wildlife, Oregon Coastal Management Program, USDA Forest Service attended to discuss their joint concerns about the future outcomes under climate change for the estuary. Main management concerns included the persistence of the tidal marsh and other habitats with SLR and the lack of upland areas for habitat transitions. In particular, participants wanted to maintain the functioning ecosystems to provide habitat for migratory birds, important fisheries, and local recreation and economic opportunities. These results will allow the USFWS to assess the relative risk of SLR across their refuges and prioritize areas for monitoring and future research. Specifically at Siletz Bay, our results provide a guide for management actions to mitigate marsh loss under SLR, namely, the acquisition of adjacent upland areas for marsh restoration and transition.

Table 11. Three workshops to disseminate site-specific SLR modeling results were held by the USGS to engage resource managers and their partners.

Site	Dates	Workshop location	Number of participants
Nisqually	10/21 - 10/22/14	DuPont, WA	14
Willapa	11/20 - 11/21/14	Long Beach, WA	10
Siletz	11/12 - 11/13/14	Newport, OR	16

Other outreach materials

Presentations and posters:

Buffington, K. , Dugger, B., McDonald, G., Thorne, K., Takekawa, J., Guntenspergen, G., Ambrose, R., Freeman, C., Powelson, K., Holmquist, J., Brown, L. Projected tidal marsh response to sea-level rise along the Pacific coast. Pacific Northwest Climate Change Conference, Seattle, WA, Sept. 2014.

Buffington, K. , Takekawa, J., Dugger, B., McDonald, G., Thorne, K., Guntenspergen, G., Ambrose, R., Ganju, N., Barnard, P., Hall, A., Freeman, C., Powelson, K., Brown, L., Holmquist, J. Coastal ecosystem response to climate change: Assessing sea-level rise and storm impacts to Pacific coasts salt marshes. Pacific Northwest Climate Change Conference, Portland, OR, Sept. 2013.

Buffington, K., Thorne, K., Swanson, K., Drexler, J., Casazza, M., Overton, C., and Takekawa, J. Prospects for conserving endangered wildlife populations in Pacific coast salt marshes under expected sea-level rise. International Conference on Climate Change, Seattle, WA. June 2012.

Buffington, K., Takekawa, J., Thorne, K., Swanson, K., Schoellhamer, D., and Drexler, J. Evaluating the effects of projected sea-level rise on tidal marsh habitats along the Pacific coast; an interdisciplinary approach. National Landscape Conservation Cooperative conference, Denver, CO, March 2012.

Freeman C., Thorne K., Takekawa J., Buffington K., Dugger B., de la Cruz, S., Guntenspergen G. Marshes to mudflats: climate change effects along a latitudinal gradient in the Pacific Northwest. NP LCC meeting, July 2014.

Janousek CN, Mayo C, Thorne K, Takekawa J. Inter-specific and geographic variability in elevation-productivity relationships in northeast Pacific tidal marshes. Joint Aquatic Sciences Meeting, Portland, OR, May 2014.

Thorne K., Takekawa J., Dugger B., MacDonald G., Gutenspergen G., Ambrose R.. A regional multidisciplinary approach to assess climate change impacts to Pacific coast wetlands for informing adaptation strategies. National Workshop on Large Landscape Conservation, Washington D.C. Oct. 2014.

Thorne, K. Pacific coast tidal marsh modeling with sea-level rise on Pacific coast Refuges, South Bay Salt Pond managers group, Oakland, CA, Oct. 2014

Thorne, K. and Lowe, R. Siletz NWR sea-level rise marsh modeling results for management decision making. North Pacific Climate Change Conference, Seattle, WA, Sept. 2014

Thorne, K. Buffington, K., Thuy-Vy D. B., Tsao D., Spragens K. and Takekawa, J.Y. Understanding how climate change and storm events can affect salt marsh wildlife. Coastal Research Federation Conference, San Diego, Nov. 2013.

Peer-reviewed papers in progress:

Thorne KM, Dugger B, Takekawa J, Buffington KJ, Janousek CN, MacDonald G, Ambrose R, In Prep. Tidal marsh vulnerability with sea-level rise along a latitudinal gradient.

Buffington KJ, Janousek CN, Thorne K, Dugger B, Takekawa J. In Prep. Correcting positive bias in tidal marsh lidar with vegetation indices from multispectral imagery.

Buffington KJ, Janousek CN, Thorne K, Dugger B, Takekawa J. In Prep. Organic and mineral accumulation rates across Pacific Northwest tidal marshes

Buffington KJ, Janousek CN, Thorne K, Dugger B, Takekawa J. In Prep. Assessing the relative vulnerability of Pacific Northwest tidal marshes to sea-level rise with a processes-based elevation model.

Janousek CN, Buffington KJ, Thorne KM, Guntenspergen GR, Takekawa JY, Dugger BD. In Prep. Species-level variation in productivity and fecundity along inundation gradients in Pacific coast tidal marshes.

Janousek CN, Thorne K, Takekawa J. In Prep. Zonation of tidal marsh plants varies at local and regional scales.

Janousek CN, Thorne K, Buffington K, Takekawa J. In Prep. Latitudinal and local drivers of plant diversity in temperate salt marshes.

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Works Cited

Baldwin, B.G., Goldman, D.H., Keil, D.J., Patterson, R., Rosatti, T.J., and Wilken, D.H., 2012. The Jepson Manual: Vascular Plants of California, 2nd ed.: Berkeley, University of California Press.

Brand, L.A., Smith L.M., Takekawa, J.Y., Athearn, N.D., Taylor, K., Shellenbarger, G.G., Schoellhamer, D.H., and Spenst, R. 2012. Trajectory of early tidal marsh restoration: Elevation, sedimentation and colonization of breached salt marsh ponds in the northern San Francisco Bay. Ecological Engineering 42: 19-29.

Callaway, J.C., Delaune, R.D., and Patrick, W.H. 1996. Chernobyl 137Cs used to determine sediment accretion rates at selected northern European coastal wetlands: Limnology and Oceanography 41: 444–450.

Cook, T., Meyers, S.C. and Sundberg S. eds. 2013. Oregon Vascular Plant Checklist. http://www.oregonflora.org/checklist.php.

Department of the Interior. 2012. National fish, wildlife, and plants climate adaptation strategy. National Fish, Wildlife, and Plants Climate Adaptation Partnership.

Deverel, S.J., Drexler, J.Z., Ingrum, T., and Hart, C. 2008. Simulated Holocene, recent and future accretion in channel marsh islands and impounded marshes for subsidence mitigation, Sacramento-San Joaquin Delta, California, USA.

Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M., van Angelen, J. H., and van de Broeke, M. R. 2014. An improved mass balance budget for the Greenland ice sheet. Geophyiscal Research Letters 41:1944-8007.

Gedan, K.B., Silliman, B.R., and Bertness, M.D. 2009. Centuries of human-driven change in salt marsh ecosystems.: Annual Review of Marine Science 1:117–41, doi:10.1146/annurev.marine.010908.163930.

Heiri, O., Lotter, A.F., and Lemcke, G. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results: Journal of Paleolimnology 25:101–110.

Huppert, D.D., Moore, A., and Dyson, K. 2009. Impacts of climate change on the coasts of Washington State:, 285–309 p.

IPCC. 2014. Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change:, 132 p.

Janousek C.N., and Folger, C.L. 2012. Patterns of distribution and environmental correlates of macroalgal assemblages and sediment chlorophyll a in Oregon tidal wetlands. Journal of Phycology 48:1448-1457.

Janousek, C.N., and Folger, C.L. 2014. Variation in tidal wetland plant diversity and composition within and among coastal estuaries: assessing the relative importance of environmental gradients: Journal of Vegetation Science 25:534–545.

Jevrejeva, S., Moore, J.C., and Grinsted, A. 2012. Sea level projections to AD2500 with a new generation of climate change scenarios: Global and Planetary Change 80-81:14–20, doi: 10.1016/j.gloplacha.2011.09.006.

Kirwan, M.L., and Megonigal, J.P. 2013. Tidal wetland stability in the face of human impacts and sea-level rise: Nature 504:53–60, doi: 10.1038/nature12856.

McMillan, M., A. Shepherd, A. Sundal, K. Briggs, A. Muir, A. Ridout, A. Hogg, and D. Wingham. 2014. Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters 41:3899–3905.

Marani, M. D'Aplaos, A., Lanzoni, S., Carniello, L., and Rinald A. 2010. The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics. Journal of Geophysical Research 115(F4): F04004.

Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., and Cahoon, D.R. 2002. Responses of coastal wetlands to rising sea level: Ecology 83:2869–2877.

National Oceanic and Atmospheric Administration. 2003. Computational Techniques for Tidal Datums Handbook. NOAA Special Publication NOS CO-OPS 2.

National Research Council. 2012. Sea-level rise for the coasts of California, Oregon, and Washington: past, present, and future. National Academy of Sciences: The National Academies Press.

Ritchie, J., and McHenry, J.R. 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. Journal of Environmental Quality 19:215:233.

Scavia, D., Field, J.C., Boesch, D.F., Buddemeier, R.W., Burkett, V., Cayan, D.R., Fogarty, M., Harwell, M.A., Howarth, R.W., Mason, C., Reed, D.J., Royer, T.C., Sallenger, A.H., and Titus, J.G. 2002. Climate change impacts on U.S. coastal and marine ecosystems: Estuaries 25:149–164.

Schile, L.M., Callaway, J.C., Morris, J.T., Stralberg, D., Parker, V.. T., and Kelly, M. 2014. Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency: PloS One 9:e88760, doi: 10.1371/journal.pone.0088760.

Slangen, A.B.A., Carson, M., Katsman, C.A., van de Wal, R.S.W., Köhl, A., Vermeersen, L.L.A., and Stammer, D. 2014. Projecting twenty-first century regional sea-level changes: Climatic Change 124:317–332, doi: 10.1007/s10584-014-1080-9.

Swanson, K.M., Drexler, J.Z., Schoellhamer, D.H., Thorne, K.M., Casazza, M.L., Overton, C.T., Callaway, J.C., and Takekawa, J.Y. 2014, Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary: Estuaries and Coasts 37:476–492, doi: 10.1007/s12237-013-9694-0.

Takekawa, J.Y., Woo, I., Athearn, N.D., Demers, S., Gardiner, R.J., Perry, W.M., Ganju, N.K., Shellenbarger, G.G. and Schoellhamer, D.H. 2010. Measuring sediment accretion in early tidal marsh restoration. Wetlands Ecology and Management 18:297-305.

Tucker, C.J. 1979. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. Remote Sensing of Environment 8:127-150.

UNESCO. 1983. Algorithms for computation of fundamental properties of seawater. UNESCO technical papers in marine science 44:1-55.

USFWS. 2010. Rising to the urgent challenge: Strategic Plan for Responding to Accelerating Climate Change.

Vermeer, M., and Rahmstorf, S. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences of the United States of America 106:21527–32, doi: 10.1073/pnas.0907765106.

Weston, N. B. 2014. Declining Sediments and Rising Seas: an Unfortunate Convergence for Tidal Wetlands. Estuaries and Coasts 37:1–23.

Appendix

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Padilla Marsh, Padilla Bay, Skagit County, Washington, USA

Photo: K. Turner, USGS

Summary:

- *Study site size*: 5.2 hectares
- *Location*: 47° 05' 55" N latitude, 122° 04' 60" W longitude.
- *Site management*: Padilla Bay National Estuarine Research Reserve (NOAA)
- *Site vegetation and elevation survey*: 31 August – 7 September 2012
- *Sample size*: 76 (elevation data points), 19 (vegetation quadrats)
- *Marsh elevation model*: Padilla was the highest study site in the Pacific Northwest region with 96% of the elevation data points above MHHW.
- *Plant community composition*: *Distichlis spicata* had the highest frequency of occurrence at the site. *Sarcocornia perennis* was also common.
- *Bathymetric surveys*: 50.6 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics:* Sediment cores were not collected at Padilla marsh. WARMER parameters were based on core data obtained at Port Susan, WA (see Table B4).
- *Salinity monitoring*: April 2013 – May 2014. Weekly maximum salinity usually ranged between 25-30 during the study period. The maximum recorded salinity throughout the study period was 30 PSU.

- *Calculated tidal datums*: MHHW is at 2.37 m NAVD88; MHW is at 2.13 m NAVD88.
- *Sea-level rise marsh response modeling:* Under the low NRC SLR projection (12 cm), Padilla is projected to become gradually dominated by high (51%) and transitional (49%) marsh over the coming century. Under the NRC's mid SLR projection (63 cm), high marsh initially increases from 2010 to 2040, but then decreases after 2050. By 2110 most of the site is low marsh. Under the NRC's high SLR projection (142 cm), there is a relatively rapid change in habitat composition with the site losing high marsh by 2070, mid marsh by 2080, and low marsh by 2090.

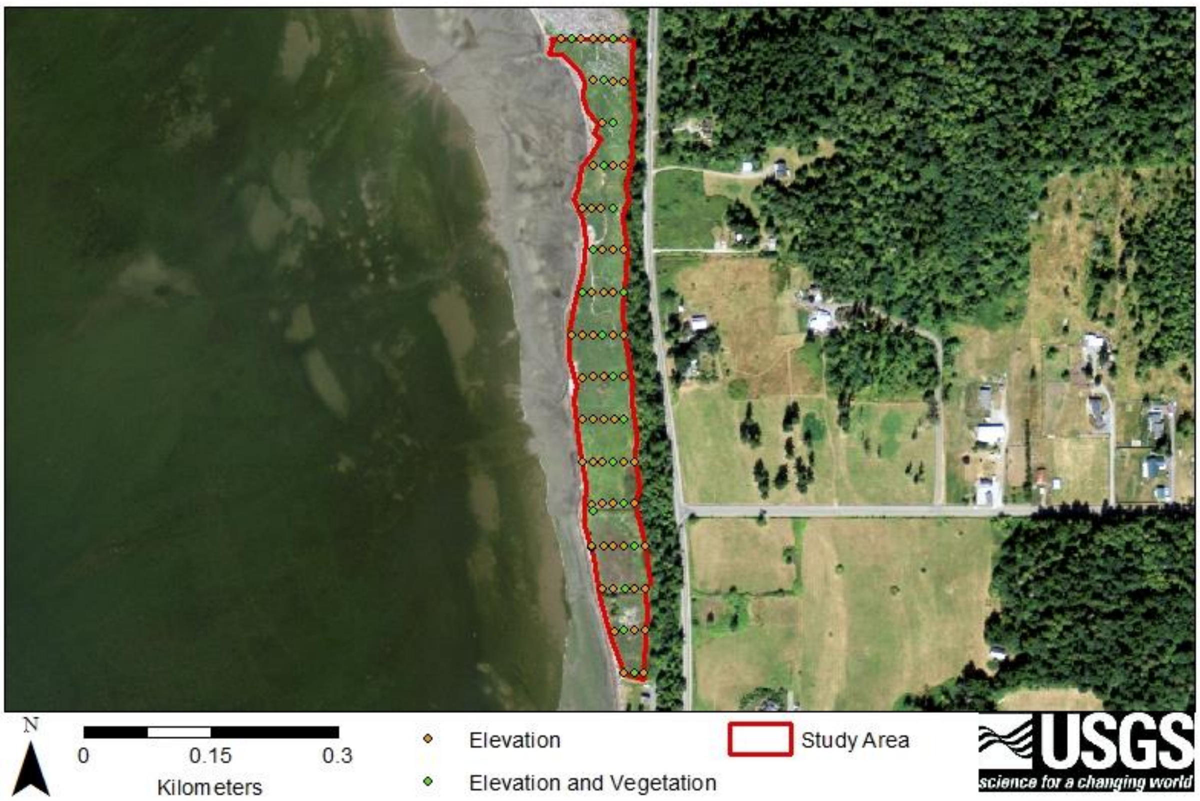

Figure A1. Distribution of elevation and vegetation survey points at Padilla.

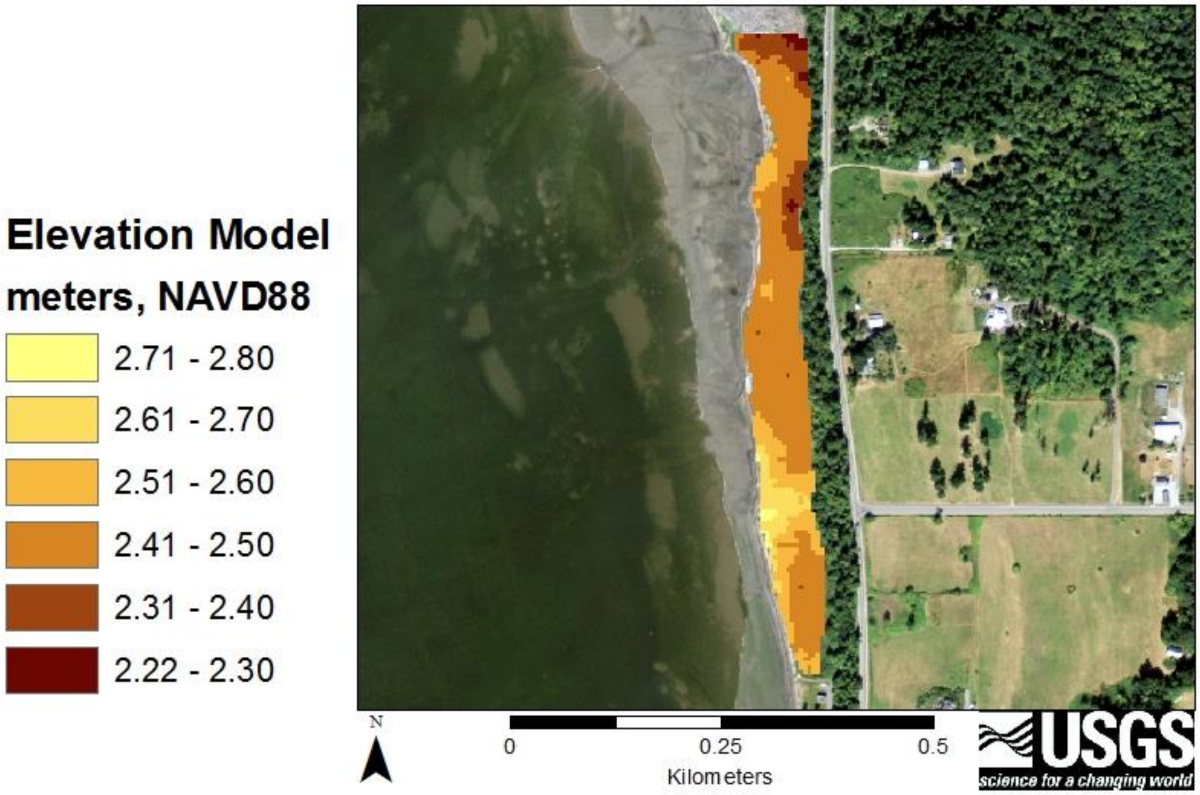

Figure A2. Elevation model (3 m resolution) developed from RTK GPS survey data.

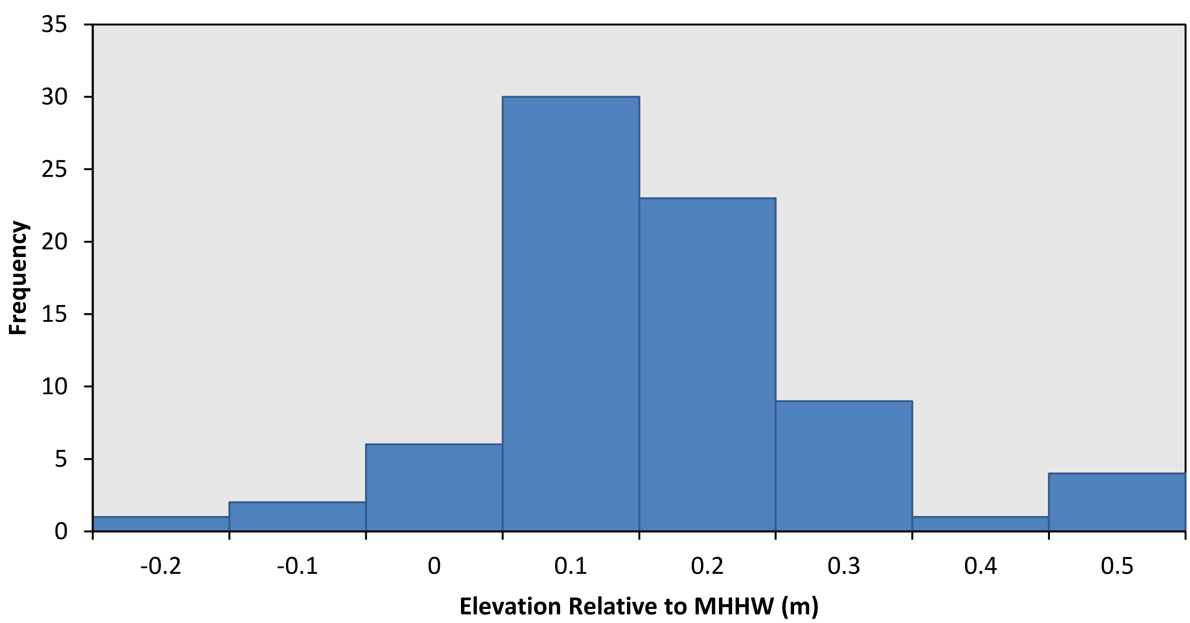

Figure A3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW) at Padilla.

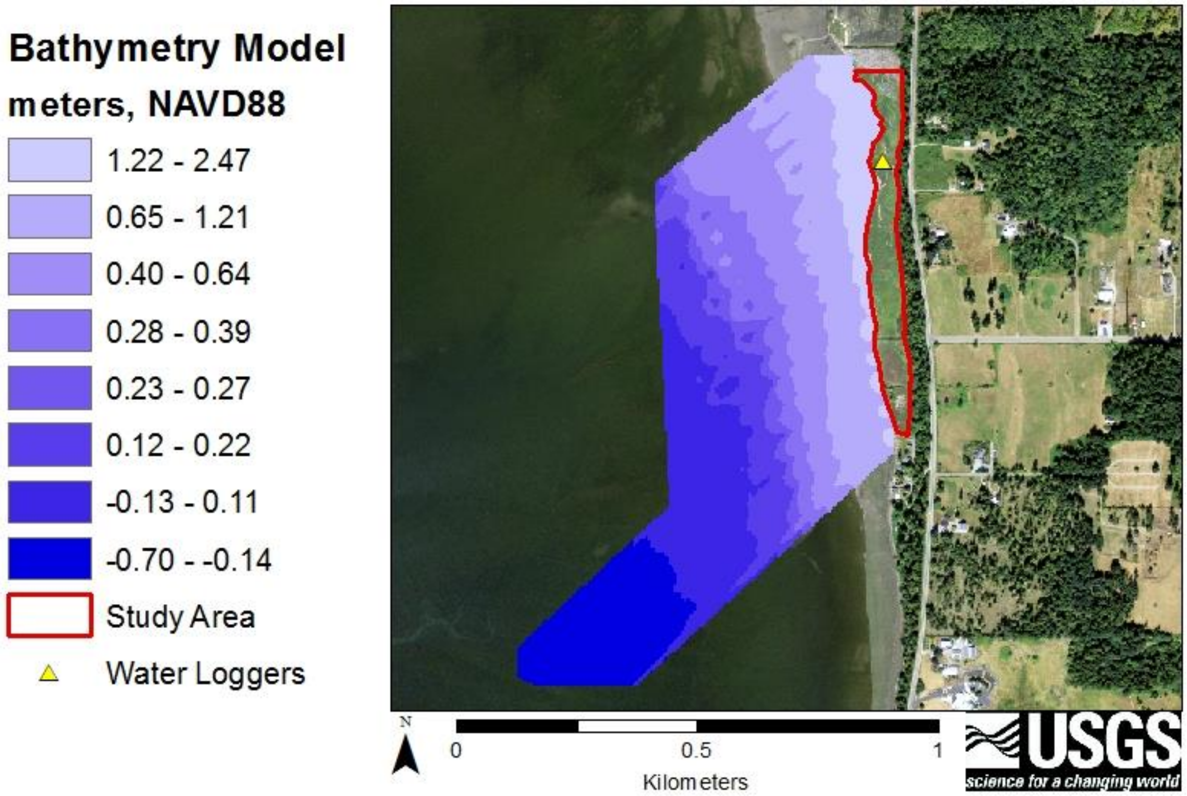

Figure A4. Near-shore bathymetry model at Padilla. Water level logger locations are shown within the marsh study site.

Table A1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Padilla. NA = not determined.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Distichlis spicata	Native perennial grass	84	56	28
Sarcocornia perennis	Native perennial forb	47	23	16
Atriplex prostrata	Non-native annual forb	26	5	18
Typha latifolia	Native perennial forb	11	2	82
Hordeum brachyantherum	Native perennial grass	11	1	49
Undetermined species	NA	11	0	8
Deschampsia cespitosa	Native perennial grass	5	5	30
Symphyotrichum subspicatum	Native perennial forb	5	4	125
Leymus mollis	Native perennial grass	5	1	26
Agrostis stolonifera	Non-native perennial grass	5	0	28
Oenanthe sarmentosa	Native perennial forb	5	0	30
Rumex crispus	Non-native bi-perennial forb	5	0	28
Cirsium vulgare	Non-native biennial forb	5	0	53
Rubus armeniacus	Non-native shrub	5	0	43
Vicia gigantea	Native perennial legume	5	0	33

Table A2. Mean percent cover of dominant plant species by marsh zone at Padilla. Zones were defined by degree of flooding by high tides. DisSpi = *Distichlis spicata*; SarPer = *Sarcocornia perennis*; AtrPro = *Atriplex prostrata*; SymSub = *Symphyotrichum subspicatum*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.518 to 0.258	1	*Insufficient sample size*
High	3-25	0.257 to 0.026	12	DisSpi (59), SarPer (30), AtrPro (7), SymSub (7)
Middle	25-50	0.025 to -0.130	4	DisSpi (43), SarPer (21), AtrPro (4)
Low	>50	-0.131 to -0.313	2	DisSpi (95)

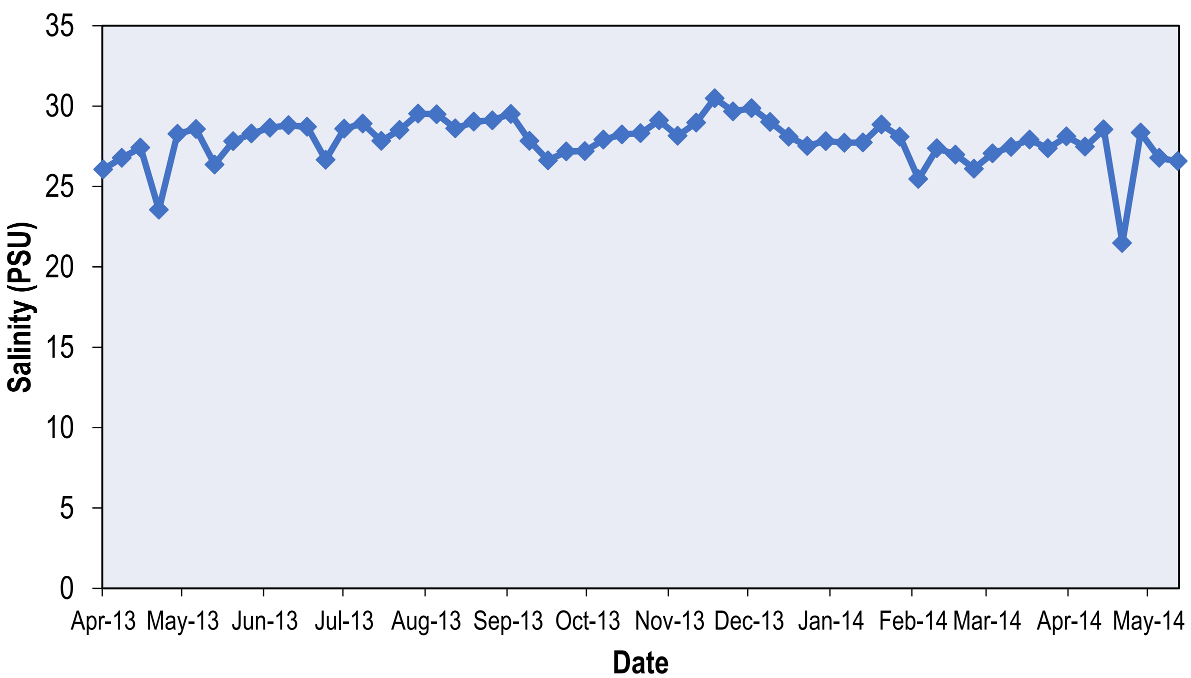

Figure A5. Average weekly maximum salinity from April 2013 – May 2014 at Padilla. Data are from the Bayview NERR water quality monitoring station (NOAA).

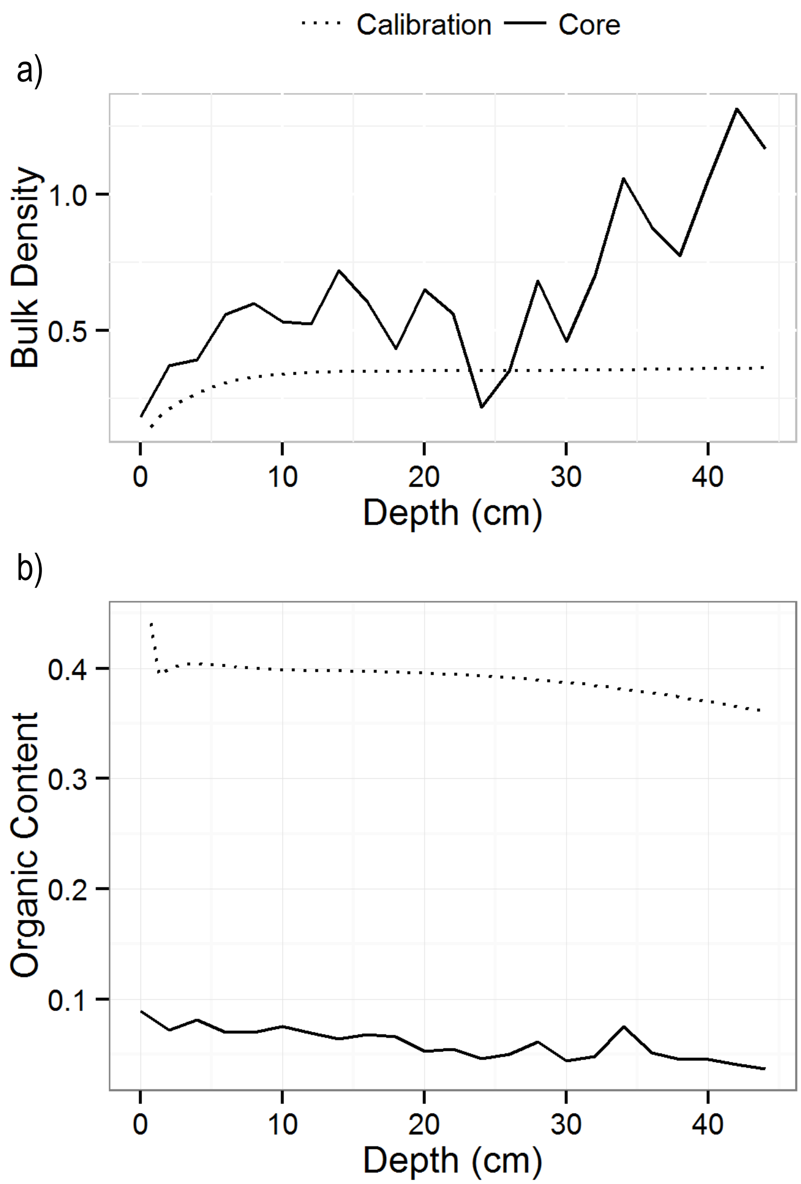

Figure A6. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table A3. Model input parameters for Padilla. Sediment accumulation rate is reported at 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})	1.23	Core calibration
Elevation of peak biomass (cm, MSL)	149	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	69	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0472	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	88	Core
Porosity depth (%)	60	Core
Refractory carbon (%)	43.7	Core
Maximum astronomical tide (cm, MSL)	167	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.98	Port Townsend tide gauge (NOAA, 9444900)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

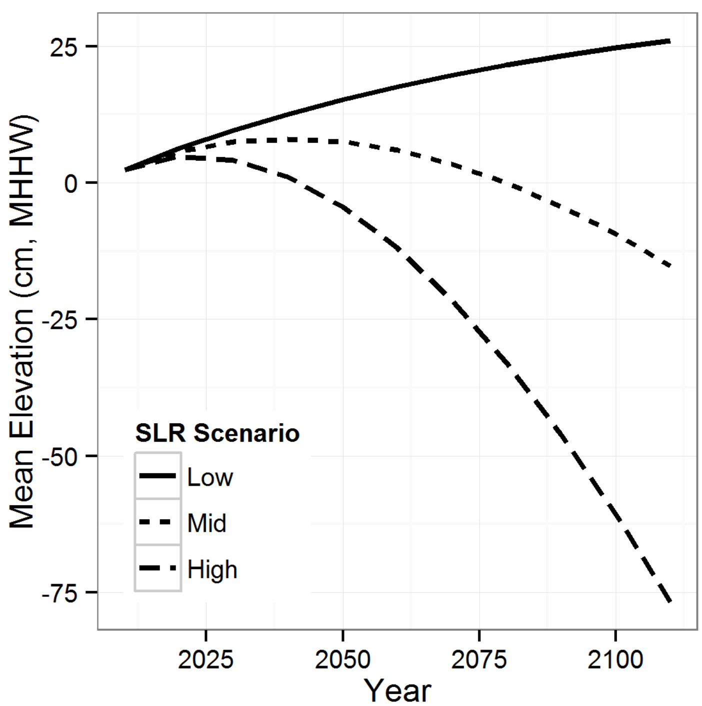

Figure A7. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Padilla from 2010 to 2110 under low, mid, and high NRC sea-level rise (SLR) scenarios.

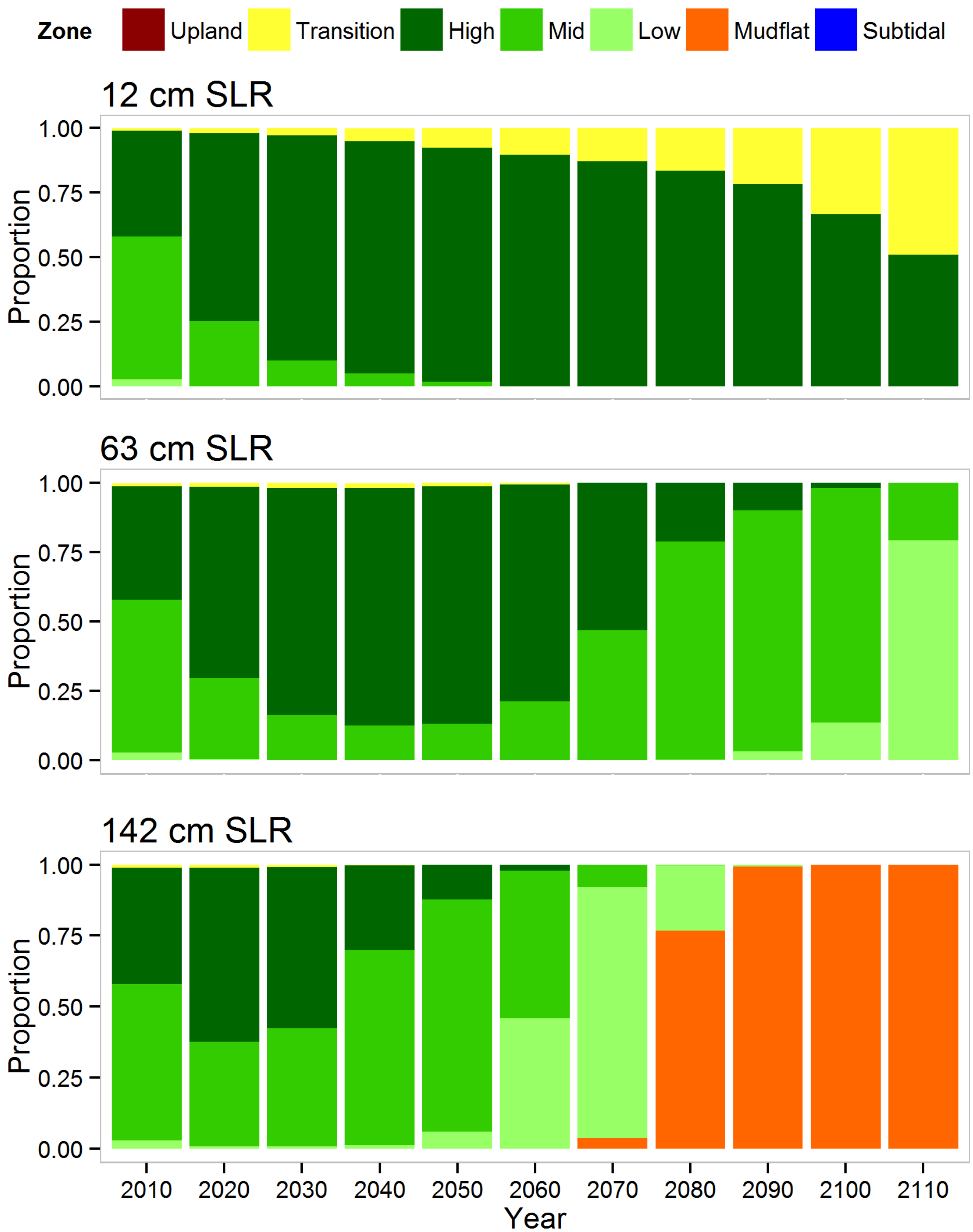

Figure A8. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table A4. 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)		
	2010	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	1	8	49	1	1	0	1	0	0
High	41	90	51	41	86	0	41	12	0
Mid	55	2	0	55	13	21	55	82	0
Low	3	0	0	3	0	79	3	6	0
Mudflat	0	0	0	0	0	0	0	0	100
Subtidal	0	0	0	0	0	0	0	0	0

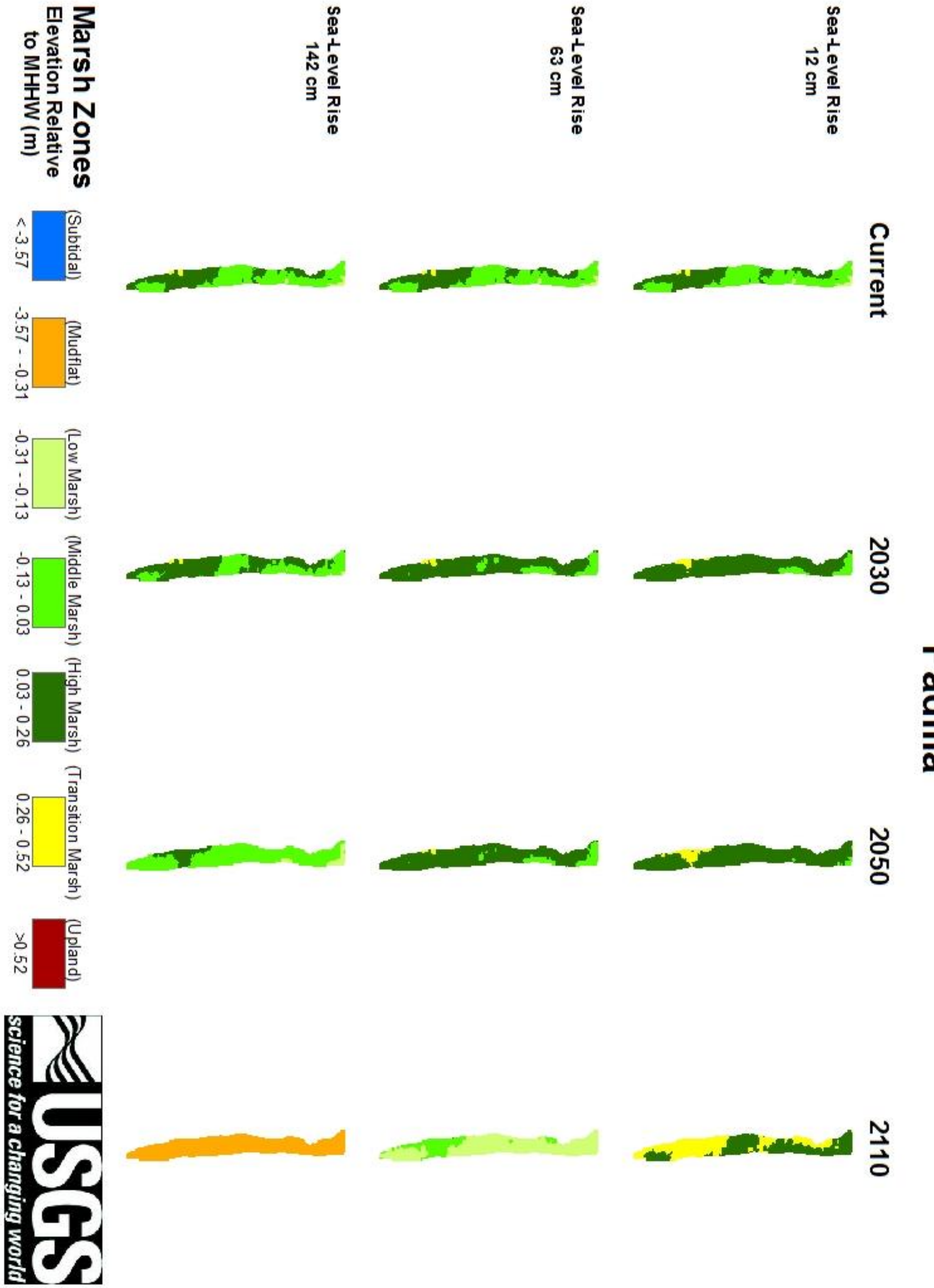

Figure A9. Projected habitat distribution at Padilla for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

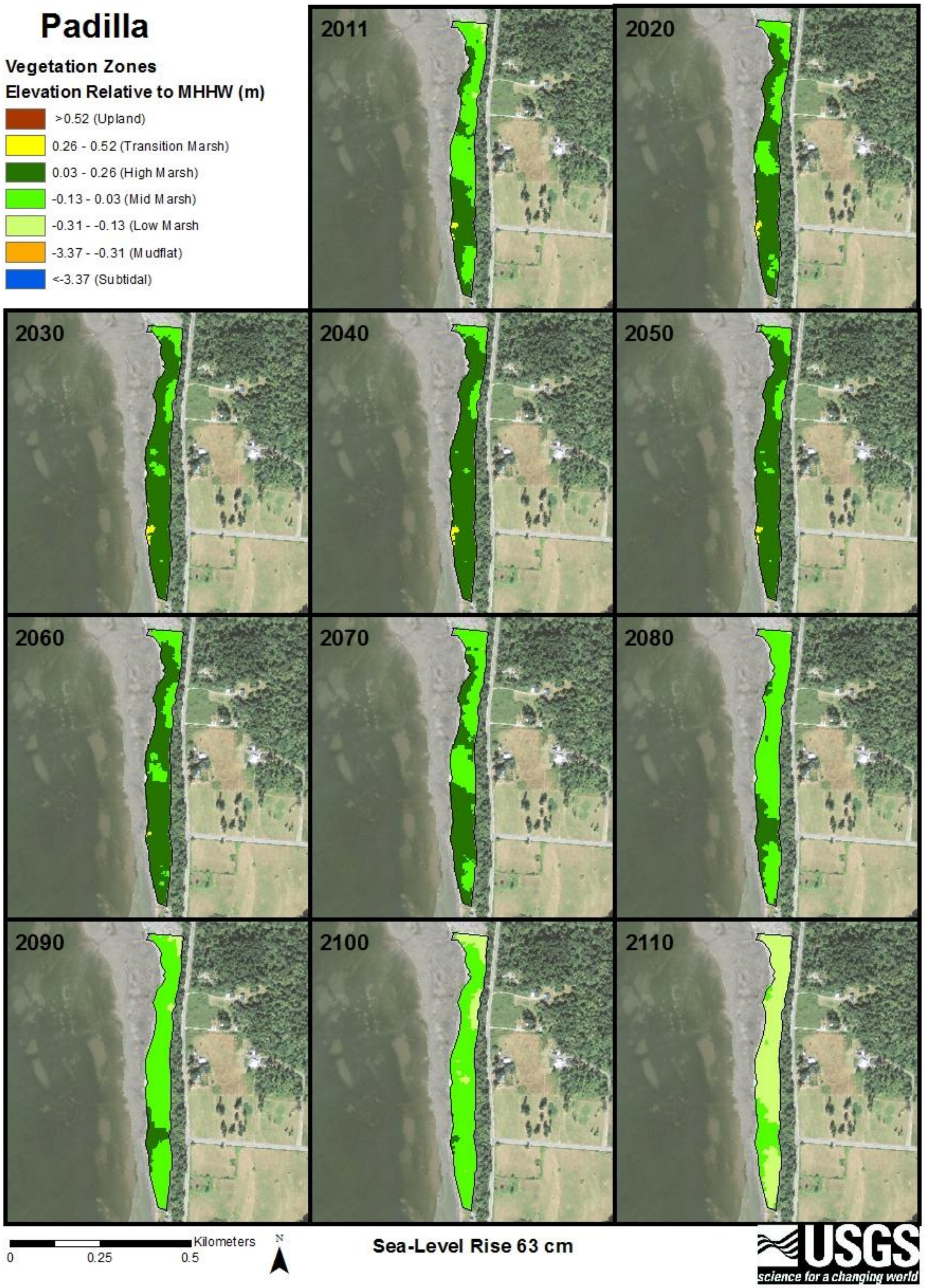

Figure A10. Projected changes in Padilla elevation zones under the mid NRC sea-level rise scenario (63 cm).

Port Susan, Port Susan Bay, Snohomish County, Washington, USA

Photo: K. Turner, USGS

Summary:

- *Study site size*: 51.5 hectares
- *Location*: 48° 11' 35" N latitude, 122° 21' 55" W longitude.
- *Site management*: The Nature Conservancy
- *Site vegetation and elevation survey*: 1-9 October 2012
- *Sample size*: 897 (elevation data points), 210 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was below MHHW, with only 20% of elevation points occurring above MHHW.
- *Plant community composition*: *Schoenoplectus pungens* was the most frequently occurring species at the site. *Agrostis stolonifera* was also common.
- *Bathymetric surveys*: 319.1 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: mineral accumulation rate = 2.04 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.037 g cm^{-2} yr^{-1}; net accretion = 2.077 cm yr^{-1}.

- *Water monitoring data collection*: water level (April 2011 – December 2014); conductivity (August 2013 – December 2013). Water level and conductivity monitoring is ongoing.
- *Salinity*: Maximum weekly salinities at the site ranged between polyhaline and mesohaline conditions during the study period.
- *Calculated tidal datums*: MHHW is at 2.71 m NAVD88; MHW is at 2.47 m NAVD88.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during January 2014; minimum monthly inundation occurred during October 2013.
- *Sea-level rise marsh response modeling:* Presently, Port Susan is dominated by low marsh with very little area in higher elevation zones. Under the NRC's low sea-level rise scenario (12 cm), the site is projected to have modest areal gains in mid and high marsh. However, under mid sea-level rise (63 cm) the marsh continues to be dominated by low marsh while mid marsh is lost by 2100. Under high sea-level rise (142 cm) mudflat gradually replaces most low marsh habitat between 2060 and 2110.

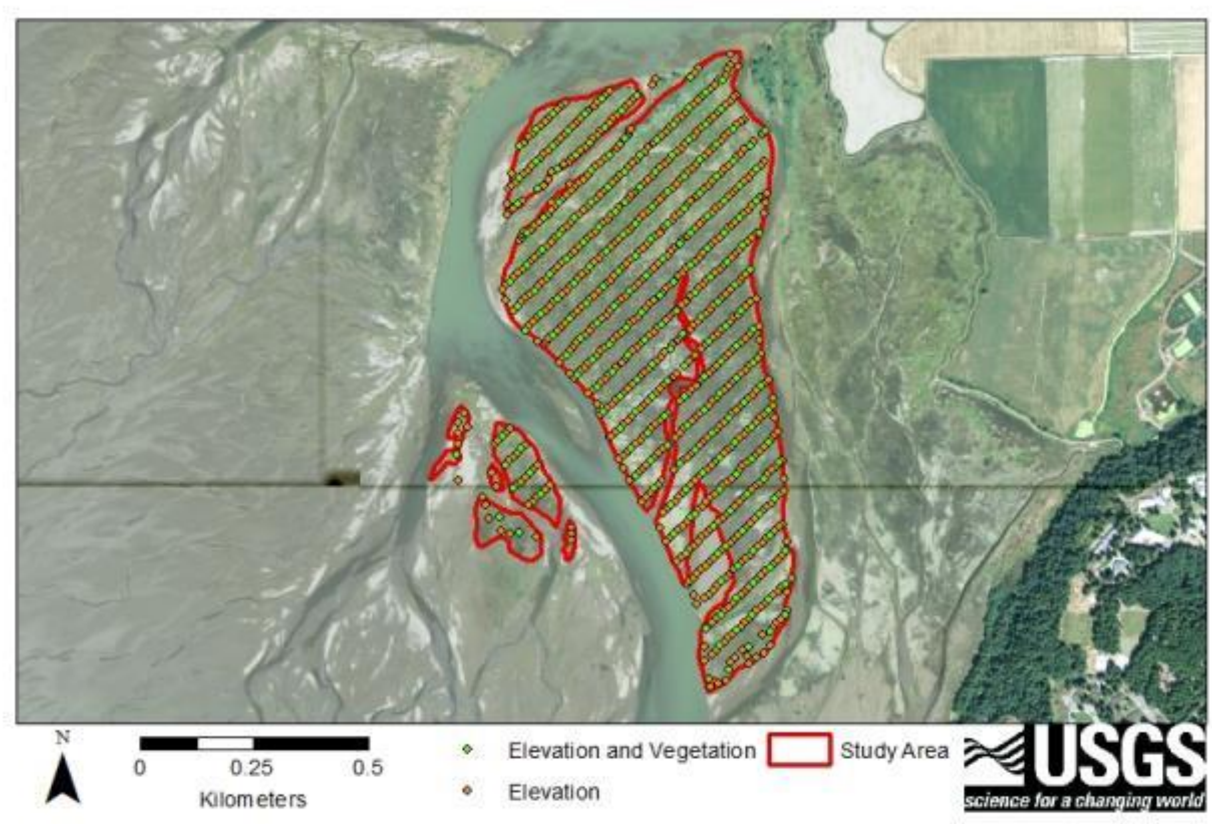

Figure B1. Distribution of elevation and vegetation survey points at Port Susan.

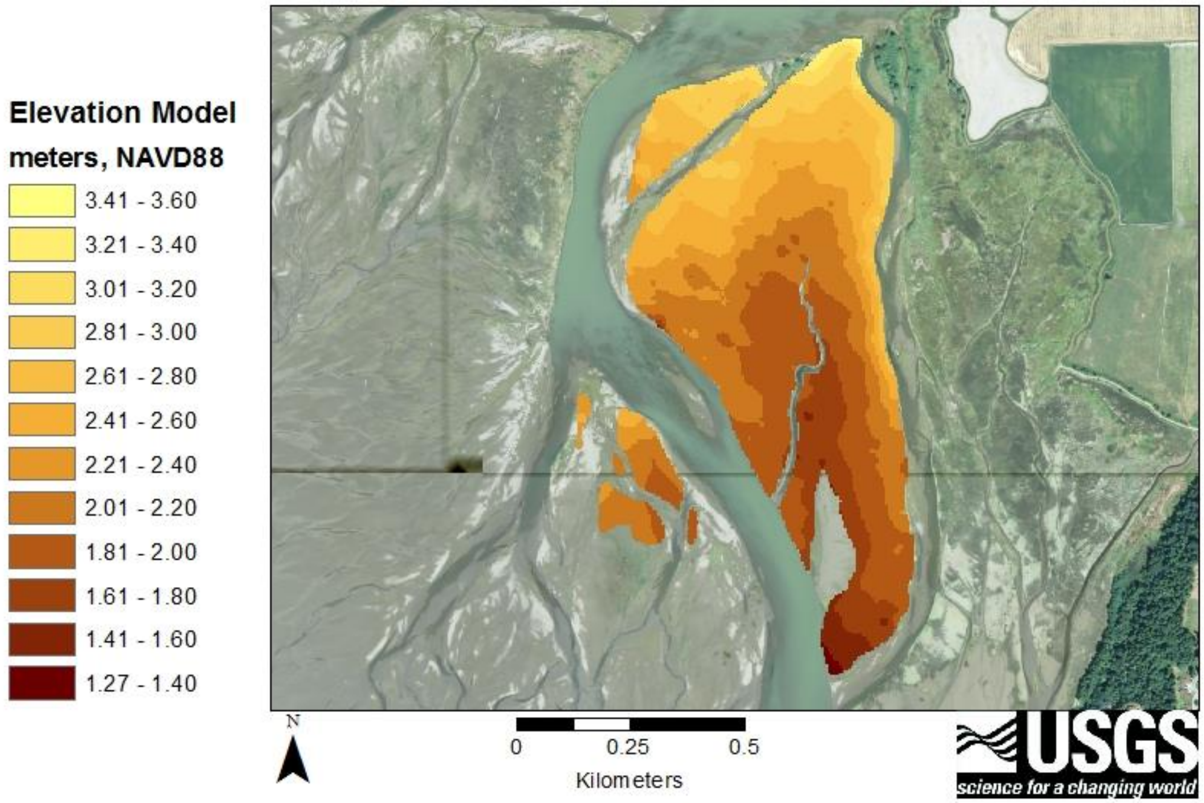

Figure B2. Elevation model (3 m resolution) developed from RTK GPS survey data.

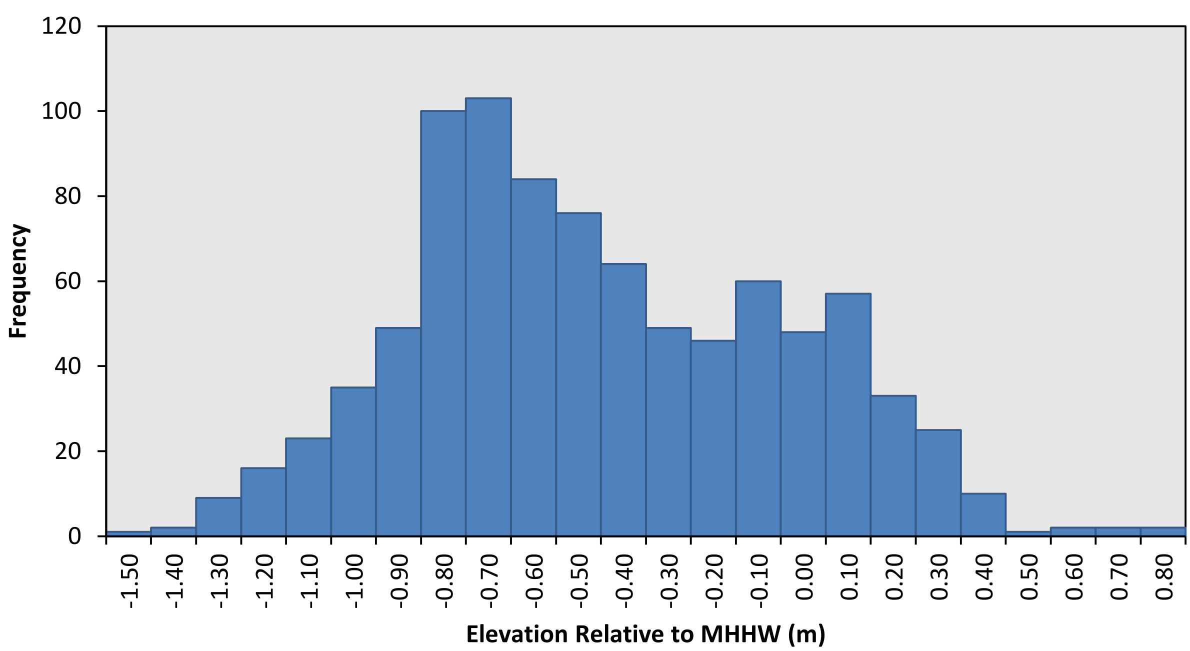

Figure B3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW) at Port Susan.

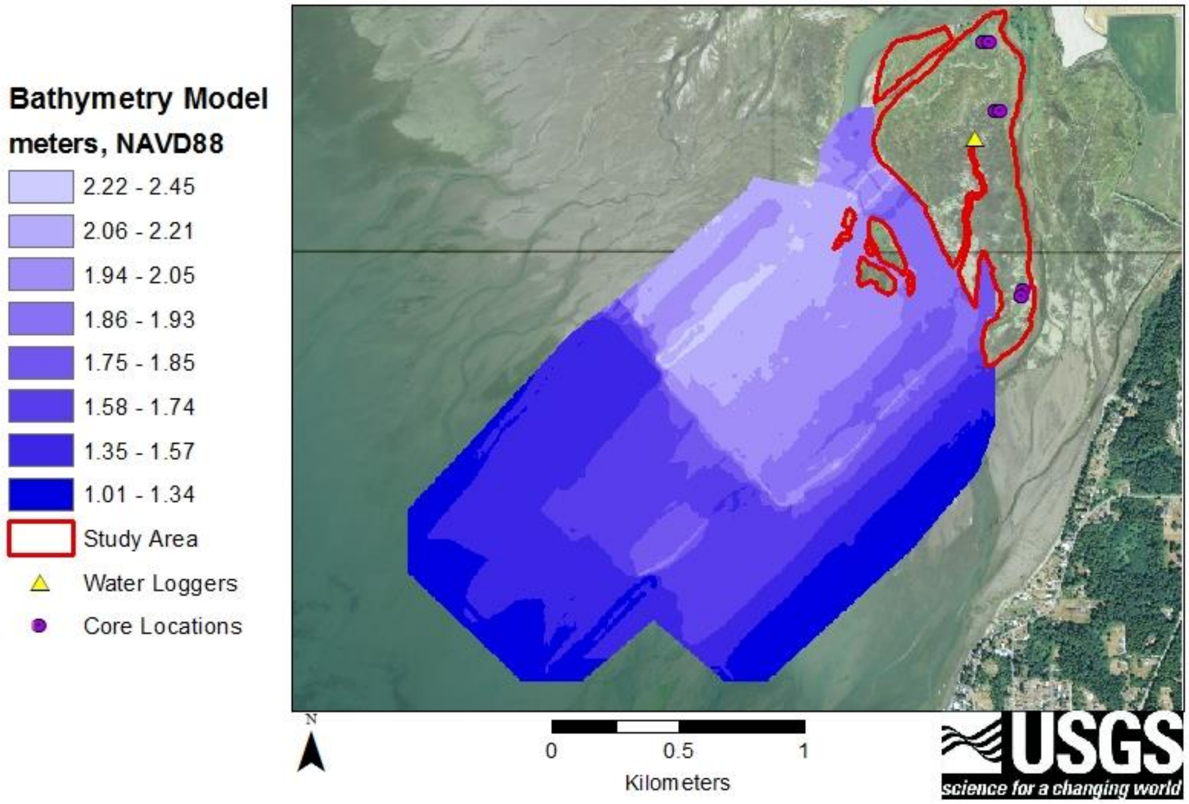

Figure B4. Near-shore bathymetry model for Port Susan. Water level logger and core locations are shown within the marsh study site.

Table B1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Port Susan. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Schoenoplectus pungens	Native perennial sedge	57	25	50
Agrostis stolonifera	Non-native perennial grass	48	19	31
Carex lyngbyei	Native perennial sedge	30	7	41
Potentilla anserina	Native ann-perennial forb	28	4	26
Juncus balticus	Native perennial rush	28	11	45
Triglochin maritima	Native perennial forb	25	2	39
Deschampsia cespitosa	Native perennial grass	12	5	85
Cotula coronopifolia	Non-native perennial forb	12	0	10
Bolboschoenus maritimus	Native perennial sedge	11	1	99
Lotus corniculatus	Non-native perennial legume	10	4	32
Symphyotrichum subspicatum	Native perennial forb	10	2	52
Lilaeopsis occidentalis	Native perennial forb	8	0	7
Juncus acuminatus	Native perennial rush	7	1	40
Schedonorus arundinaceus	Non-native perennial grass	5	1	42
Schenoplectus sp.	Sedge	5	1	111
Distichlis spicata	Native perennial grass	4	0	39
Eleocharis palustris	Native perennial sedge	4	1	18
Ranunculus cymbalaria	Native forb	2	0	9
Undetermined Poaceae	Grass	2	0	32
Phalaris arundinacea	Non-native perennial grass	2	1	73
Typha latifolia	Native perennial forb	2	0	143
Eleocharis parvula	Native perennial sedge	1	0	1
Cirsium arvense	Non-native perennial forb	1	0	101
Atriplex sp.	Forb	1	0	33
Rumex crispus	Non-native bi-perennial forb	1	0	88
Jaumea carnosa	Native perennial forb	1	0	1
Cuscuta pacifica	Native ann-perennial parasite	0	NA	NA
Elymus repens	Non-native perennial grass	0	0	20
Solanum dulcamara	Non-native perennial forb	0	0	23

Table B2. Mean percent cover of dominant plant species by marsh zone at Port Susan. Zones were defined by degree of flooding by high tides. AgrSto = *Agrostis stolonifera;* CarLyn = *Carex lyngbyei;* CirArv = *Cirsium arvense*; DesCes = *Deschampsia cespitosa;* LotCor = *Lotus corniculatus;* JunBal = *Juncus balticus;* PhaAru = *Phalaris arundinacea*; PotAns = *Potentilla anserina*; SchPun = *Schoenoplectus pungens;* NA = not sampled.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.707 to 0.352	2	LotCor (45), PhaAru (38), JunBal (25), CirArv (5)
High	3-25	0.351 to 0.036	22	JunBal (36), AgrSto (24), PotAns (20), LotCor (18)
Middle	25-50	0.035 to -0.178	31	JunBal (21), AgrSto (21), DesCes (20), PotAns (9)
Low	>50	-0.179 to -1.185	155	SchPun (34), AgrSto (18), CarLyn (8), JunBal (5)

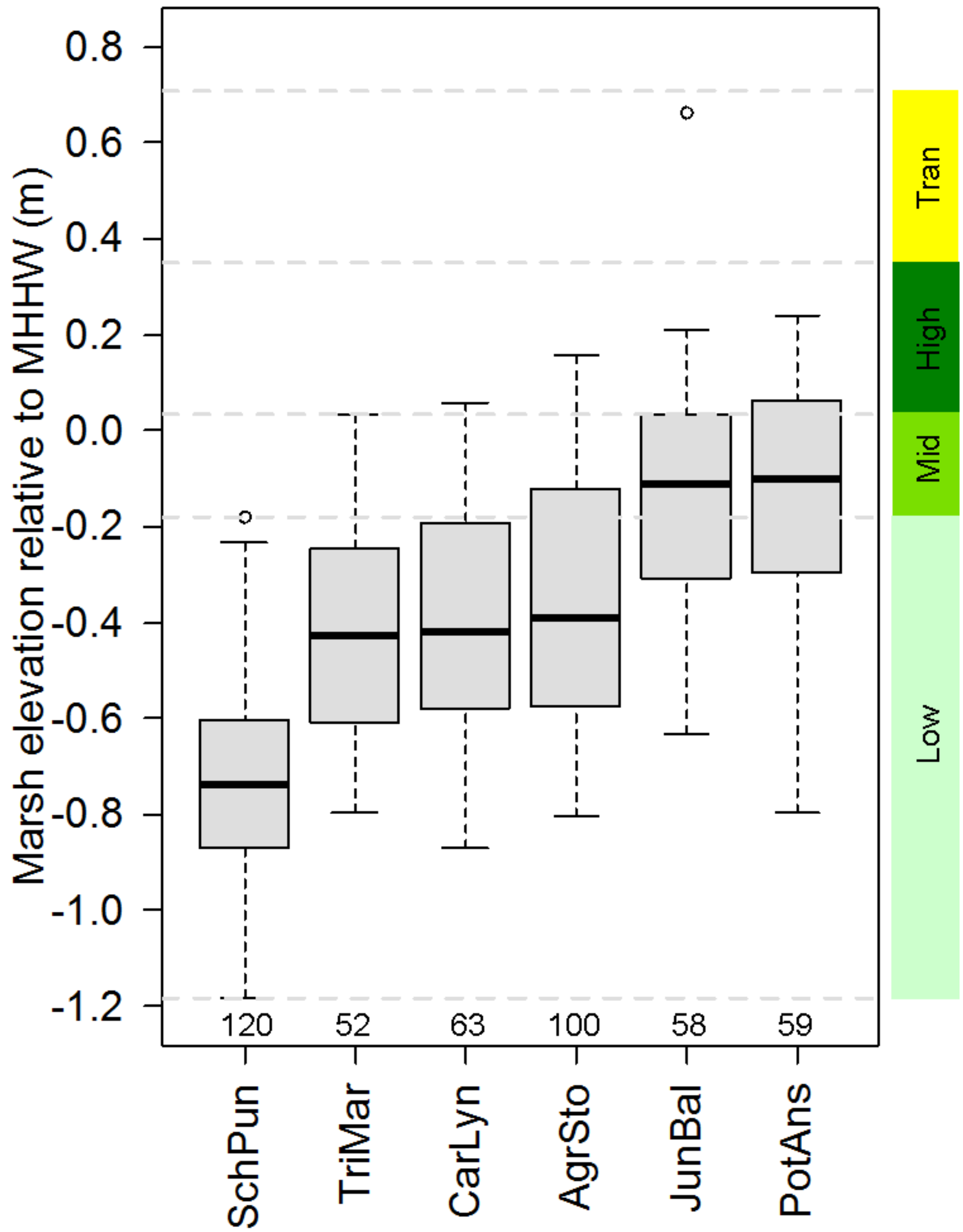

Figure B5. Elevation distribution of the six most common vascular plant species at Port Susan. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 210 plots). Marsh elevation zones (low, middle, high and transition) are illustrated at right. SchPun = *Schoenoplectus pungens*; TriMar = *Triglochin maritima*; CarLyn = *Carex lyngbyei*; AgrSto = *Agrostis stolonifera*, JunBal = *Juncus balticus*, PotAns = *Potentilla anserina*.

Table B3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level logger	547226	5337780
Deep core locations	547424	5337179
	547312	5337890
	547266	5338163

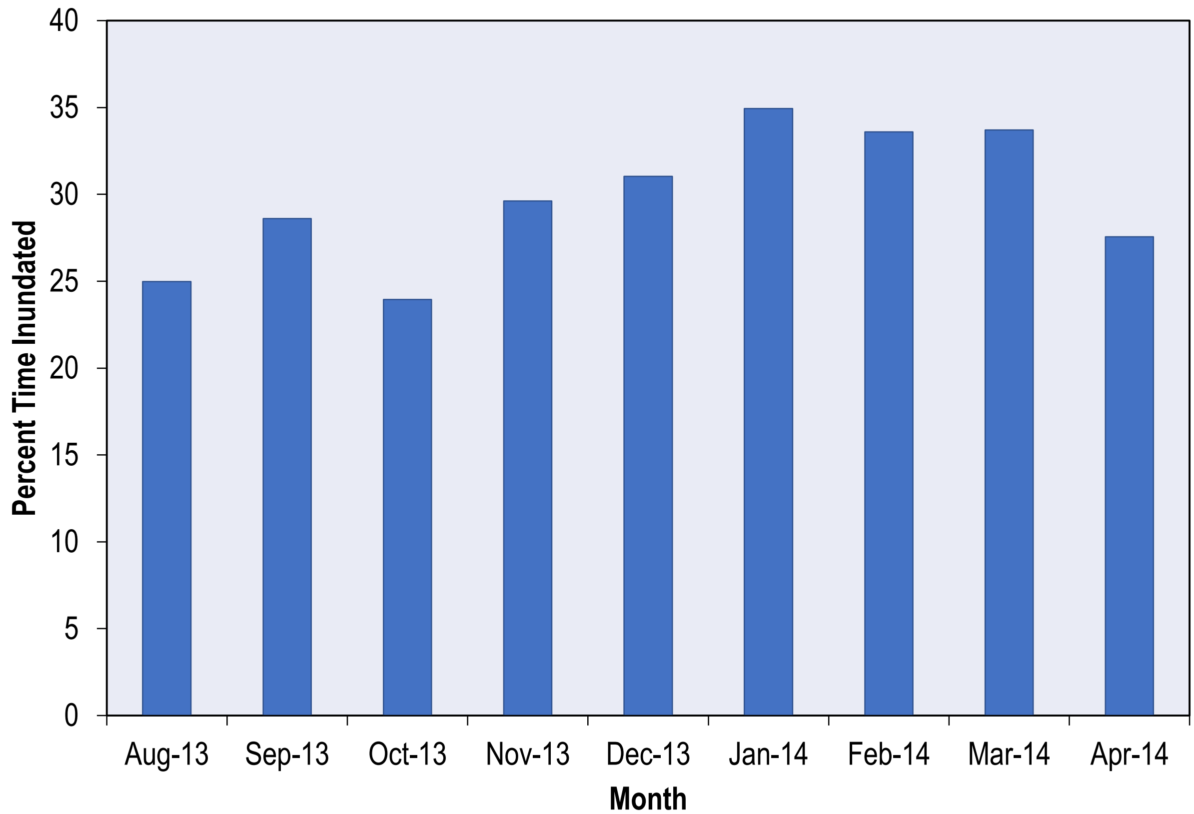

Figure B6. Average monthly inundation of the study site based on an average marsh elevation. Water levels were determined with a water level logger deployed at 1.18 m above NAVD88.

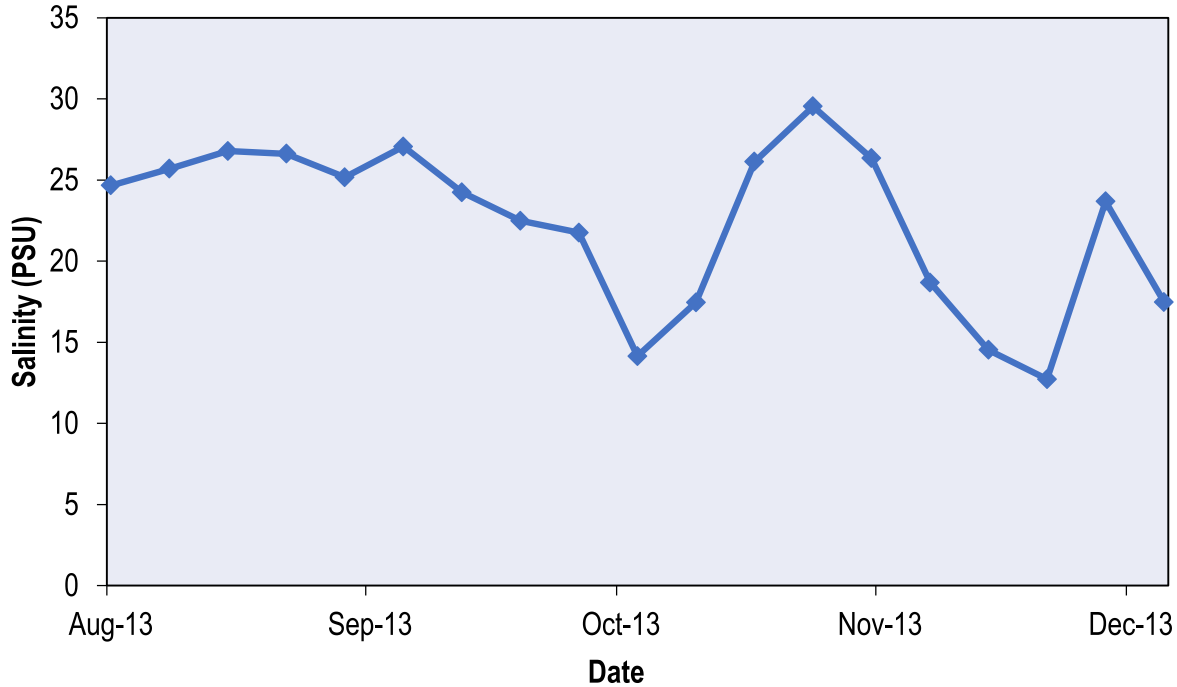

Figure B7. Average weekly maximum salinity, in practical salinity units (PSU) from August 2013 – December 2013 at Port Susan. Seawater is approximately 35 PSU.

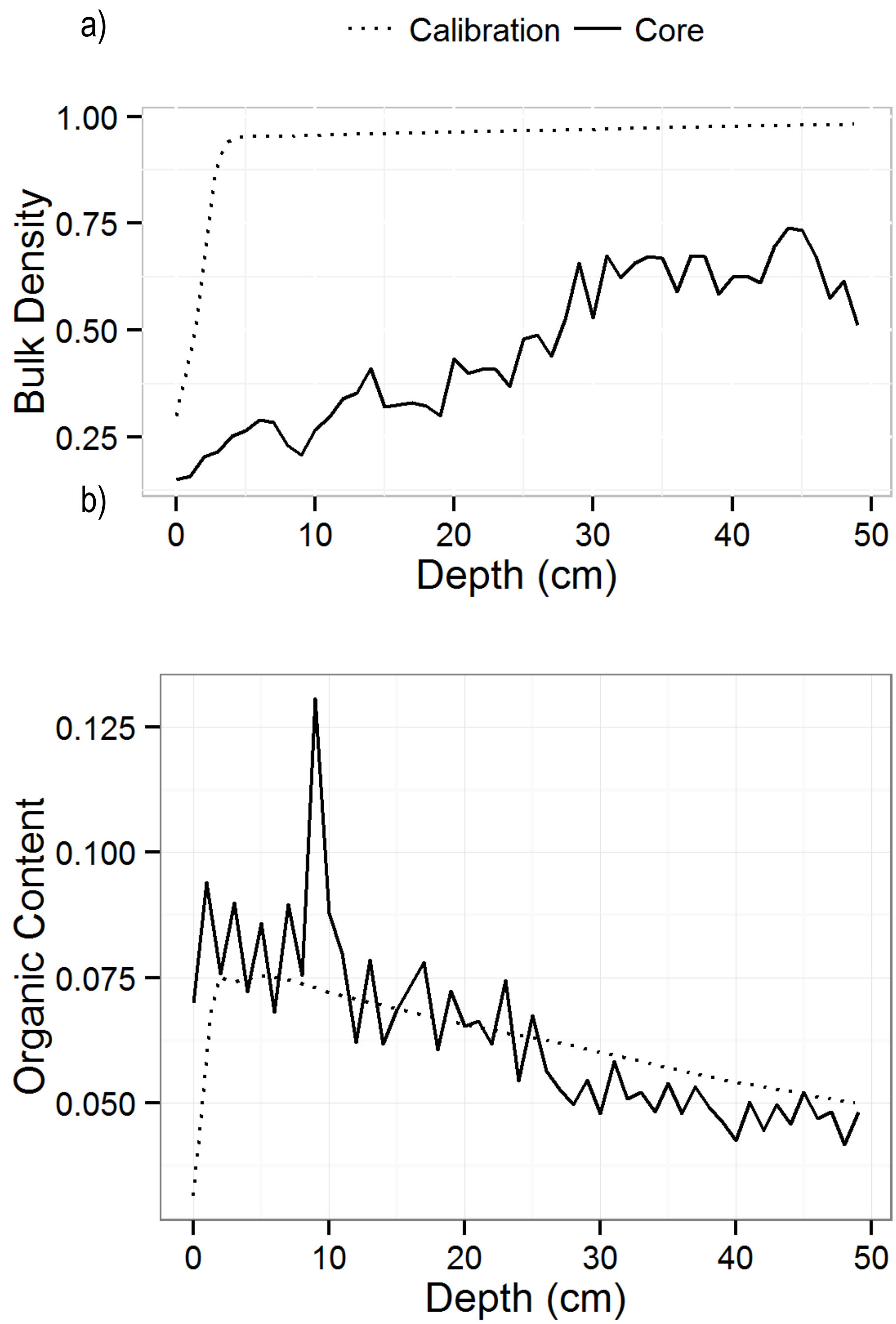

Figure B8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table B4. Model input parameters for Port Susan. 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})	0.84	Core calibration
Elevation of peak biomass (cm, MSL)	152	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	-9	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0408	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	88	Core
Porosity depth (%)	60	Core
Refractory carbon (%)	43.7	Core
Maximum astronomical tide (cm, MSL)	253	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.98	Port Townsend tide gauge (NOAA, 9444900)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

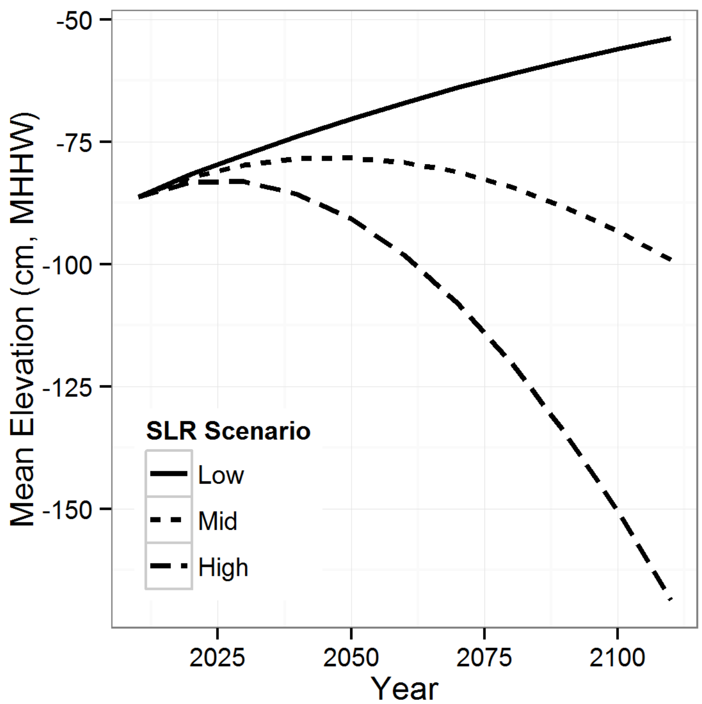

Figure B9. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Port Susan from 2010 to 2110 under low, mid, and high NRC sea-level rise (SLR) scenarios.

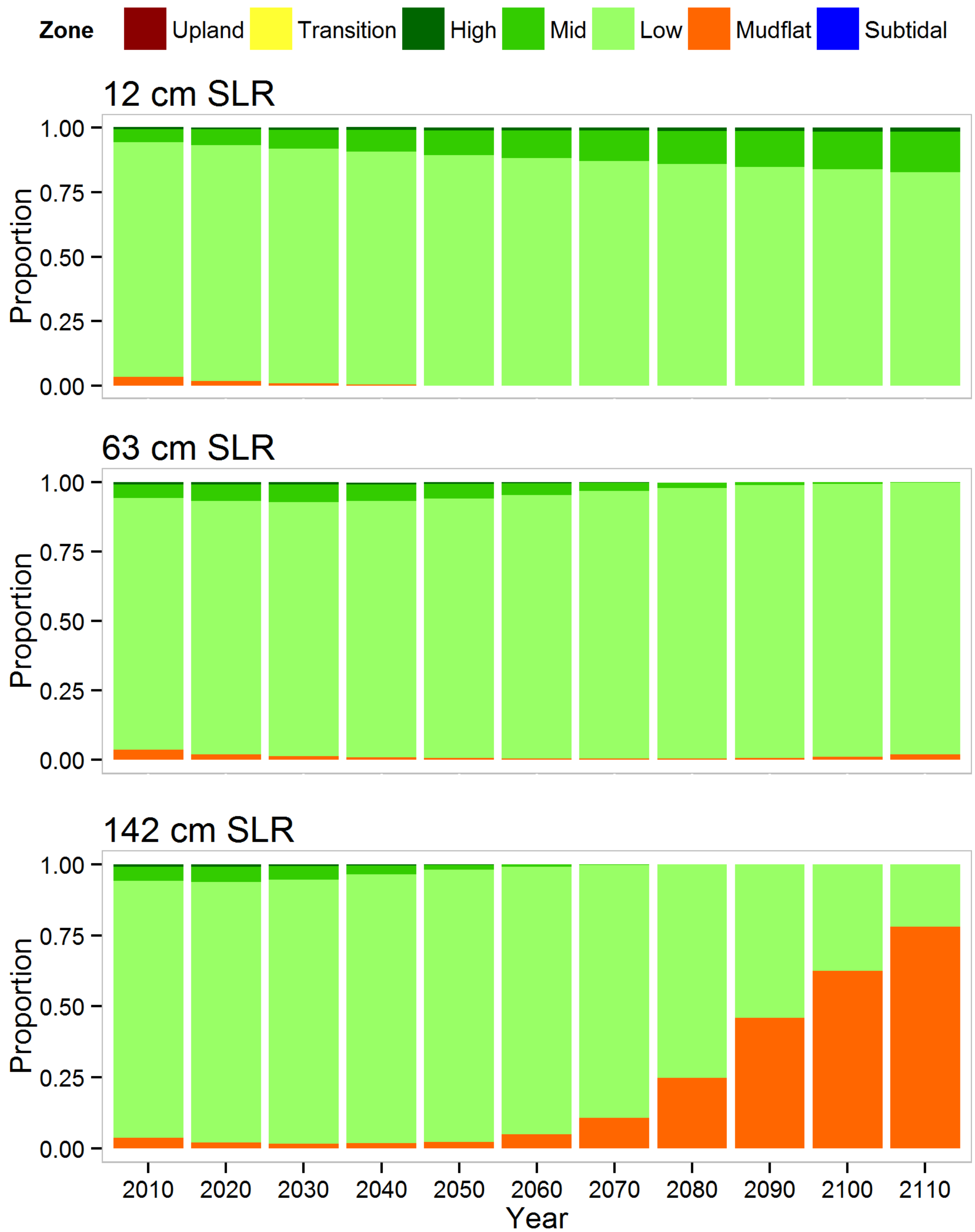

Figure B10. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table B5. Percentage of habitat area modeled for three sea-level rise scenarios for 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
	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	2	1	1	0	1	0	0
Mid	5	10	15	5	5	0	5	2	0
Low	91	89	83	91	93	98	91	96	22
Mudflat	3	0	0	3	1	2	3	2	78
Subtidal	0	0	0	0	0	0	0	0	0

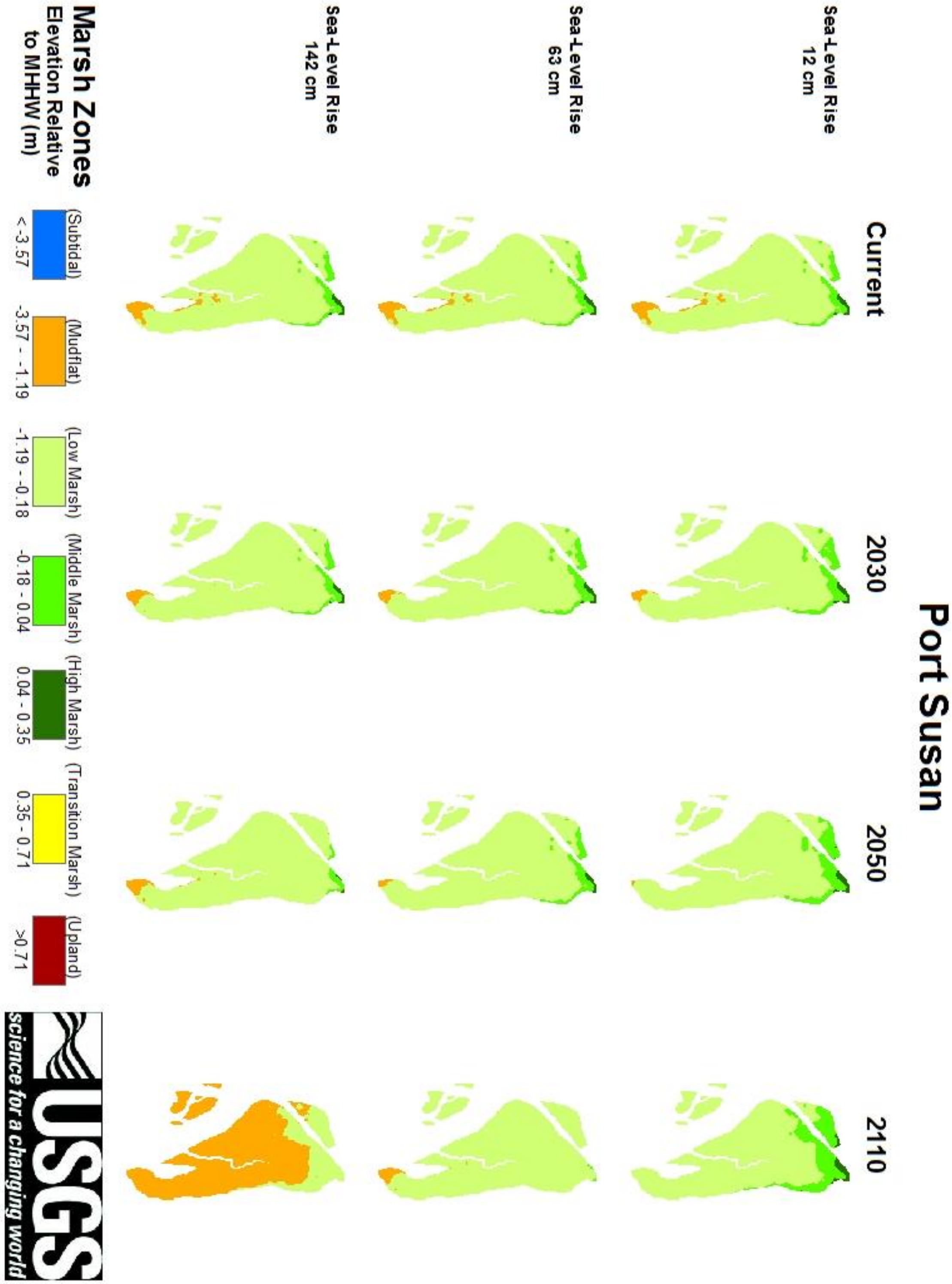

Figure B11. Projected habitat distribution at Port Susan for 2030, 2050 and 2110 with the WARMER model under three sea-level rise scenarios.

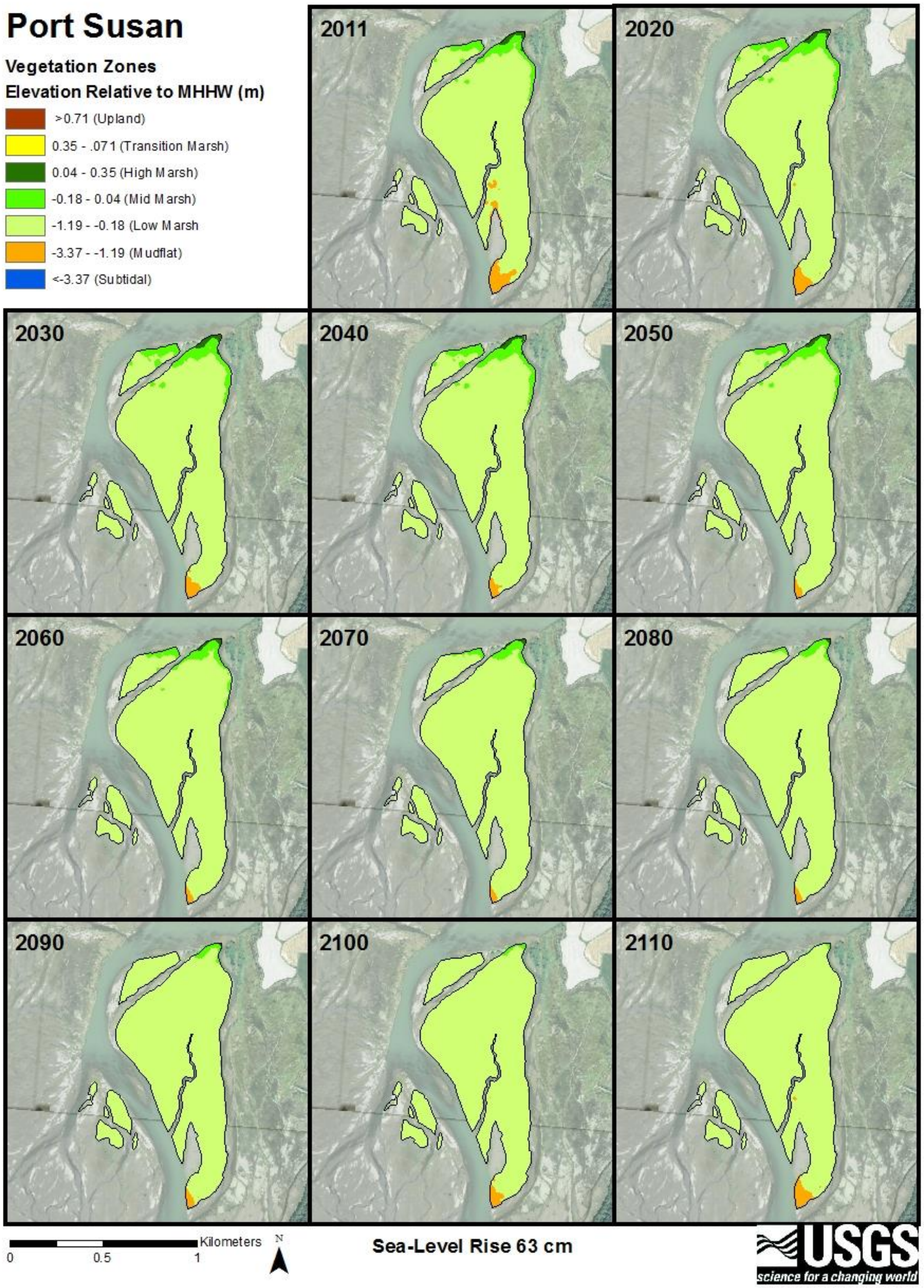

Figure B12. Projected changes in the distribution of Port Susan habitat zones under the NRC's mid (63 cm) sea-level rise scenario.

Skokomish marsh, Skokomish Estuary, Mason County, Washington, USA

Photo: K Powelson, USGS

Summary:

- *Study site size*: 28.8 hectares
- *Location*: 47° 20' 30" N latitude, 123° 08' 24" W longitude.
- *Site management*: Skokomish Indian Tribe
- *Site vegetation and elevation survey*: 26-28 September 2012
- *Sample size*: 605 (elevation data points), 128 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was above MHHW, with 57% of elevation data points occurring above MHHW.
- *Plant community composition*: *Distichlis spicata* was the most frequently-occurring species. *Jaumea carnosa* and *Sarcocornia perennis* were also common.
- *Bathymetric surveys*: 59.3 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: mineral accumulation rate = 0.067g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.0092 g cm^{-2} yr^{-1}; net accretion = 0.076 $cm^{-2}yr^{-1}$.

- *Water level and salinity monitoring*: water level (October 2012 – April 2014); conductivity (August 2013 – May 2014). Water level and conductivity monitoring is ongoing.
- *Salinity*: The maximum recorded salinity throughout the study period was 34 PSU.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during March 2014; minimum monthly inundation during October 2013
- *Calculated tidal datums*: MHHW is at 2.76 m NAVD88; MHW is at 2.48 m NAVD88.
- *Sea-level rise marsh response modeling*: Under the low NRC SLR projection (12 cm), the composition of marsh zones remains relatively unchanged over the coming century. Under the NRC's mid SLR projection (63 cm), there is a gradual loss of high marsh between 2020 and 2070, and total loss of mid marsh by 2110. Under the NRC's high SLR projection (142 cm), loss of middle and high marsh occurs more rapidly: by 2070, the site is projected to be comprised of low marsh and some mudflat. By 2110, the site is projected to be predominately mudflat, with a small percentage of low marsh remaining.

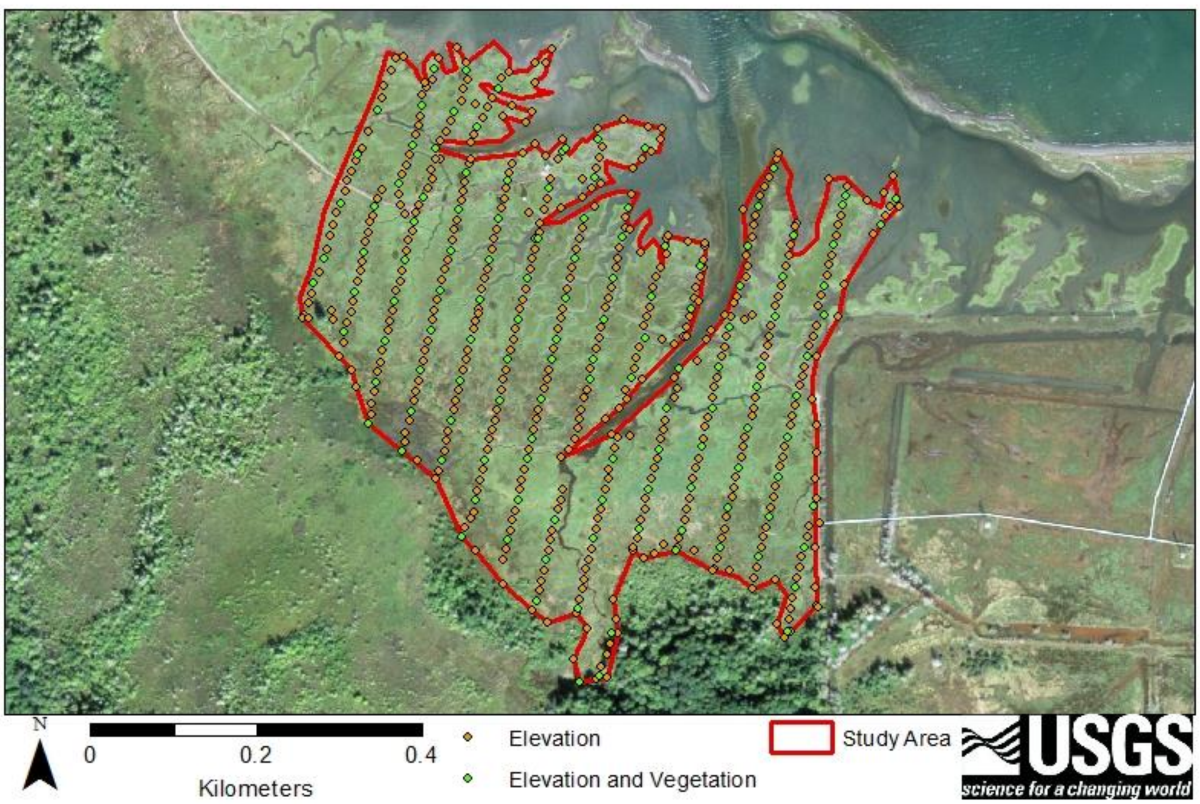

Figure C1. Distribution of elevation and vegetation survey points at Skokomish.

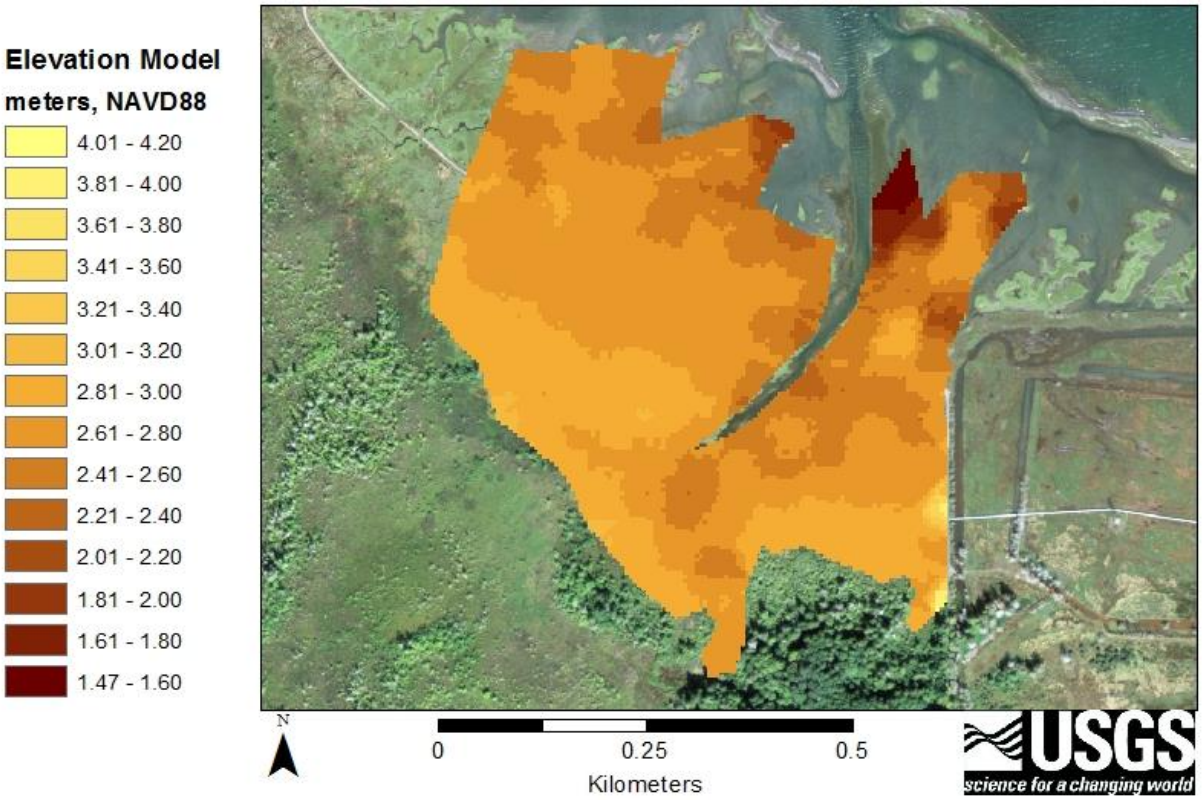

Figure C2. Elevation model (3 m resolution) developed from RTK GPS survey data.

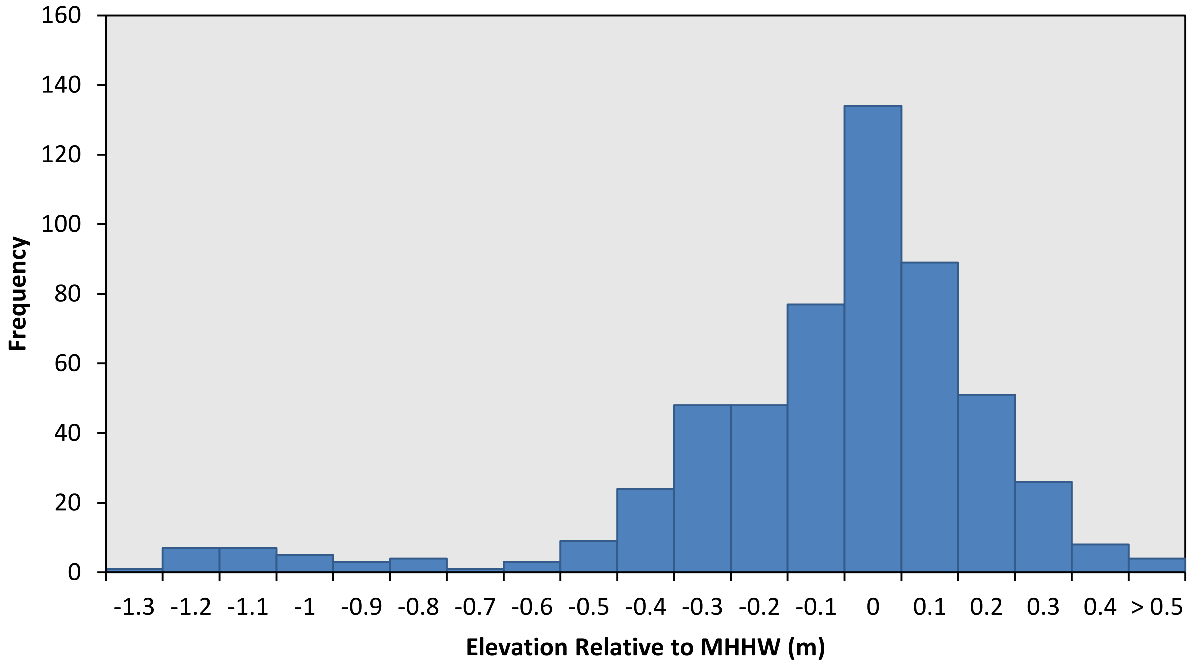

Figure C3. Frequency distribution of marsh surface elevation data points relative to local mean higher high water (MHHW) at Skokomish.

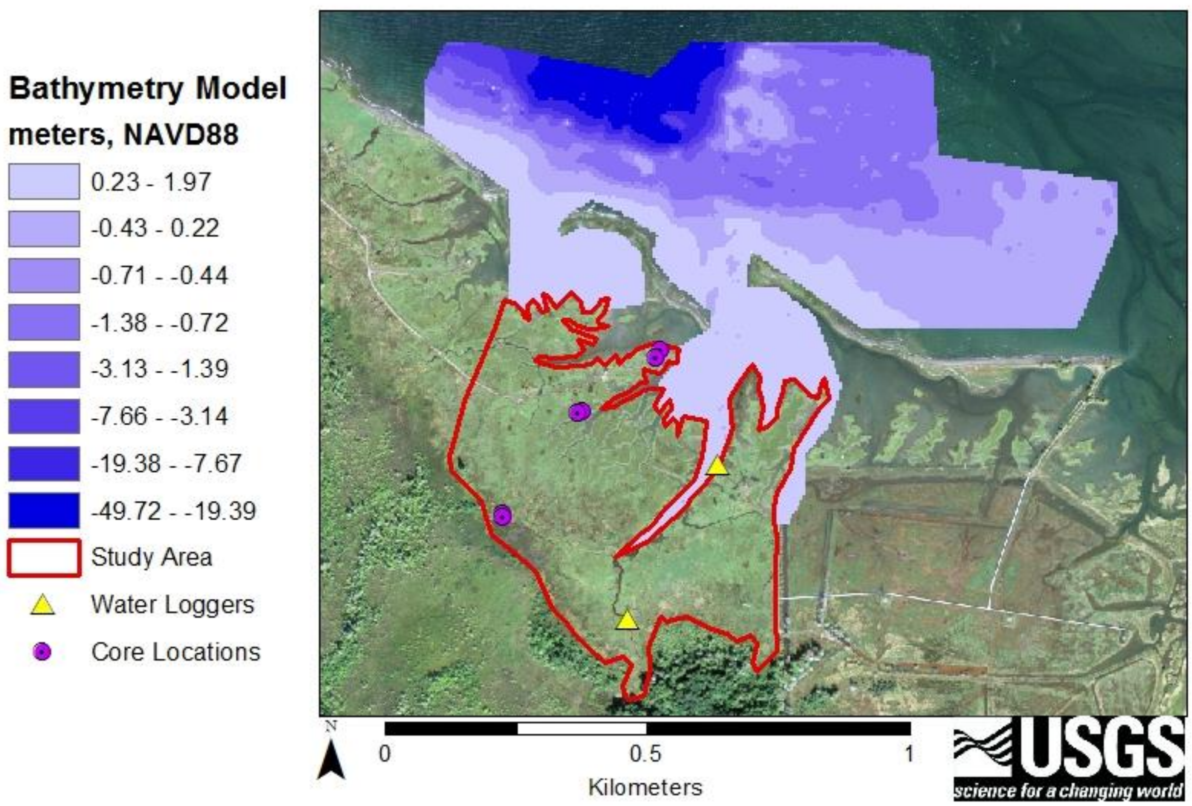

Figure C4. Near-shore bathymetry model for Skokomish. Water level logger and core locations are shown within the marsh study site.

Table C1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Skokomish. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Distichlis spicata	Native perennial grass	82	31	29
Jaumea carnosa	Native perennial forb	70	41	17
Sarcocornia perennis	Native perennial forb	63	19	20
Atriplex prostrata	Non-native annual forb	34	4	25
Juncus spp.*	Rush	29	15	48
Plantago maritima	Native perennial forb	26	5	26
Grindelia integrifolia	Native perennial forb	23	2	30
Glaux maritima	Native perennial forb	21	1	18
Triglochin maritima	Native perennial forb	16	1	37
Potentilla anserina	Native ann-perennial forb	9	1	37
Agrostis stolonifera	Non-native perennial grass	8	2	57
Hordeum brachyantherum	Native perennial grass	8	0	50
Deschampsia cespitosa	Native perennial grass	4	1	88
Schoenoplectus tabernaemontani	Native perennial sedge	3	1	64
Symphyotrichum subspicatum	Native perennial forb	3	1	42
Carex lyngbyei	Native perennial sedge	3	1	64
Cuscuta pacifica	Native ann-perennial parasite	2	NA	NA
Hordeum jubatum	Native ann-perennial grass	2	0	30
Fabaceae species	Legume	1	1	41
Achillea millefolium	Native perennial forb	1	0	39
Elymus repens	Non-native perennial grass	1	0	69

* Includes *J. balticus* (native) and *J. gerardii* (non-native).

Table C2. Mean percent cover of dominant plant species by marsh zone at Skokomish. Zones were defined by degree of flooding by high tides. AtrPro = *Atriplex prostrata*; DisSpi = *Distichlis spicata*; JauCar = *Jaumea carnosa*; *Juncus* = *J. balticus* (native) and *J. gerardii* (non-native); SarPer = *Sarcocornia perennis*; TriMar = *Triglochin maritima.*

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.796 to 0.396	1	*Insufficient sample size*
High	3-25	0.395 to 0.040	30	Juncus (37), DisSpi (28), SarPer (13), AtrPro (9)
Middle	25-50	0.039 to -0.200	66	JauCar (55), DisSpi (41), SarPer (18), Juncus (12)
Low	>50	-0.201 to -1.296	31	JauCar (47), SarPer (29), DisSpi (15), TriMar (3)

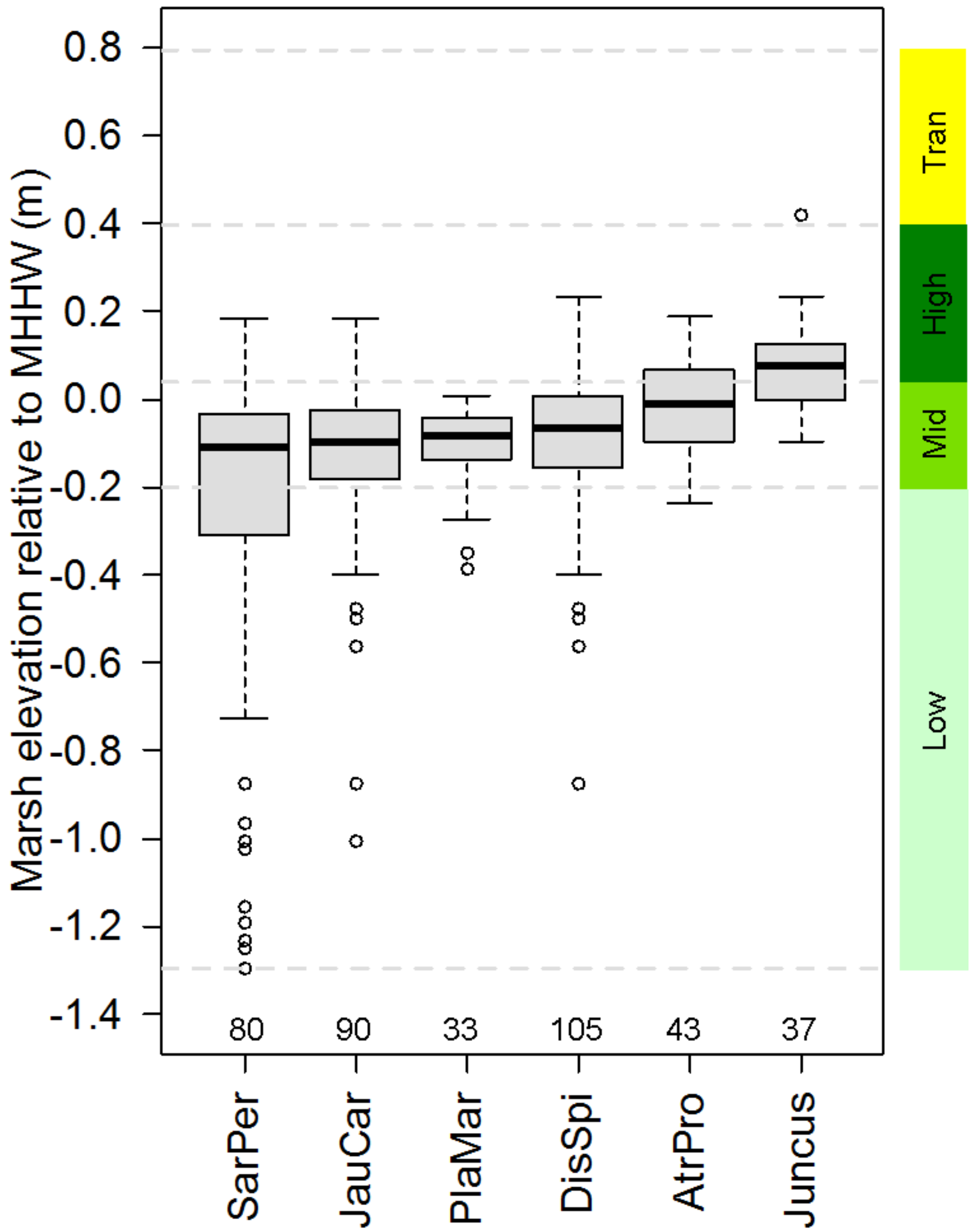

Figure C5. Elevation distribution of the six most common vascular plant species at Skokomish. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 128 plots). Marsh elevation zones (low, middle, high and transition) are illustrated at right. AtrPro = *Atriplex prostrata*; DisSpi = *Distichlis spicata;* JauCar = *Jaumea carnosa*; Juncus = *J. balticus* (native) and *J. gerardii* (non-native); PlaMar = *Plantago maritima;* SarPer = *Sarcocornia perennis*.

Table C3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	489429	5243136
	489259	5242835
Deep core locations	489325	5243350
	489177	5243233
	489027	5243038

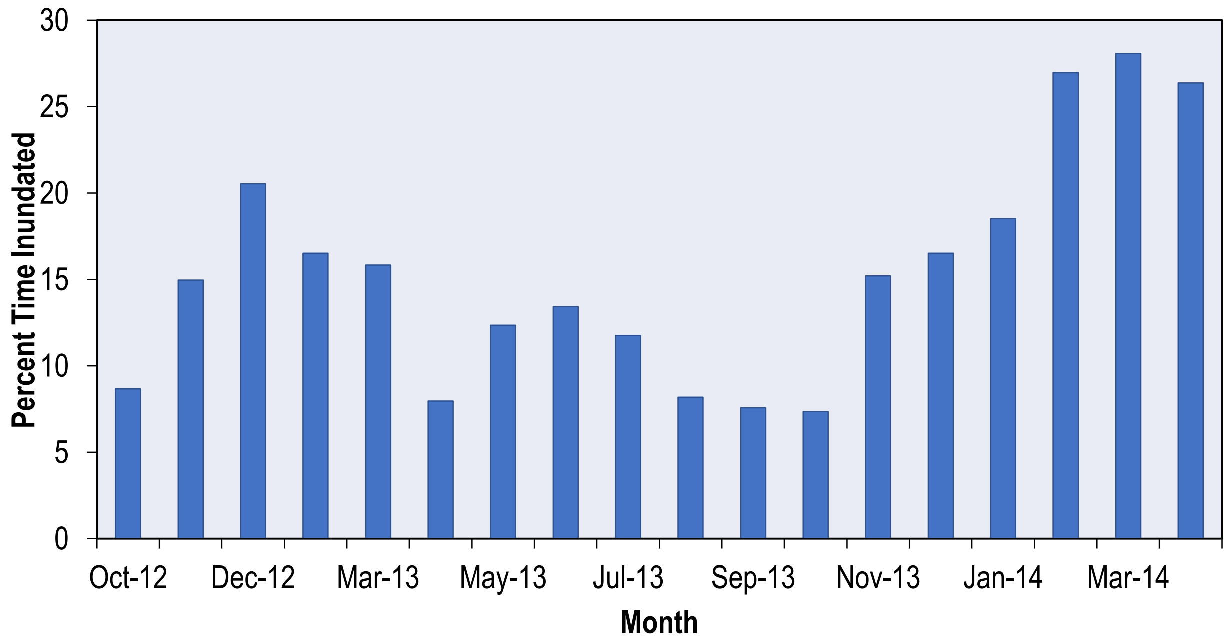

Figure C6. Average monthly inundation of the study site based on an average marsh elevation. Water levels were determined with a water logger deployed at 0.85 m (NAVD88).

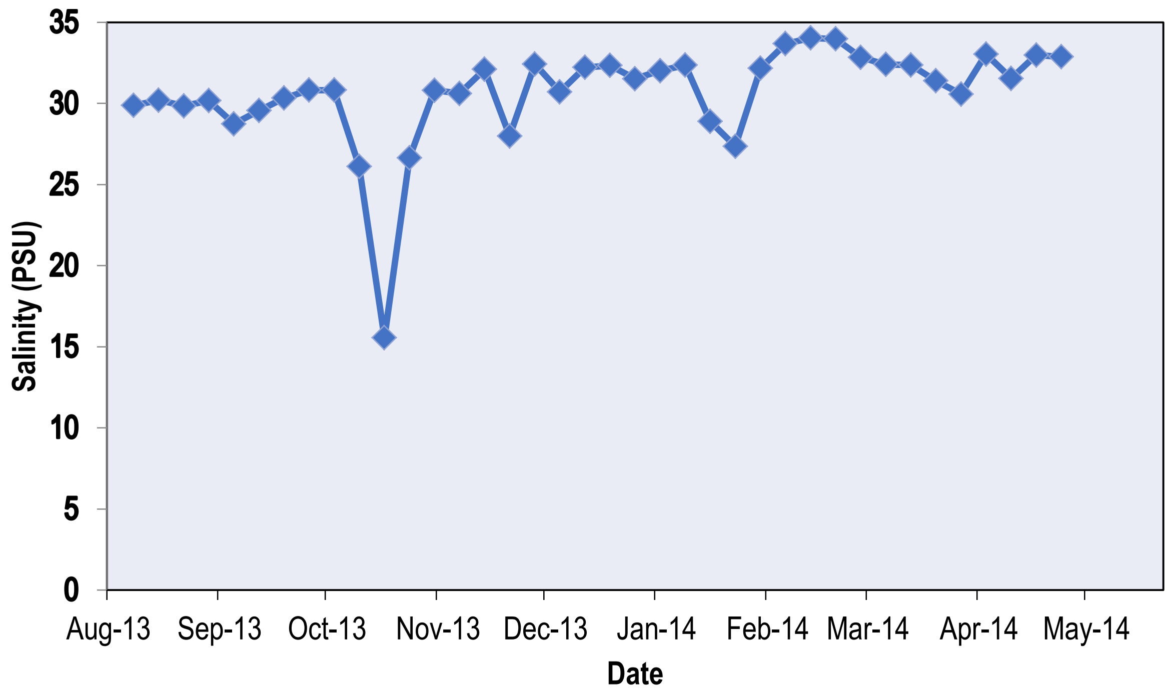

Figure C7. Average weekly maximum salinity from August 2013 – May 2014 at Skokomish. Seawater is approximately 35 PSU.

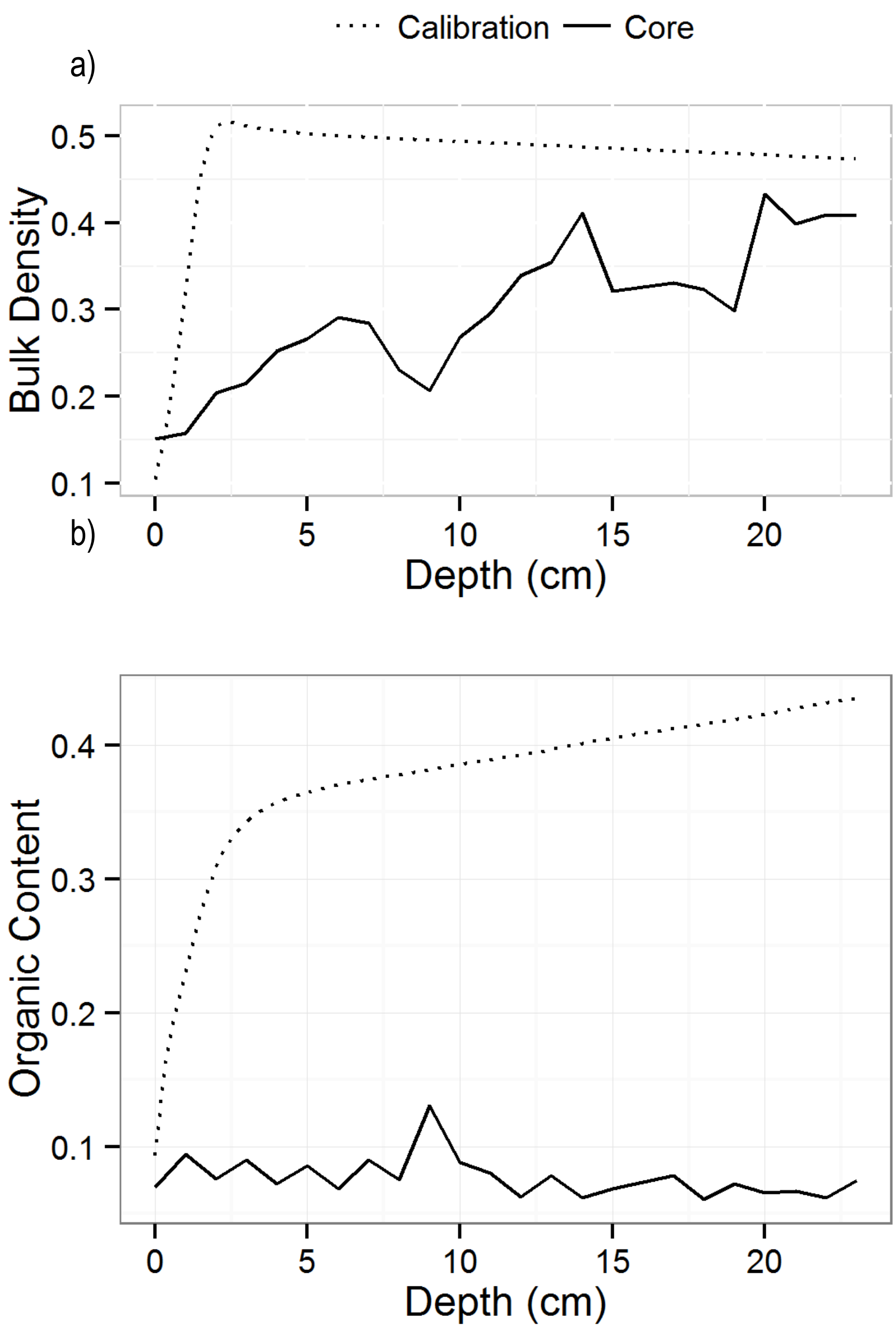

Figure C8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table C4. Model input parameters for Skokomish. 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})	0.075	Core calibration
Elevation of peak biomass (cm, MSL)	164	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	25	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0097	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub. data
Porosity surface (%)	95	Core
Porosity depth (%)	72	Core
Refractory carbon (%)	61	Core
Maximum astronomical tide (cm, MSL)	236	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.97	Tacoma tide gauge (NOAA, 9446484)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

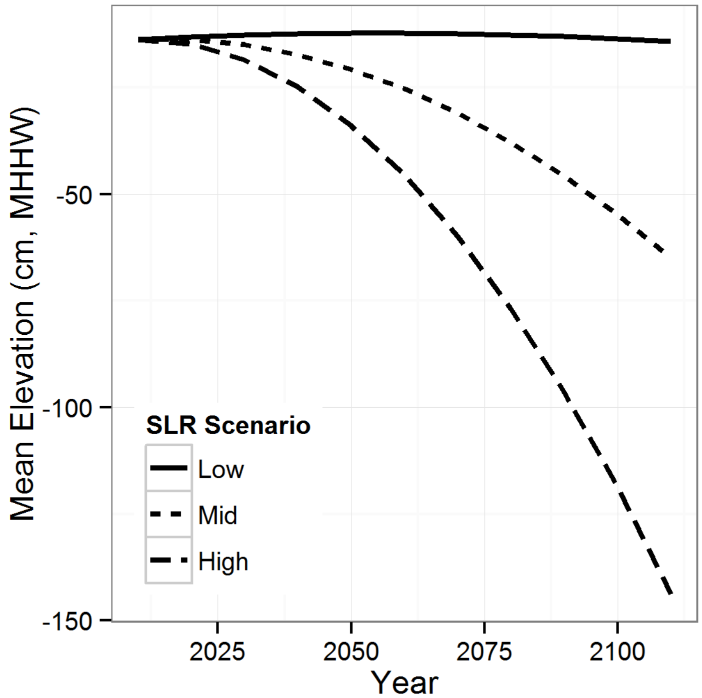

Figure C9. WARMER model results for average marsh elevation change at Skokomish from the present day to the year 2110 under low, mid, and high sea-level rise (SLR) scenarios.

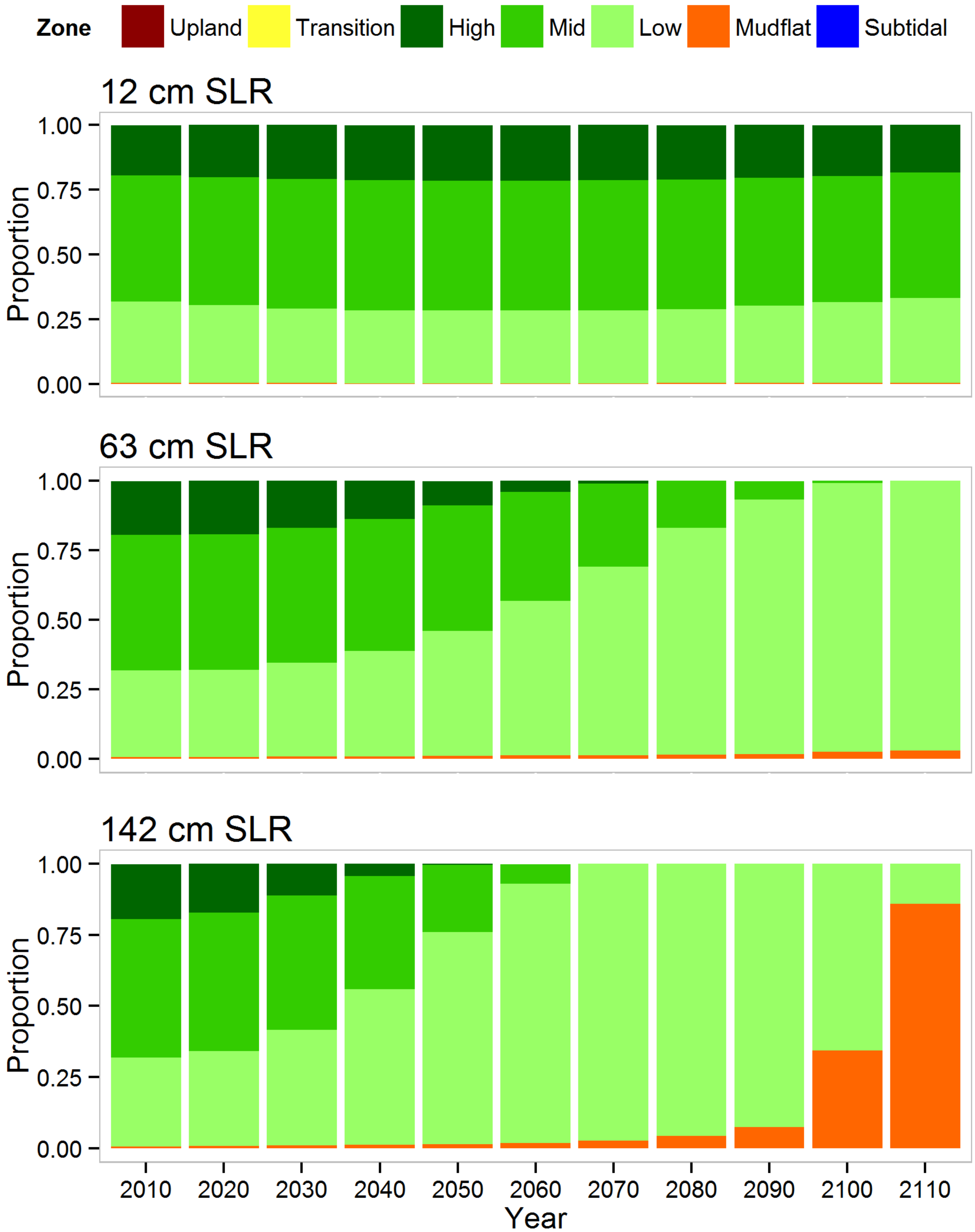

Figure C10. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table C5. Percentage of habitat area modeled for three sea-level rise scenarios for 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
	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	20	21	18	20	9	0	20	1	0
Mid	49	50	48	49	45	0	49	24	0
Low	31	28	33	31	45	97	31	74	14
Mudflat	0	1	1	0	1	3	0	1	86
Subtidal	0	0	0	0	0	0	0	0	0

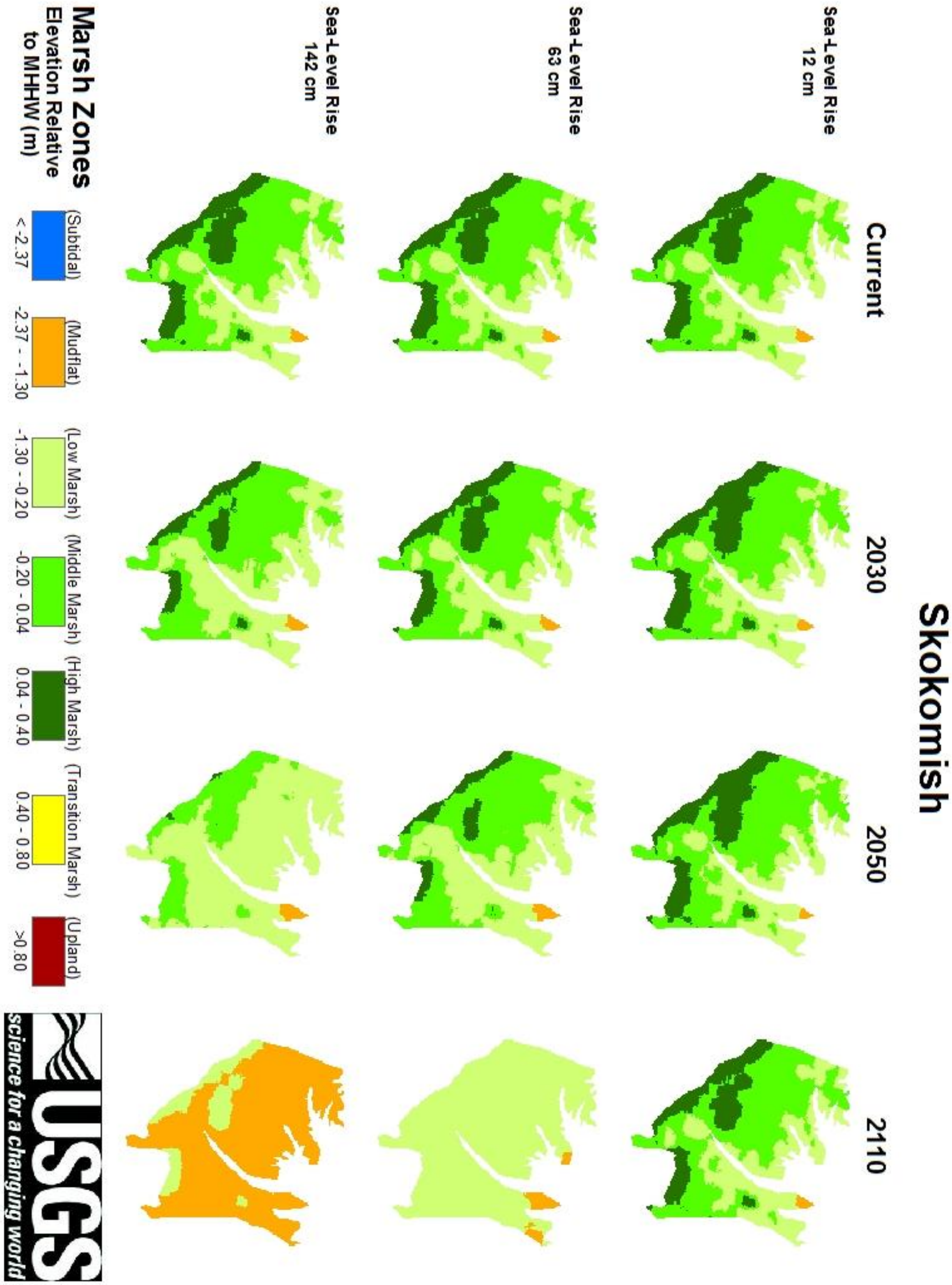

Figure C11. Projected habitat distribution at Skokomish for 2030, 2050 and 2110 with the WARMER model under three sea-level rise scenarios.

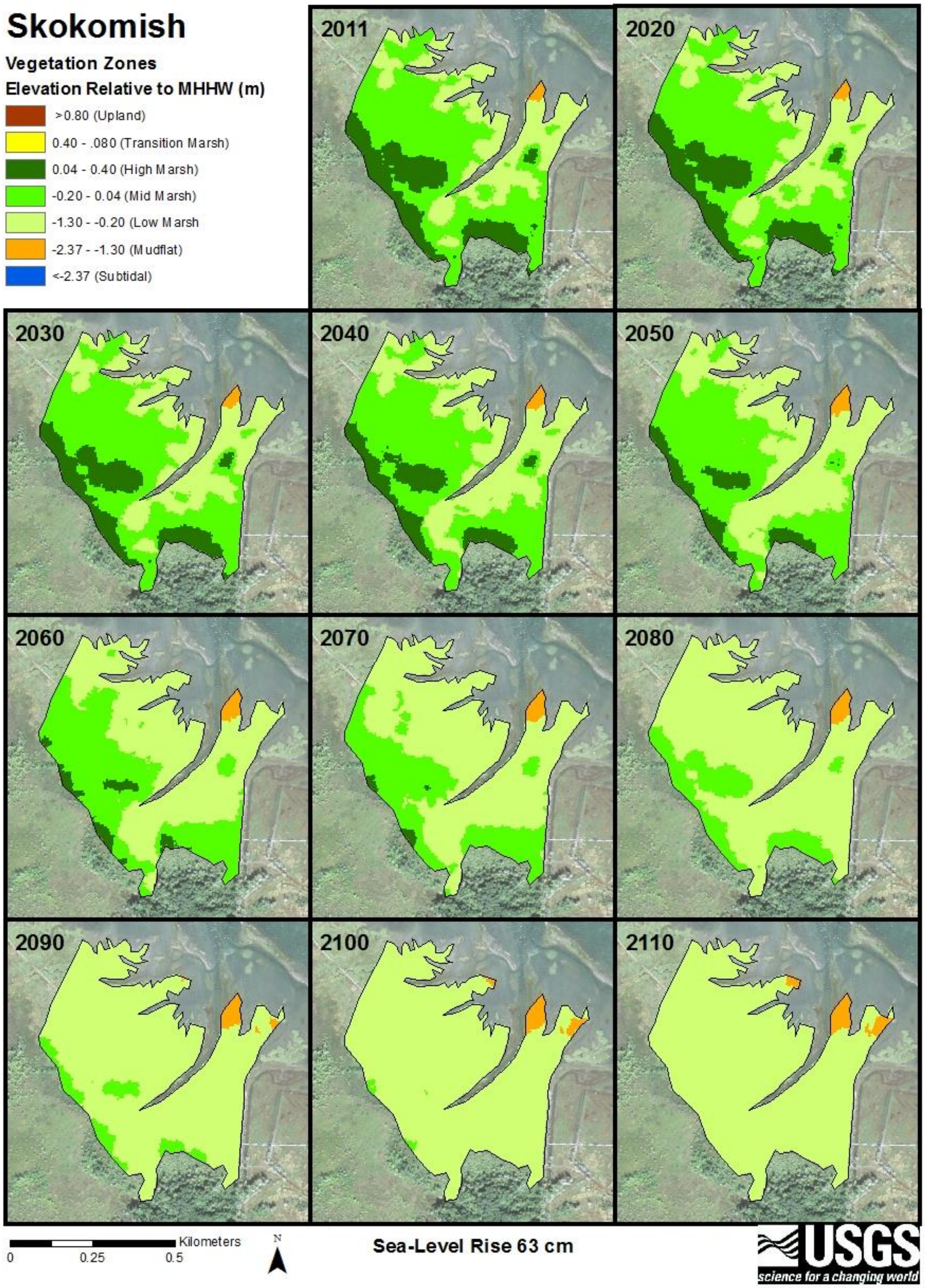

Figure C12. Projected changes in the distribution of Skokomish habitat zones under the NRC's mid (63 cm) sea-level rise scenario.

Nisqually Marsh, Nisqually National Wildlife Refuge, Thurston County, Washington, USA

Photo: M. Davis, USGS

Summary:

- *Study site size*: 59.9 hectares
- *Location*: 47° 05' 31" N latitude, 122° 41' 35" W longitude.
- *Site management*: U.S. Fish and Wildlife Service (Nisqually National Wildlife Refuge)
- *Site vegetation and elevation survey*: 31 August – 7 September 2012
- *Sample size*: 1072 (elevation data points), 245 (vegetation quadrats)
- *Marsh elevation model*: This site was among the lowest study sites in the Pacific Northwest, with only 6% of elevation data points occurring above MHHW.
- *Plant community composition*: *Distichlis spicata* was the most frequently-occurring species at the site. *Sarcocornia perennis* and *Jaumea carnosa* were also common.
- *Bathymetric surveys*: 124.9 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: sediment accumulation rate = 0.39 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.018 g cm^{-2} yr^{-1}; net accretion = 0.50 cm yr^{-1}.

- *Water inundation and salinity monitoring*: water level (January 2013 – December 2013); conductivity (August 2013 – October 2013). Water level and conductivity monitoring is ongoing.
- *Salinity*: Maximum weekly salinity was very consistent during the study period, ranging from about 28-29.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during January 2013; minimum monthly inundation during February 2013.
- *Calculated tidal datums*: MHHW is at 3.11 m NAVD88; MHW is at 2.82 m NAVD88.
- *Sea-level rise marsh response modeling*: Under the NRC low SLR projection (12 cm), high marsh habitat gradually expands until more than 75% of the site is high marsh at 2110. Under the NRC's mid SLR projection (63 cm), high marsh is lost by 2090 and the site becomes mostly low marsh (with some mid marsh) by 2110. Under the NRC's high SLR projection (142 cm), high marsh is lost by 2060, mid marsh is lost by 2070 and the site becomes mostly mudflat by 2110.

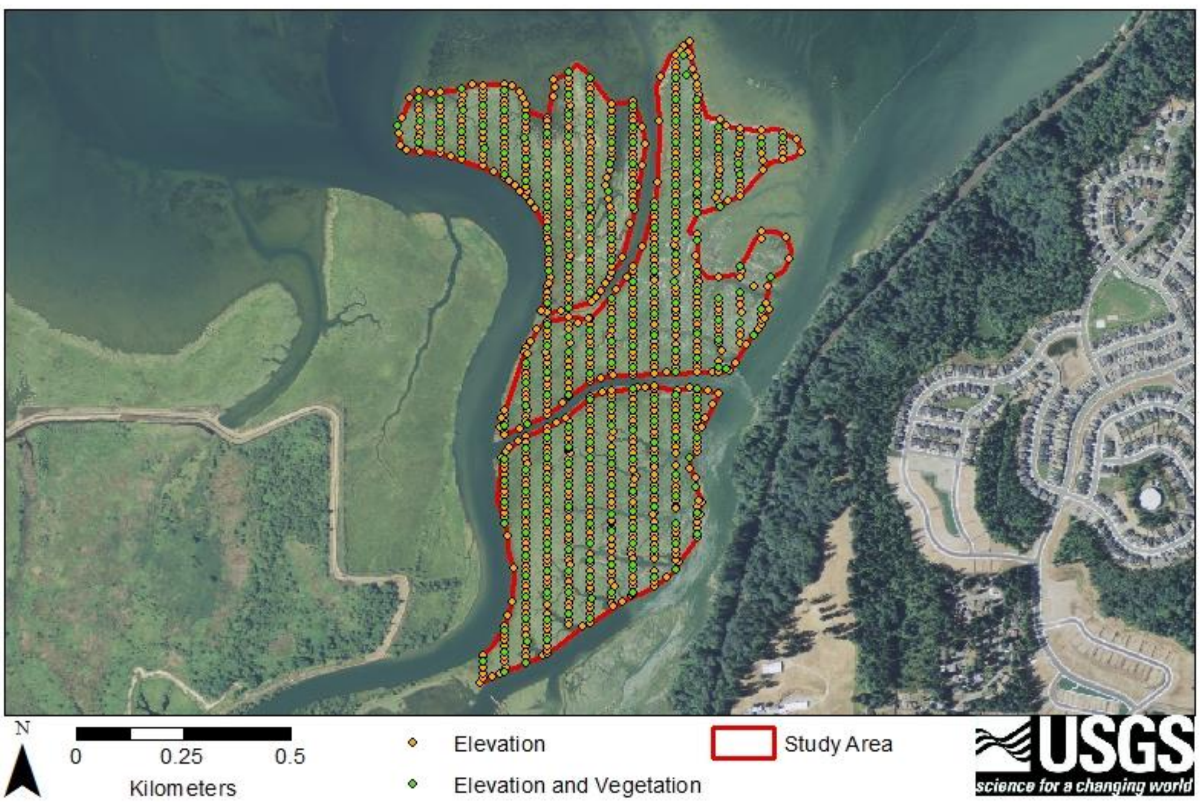

Figure D1. Distribution of elevation and vegetation survey points at Nisqually.

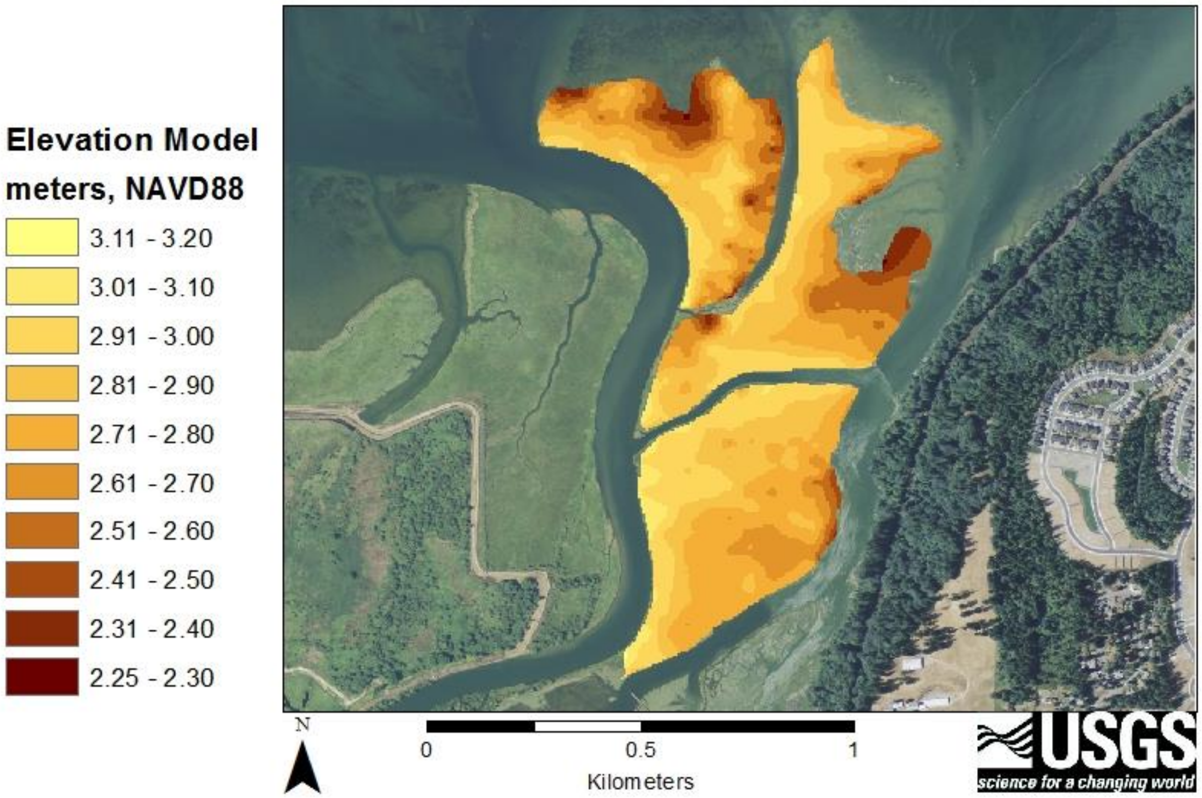

Figure D2. Elevation model (3 m resolution) developed from RTK GPS survey data.

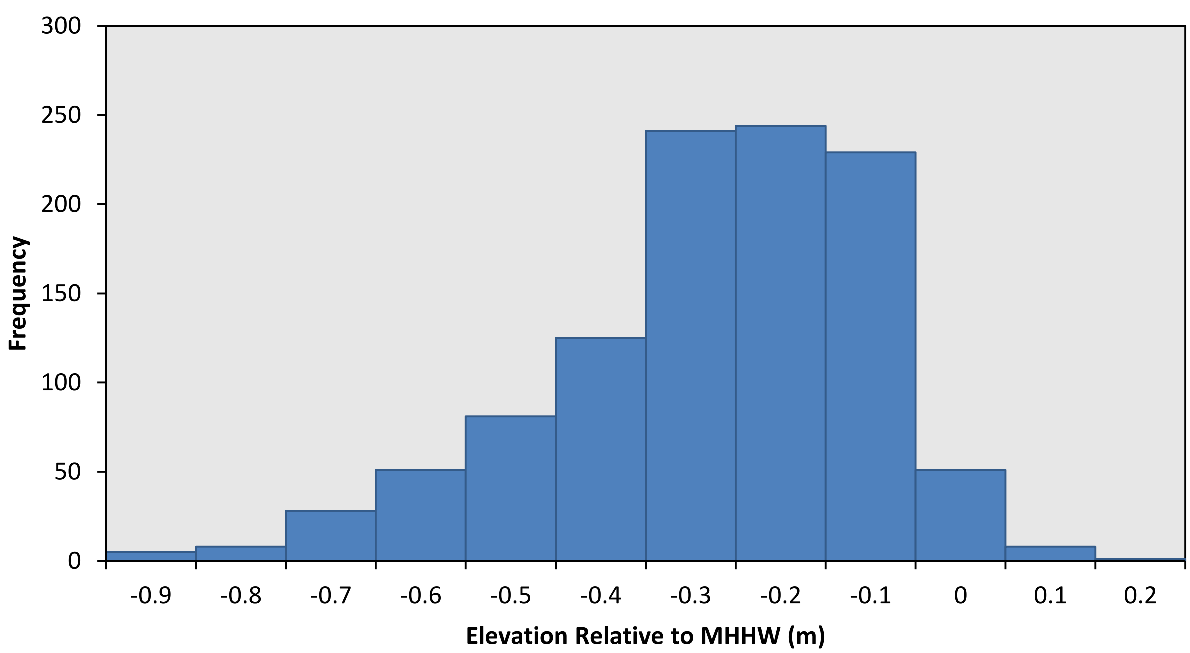

Figure D3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW) at Nisqually.

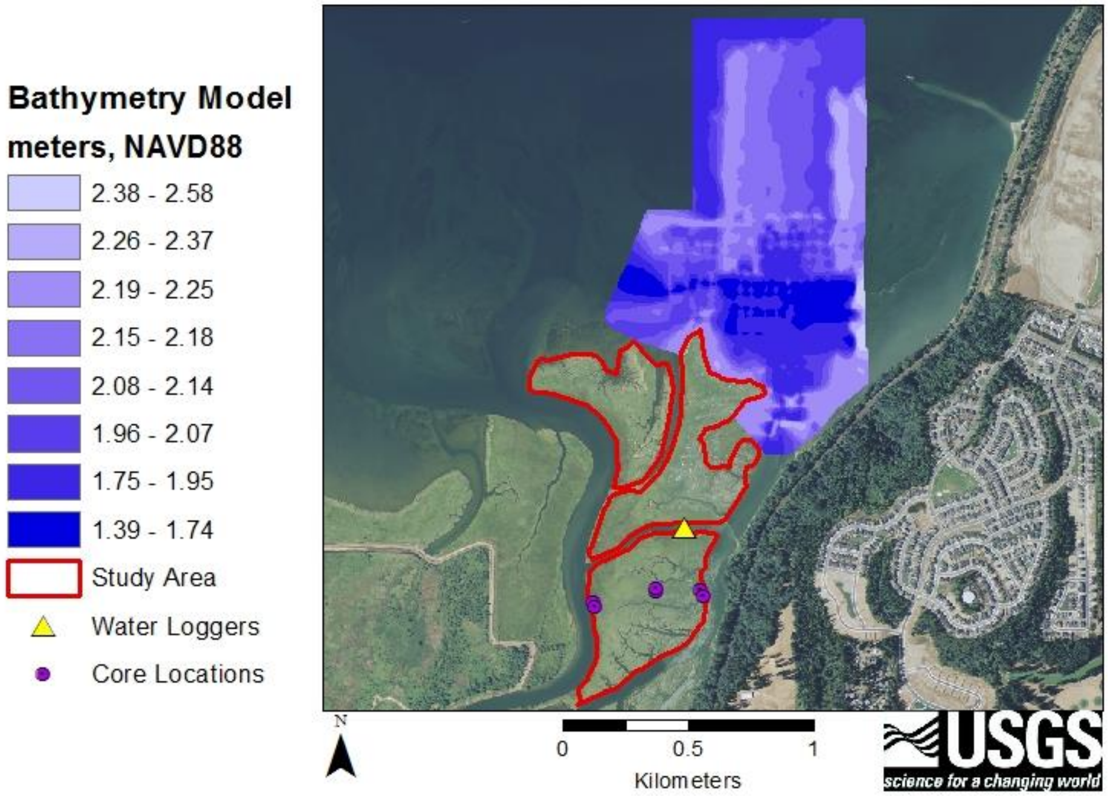

Figure D4. Near-shore bathymetry model at Nisqually. Water level logger and core locations are shown within the marsh study site.

Table D1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Nisqually. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Distichlis spicata	Native perennial grass	86	51	21
Sarcocornia perennis	Native perennial forb	56	15	14
Jaumea carnosa	Native perennial forb	55	18	11
Grindelia integrifolia	Native perennial forb	34	3	21
Triglochin maritima	Native perennial forb	34	3	34
Plantago maritima	Native perennial forb	23	4	27
Carex lyngbyei	Native perennial sedge	21	5	47
Glaux maritima	Native perennial forb	21	1	16
Atriplex prostrata	Non-native annual forb	18	0	16
Spergularia sp.	Forb	11	1	13
Potentilla anserina	Native ann-perennial forb	11	1	26
Symphyotrichum subspicatum	Native perennial forb	10	4	46
Agrostis stolonifera	Non-native perennial grass	10	3	41
Juncus balticus	Native perennial rush	8	2	37
Deschampsia cespitosa	Native perennial grass	6	2	54
Puccinellia sp.	Grass	4	0	28
Cuscuta pacifica	Native ann-perennial parasite	4	NA	NA
Phalaris arundinacea	Non-native perennial grass	3	2	61
Elymus repens	Non-native perennial grass	2	1	52
Lactuca serriola	Non-native annual forb	2	0	19
Hordeum jubatum	Native ann-perennial grass	2	0	40
Cirsium arvense	Non-native perennial forb	1	0	51
Achillea millefolium	Native perennial forb	1	0	19
Schedonorus arundinaceus	Non-native perennial grass	1	0	83
Angelica lucida	Native perennial forb	0	0	23
Bolboschoenus maritimus	Native perennial sedge	0	0	22
Plantago lanceolata	Non-native perennial forb	0	0	15
Hordeum brachyantherum	Native perennial grass	0	0	38
Poaceae sp.	Grass	0	0	22

Table D2. Mean percent cover of dominant plant species by marsh zone at Nisqually. Zones were defined by degree of flooding by high tides. CarLyn = *Carex lyngbyei*; DisSpi = *Distichlis spicata*; JauCar = *Jaumea carnosa*; SarPer = *Sarcocornia perennis*; SymSub = *Symphyotrichum subspicatum*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.965 to 0.480	0	*Insufficient sample size*
High	3-25	0.479 to 0.048	1	*Insufficient sample size*
Middle	25-50	0.047 to -0.242	82	DisSpi (41), JauCar (18), SarPer (11), SymSub (7)
Low	>50	-0.243 to -0.960	162	DisSpi (57), JauCar (19), SarPer (17), CarLyn (4)

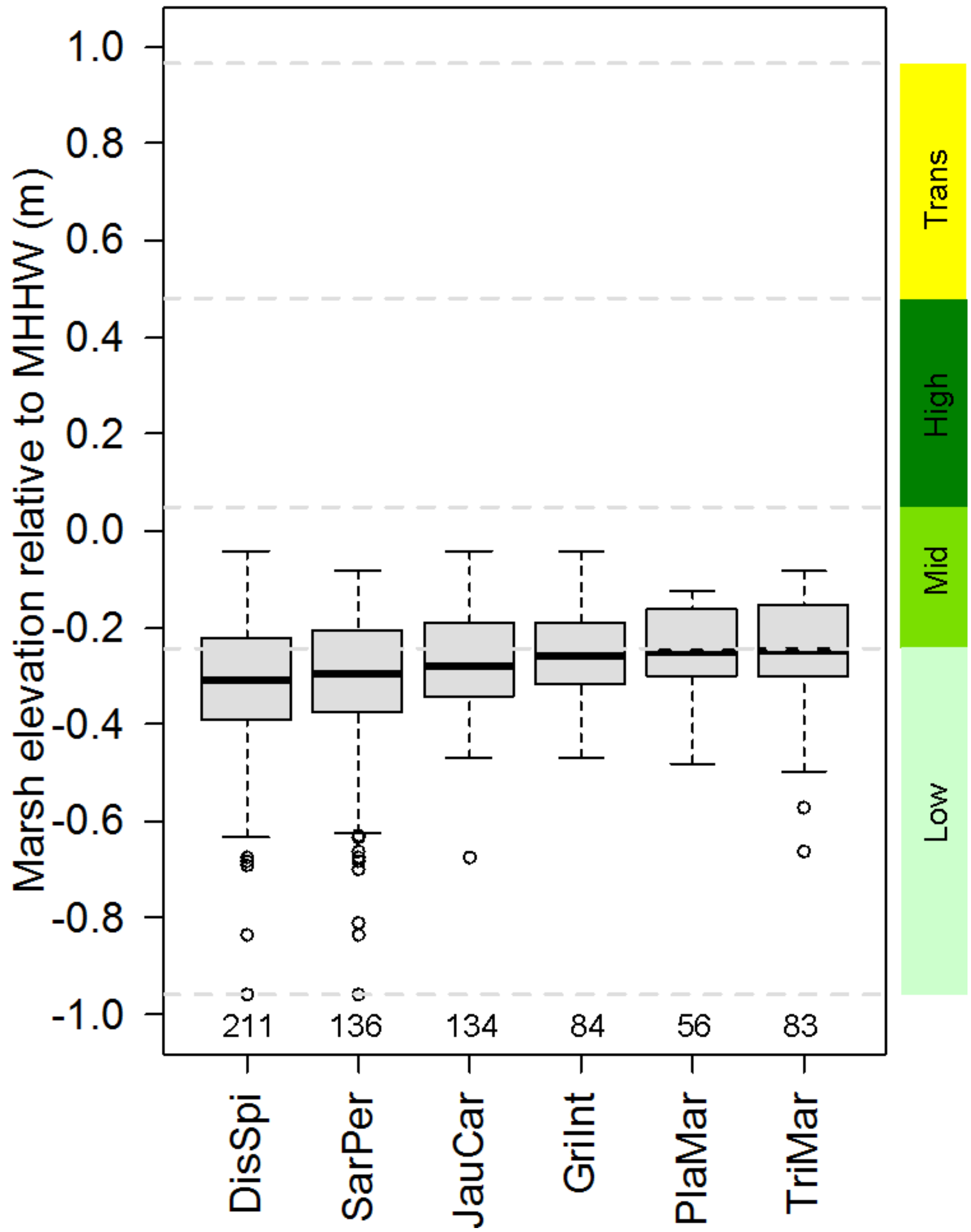

Figure D5. Elevation distribution of the six most common vascular plant species at Nisqually. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 245 plots). Marsh elevation zones (low, middle, high and transition) are illustrated at right. DisSpi = *Distichlis spicata*; SarPer = *Sarcocornia perennis*; JauCar = *Jaumea carnosa*; GriInt = *Grindelia integrifolia*; PlaMar = *Plantago maritima*; TriMar = *Triglochin maritima*.

Table D3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level logger	547226	5337780
Deep core locations	523469	5215431
	523290	5215421
	523045	5215380

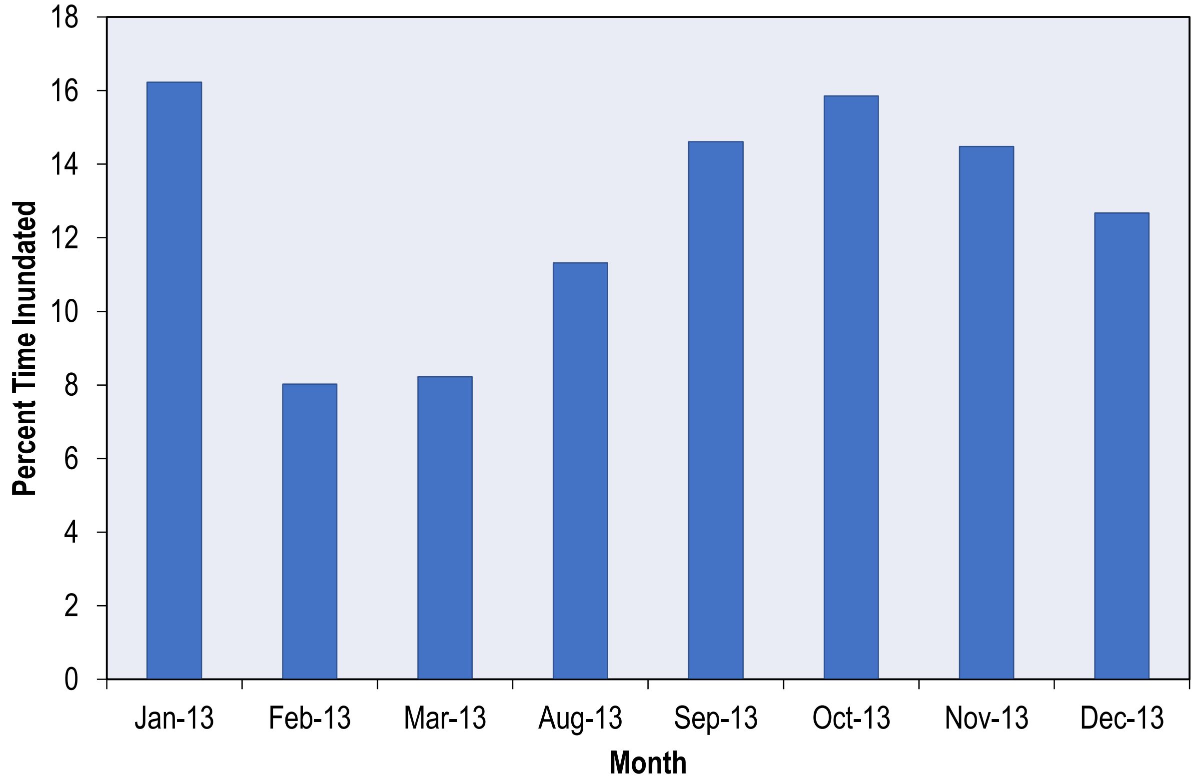

Figure D6. Average monthly inundation of the study site based on an average marsh elevation. Water levels were determined with a water logger deployed at 0.14 m (NAVD88).

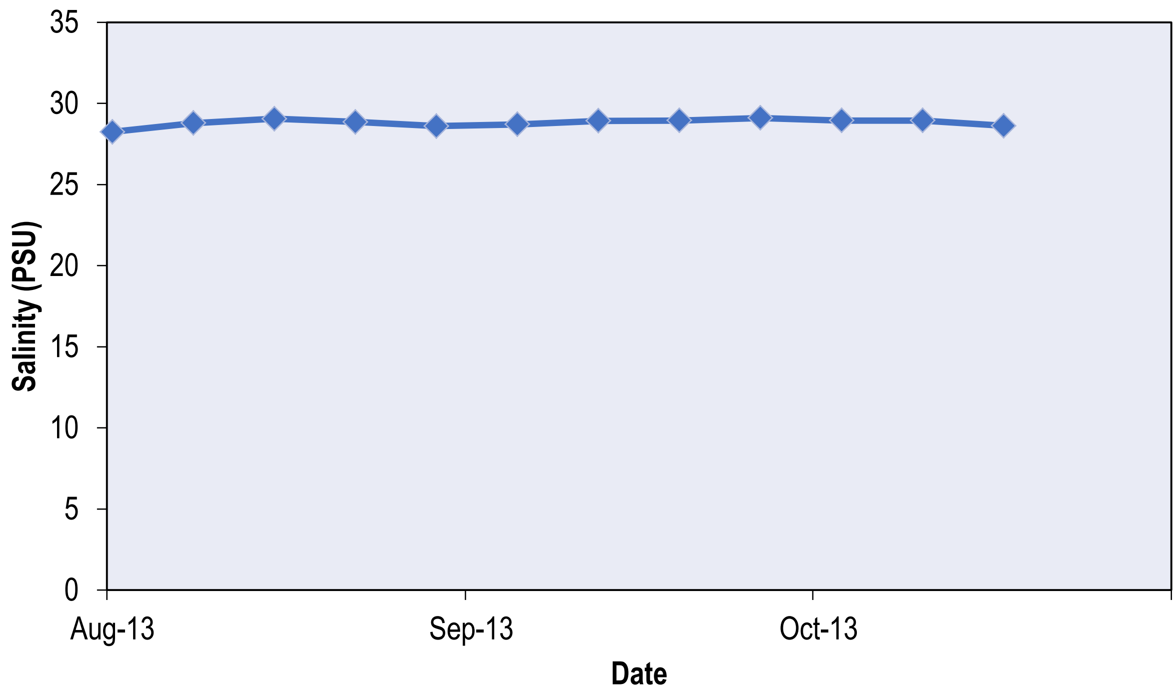

Figure D7. Average weekly maximum salinity from July 2013 – November 2013 at Nisqually. Seawater is approximately 35 PSU.

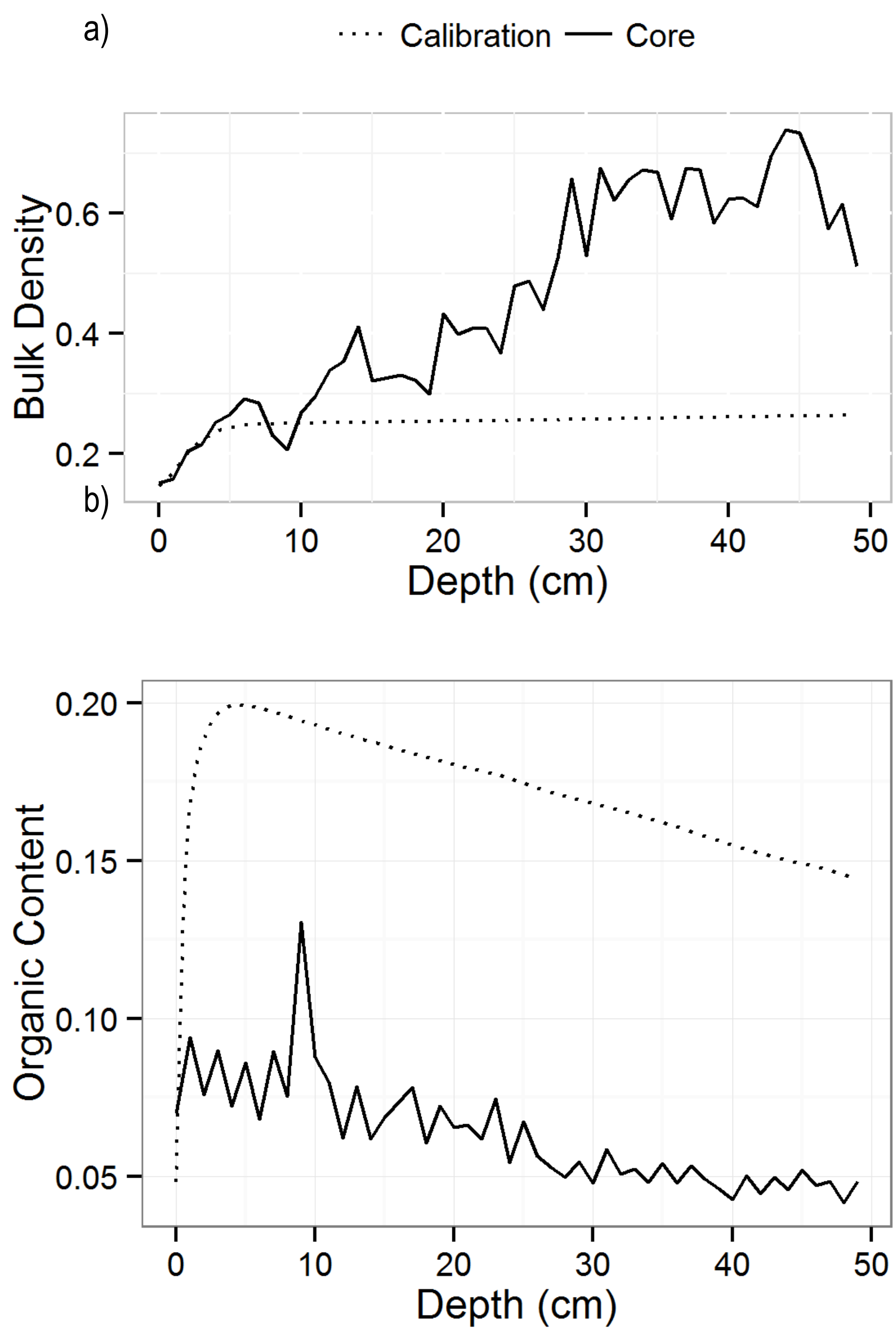

Figure D8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table D4. Model input parameters for Nisqually. 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})	0.24	Core calibration
Elevation of peak biomass (cm, MSL)	175	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	105	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.012	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	94	Core
Porosity depth (%)	88	Core
Refractory carbon (%)	59.7	Core
Maximum astronomical tide (cm, MSL)	286	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.97	Tacoma tide gauge (NOAA, 9446484)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

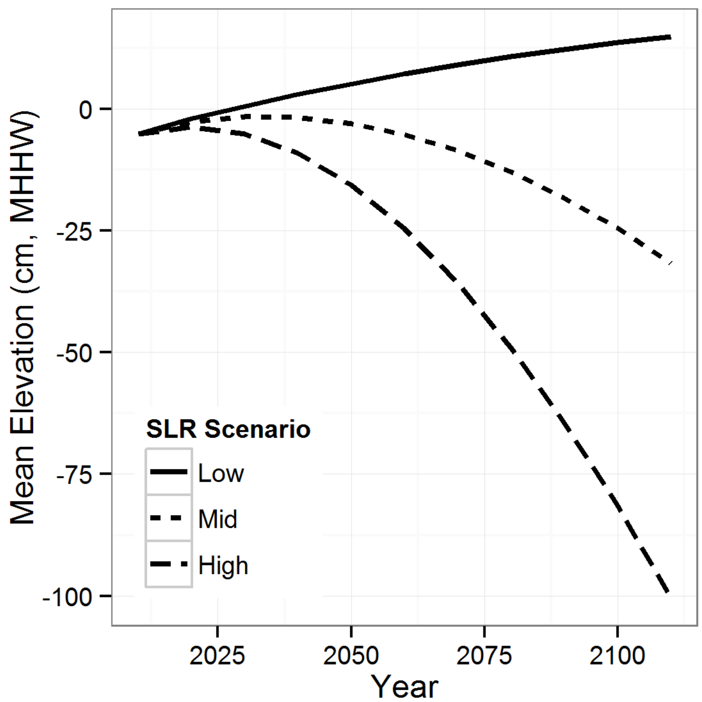

Figure D9. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Nisqually from 2010 to 2110 under low, mid, and high sea-level rise (SLR) scenarios.

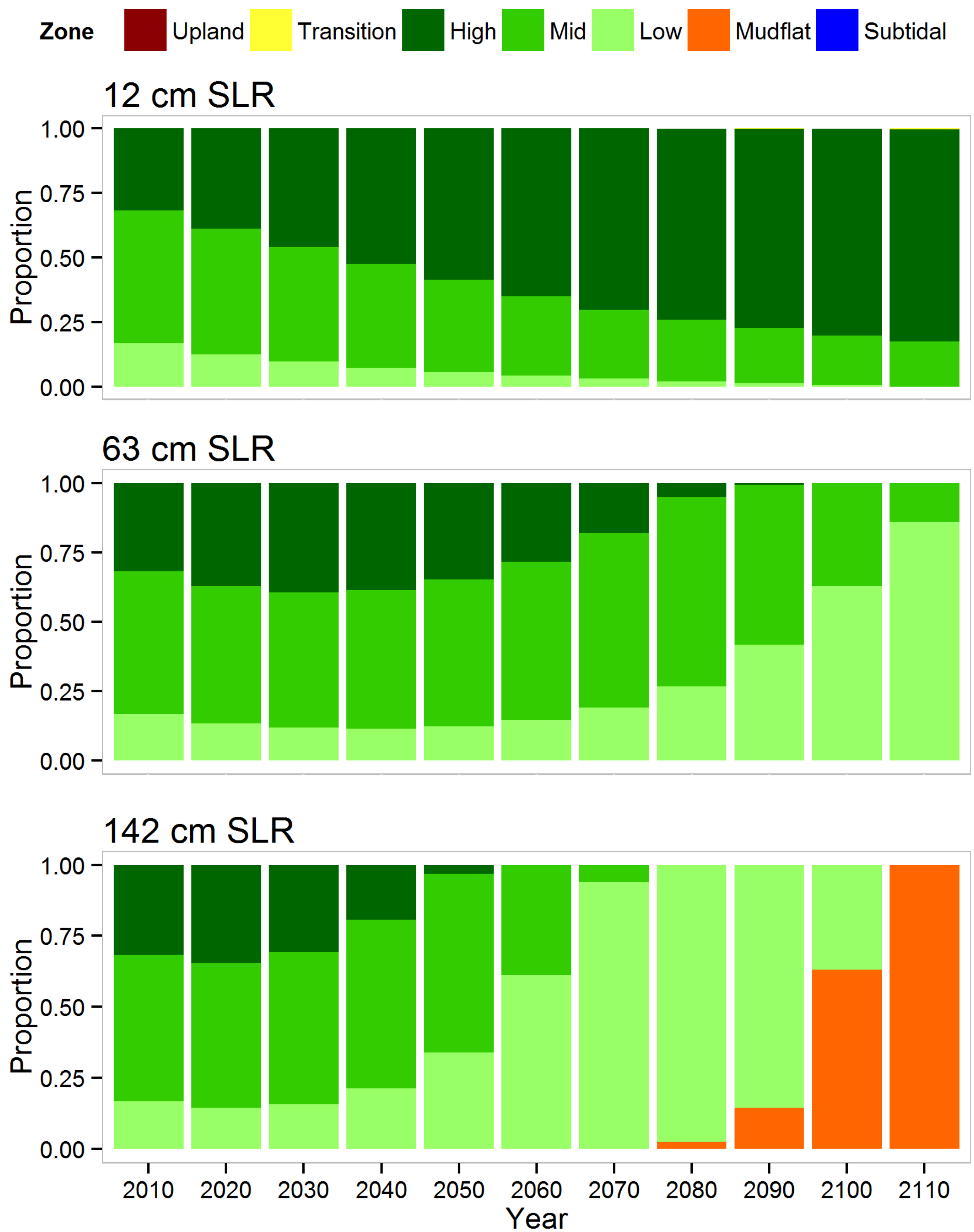

Figure D10. Model projections for change in the relative proportion of upland, transitional, high, mid, and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table D5. 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)		
	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	32	58	82	32	35	0	32	3	0
Mid	51	36	18	51	53	14	51	63	0
Low	17	6	0	17	12	86	17	34	0
Mudflat	0	0	0	0	0	0	0	0	100
Subtidal	0	0	0	0	0	0	0	0	0

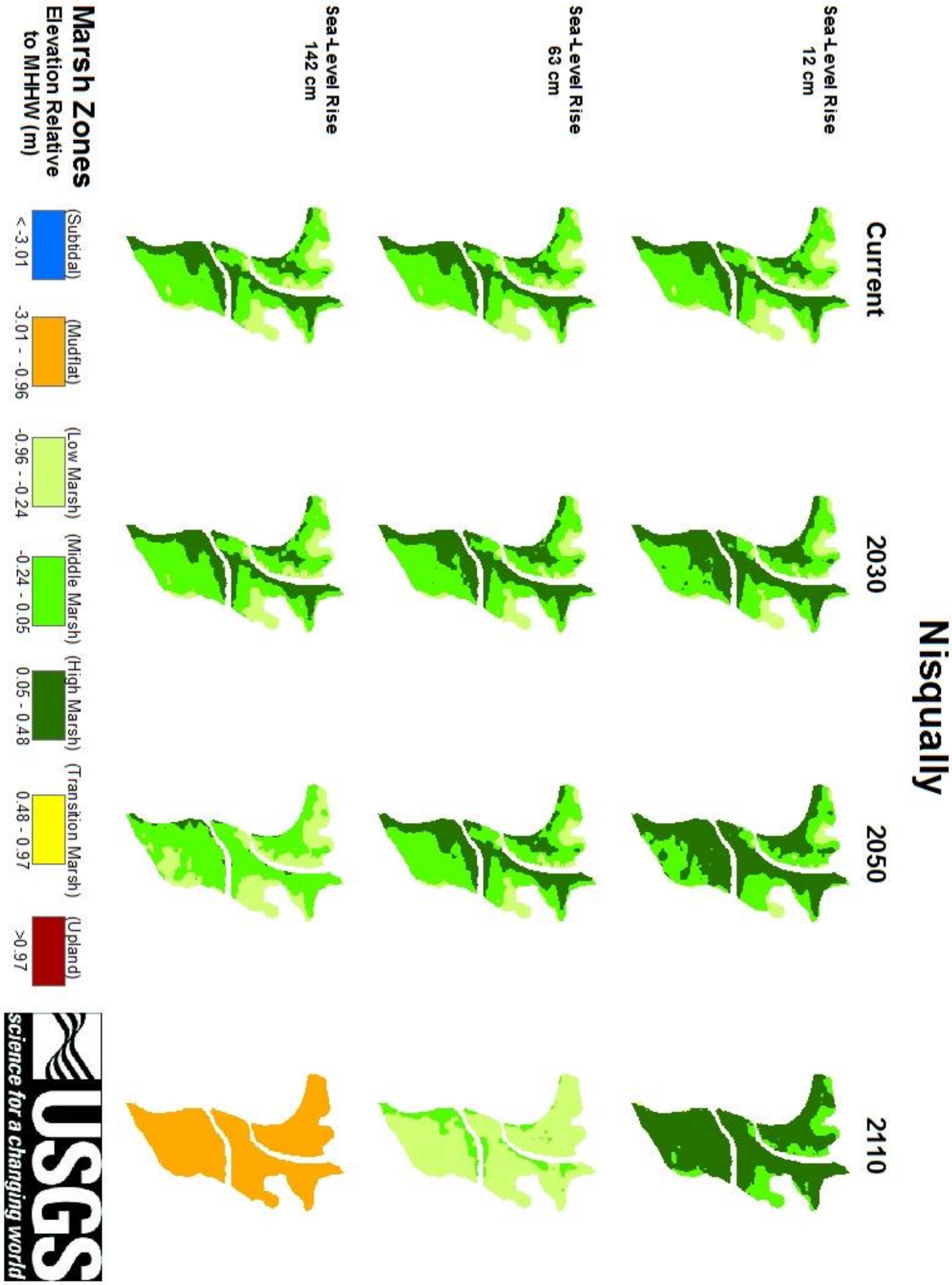

Figure D11. Projected habitat distribution at Nisqually for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

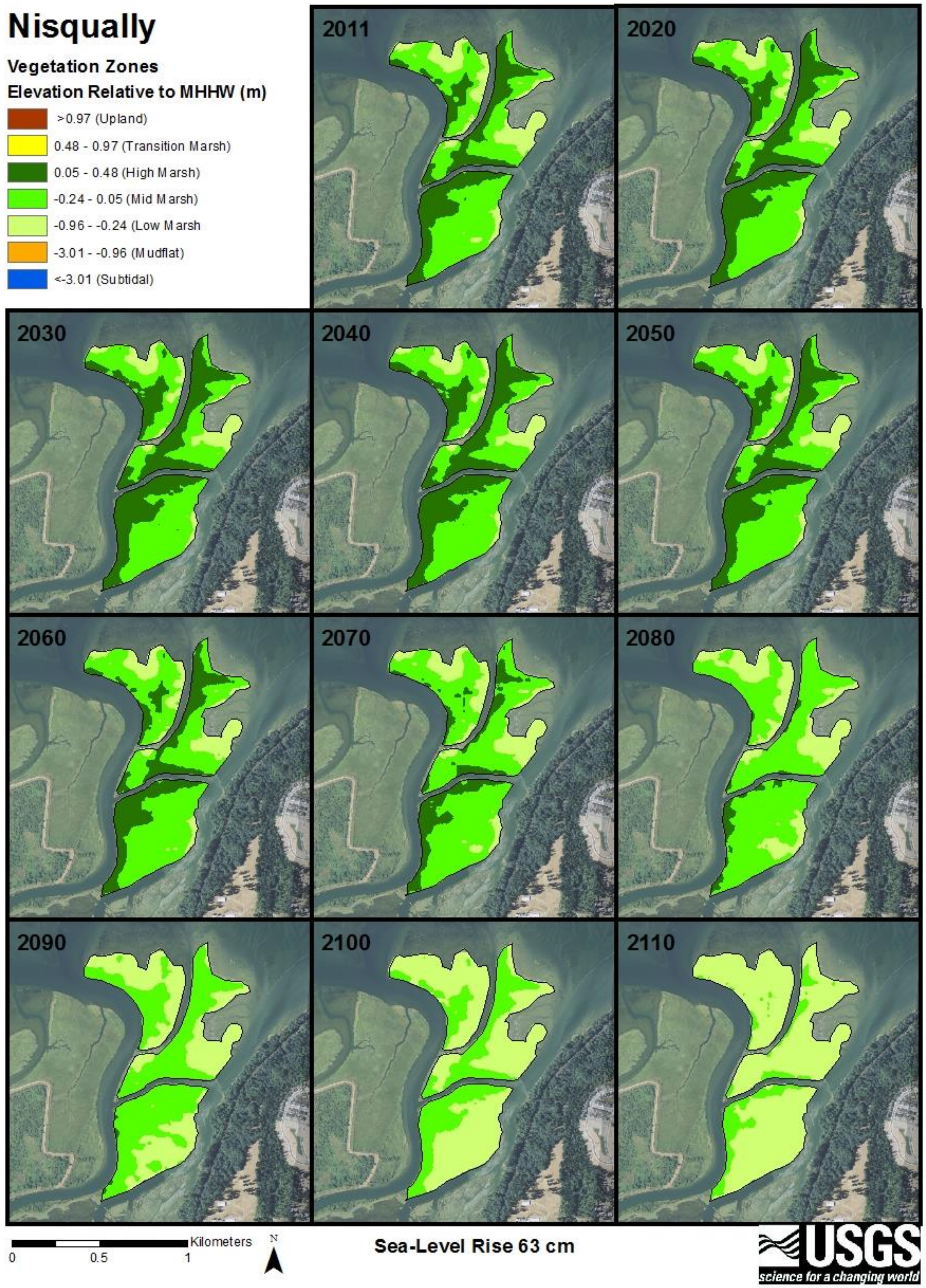

Figure D12. Projected changes in Nisqually elevation zones under the mid NRC sea-level rise scenario (63 cm).

Grays Harbor, Grays Harbor National Wildlife Refuge, Grays Harbor County, Washington, USA

Photo: K Powelson, USGS

Summary:

- *Study site size*: 67.8 hectares
- *Location*: 46° 58' 47"N latitude, 123° 55' 60"W longitude.
- *Site management*: U.S. Fish and Wildlife Service (Grays Harbor National Wildlife Refuge)
- *Site vegetation and elevation survey*: 31 August – 7 September 2012
- *Sample size*: 1192 (elevation data points), 271 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was above MHHW, with 73% of elevation data points occurring above MHHW
- *Plant community composition*: *Carex* spp. (usually *C. lyngbyei* but perhaps including instances of *C. obnupta*) had the highest frequency of occurrence. *Agrostis stolonifera* and *Triglochin maritima* also occurred frequently.
- *Bathymetric surveys*: 117.3 ha of nearshore habitat were mapped adjacent to the study area.

- *Soil characteristics*: WARMER accumulation rates for this site were: mineral accumulation rate = 0.55 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.0159 g cm^{-2} yr^{-1}; net accretion = 0.5659 cm yr^{-1}.
- *Water inundation and salinity monitoring*: water level (October 2012 – November 2013); conductivity (November 2013 – May 2014). Water level and conductivity monitoring is ongoing.
- *Salinity*: The site had euhaline conditions (33-36) from Nov 2013 to Feb 2014, but was somewhat fresher (26-29) from March 2014 to May 2014 during the rainy season.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during December 2012; minimum monthly inundation occurred during June 2013
- *Calculated tidal datums*: MHHW is at 2.39 m NAVD88; MHW is at 2.17 m NAVD88.
- *Sea-level rise marsh response modeling*: Under the NRC's low SLR projection (12 cm), high marsh at Grays Harbor is projected to expand until the whole site is high marsh by 2080. Under the mid SLR projection (63 cm), high marsh gradually replaces some middle and low marsh between 2010 and 2080. By 2110, the site consists of mostly high marsh, with some remaining mid marsh habitat. Under the NRC's high SLR projection (142 cm), high marsh initially becomes more abundant at the site, but then begins to decrease after 2050 and is lost by 2090. At 2110, the site is projected to consist mostly of low marsh with some mid marsh remaining.

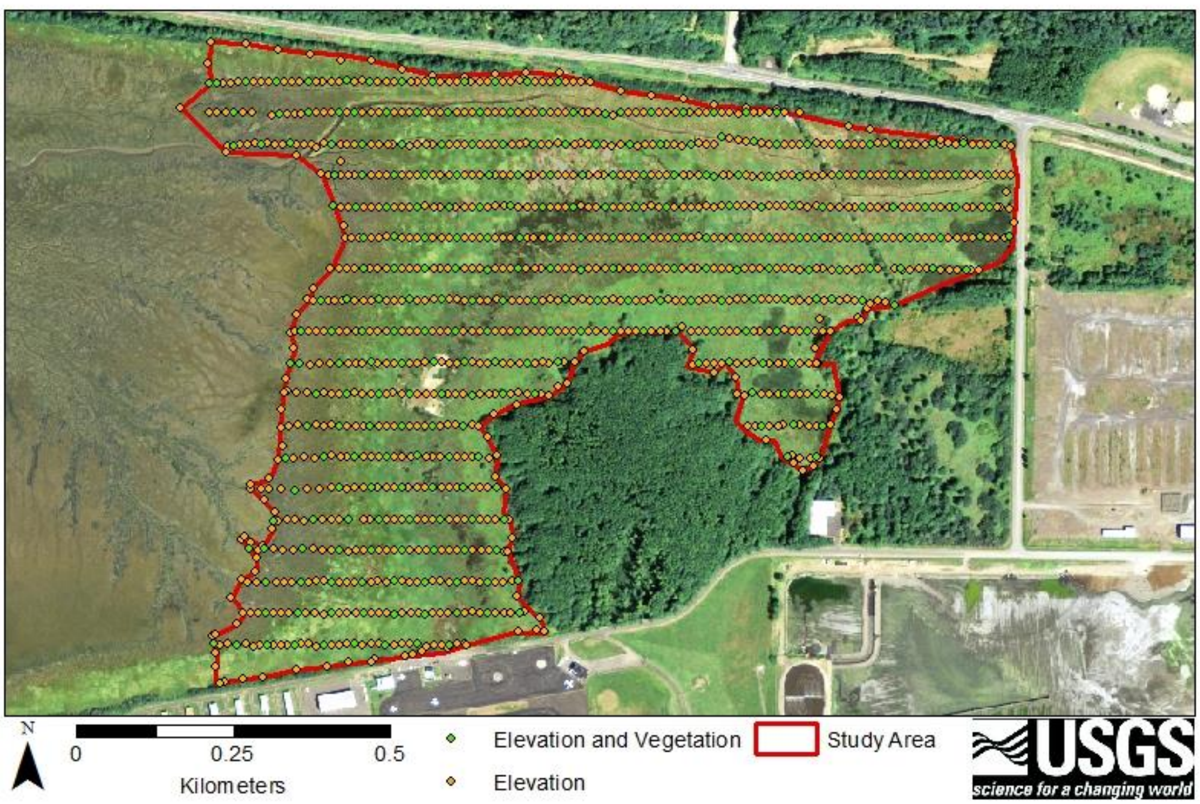

Figure E1. Distribution of elevation and vegetation survey points at Grays Harbor.

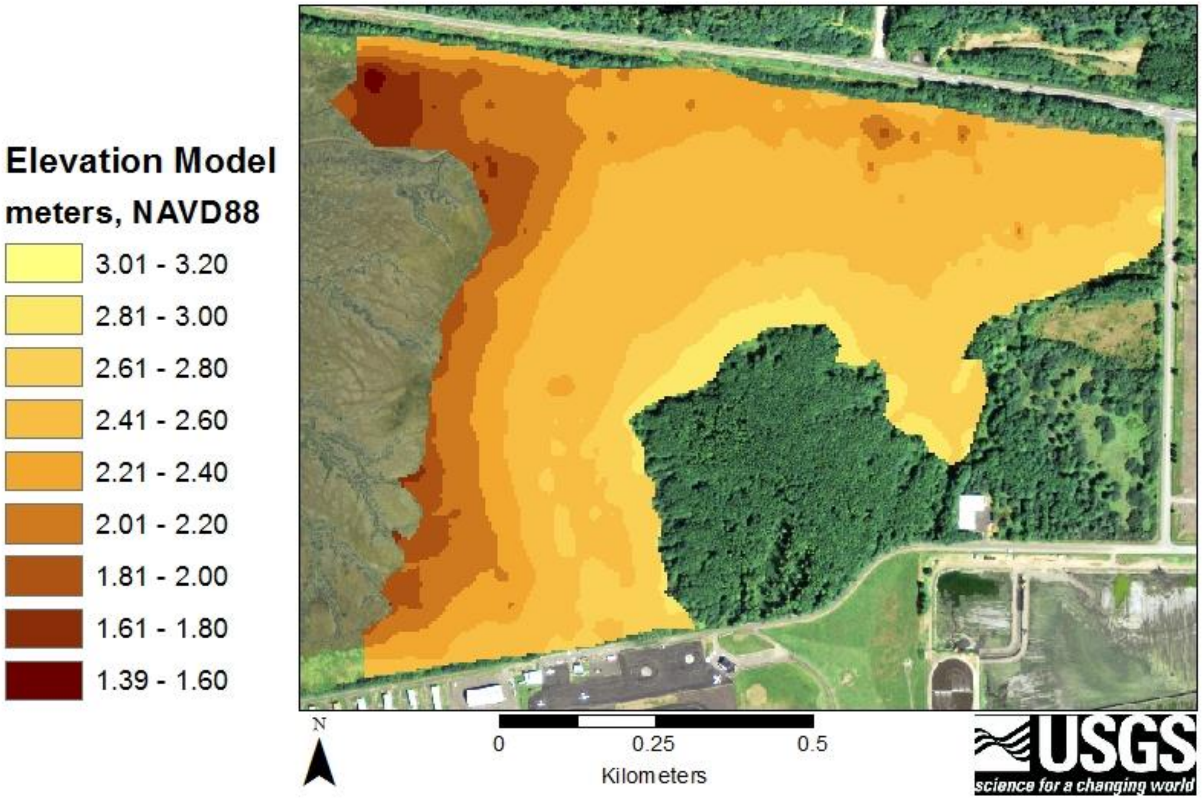

Figure E2. Elevation model (3 m resolution) developed from RTK GPS survey data.

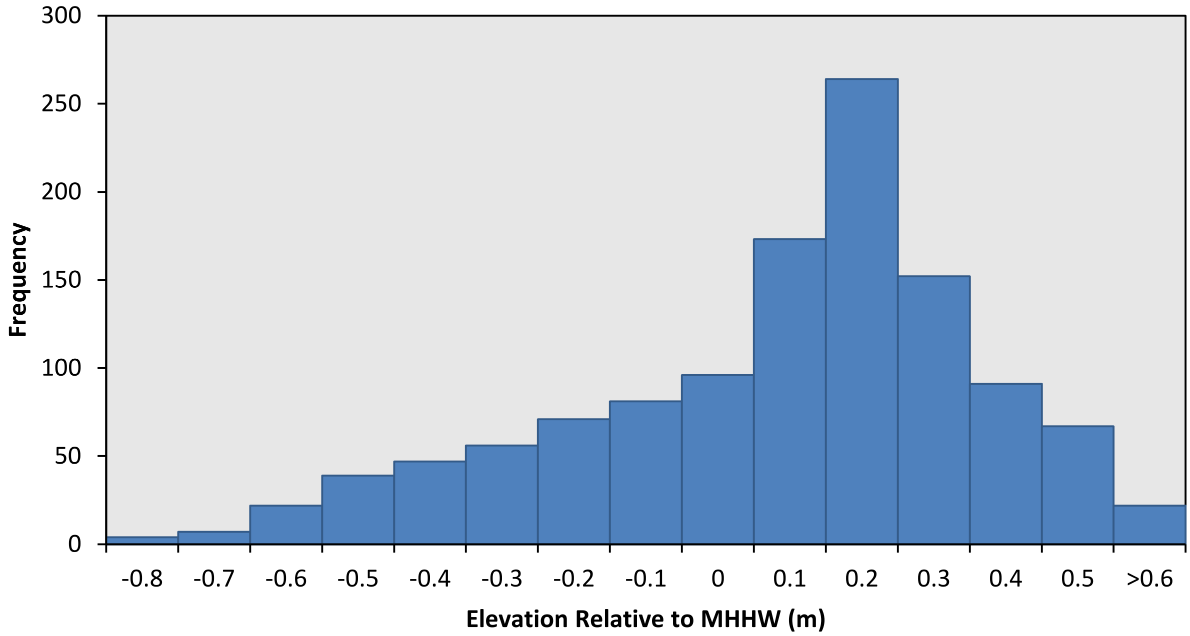

Figure E3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW) at Grays Harbor.

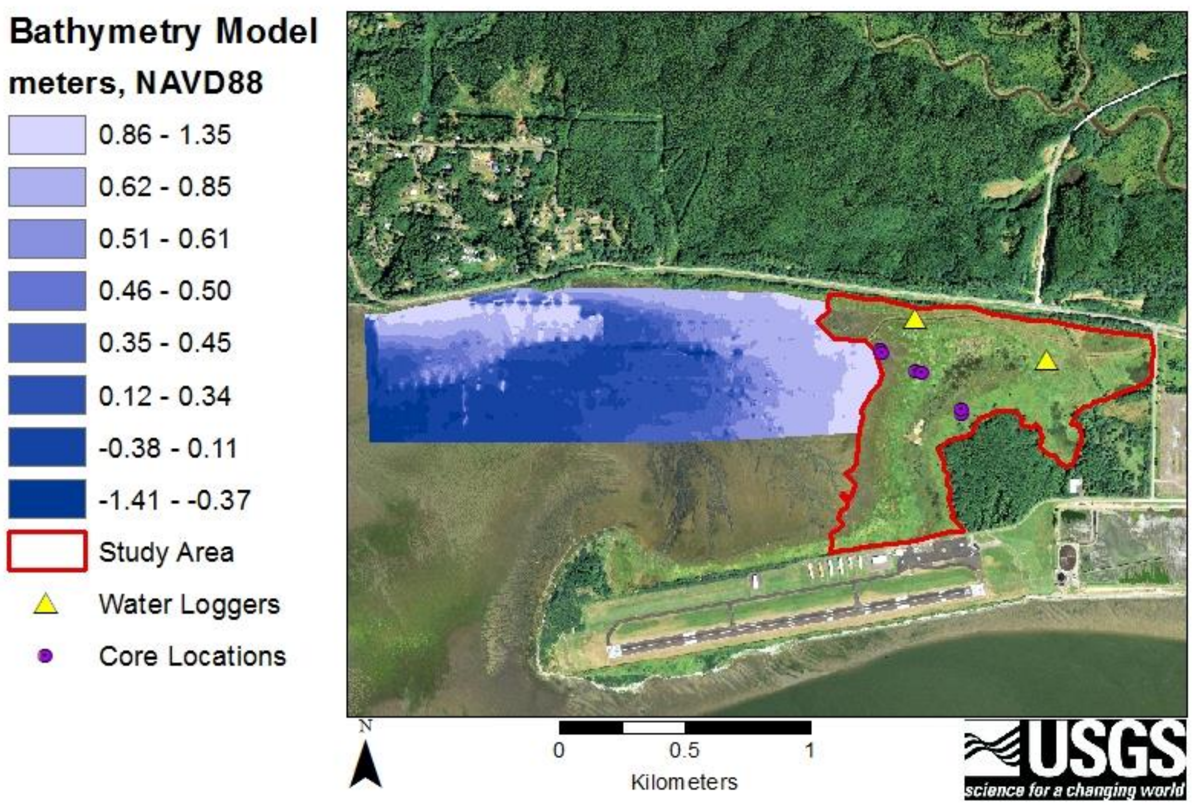

Figure E4. Near-shore bathymetry model at Grays Harbor. Water level logger and core locations are shown within the marsh study site.

Table E1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Grays Harbor.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Carex spp.*	Native perennial sedge	47	35	71
Agrostis stolonifera	Non-native perennial grass	39	18	47
Triglochin maritima	Native perennial forb	36	12	47
Potentilla anserina	Native ann-perennial forb	25	10	44
Sarcocornia perennis	Native perennial forb	20	10	26
Distichlis spicata	Native perennial grass	15	8	39
Deschampsia cespitosa	Native perennial grass	10	5	68
Vicia gigantea	Native perennial legume	7	3	49
Oenanthe sarmentosa	Native perennial forb	7	4	74
Juncus balticus	Native perennial rush	6	4	25
Bolboschoenus maritimus	Native perennial sedge	6	3	84
Typha latifolia	Native perennial forb	4	2	166
Holcus lanatus	Non-native ann-perennial forb	2	1	39
Plantago maritima	Native perennial forb	1	1	31
Galium trifidum	Native ann-perennial forb	1	0	41
Phalaris arundinacea	Non-native perennial grass	1	1	103
Stellaria humifusa	Native perennial forb	1	0	52
Poaceae sp.	Grass	0	0	41
Atriplex prostrata	Non-native annual forb	0	0	29
Hordeum brachyantherum	Native perennial grass	0	0	30
Festuca sp.	Grass	0	0	72

* Includes mostly *C. lyngbyei*, but perhaps also instances of *C. obnupta*.

Table E2. Mean percent cover of dominant plant species by marsh zone at Grays Harbor. Zones were defined by degree of flooding by high tides. AgrSto = *Agrostis stolonifera*; Carex = *C. lyngbyei*, but perhaps also instances of *C. obnupta*; DesCes = *Deschampsia cespitosa*; DisSpi = *Distichilis spicata*; *OenSar* = *Oenanthe sarmentosa*; PotAns = *Potentilla anserina;* TriMar = *Triglochin maritima*; VicGig = *Vicia gigantea*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.884 to 0.459	9	PotAns (34), VicGig (31), Carex (28), OenSar (9)
High	3-25	0.458 to 0.021	164	Carex (37), AgrSto (22), PotAns (14), TriMar (10)
Middle	25-50	0.020 to -0.225	47	Carex (54), AgrSto (28), DesCes (12), DisSpi (9)
Low	>50	-0.226 to -0.791	51	SarPer (41), TriMar (24), DesCes (18), Carex (12)

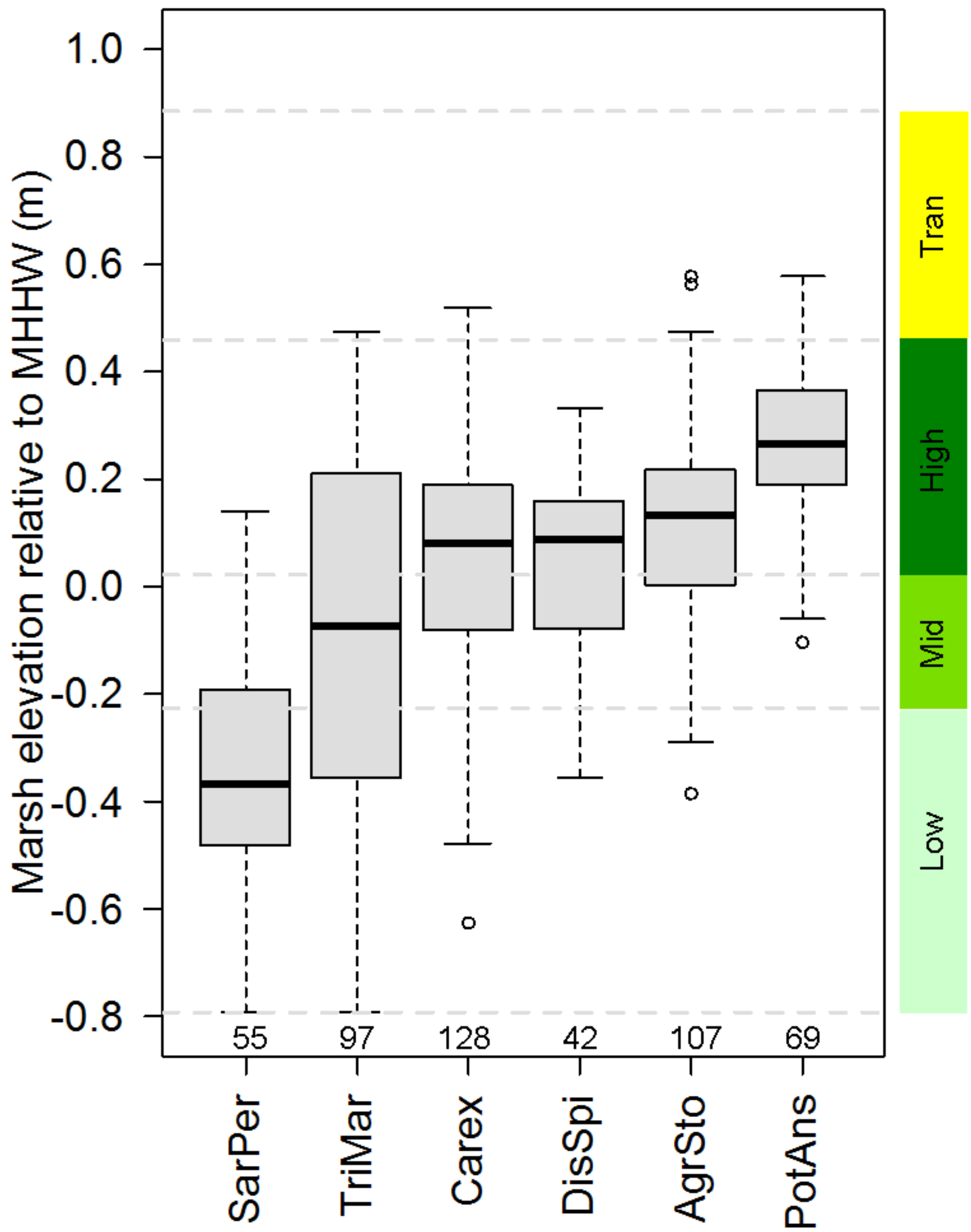

Figure E5. Elevation distribution of the six most common vascular plant species at Grays Harbor. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 271 plots). The range of marsh elevation zones (low, middle, and high marsh) are illustrated at right. SarPer = *Sarcocornia perennis*; TriMar = *Triglochin maritima*, Carex = *Carex* spp. (mostly *C. lyngbyei*, but including *C. obnupta*); DisSpi = *Distichlis spicata*, AgrSto = *Agrostis stolonifera*; PotAns = *Potentilla anserina*.

Table E3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	429762	5203420
	429239	5203585
Deep core locations	429103	5203466
	429244	5203380
	429427	5203208

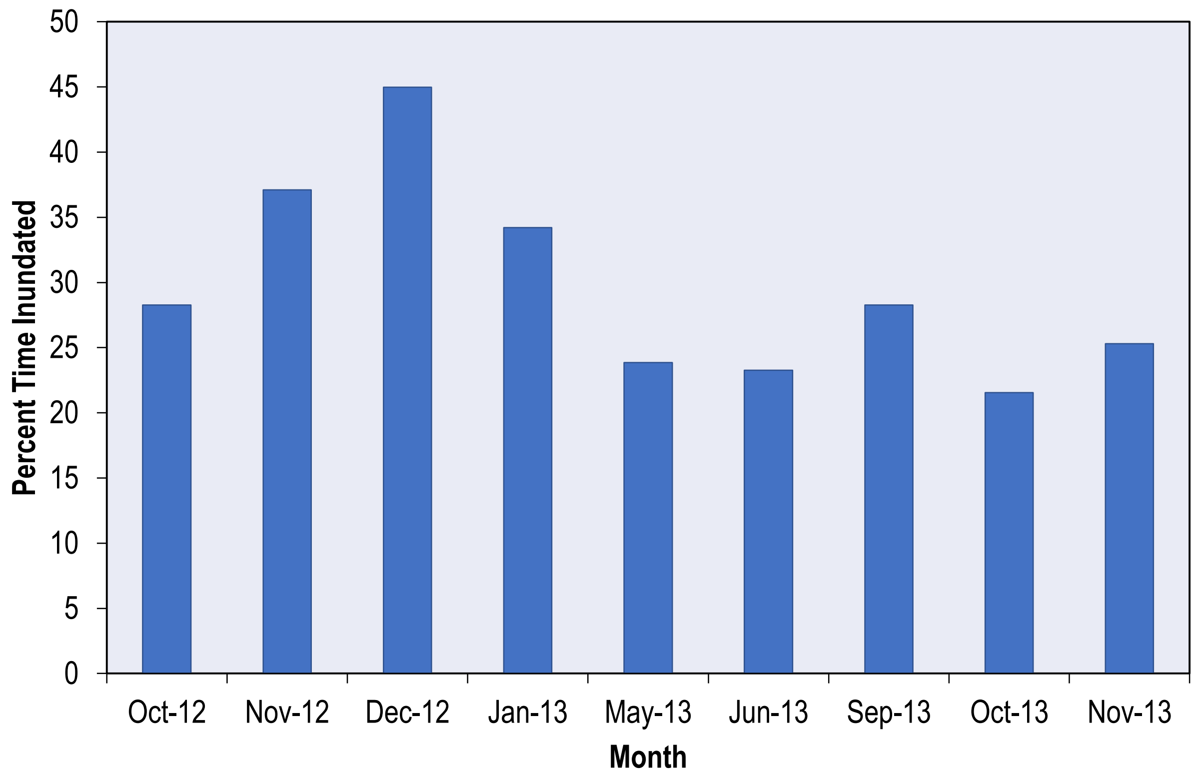

Figure E6. Average monthly inundation of the study site based on an average marsh elevation. Water levels were determined with a water level logger deployed at 1.01 m (NAVD88).

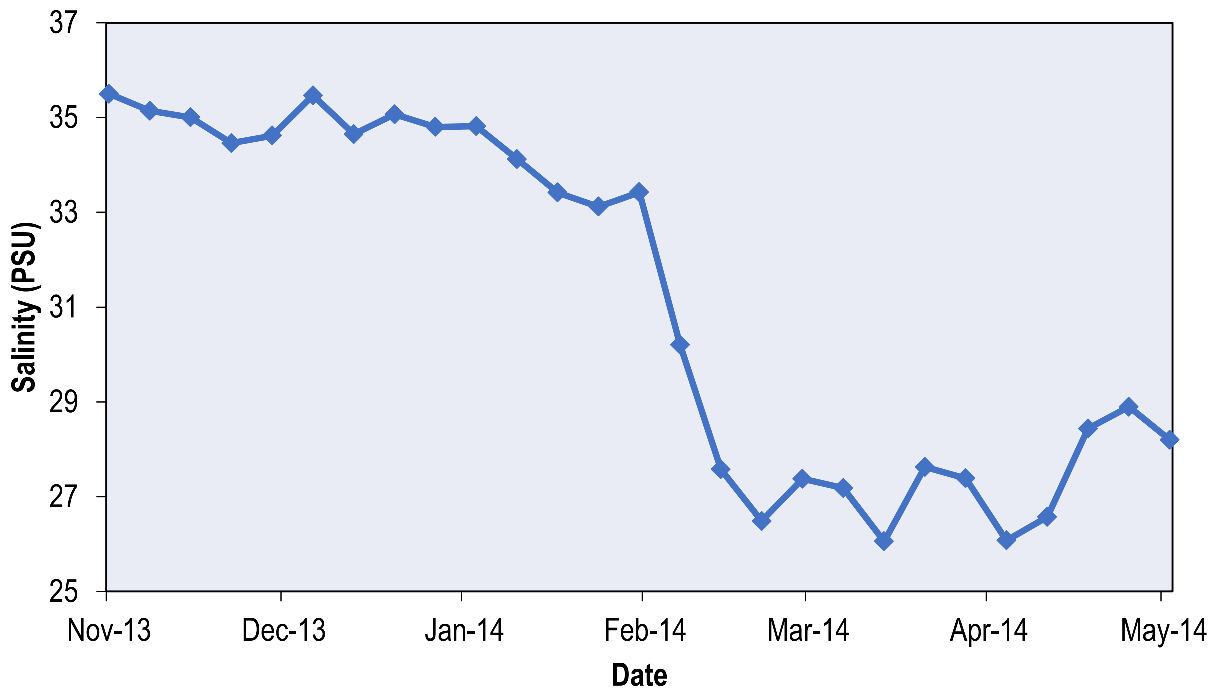

Figure E7. Average weekly maximum salinity from November 2013 – May 2014 at Grays Harbor. Seawater is approximately 35 PSU.

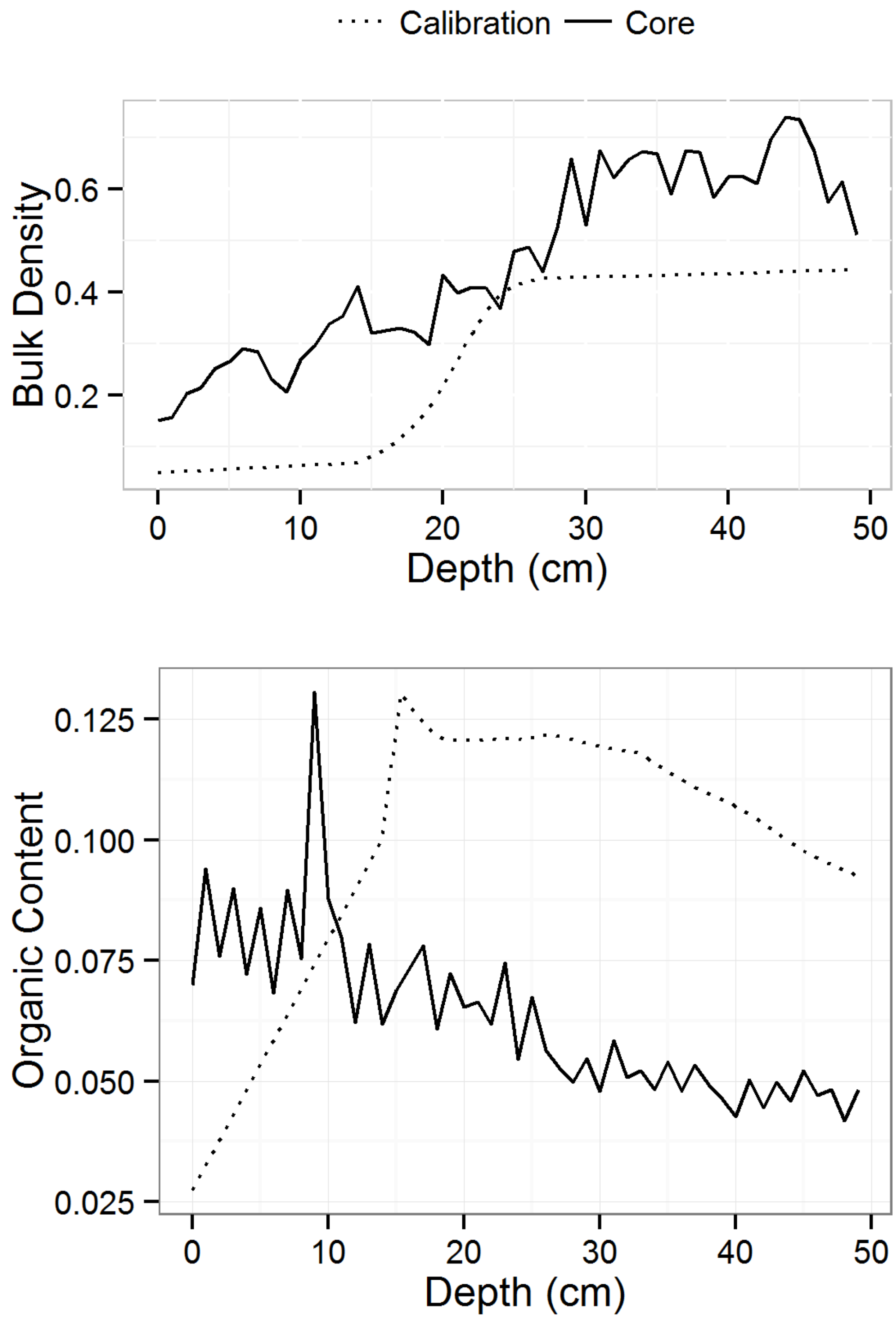

Figure E8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table E4. Model input parameters for Grays Harbor. 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})	1.67	Core calibration
Elevation of peak biomass (cm, MSL)	159	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	11	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0677	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	98	Core
Porosity depth (%)	81	Core
Refractory carbon (%)	52.5	Core
Maximum astronomical tide (cm, MSL)	200	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.05	Westport tide gauge (NOAA, 9441102)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

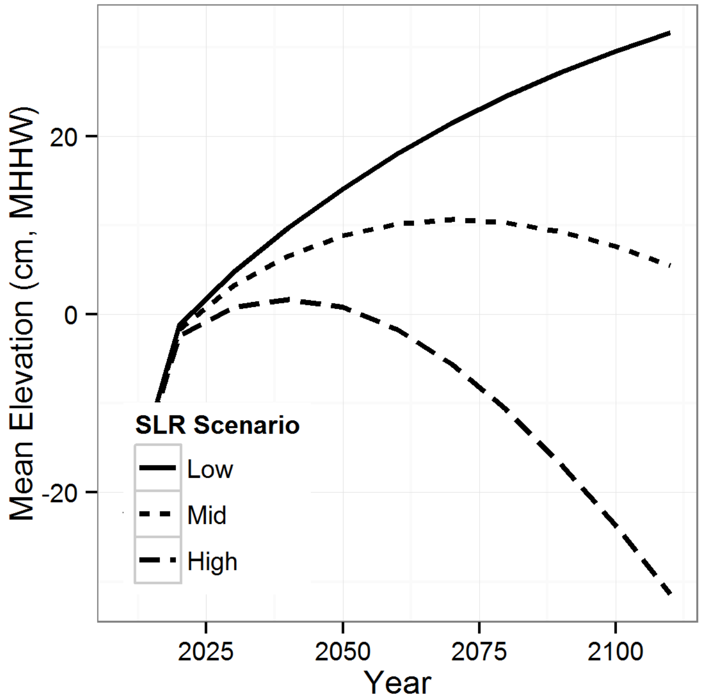

Figure E9. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Grays Harbor from 2010 to 2110 under low, mid, and high NRC sea-level rise (SLR) scenarios.

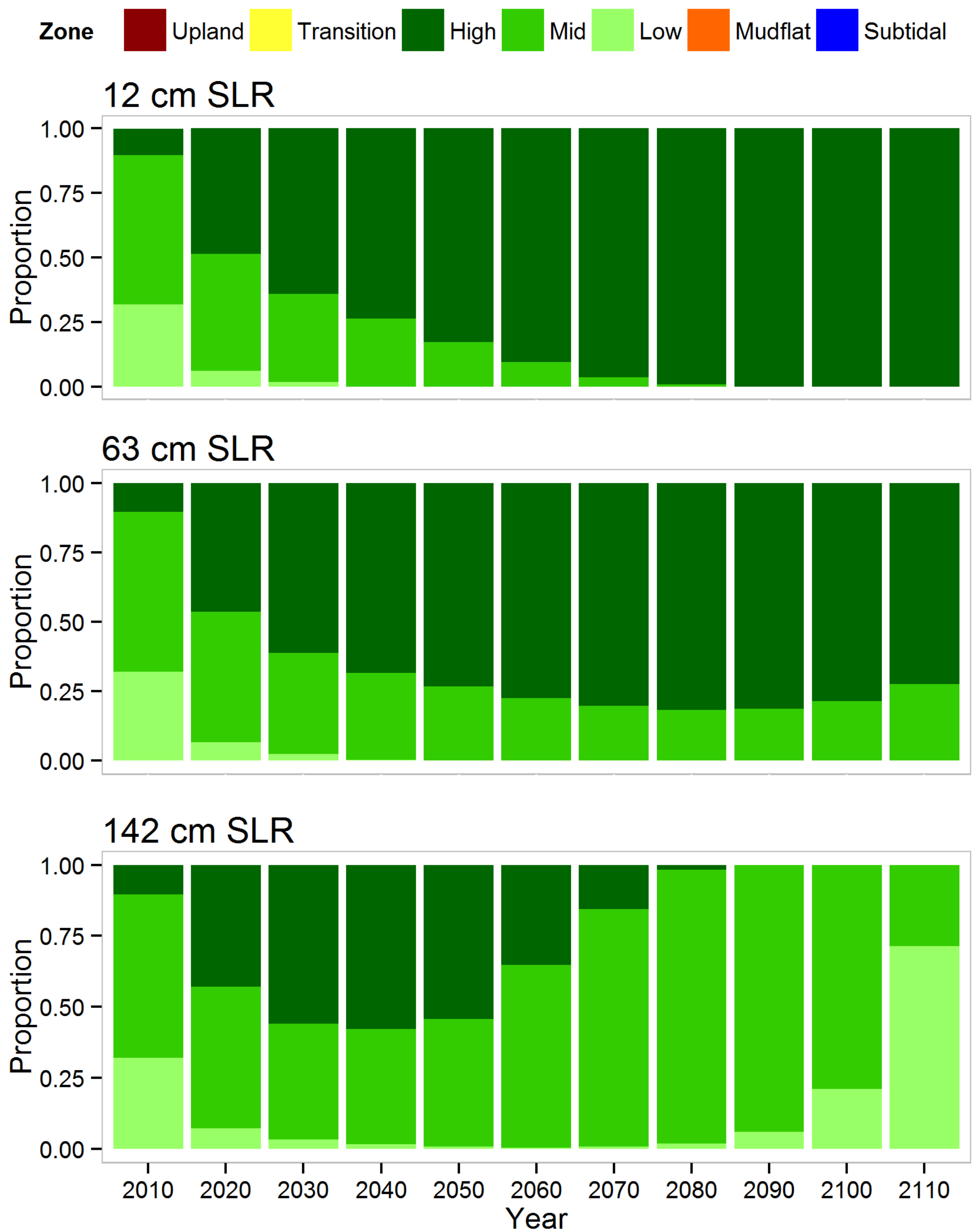

Figure E10. Model projections for change in the relative proportion of upland, transitional, high, mid, and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table E5. 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)		
	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	10	83	100	10	73	72	10	54	0
Mid	58	17	0	58	27	28	58	45	29
Low	32	0	0	32	0	0	32	1	71
Mudflat	0	0	0	0	0	0	0	0	0
Subtidal	0	0	0	0	0	0	0	0	0

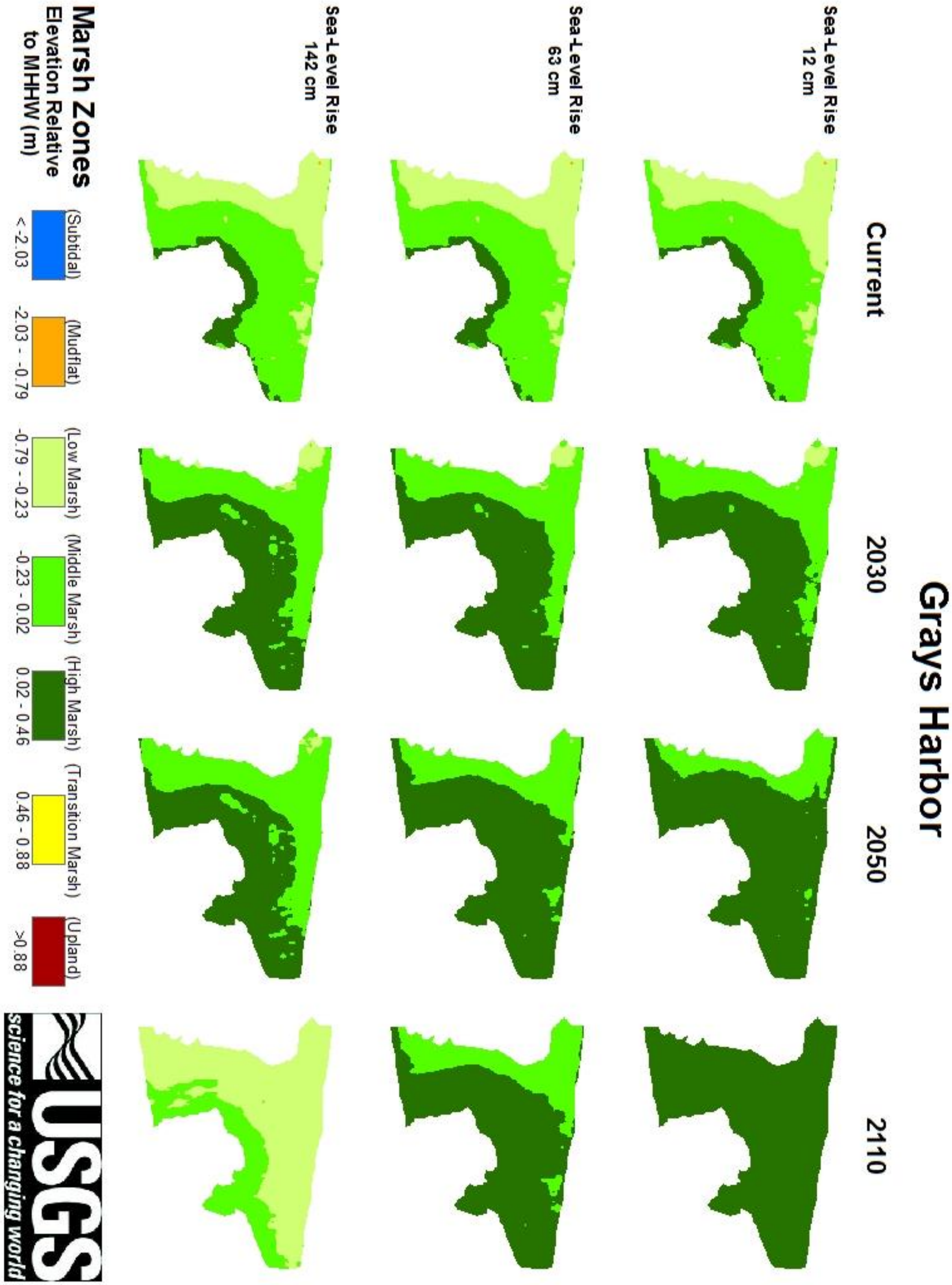

Figure E11. Projected habitat distribution at Grays Harbor for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

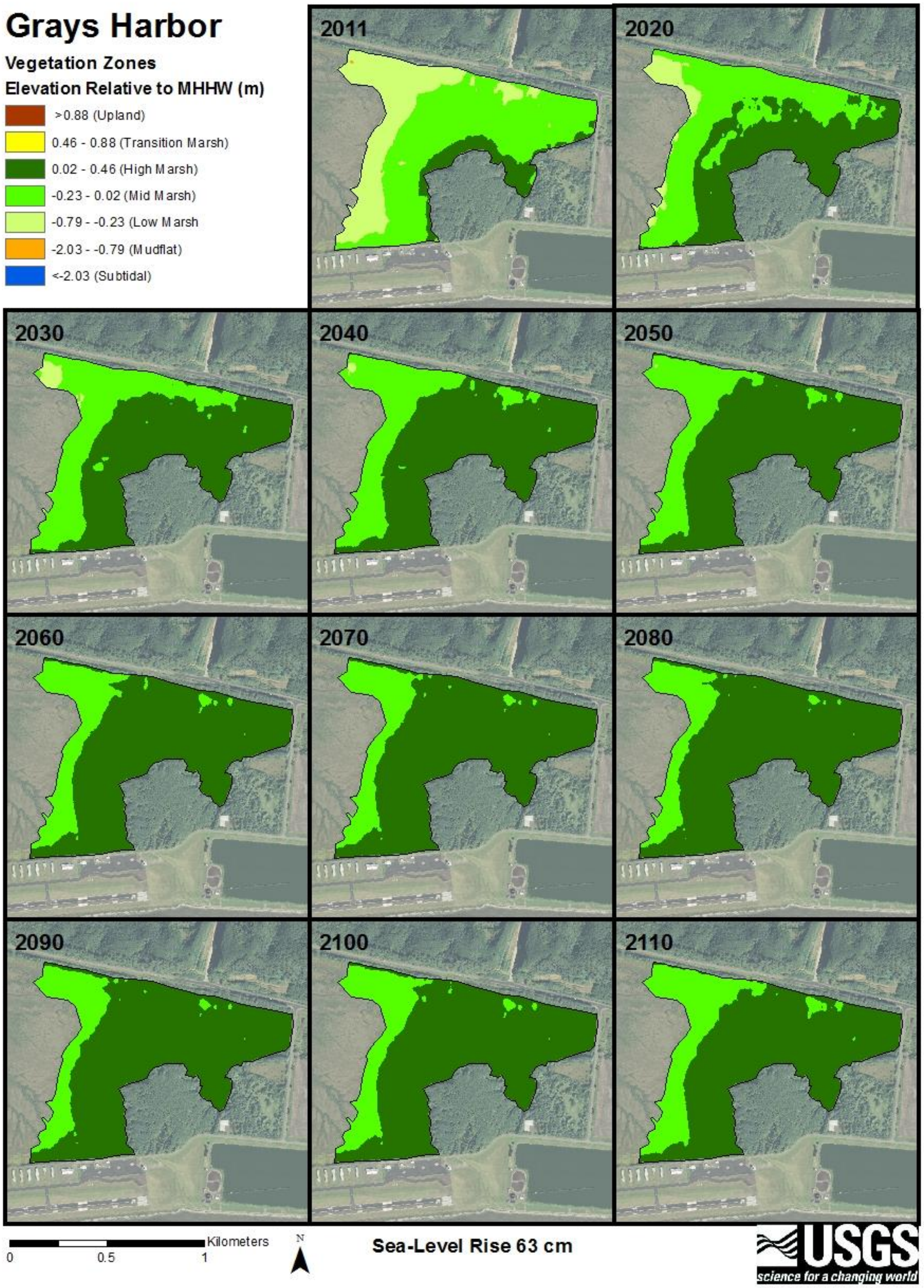

Figure E12. Projected changes in Grays Harbor elevation zones under the mid NRC sea-level rise scenario (63 cm).

Willapa, Tartlatt Slough, Willapa Bay National Wildlife Refuge**,** Pacific County, Washington, USA

Photo: K. Powelson, USGS

Summary:

- *Study site size*: 74.8 hectares
- *Location*: 46° 22' 32"N latitude, 124° 00' 21"W longitude.
- *Site management*: U.S. Fish and Wildlife Service (Willapa Bay National Wildlife Refuge)
- *Site vegetation and elevation survey*: 12-17 September 2012
- *Sample size*: 1230 (elevation data points), 276 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was above MHHW, with 56% of elevation data points occurring above MHHW.
- *Plant community composition*: *Distichlis spicata* was the most frequently occurring species. *Triglochin maritima* and *Sarcocornia perennis* were also very common.
- *Bathymetric surveys*: 84.1 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: sediment accumulation rate = 1.53 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.024 g cm^{-2} yr^{-1}; net accretion = 1.554 cm yr^{-1}.

- *Water inundation and salinity monitoring*: water level (October 2012 – July 2013); conductivity (August 2013 – December 2013). Water level and conductivity monitoring is ongoing.
- The maximum recorded salinity throughout the study period was 35 PSU.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during January 2013; minimum monthly inundation occurred during October 2012 and July 2013.
- *Calculated tidal datums*: MHHW is at 2.24 m NAVD88; MHW is at 2.01 m NAVD88.
- *Sea-level rise marsh response modeling*: Under the NRC low SLR projection (12 cm), Willapa Bay gains high and middle marsh habitat and low marsh is lost by 2060. Under the NRC's mid SLR projection (63 cm), the site is projected to have a temporary expansion of mid marsh, followed by loss of high marsh by 2110. Under the NRC's high SLR projection (142 cm), high marsh is lost by 2080, mid marsh is lost by 2090, and the site is projected to consist primarily of low marsh with some mudflat by 2110.

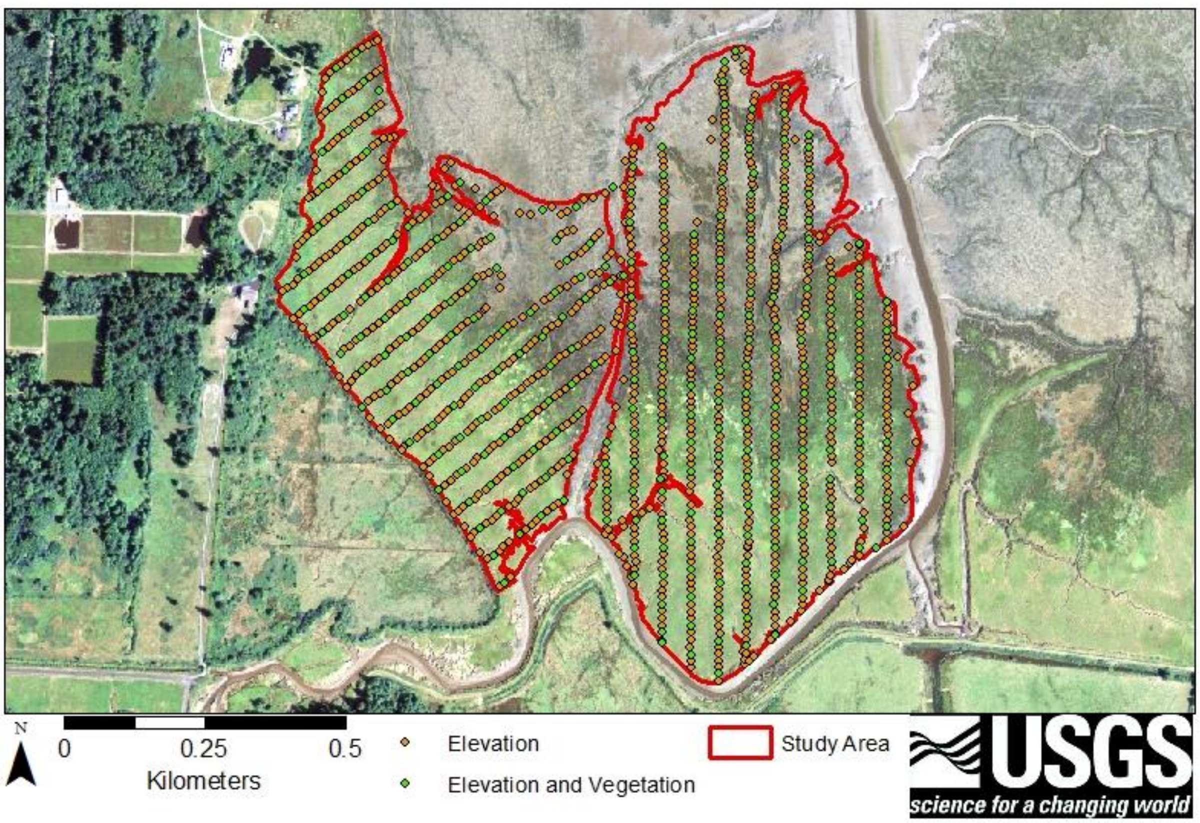

Figure F1. Distribution of elevation and vegetation survey points at Willapa.

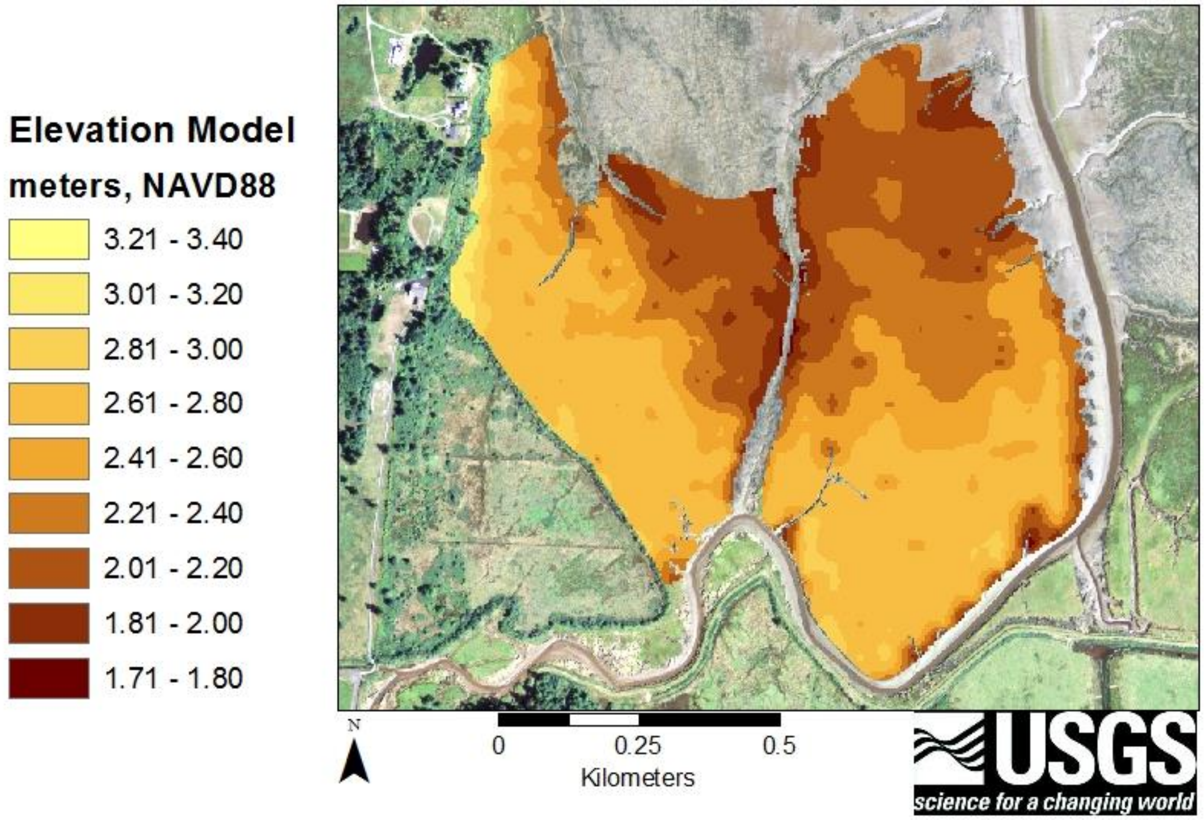

Figure F2. Elevation model (3 m resolution) developed from RTK GPS survey data.

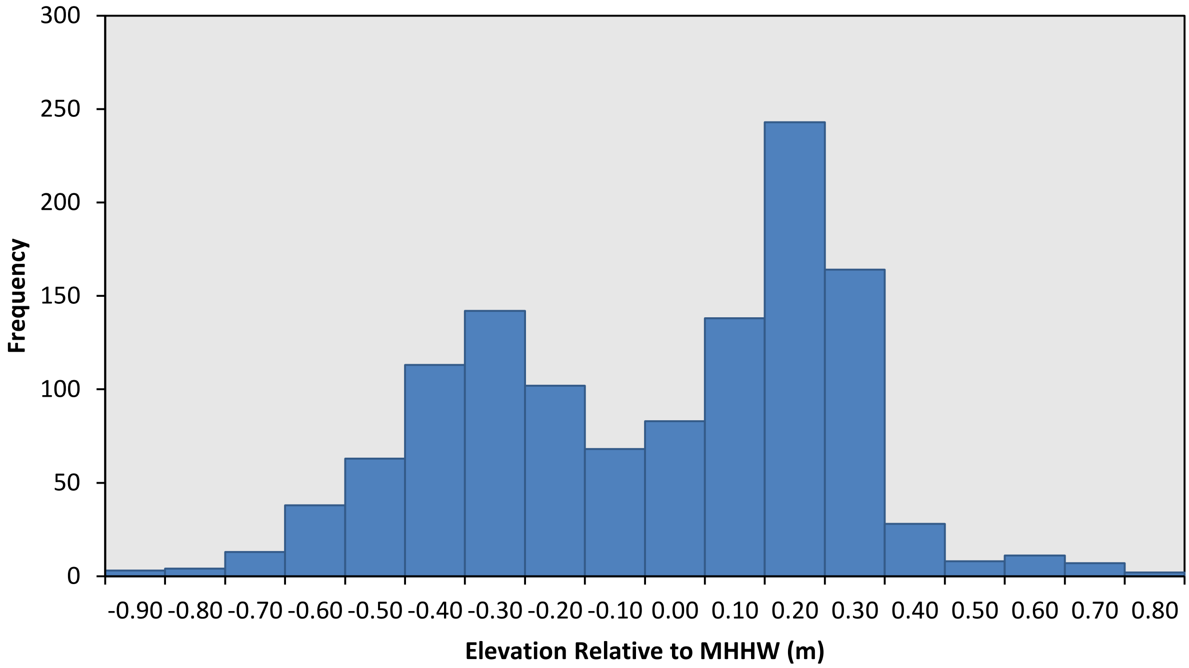

Figure F3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW) at Willapa.

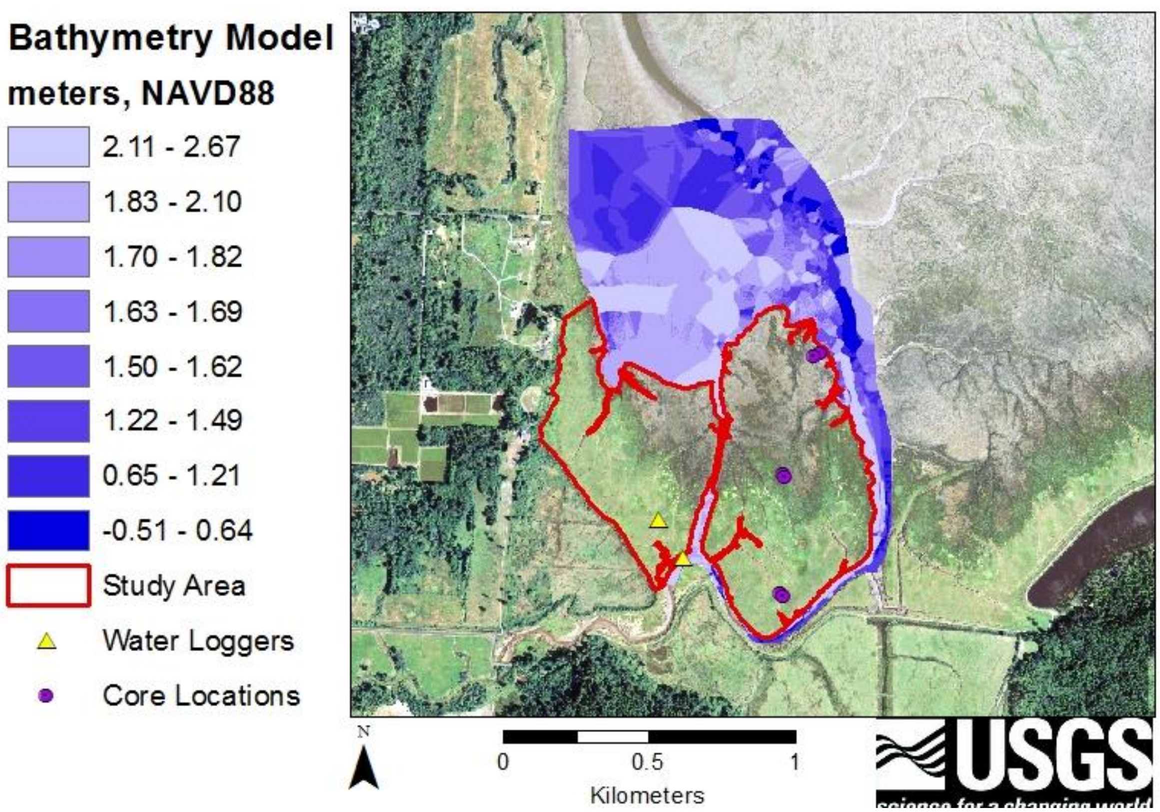

Figure F4. Near-shore bathymetry model for Willapa. Water level logger and core locations are shown within the marsh study site.

Table F1. Frequency of occurrence, percent cover, and height of vascular plant species encountered in sample plots at Willapa. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Distichlis spicata	Native perennial grass	62	38	35
Triglochin maritima	Native perennial forb	48	13	38
Sarcocornia perennis	Native perennial forb	42	14	23
Deschampsia cespitosa	Native perennial grass	41	17	61
Carex lyngbyei	Native perennial sedge	34	14	59
Jaumea carnosa	Native perennial forb	12	4	24
Stellaria humifusa	Native perennial forb	11	1	30
Agrostis stolonifera	Non-native perennial grass	7	3	36
Spergularia canadensis	Native annual forb	7	0	6
Atriplex prostrata	Non-native annual forb	6	0	28
Hordeum brachyantherum	Native perennial grass	6	0	58
Potentilla anserina	Native ann-perennial forb	5	2	37
Juncus balticus	Native perennial rush	2	1	52
Glaux maritima	Native perennial forb	1	0	15
Cotula coronopifolia	Non-native perennial forb	1	0	7
Cuscuta pacifica	Native ann-perennial parasite	0	NA	NA
Hordeum jubatum	Native ann-perennial grass	0	0	68
Plantago maritima	Native perennial forb	0	0	15
Symphyotrichum subspicatum	Native perennial forb	0	0	59

Table F2. Mean percent cover of dominant plant species by marsh zone at Willapa. Zones were defined by degree of flooding by high tides. AgrSto = *Agrostis stolonifera*; CarLyn = *Carex lyngbyei*; DisSpi = *Distichlis spicata*, DesCes = *Deschampsia cespitosa*; SarPer = *Sarcocornia perennis*; TriMar = *Triglochin maritima*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	1.162 to 0.603	0	*Insufficient sample size*
High	3-25	0.602 to 0.028	138	DisSpi (55), DesCes (28), CarLyn (18), AgrSto (6)
Middle	25-50	0.027 to -0.296	61	DisSpi (32), SarPer (29), TriMar (22), CarLyn (16)
Low	>50	-0.297 to -0.948	77	TriMar (26), SarPer (19), DisSpi (11), CarLyn (6)

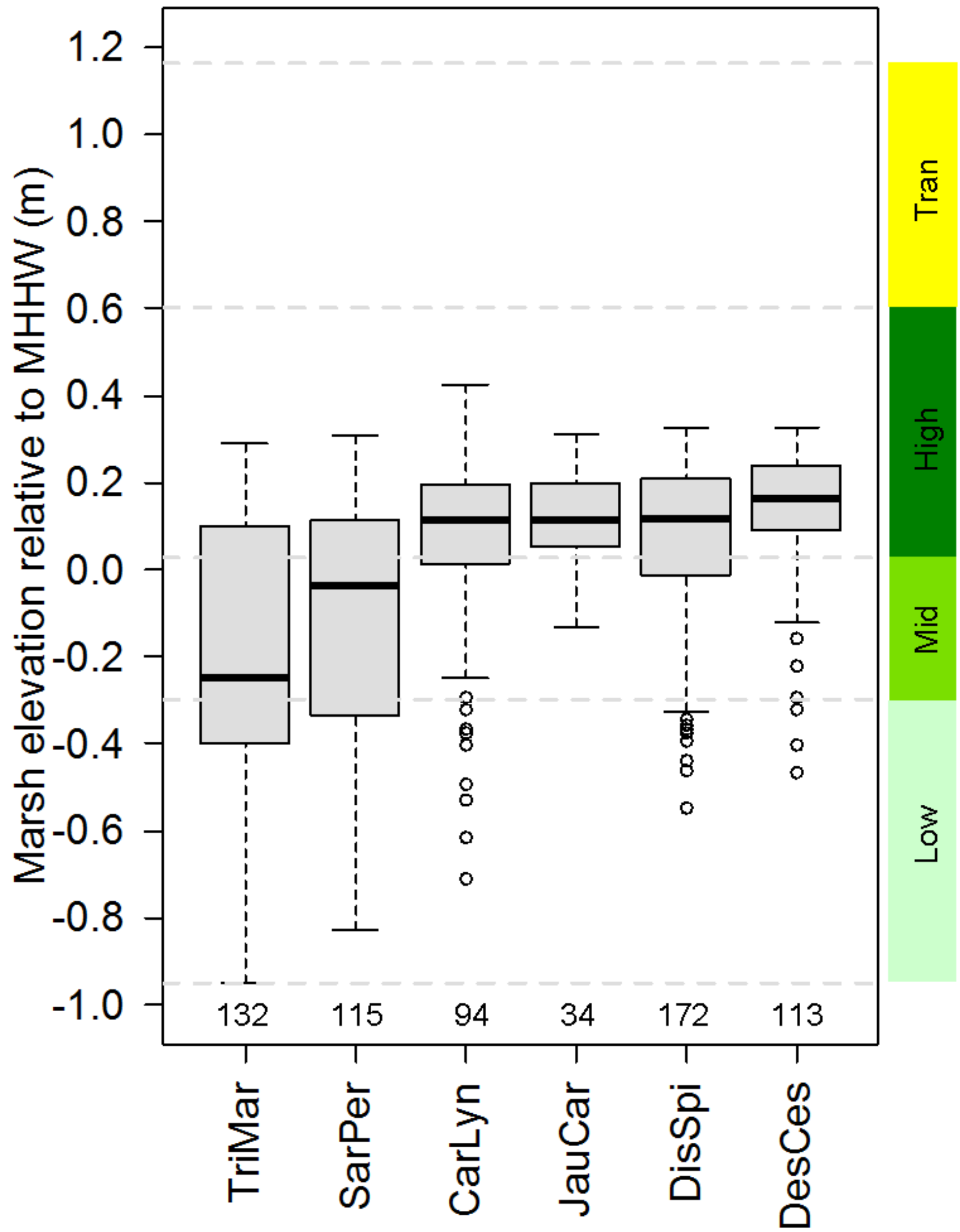

Figure F5. Elevation distribution of the six most common vascular plant species at Willapa. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 276 plots). Marsh elevation zones (low, middle, and high) are illustrated at right. TriMar = *Triglochin maritima*; SarPer = *Sarcocornia perennis*; CarLyn = *Carex lyngbyei*, JauCar = *Jaumea carnosa*, DisSpi = *Distichlis spicata*; DesCes = *Deschampsia cespitosa*.

Table F3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	422302	5135993
	422220	5136127
Deep core locations	422774	5136697
	422645	5136284
	422647	5135865

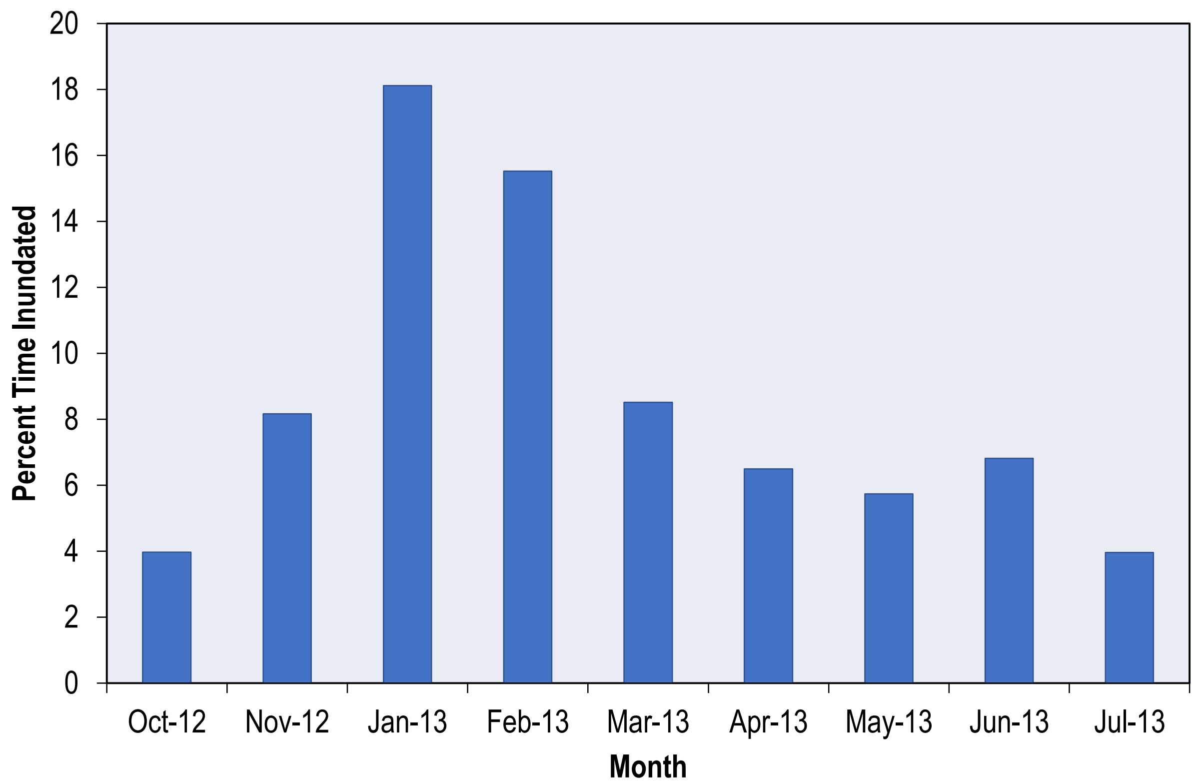

Figure F6. Average monthly inundation of the study site based on an average marsh elevation.

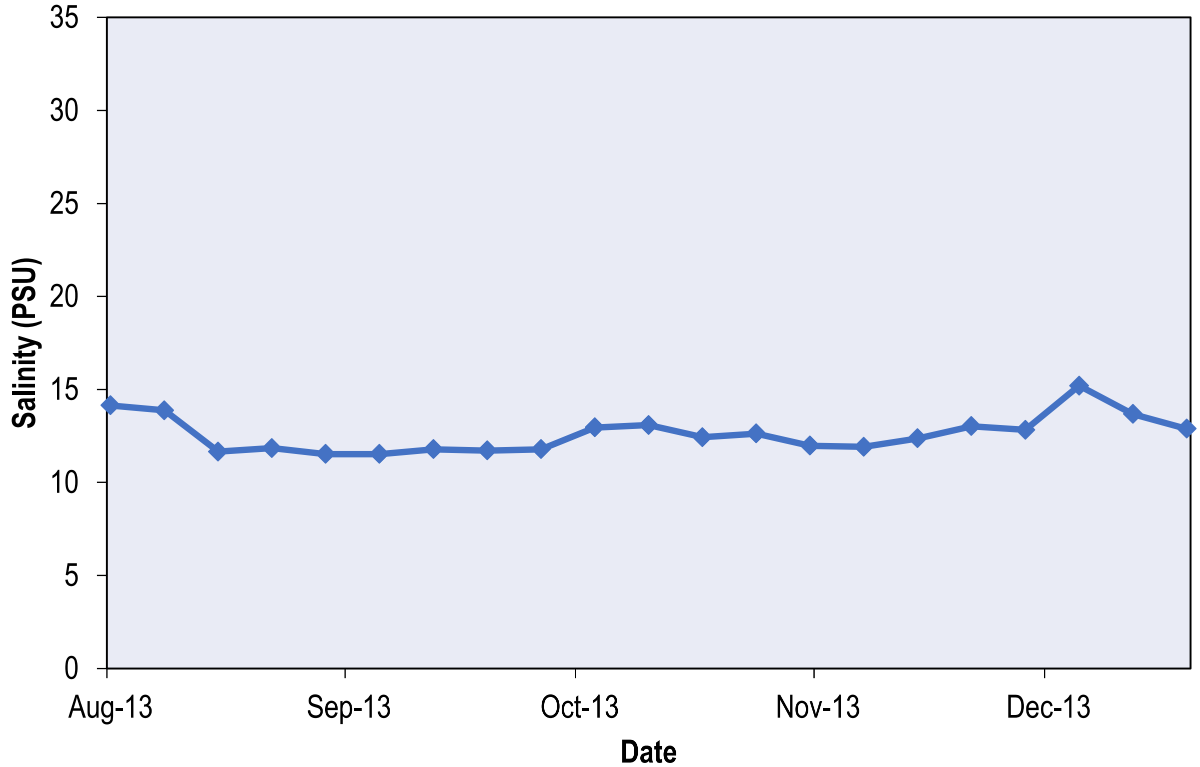

Figure F7. Maximum weekly salinity from August 2013 – December 2013 at Willapa. Seawater is approximately 35 PSU.

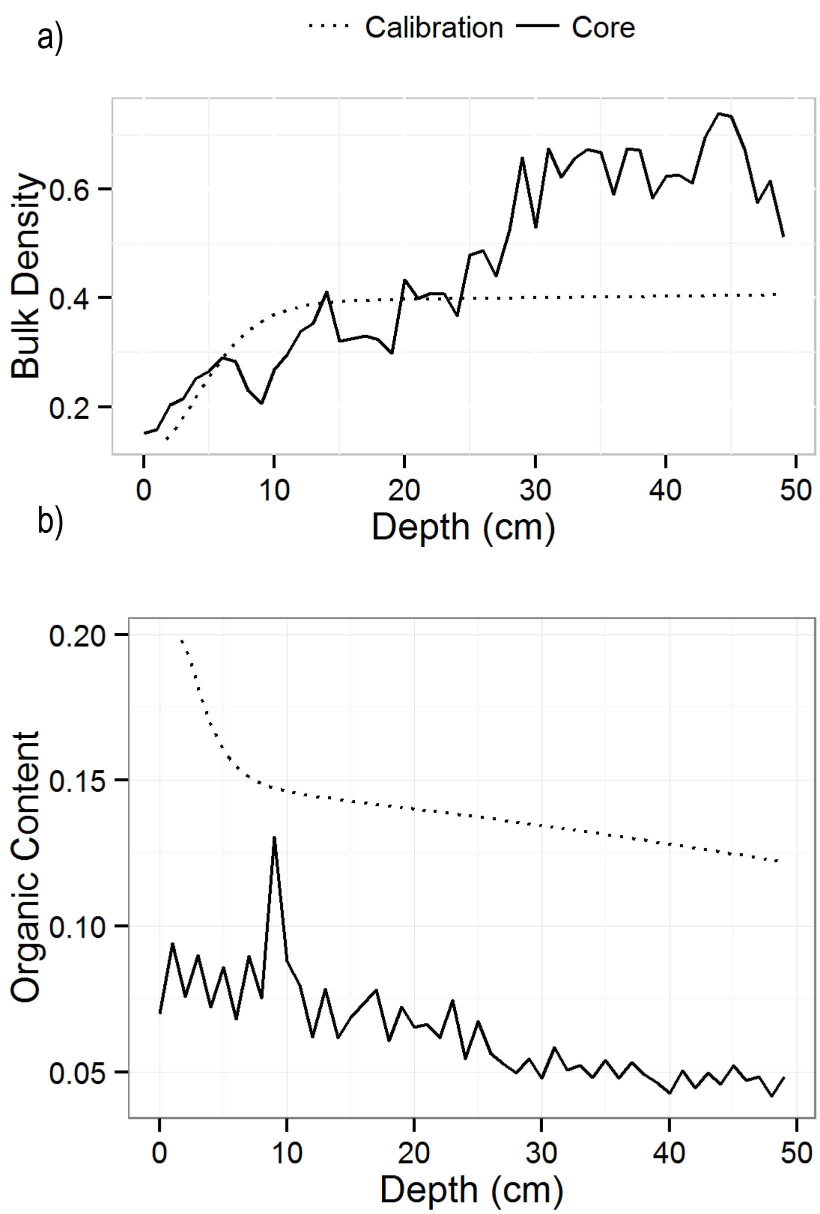

Figure F8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table F4. Model input parameters for Willapa. 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})	1.10	Core calibration
Elevation of peak biomass (cm, MSL)	163	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	40	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0252	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	92	Core
Porosity depth (%)	75	Core
Refractory carbon (%)	63.4	Core
Maximum astronomical tide (cm, MSL)	232	CERCC water logger
Historic sea-level rise (mm yr^{-1})	1.6	Toke Point tide gauge (NOAA, 9440910)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

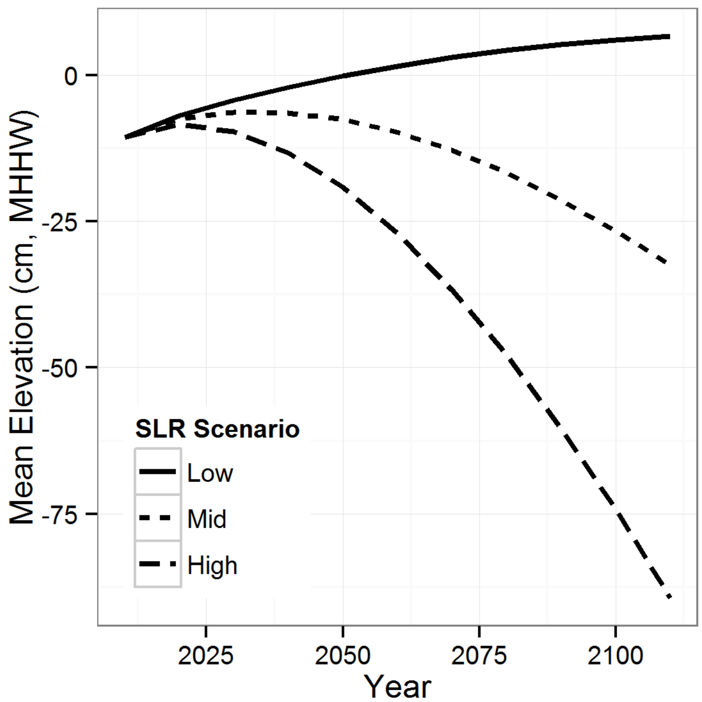

Figure F9. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Willapa from 2010 to 2110 under low, mid, and high NRC sea-level rise (SLR) scenarios.

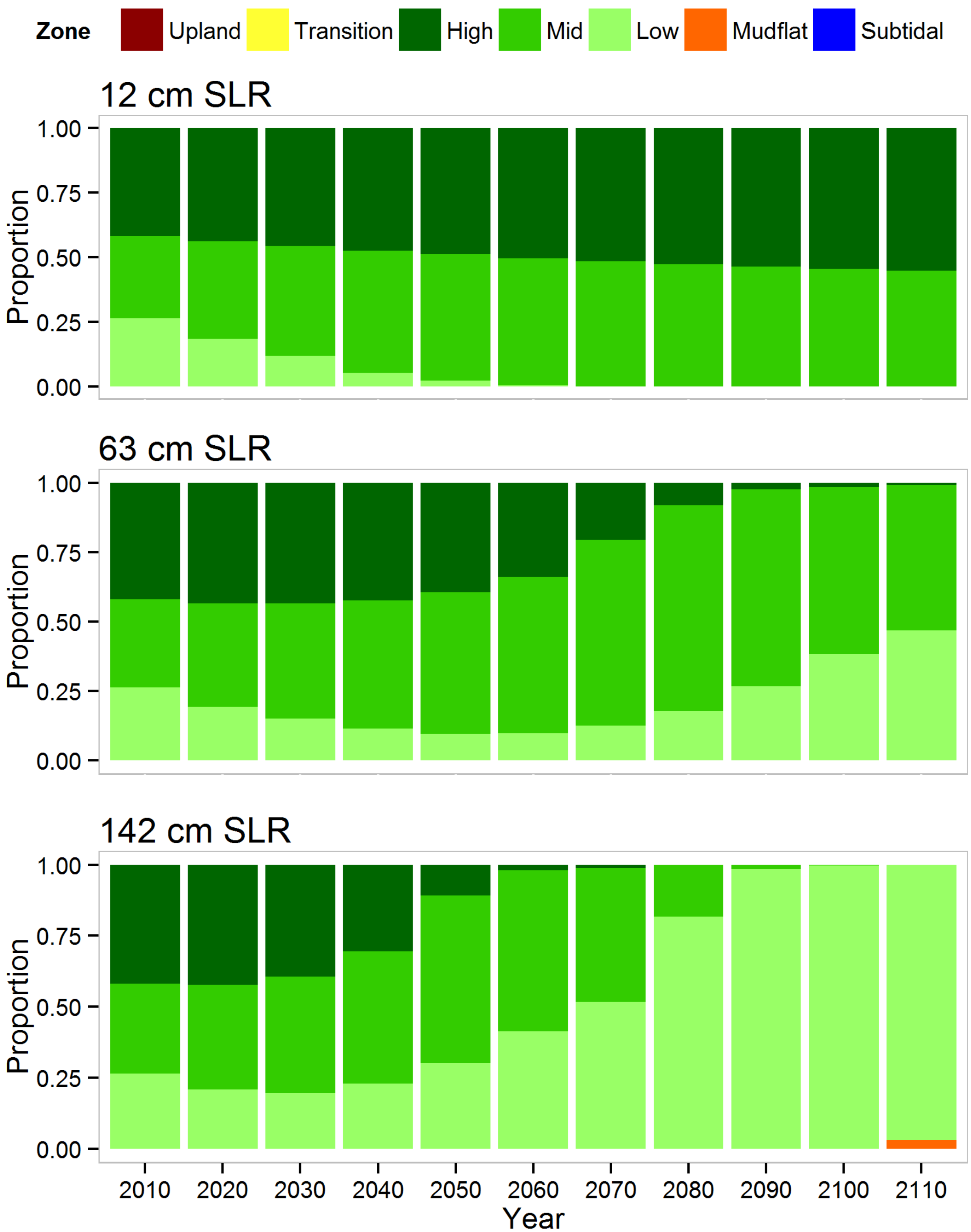

Figure F10. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table F5. 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)		
	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	42	49	55	42	39	1	42	11	0
Mid	32	49	45	32	51	52	32	59	0
Low	26	2	0	26	10	47	26	30	97
Mudflat	0	0	0	0	0	0	0	0	3
Subtidal	0	0	0	0	0	0	0	0	0

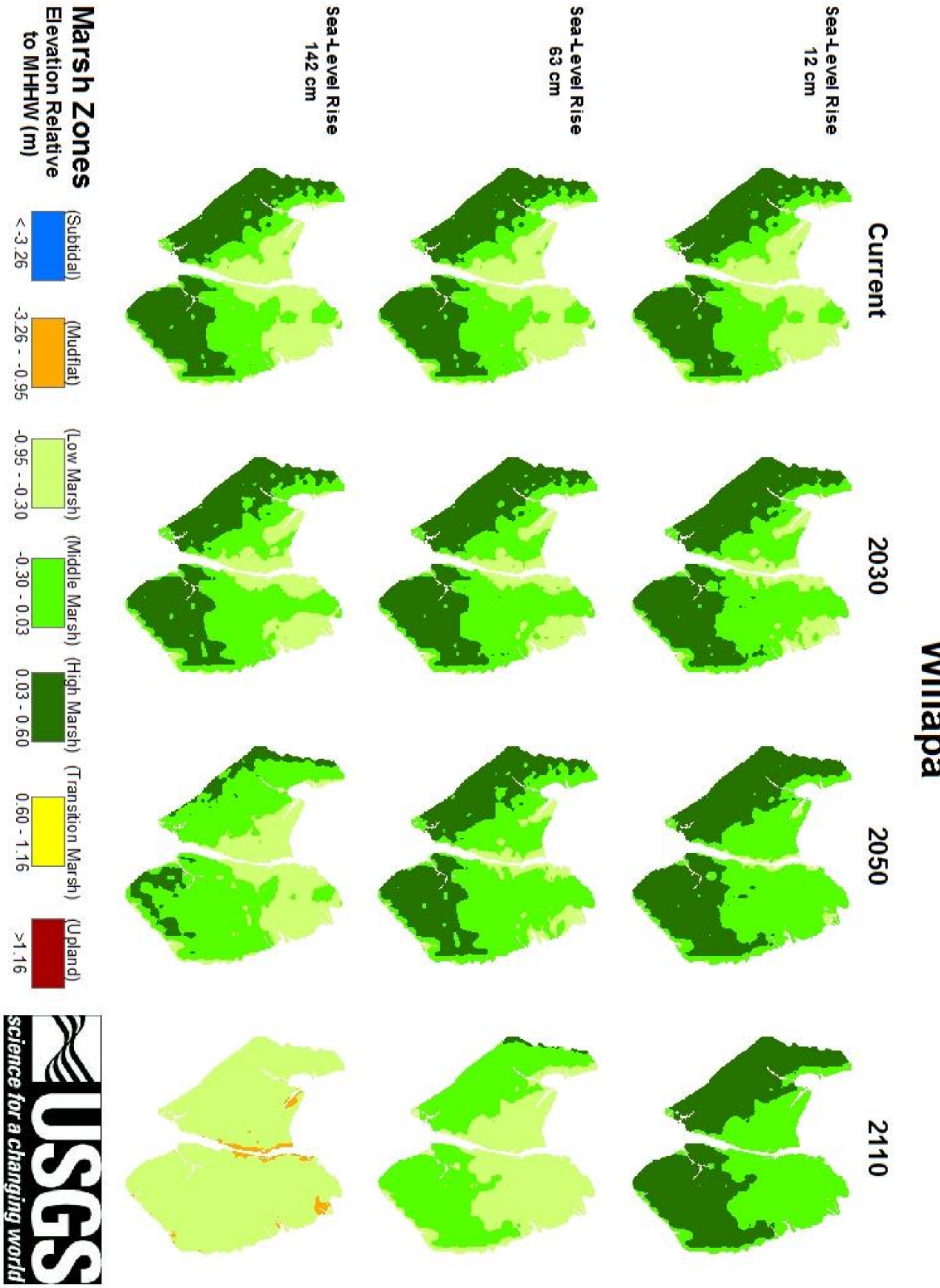

Figure F11. Projected habitat distribution at Willapa for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

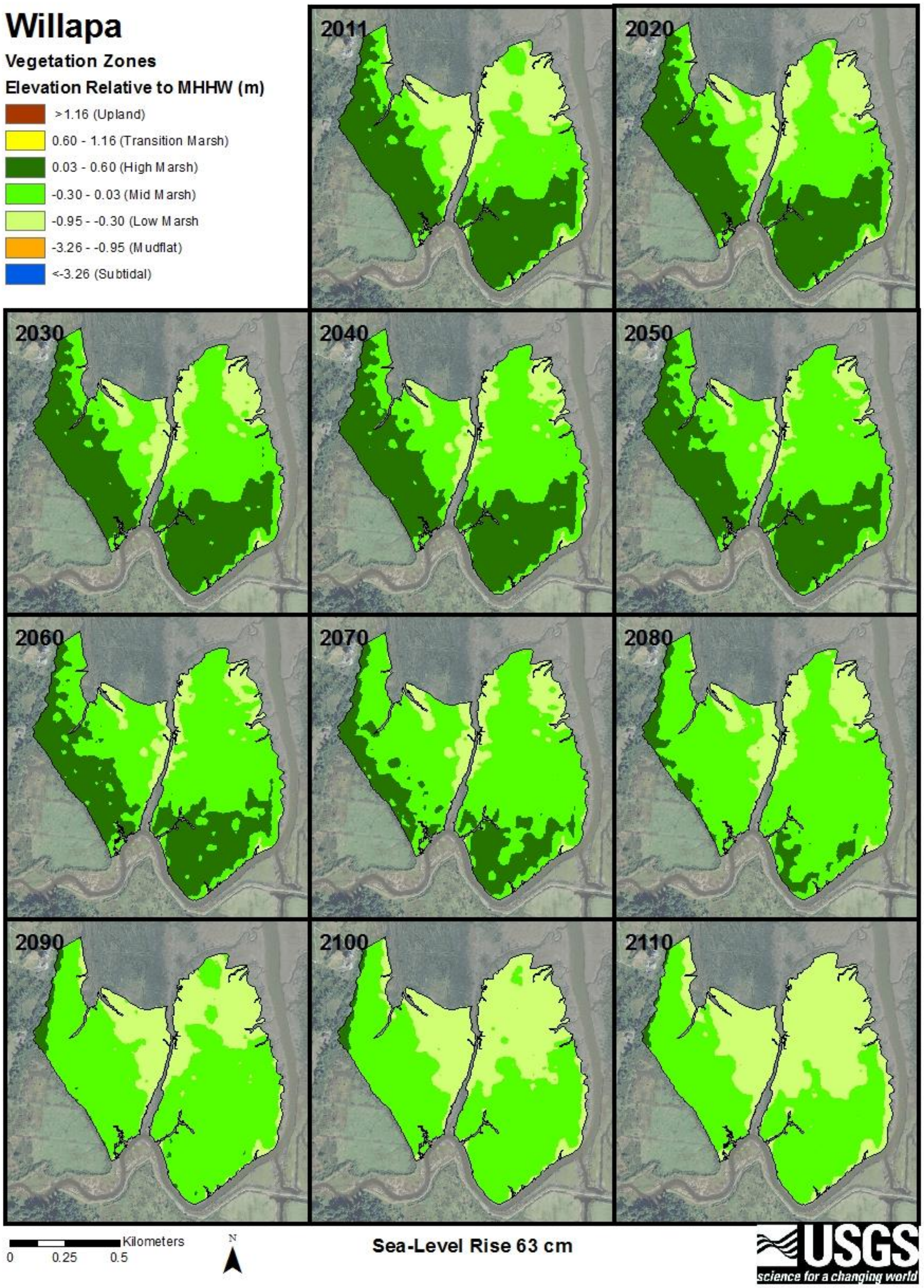

Figure F12. Projected changes in Willapa habitat zones under the mid NRC sea-level rise scenario (63 cm).

Siletz, Siletz Bay National Wildlife Refuge, Lincoln County, Oregon, USA

Photo: K Buffington, Oregon State University & USGS

Summary:

- *Study site size*: 69.2 hectares
- *Location*: 44° 53' 41"N latitude, 124° 00' 59"W longitude.
- *Site management*: U.S. Fish and Wildlife Service (Siletz National Wildlife Refuge)
- *Site vegetation and elevation survey*: 25 August – 4 September 2014
- *Sample size*: 1196 (elevation data points), 126 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was above MHHW, with 79% of elevation data points occurring above MHHW.
- *Plant community composition*: *Agrostis stolonifera* was the most frequently occurring species. *Juncus balticus*, *Potentilla anserina* and *Deschampsia cespitosa* were also common.
- *Bathymetric surveys*: Not conducted
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: sediment accumulation rate = 0.79 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.0302 g cm^{-2} yr^{-1}; net accretion = 0.8202 cm yr^{-1}.

- *Water inundation and salinity monitoring*: water level (January 2014– August 2014); conductivity (April 2014 – August 2014). Water level and conductivity monitoring is ongoing.
- The maximum recorded salinity throughout the study period was 32 PSU.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during June 2014; minimum monthly inundation during July 2014.
- *Calculated tidal datums*: MHHW is at 2.32 m NAVD88; MHW is at 2.11 m NAVD88.
- *Sea-level rise marsh response modeling*: Under the low NRC SLR projection (12 cm), Siletz becomes dominated by high and transitional marsh by 2080. Under the NRC's mid SLR projection (63 cm), the composition of marsh zones at the site remains relatively unchanged over the coming century. High marsh initially increases slightly in area but then decreases. Under the NRC's high SLR projection (142 cm), there is rapid loss of high marsh between 2050 and 2070, complete loss of mid marsh by 2100, and almost complete conversion to mudflat by 2110.

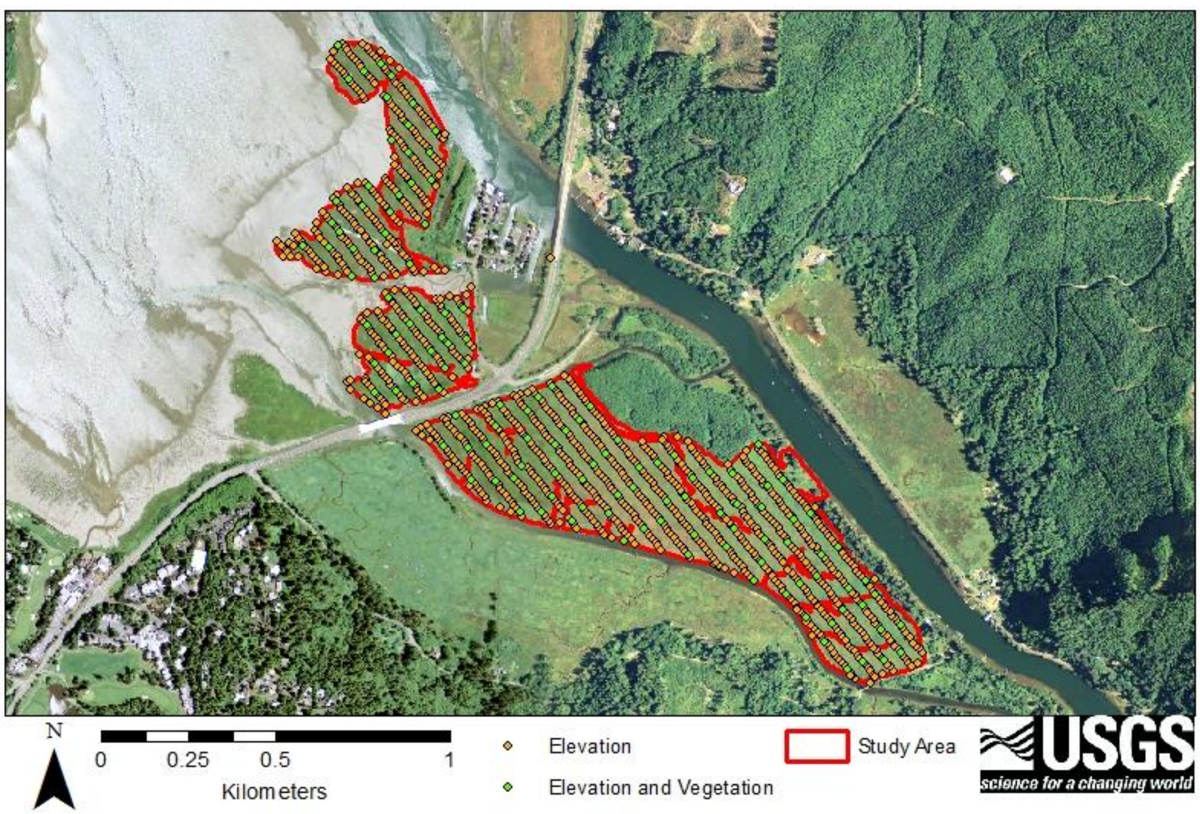

Figure G1. Distribution of elevation and vegetation survey points at Siletz.

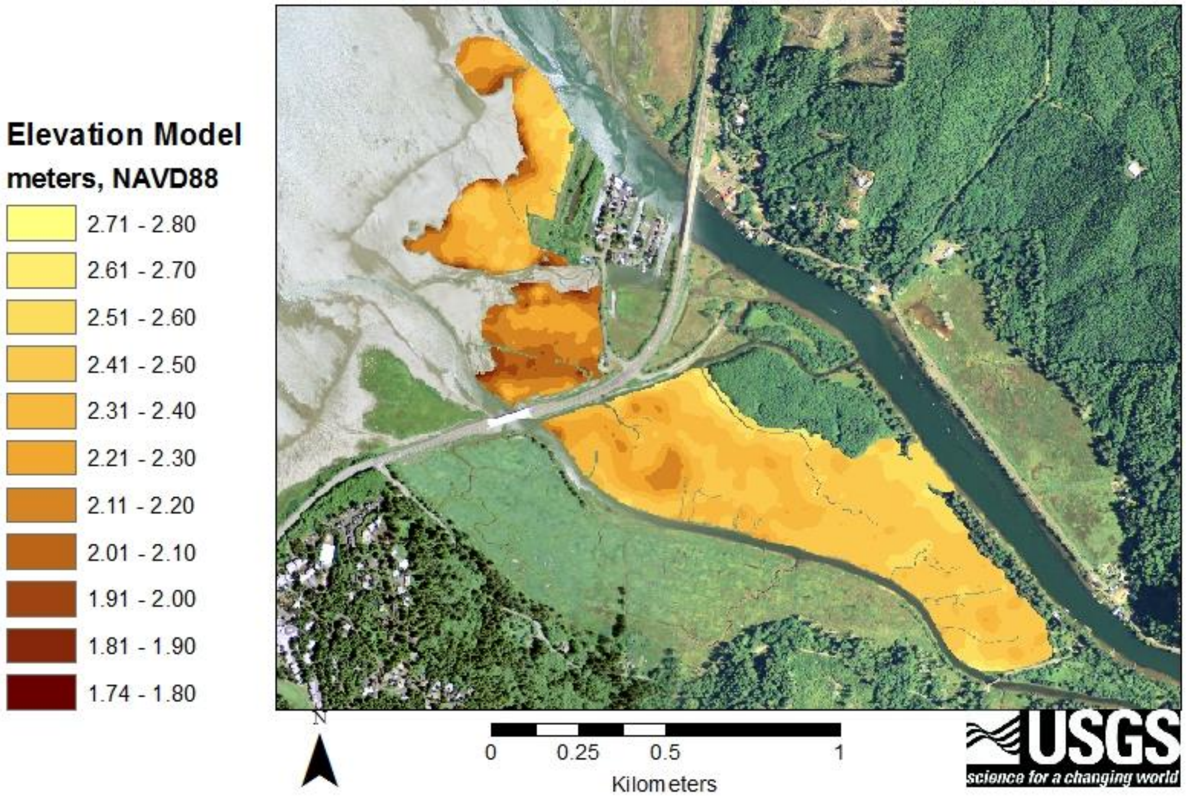

Figure G2. Elevation model (3 m resolution) developed from RTK GPS survey data.

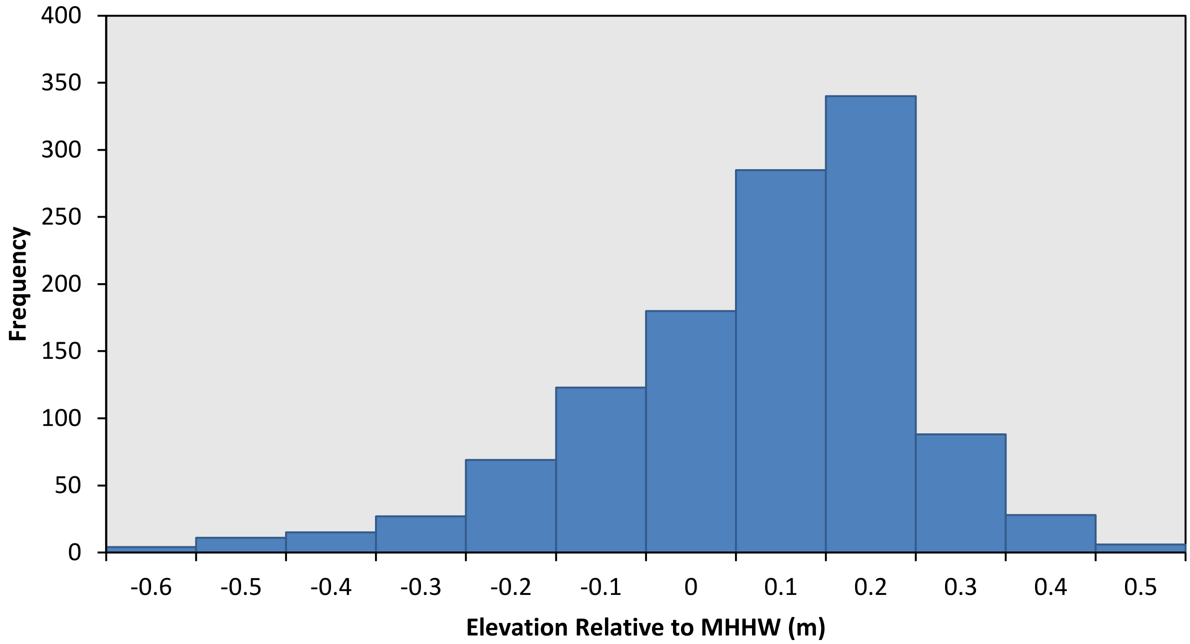

Figure G3. Frequency distribution of marsh surface elevation data points relative to local mean higher high water (MHHW) at Siletz.

Table G1. Frequency of occurrence, percent cover and height of vascular plant species encountered in sample plots at Siletz. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)
Agrostis stolonifera	Non-native perennial grass	84	59
Juncus balticus	Native perennial rush	53	22
Potentilla anserina	Native ann-perennial forb	51	23
Deschampsia cespitosa	Native perennial grass	46	16
Carex lyngbyei	Native perennial sedge	34	10
Distichlis spicata	Native perennial grass	25	6
Triglochin maritima	Native perennial forb	25	3
Sarcocornia perennis	Native perennial forb	21	6
Atriplex prostrata	Native annual forb	16	3
Glaux maritima	Native perennial forb	15	1
Symphyotrichum subspicatum	Native perennial forb	13	2
Galium trifidum	Native ann-perennial forb	9	0
Heracleum maximum	Native perennial forb	7	0
Grindelia stricta	Native perennial forb	6	2
Jaumea carnosa	Native perennial forb	6	3
Achillea millefolium	Native perennial forb	6	2
Vicia gigantea	Native perennial legume	5	0
Hordeum brachyantherum	Native perennial grass	3	0
Atriplex patula	Native annual forb	3	0
Stellaria humifusa	Native perennial forb	3	0
Cirsium sp.	Forb	2	0
Plantago maritima	Native perennial forb	2	0
Rumex sp.	Forb	2	0
Holcus lanatus	Non-native ann-perennial grass	2	0
Phalaris arundinacea	Perennial grass	1	1
Carex obnupta	Native perennial sedge	1	1
Unidentified species 1	NA	1	0
Isolepis cernua	Native annual sedge	1	0
Lathrys palustris	Native perennial legume	1	0
Lilaeopsis occidentalis	Native perennial forb	1	0
Unidentified species 2	NA	1	0

Table G2. Mean percent cover of dominant plant species by marsh zone at Siletz. Zones were defined by degree of flooding by high tides. AgrSto = *Agrostis stolonifera*; PotAns = *Potentilla anserina*; JunBal = *Juncus balticus*; DesCes = *Deschampsia cespitosa*; CarLyn = *Carex lyngbyei*; DisSpi = *Distichlis spicata*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.850 to 0.473	0	*Insufficient sample size*
High	3-25	0.472 to 0.022	72	AgrSto (63), PotAns (38), JunBal (27), DesCes (13)
Middle	25-50	0.021 to -0.235	45	AgrSto (59), CarLyn (20), DesCes (19), JunBal (17)
Low	>50	-0.236 to -0.488	9	CarLyn (34), DesCes (32), AgrSto (24), DisSpi (22)

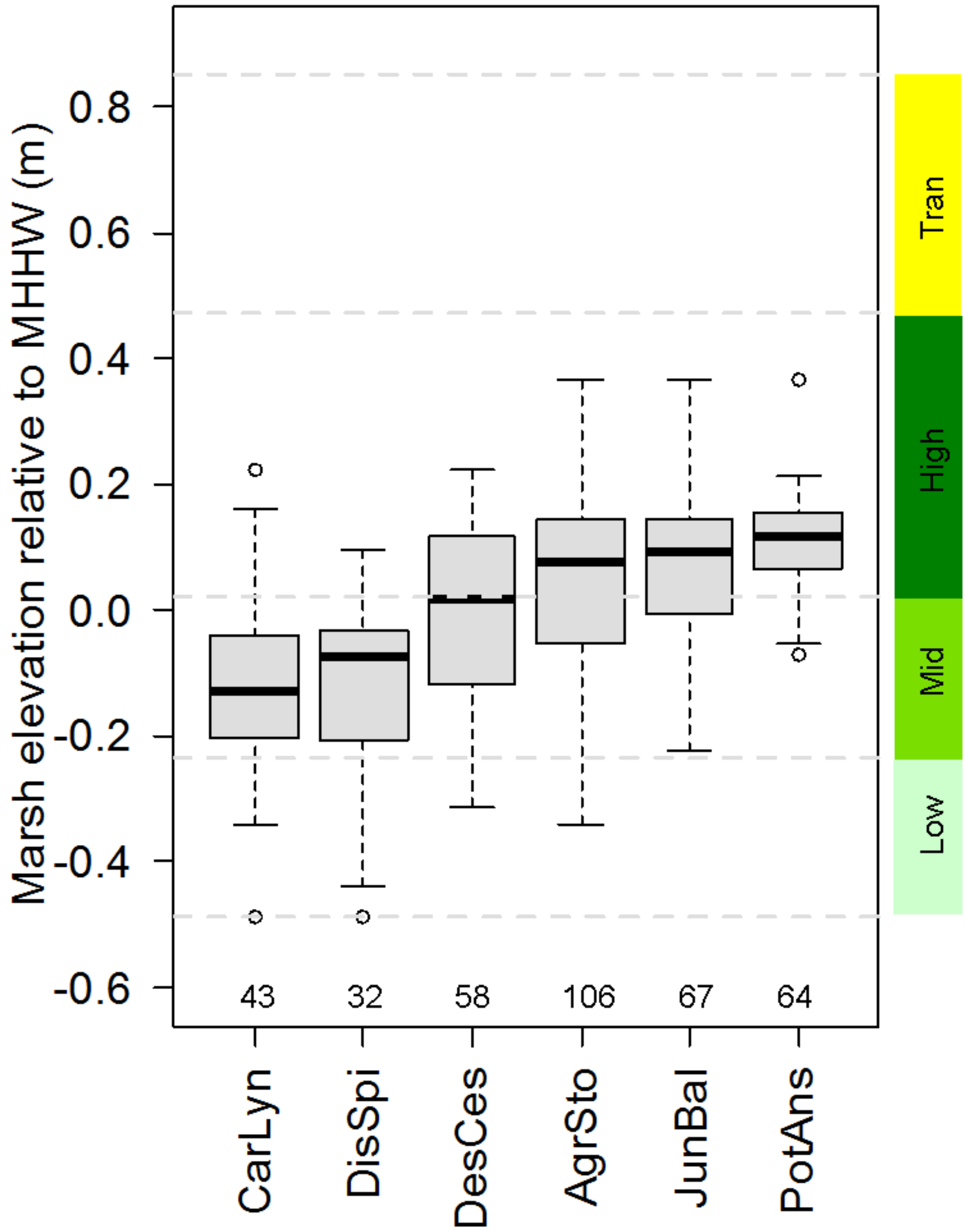

Figure G4. Elevation distribution of the six most common vascular plant species at Siletz. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 126 quadrats). Marsh elevation zones (low, middle, high and transition) are illustrated at right. CarLyn = *Carex lyngbyei*; DisSpi = *Distichlis spicata*; DesCes = *Deschampsia cespitosa*; AgrSto = *Agrostis stolonifera*; JunBal = *Juncus balticus*; PotAns = *Potentilla anserina*.

Table G3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	4971681	419970
	4971330	421129
Deep core locations	420040	4971938
	420817	4971477
	421376	4971001

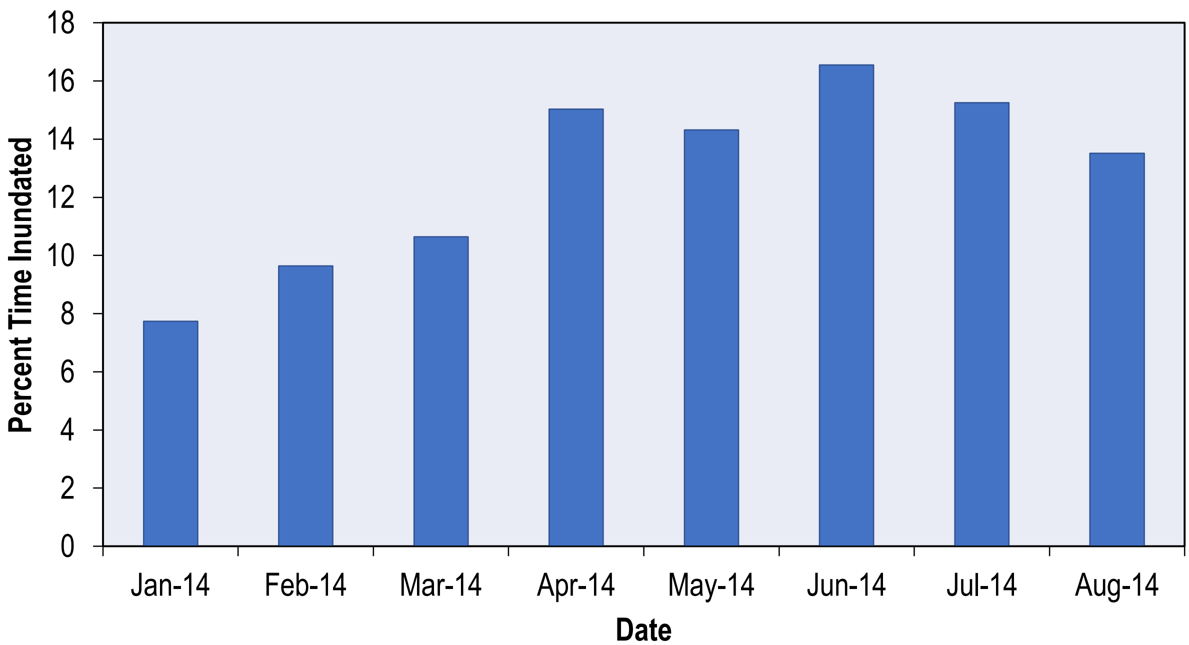

Figure G5. Average monthly inundation of the study site based on an average marsh elevation.

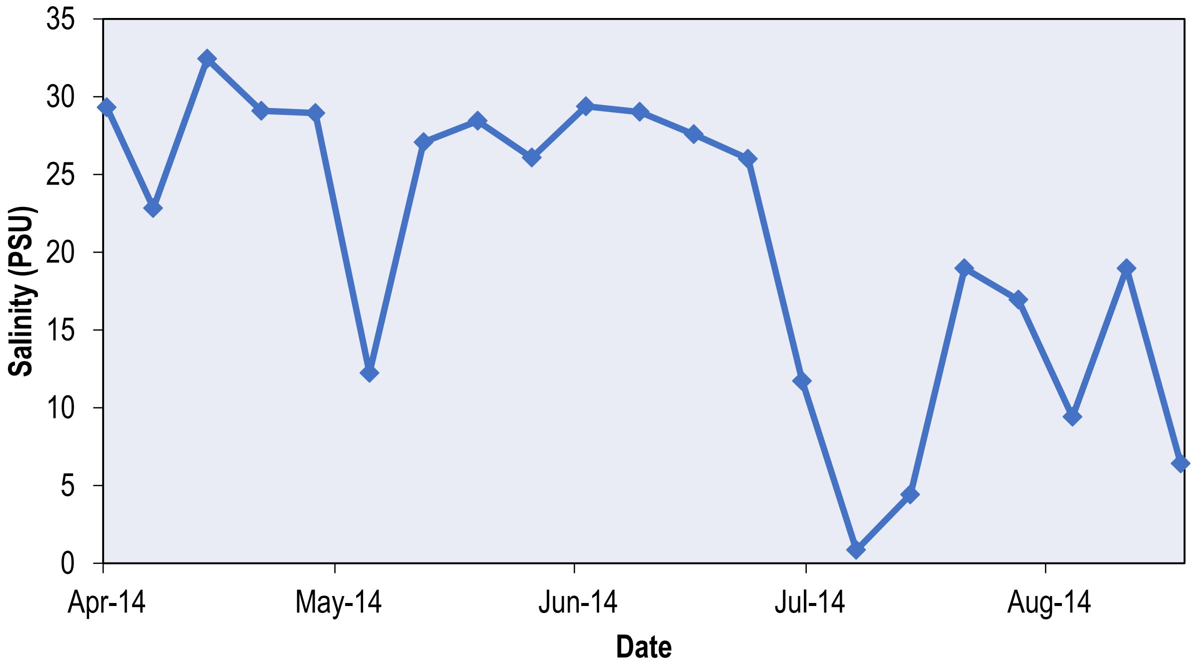

Figure G6. Average weekly maximum salinity from April 2014 – August 2014 at Siletz. Seawater is approximately 35 PSU.

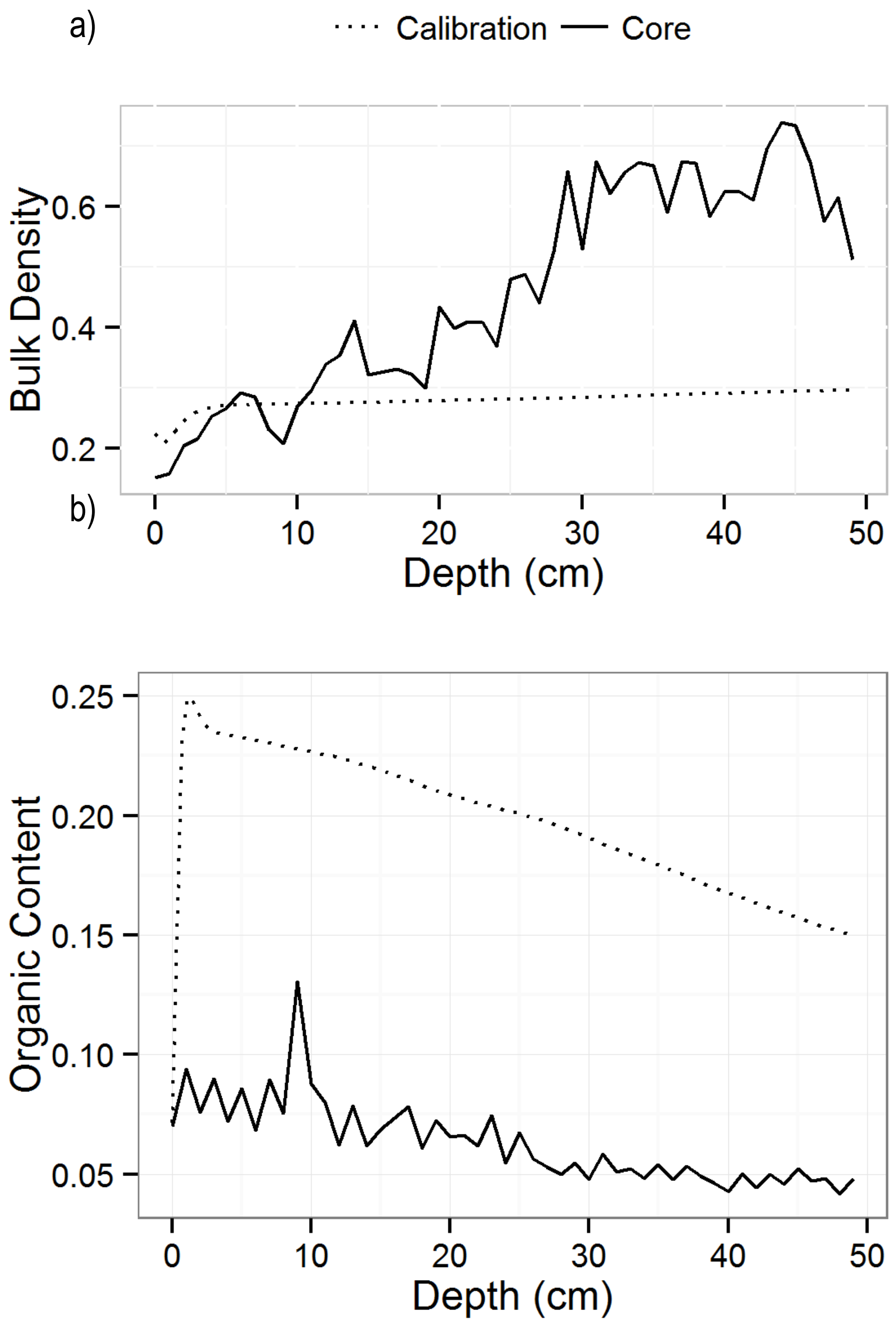

Figure G7. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table G4. Model input parameters for Siletz. 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})	0.59	Core calibration
Elevation of peak biomass (cm, MSL)	133	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	7	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0337	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	91	Core
Porosity depth (%)	86	Core
Refractory carbon (%)	40.9	Core
Maximum astronomical tide (cm, MSL)	180	CERCC water logger
Historic sea-level rise (mm yr^{-1})	2.35	South Beach tide gauge (NOAA, 9435380)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

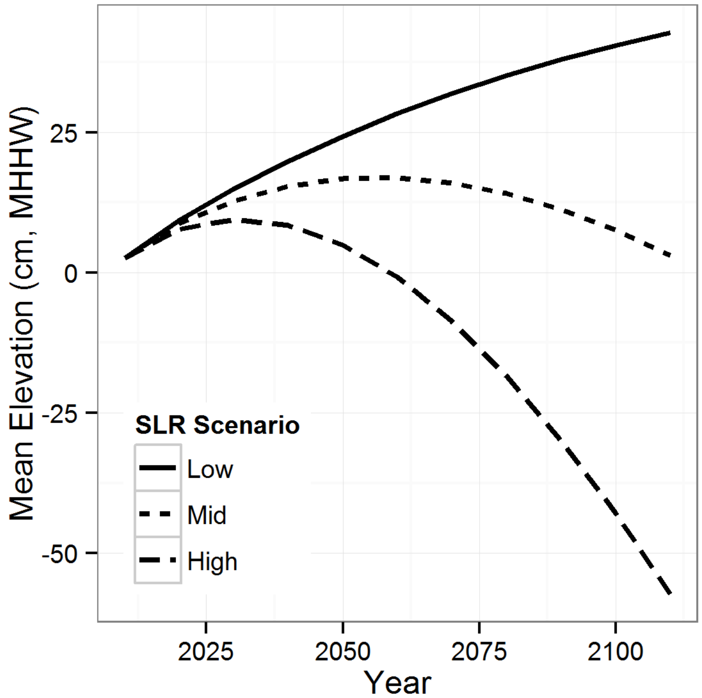

Figure G8. WARMER model projections for the change in average marsh elevation (relative to MHHW) at Siletz from 2010 to 2110 under low, mid, and high sea-level rise (SLR) scenarios.

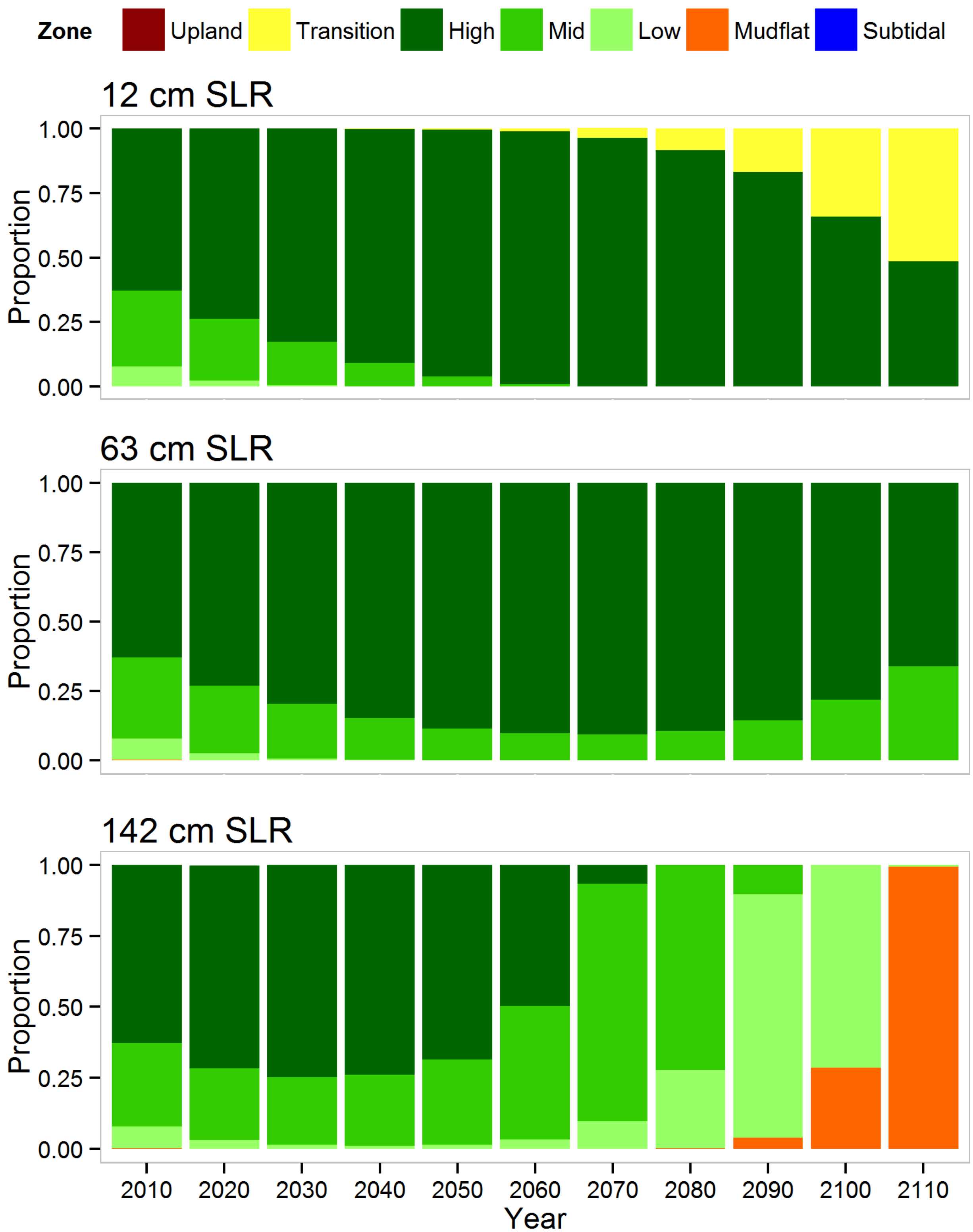

Figure G9. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) sea-level rise scenarios from 2010 to 2110 at Siletz.

Table G5. Model projections for change in the percentage of marsh elevation zones for three sea-level rise scenarios between 2010, 2050, and 2110 at Siletz.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
	2010	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	0	1	51	0	0	0	0	0	0
High	63	95	49	63	88	0	63	68	0
Mid	29	4	0	29	12	66	29	30	0
Low	8	0	0	8	0	34	8	2	1
Mudflat	0	0	0	0	0	0	0	0	99
Subtidal	0	0	0	0	0	0	0	0	0

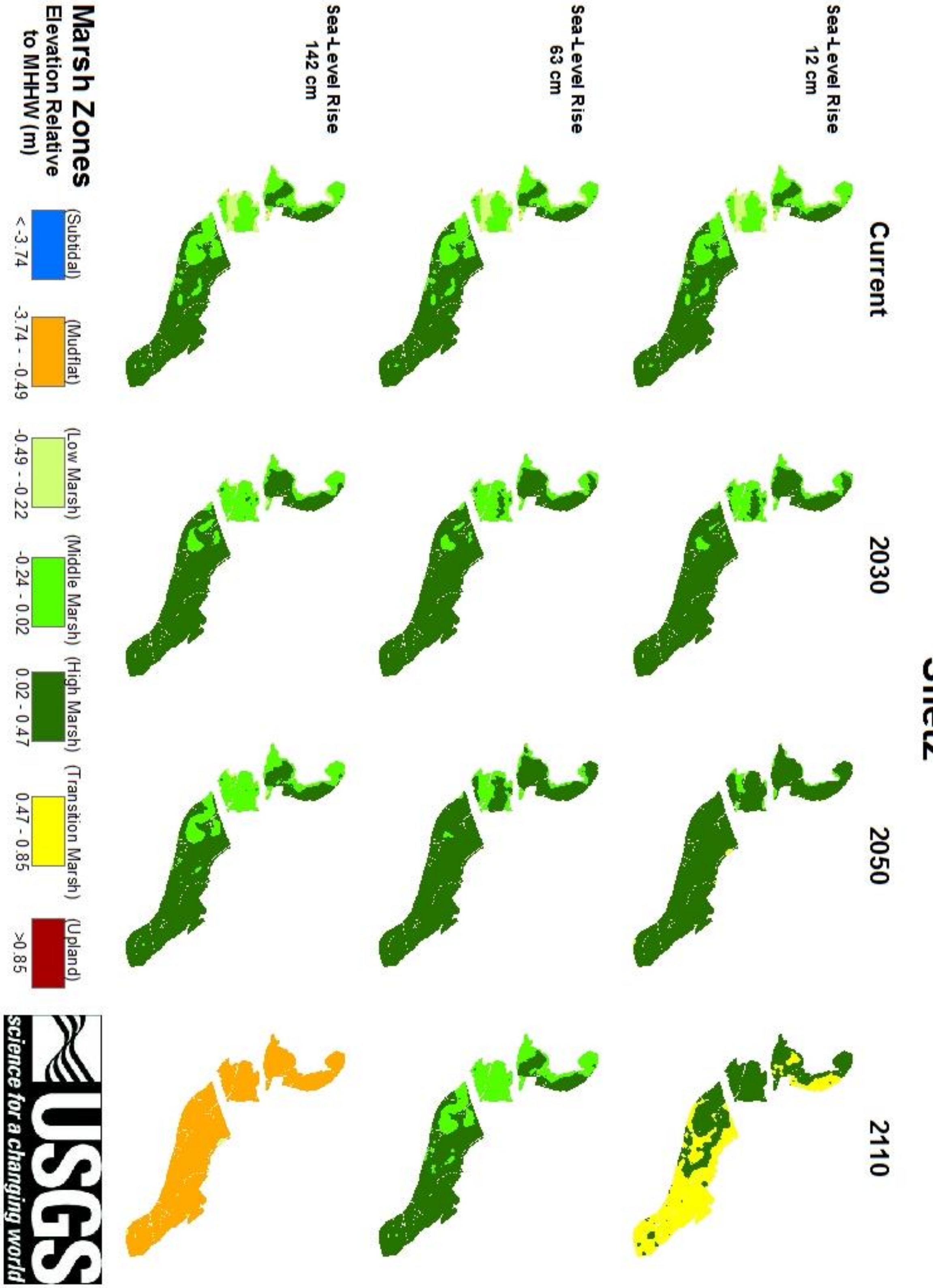

Figure G10. Projected habitat distribution at Siletz for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

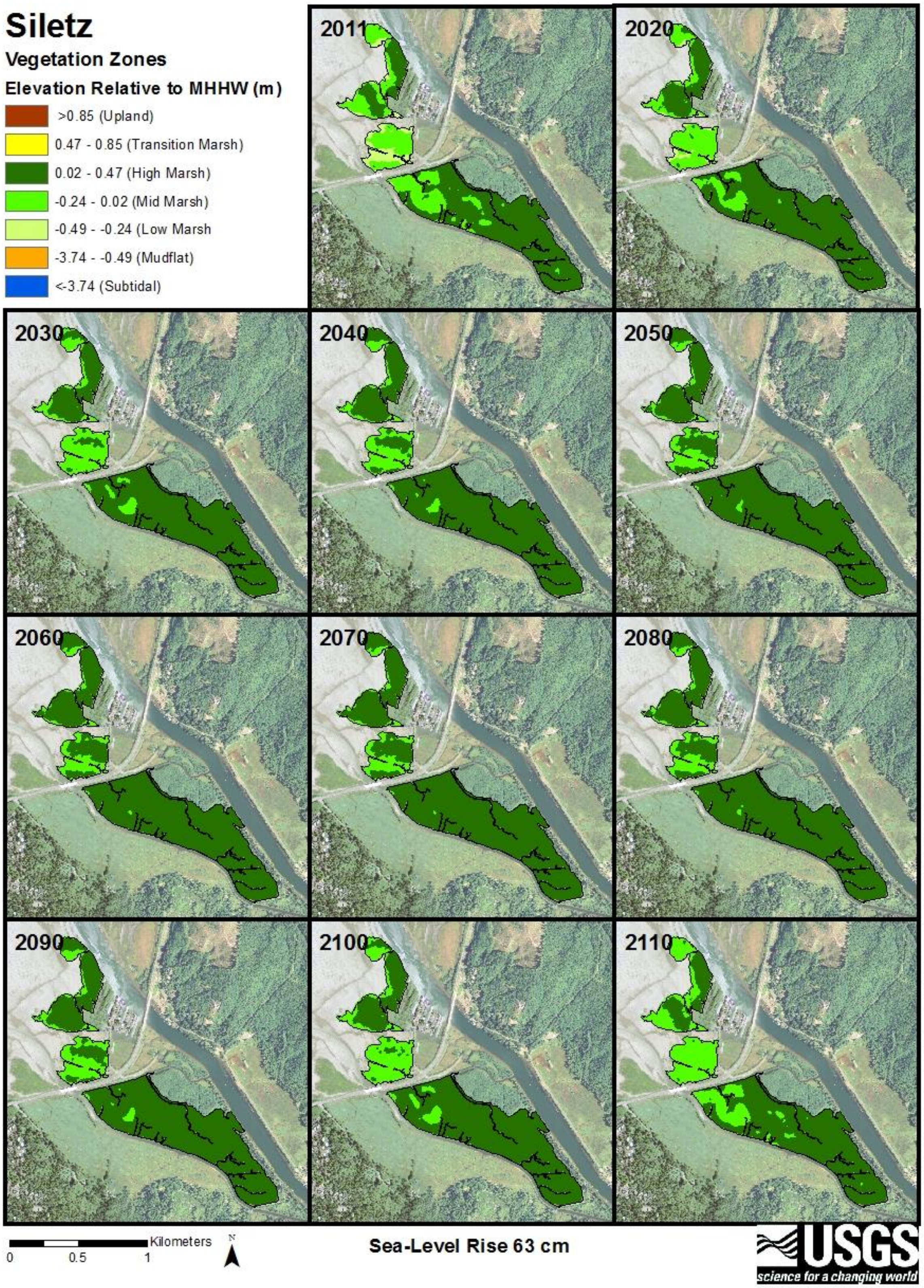

Figure G11. Projected changes in Siletz elevation zones under the mid NRC sea-level rise scenario (63 cm).

Bull Island, Coos Bay, Coos County, Oregon, USA

Photo: C Janousek, Oregon State University and USGS

Summary:

- *Study site size*: 97.2 hectares
- *Location*: 43° 22' 36"N latitude, 124° 10' 35"W longitude.
- *Site management*: South Slough National Estuarine Research Reserve (NOAA)
- *Site vegetation and elevation survey*: 10-17 October 2012
- *Sample size*: 1605 (elevation data points), 380 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was below MHHW, with only 11% of elevation points occurring above MHHW.
- *Plant community composition*: *Carex lyngbyei* was the most frequently occurring species. *Sarcocornia perennis* and *Distichlis spicata* were also common.
- *Bathymetric surveys*: 182.3 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics*: The accumulation rates used in WARMER for this site were: sediment accumulation rate = 0.19 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.0079 g cm^{-2} yr^{-1}; net accretion = 0.1979 cm yr^{-1}.

- *Water inundation and salinity monitoring*: water level (September 2012 – April 2014); conductivity (August 2013 – May 2014). Water level and conductivity monitoring is ongoing.
- *Salinity*: The maximum recorded salinity throughout the study period was 29 PSU.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during February 2014; minimum monthly inundation during May 2013.
- *Calculated tidal datums*: MHHW is at 2.33 m NAVD88; MHW is at 2.12 m NAVD88.
- *Sea-level rise marsh response modeling*: Presently, Bull Island is dominated by low marsh with about 25% mid marsh and a small amount of high marsh vegetation. Under the NRC's low sea-level rise scenario (12 cm) we project a gradual expansion of mid marsh between 2010 and 2070. However, under mid sea-level rise (63 cm) mid marsh is expected to initially increase in proportion and then begin to decrease after 2060. The site is projected to be almost completely low marsh at 2110. Under high sea-level rise (142 cm) there is loss of mid marsh by 2080 and rapid conversion of most low marsh to mudflat between 2090 and 2110.

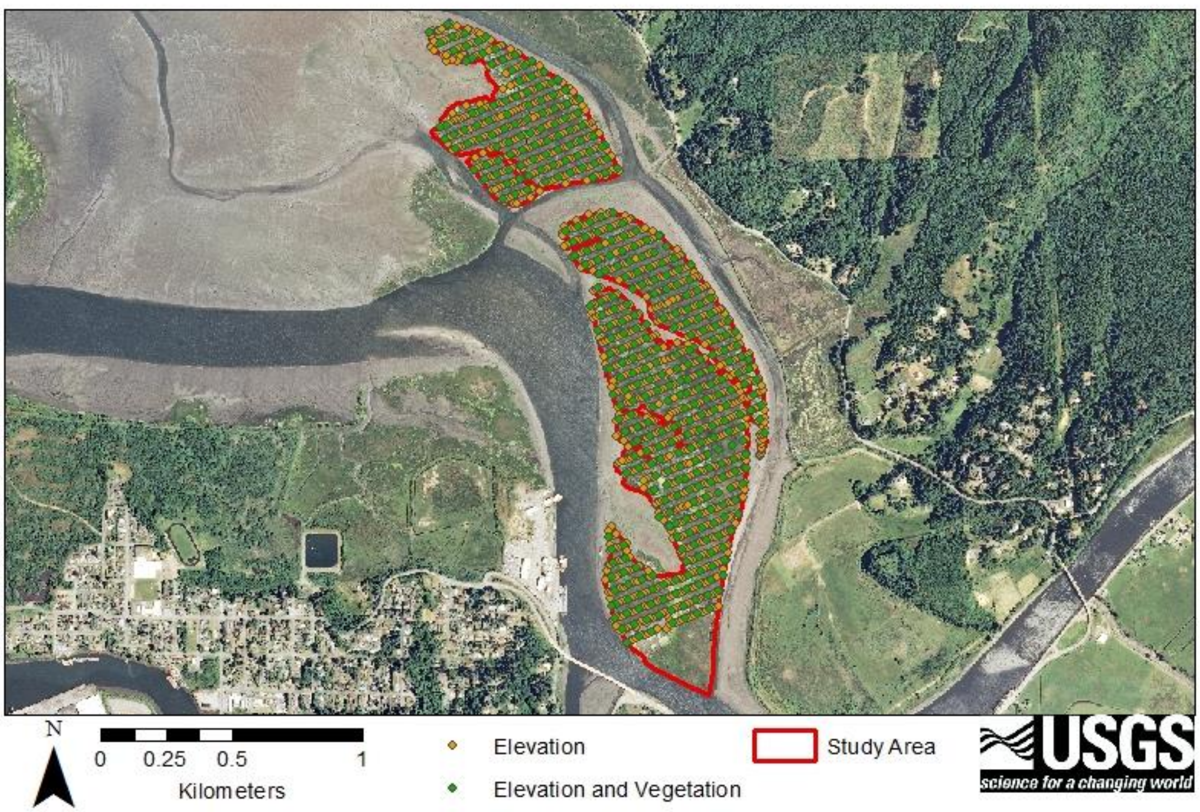

Figure H1. Distribution of elevation and vegetation survey points at Bull Island.

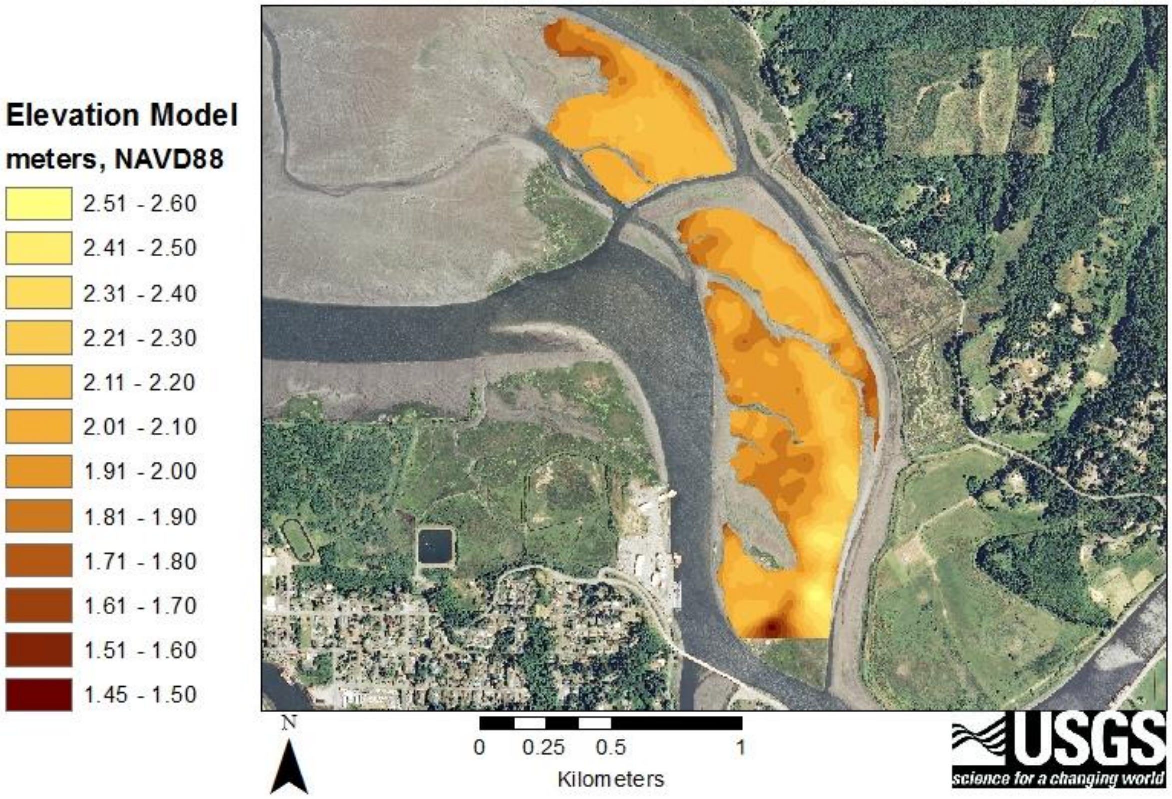

Figure H2. Elevation model (3 m resolution) developed from RTK GPS survey data.

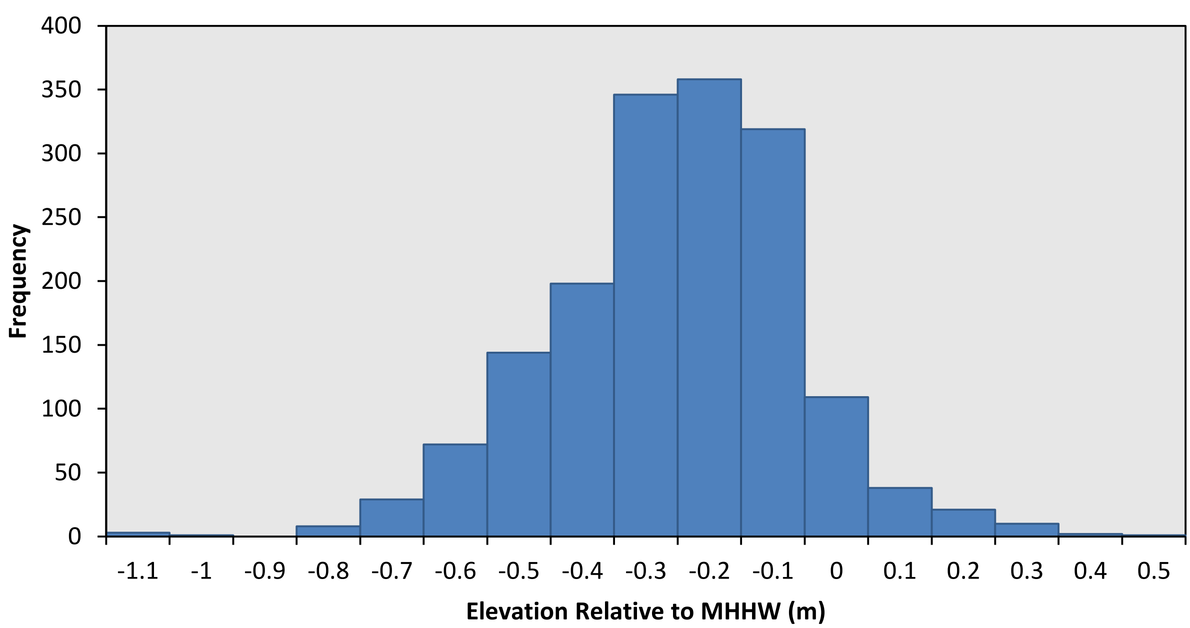

Figure H3. Frequency distribution of marsh surface elevation data points relative to local mean higher high water (MHHW) at Bull Island.

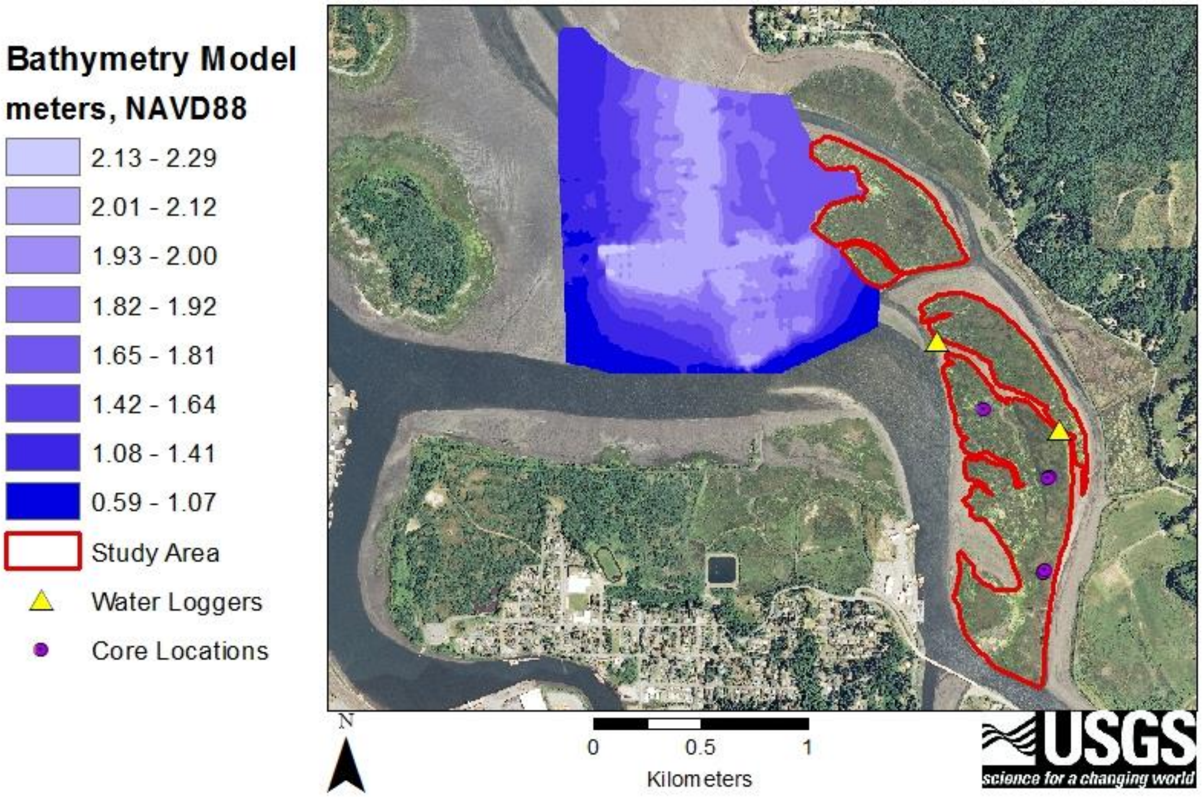

Figure H4. Near-shore bathymetry model for Bull Island. Water level logger and core locations are shown within the marsh study site.

Table H1. Vascular plant species frequency of occurrence, percent cover and height at Bull Island. NA = not measured.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Carex lyngbyei	Native perennial sedge	76	46	39
Sarcocornia perennis	Native perennial forb	49	12	28
Distichlis spicata	Native perennial grass	43	13	31
Deschampsia cespitosa	Native perennial grass	39	18	43
Triglochin maritima	Native perennial forb	23	1	34
Juncus balticus	Native perennial rush	17	9	31
Agrostis stolonifera	Non-native perennial grass	14	6	31
Jaumea carnosa	Native perennial forb	3	1	19
Isolepis cernua	Native annual sedge	1	1	3
Grindelia stricta	Native perennial forb	1	0	39
*Spergularia canadensis**	Native annual forb	1	0	5
Lilaeopsis occidentalis	Native perennial forb	1	0	2
Hordeum brachyantherum	Native perennial grass	1	0	38
Potentilla anserina	Native ann-perennial forb	1	0	24
Atriplex prostrata	Native annual forb	1	0	16
Cuscuta pacifica	Native ann-perennial parasite	0	NA	NA
Baccharis pilularis	Native perennial shrub	0	0	165
Fabaceae species	Legume	0	0	29

Table H2. Mean percent cover of dominant plant species by marsh zone at Bull Island. Zones were defined by degree of flooding by high tides. AgrSto = *Agrostis stolonifera*; CarLyn= *Carex lyngbyei*; DesCes = *Deschampsia cespitosa*; DisSpi = *Distichilis spicata*; JunBal = *Juncus balticus*; SarPer = *Sarcocornia perennis.*

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.891 to 0.496	0	*Insufficient sample size*
High	3-25	0.495 to 0.023	13	JunBal (42), DesCes (31), AgrSto (28), DisSpi (7)
Middle	25-50	0.022 to -0.246	150	CarLyn (27), DesCes (24), DisSpi (23), JunBal (19)
Low	>50	-0.247 to -0.787	217	CarLyn (63), SarPer (13), DesCes (12), DisSpi (7)

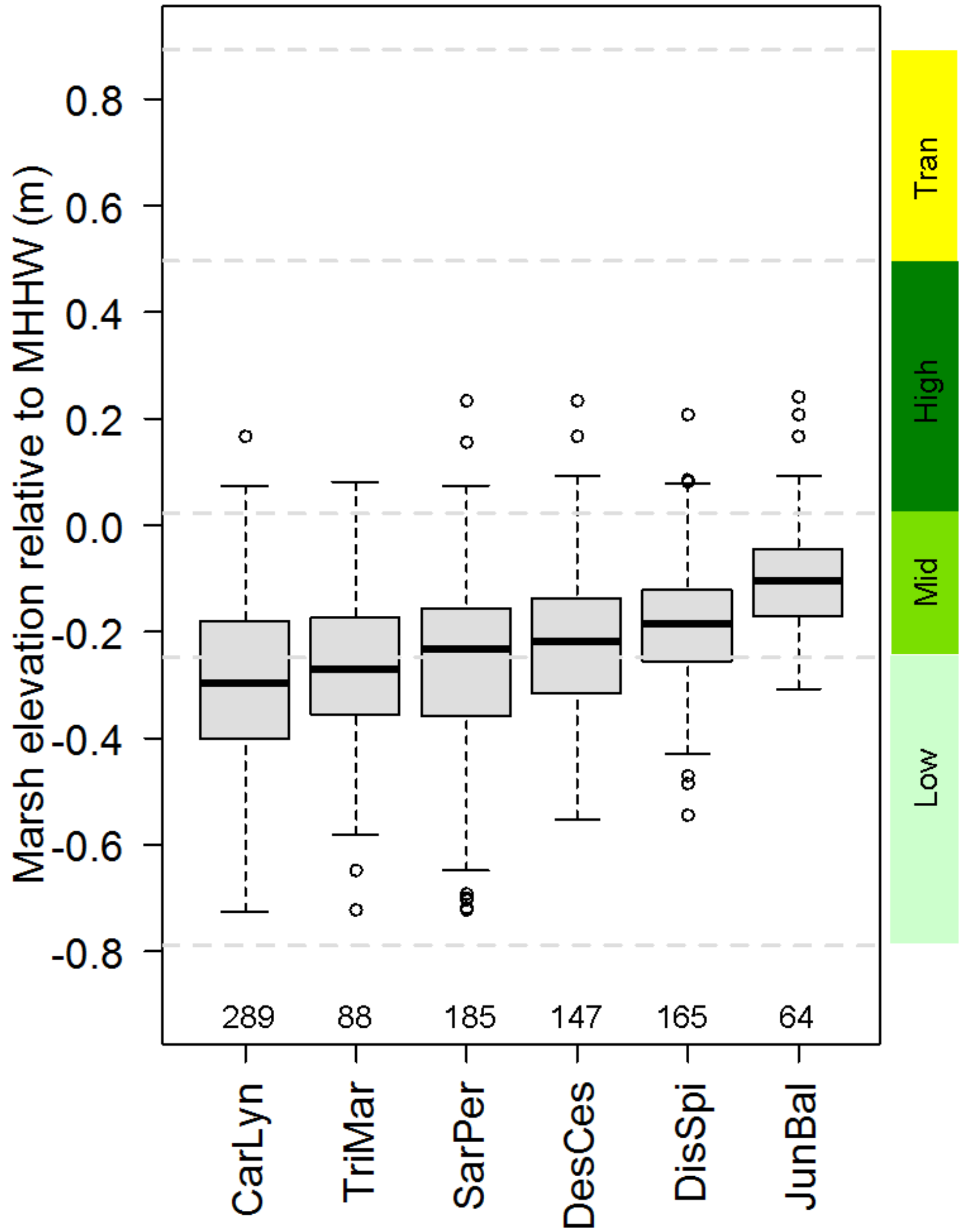

Figure H5. Elevation distribution of the six most common vascular plant species at Bull Island. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 380 plots). Marsh elevation zones (low, middle, high and transition) are illustrated at right. CarLyn= *Carex lyngbyei*; DesCes = *Descahmpsia cespitosa*; DisSpi = *Distichilis spicata*; TriMar = *Triglochin maritima;* SarPer = *Sarcocornia perennis;* JunBal = *Juncus balticus*.

Table H3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	404695	4803321
	405266	4802907
Deep core locations	405190	4802242
	405215	4802682
	404915	4803003

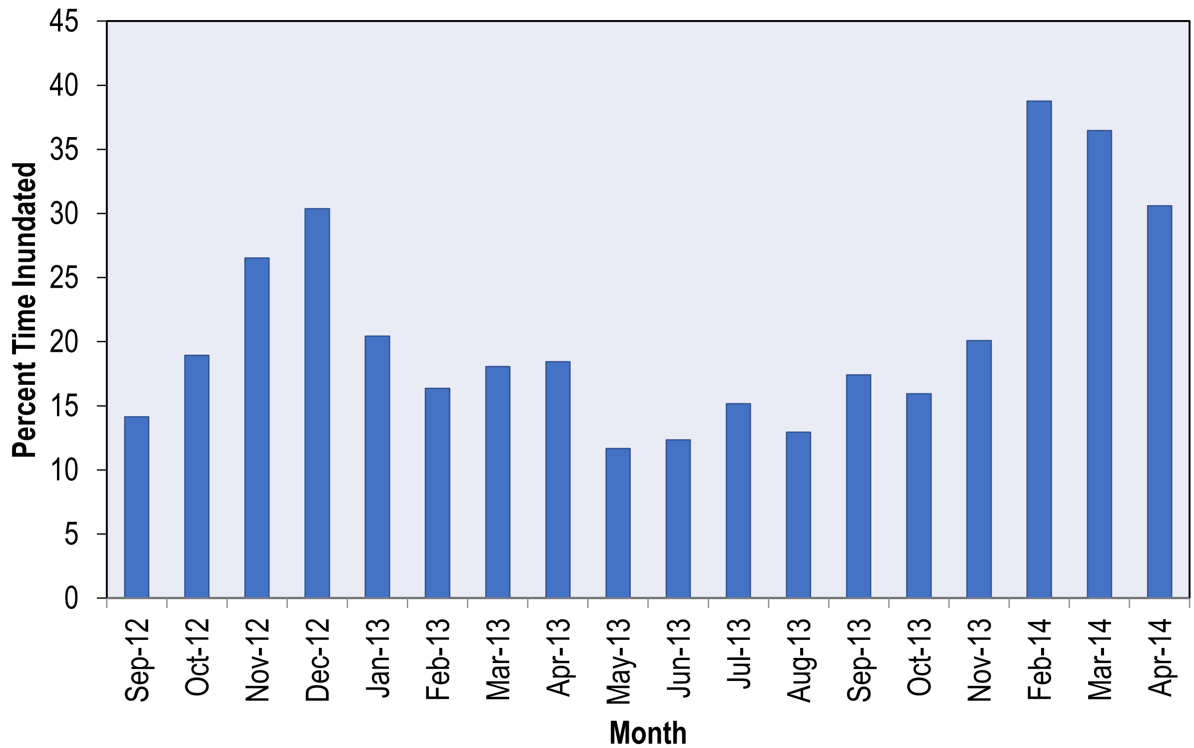

Figure H6. Average monthly inundation of the study site based on an average marsh elevation. Water levels were determined with a Hobo water logger deployed at -0.19 m NAVD88.

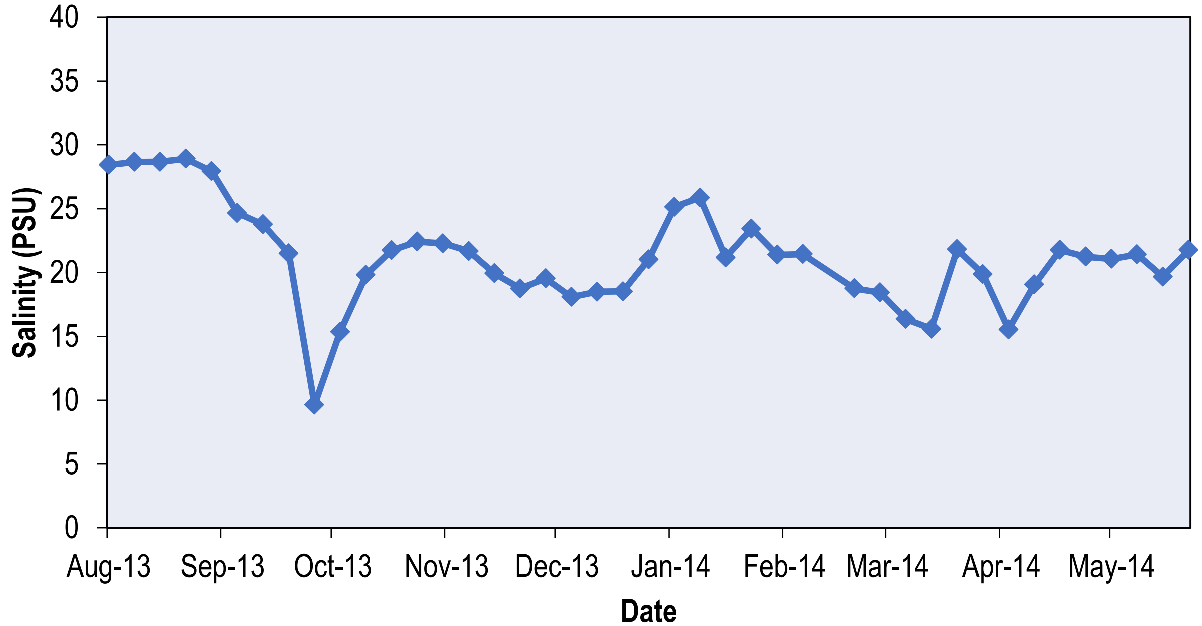

Figure H7. Average weekly maximum salinity from August 2013 – May 2014 at Bull Island. Seawater is approximately 35 PSU.

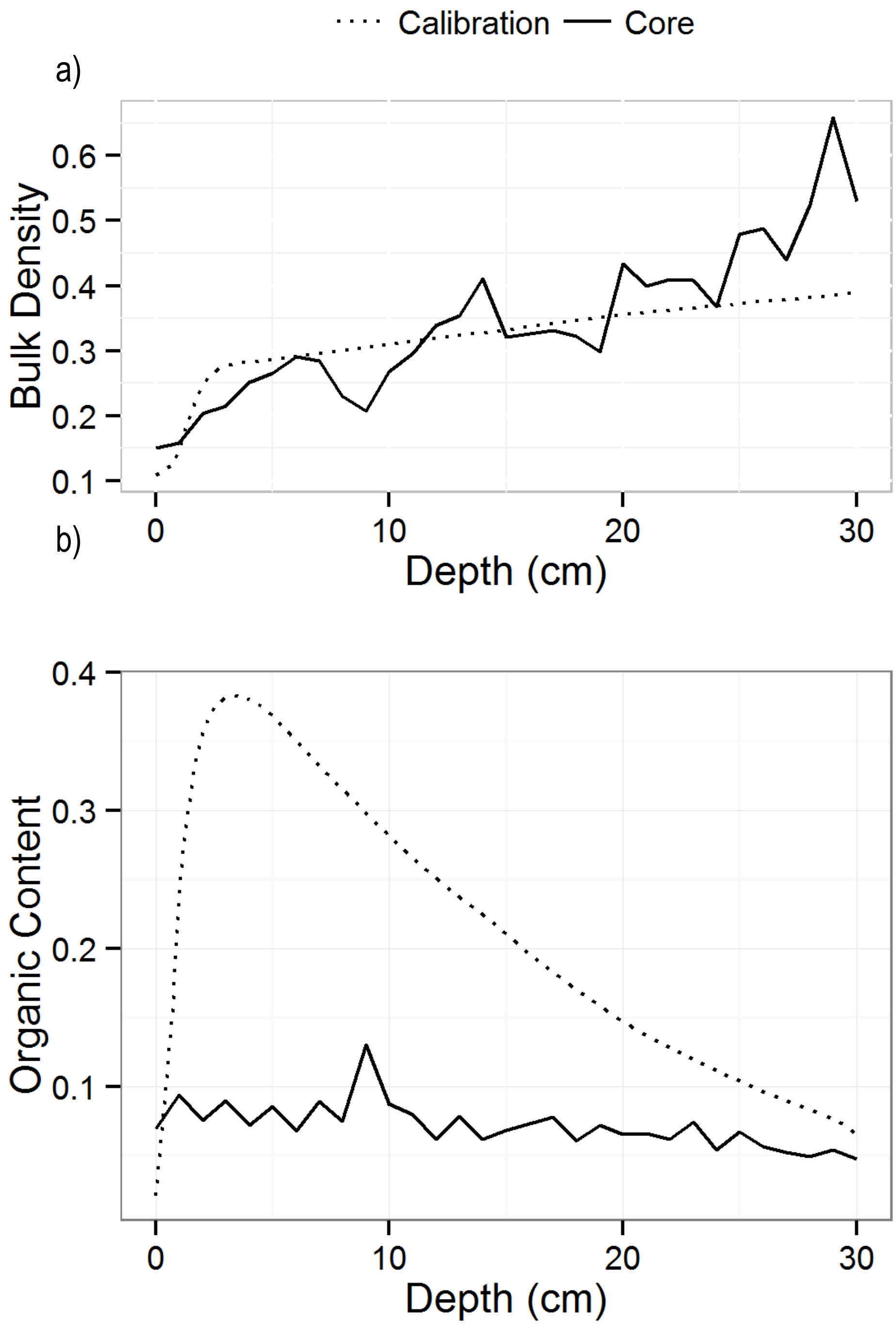

Figure H8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table H4. Model input parameters for Bull Island. 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})	0.44	Core calibration
Elevation of peak biomass (cm, MSL)	101	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	34	Field surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0051	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	95	Core
Porosity depth (%)	84	Core
Refractory carbon (%)	64.5	Core
Maximum astronomical tide (cm, MSL)	224	CERCC water logger
Historic sea-level rise (mm yr^{-1})	0.59	Charleston tide gauge (NOAA, 9432780)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

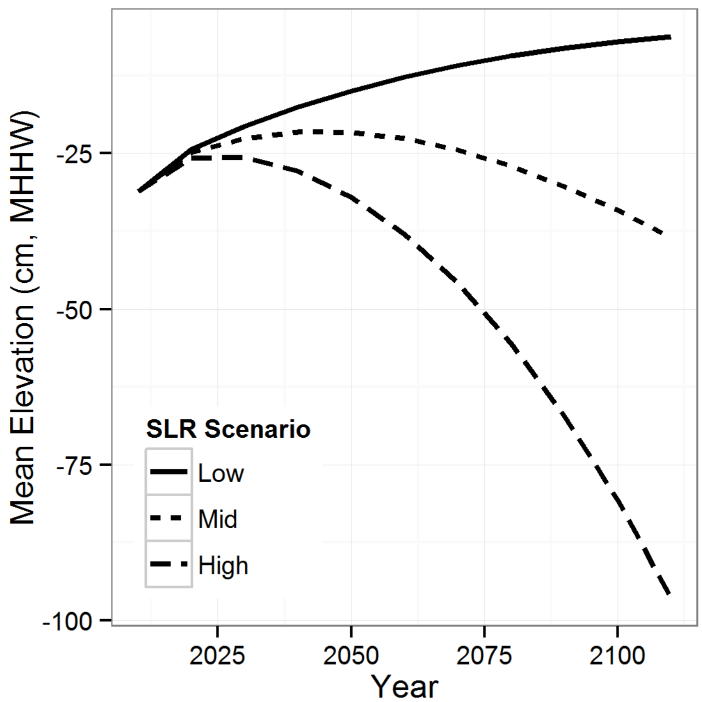

Figure H9. WARMER model results for average marsh elevation change at Bull Island from the present to the year 2110 under low, mid, and high sea-level rise (SLR) scenarios.

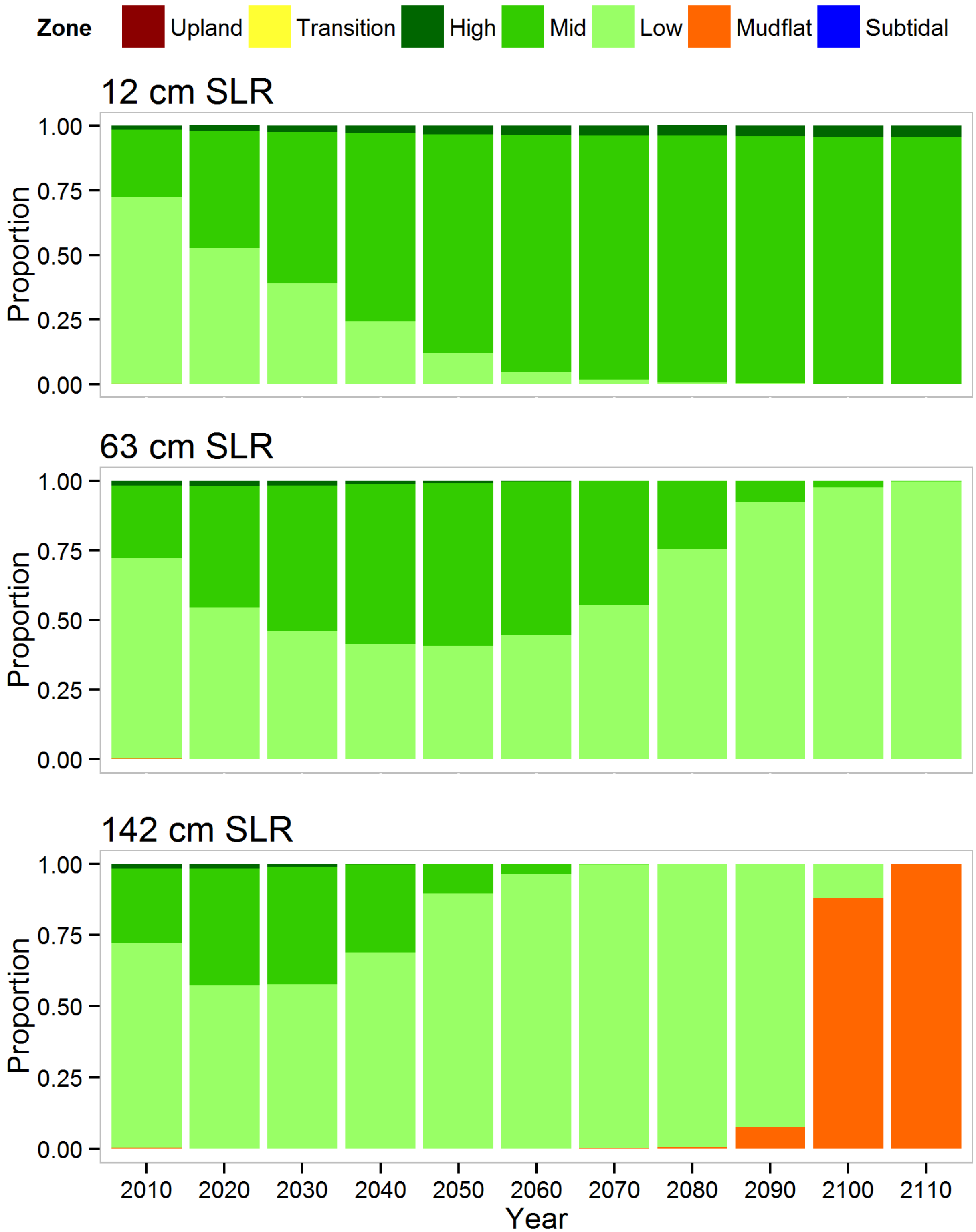

Figure H10. Model projections for change in the relative proportion of upland, transitional, high, mid and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table H5. 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)**		
	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	2	3	4	2	1	0	2	0	0
Mid	26	85	96	26	59	0	26	10	0
Low	72	12	0	72	40	0	72	90	0
Mudflat	0	0	0	0	0	100	0	0	100
Subtidal	0	0	0	0	0	0	0	0	0

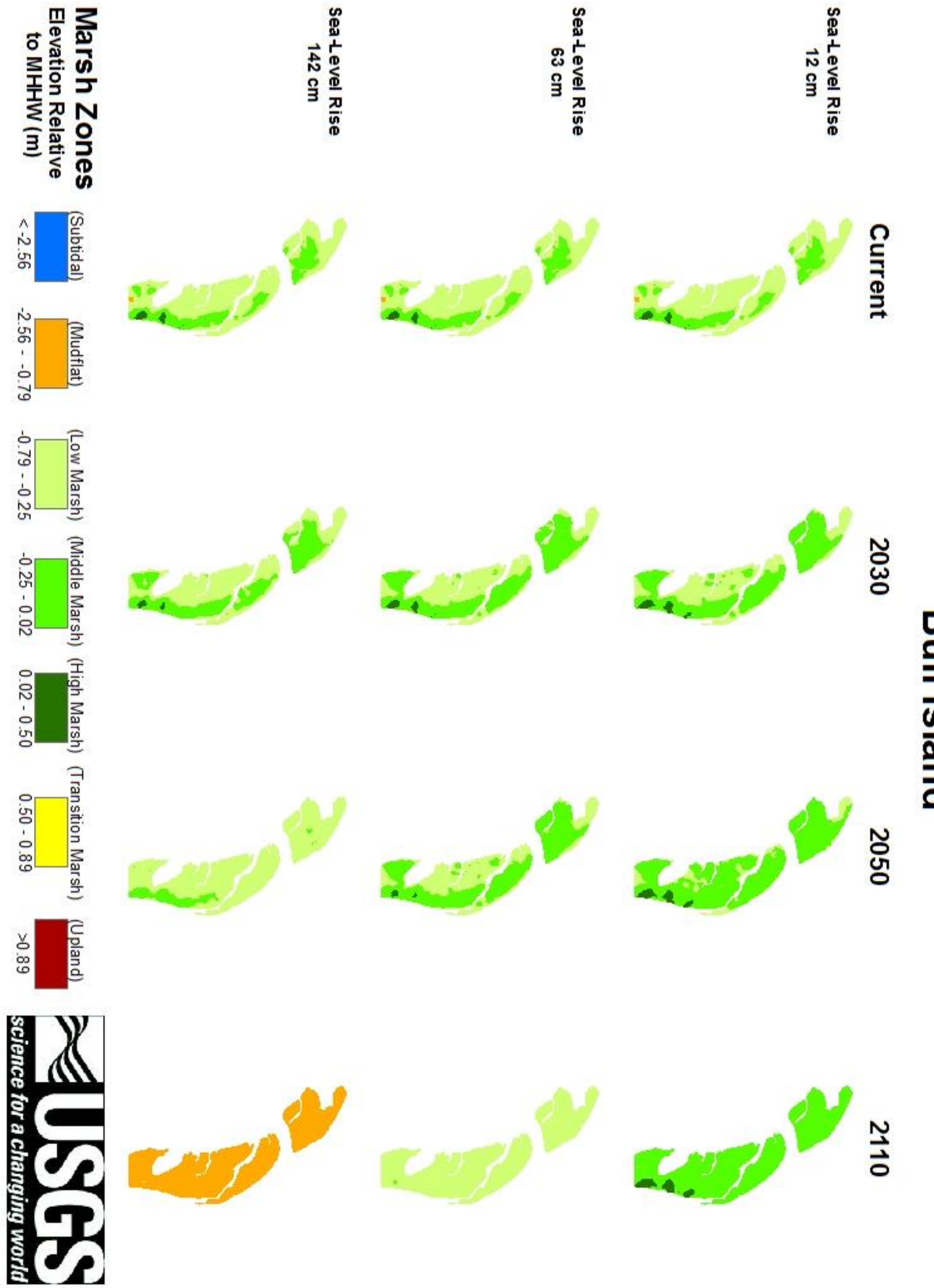

Figure H11. Projected habitat distribution at Bull Island for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

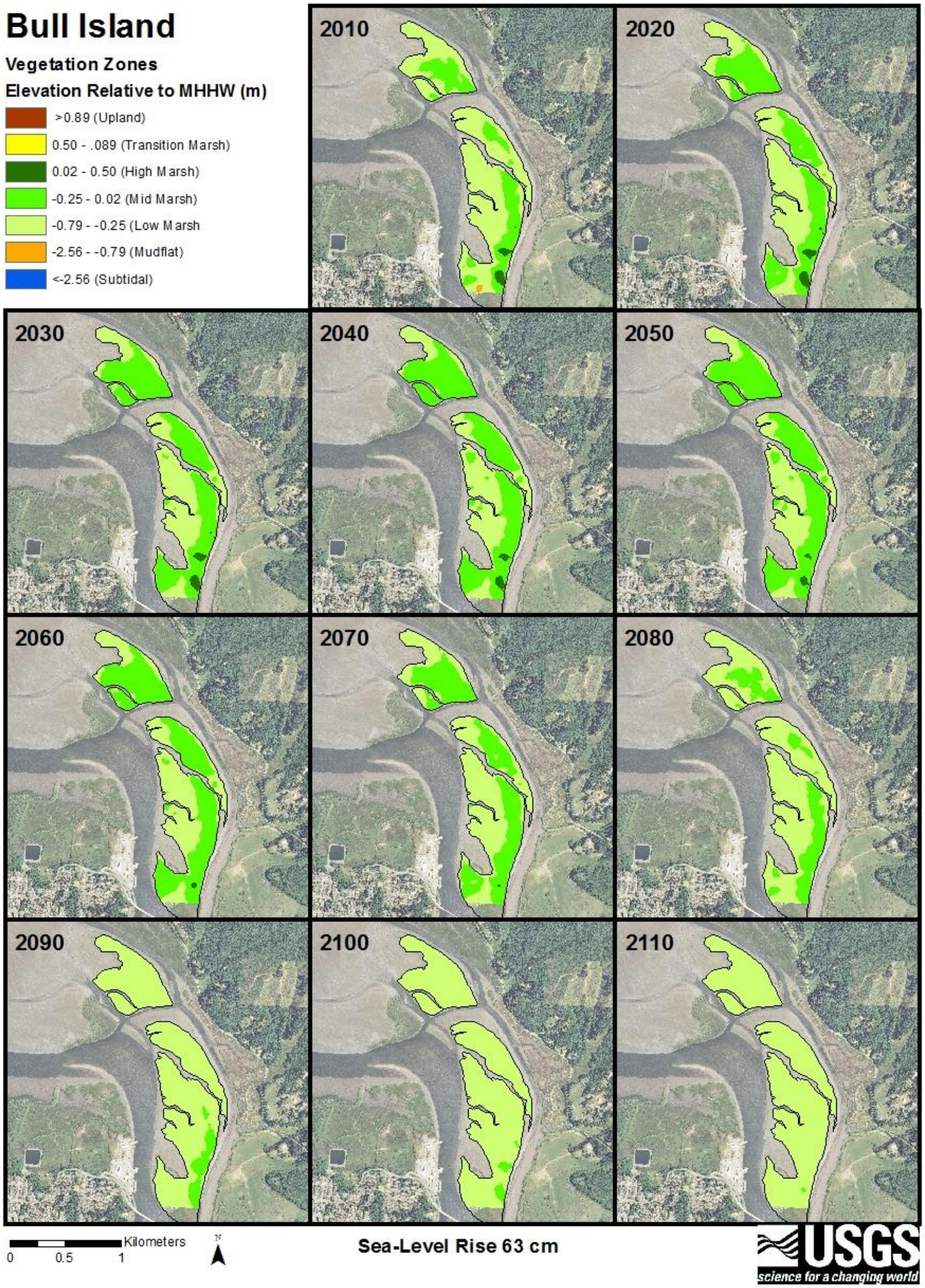

Figure H12. Projected changes in Bull Island elevation zones under the mid NRC sea-level rise scenario (63 cm).

Bandon marsh, Bandon Marsh National Wildlife Refuge, Coos County, Oregon, USA

Photo: K Powelson, USGS

Summary:

- *Study site size*: 96.7 hectares
- *Location*: 43° 07' 50"N latitude, 124° 24' 25"W longitude.
- *Site management*: U.S. Fish and Wildlife Service (Bandon National Wildlife Refuge)
- *Site vegetation and elevation survey*: 19-28 August 2012
- *Sample size*: 1710 (elevation points), 373 (vegetation quadrats)
- *Marsh elevation model*: Most of the study site was above MHHW, with 67% of elevation points occurring above MHHW.
- *Plant community composition*: *Sarcocornia perennis* was the most frequently occurring species. *Distichlis spicata*, *Jaumea carnosa* and *Deschampsia cespitosa* were also common.
- *Bathymetric surveys*: 46.7 ha of nearshore habitat were mapped adjacent to the study area.
- *Soil characteristics:* The accumulation rates used in WARMER for this site were: sediment accumulation rate = 0.22 g cm^{-2} yr^{-1}; organic matter accumulation rate = 0.0085 g cm^{-2} yr^{-1}; net accretion = 0.2285 cm yr^{-1}.

- *Water inundation and salinity monitoring*: water level (August 2013 – May 2014); conductivity (August 2013 – May 2014). Water level and conductivity monitoring is ongoing.
- *Salinity*: Weekly maximum salinity varied throughout the study period, but declined between Jan-May 2014.
- *Marsh inundation pattern*: Maximum monthly inundation occurred during February 2014; minimum monthly inundation occurred during October 2013.
- *Calculated local tidal datums*: MHHW is at 2.04 m, NAVD88; MHW is at 1.84 m NAVD88.
- *Sea-level rise marsh response modeling:* Presently, Bandon has an equal proportion of low and mid marsh vegetation with about 10% of the total area occupied by high marsh. Under the low NRC sea-level rise scenario (12 cm), modeling suggests that the site will remain relatively unchanged. However, under the NRC's mid sea-level rise scenario (63 cm) there is gradual loss of mid and high marsh between 2020 and 2110. At 2110, the site is comprised mostly of low marsh and mudflat. Under the NRC's high sea-level rise scenario (142 cm), mid and high marsh are lost more rapidly and mudflat begins to replace most vegetated marsh at the site by 2090.

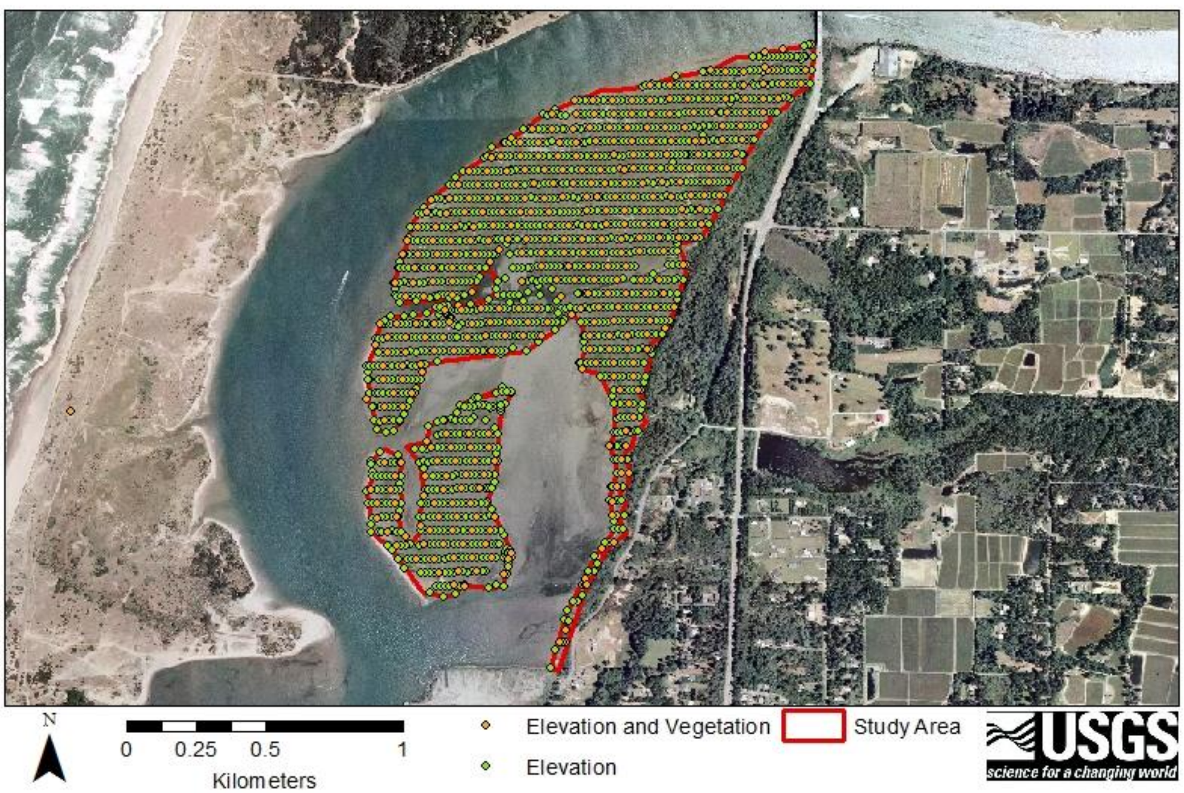

Figure I1. Distribution of elevation and vegetation survey points collected at Bandon.

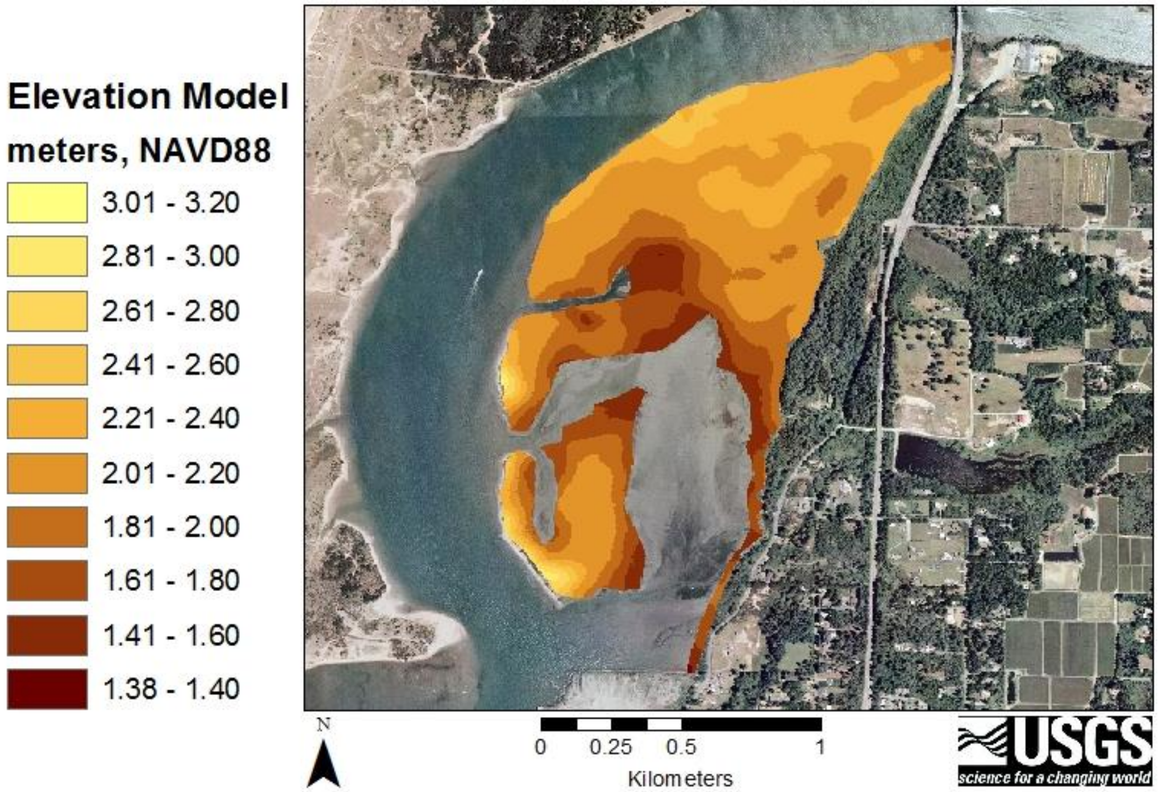

Figure I2. Elevation model (3 m resolution) developed from RTK GPS survey data.

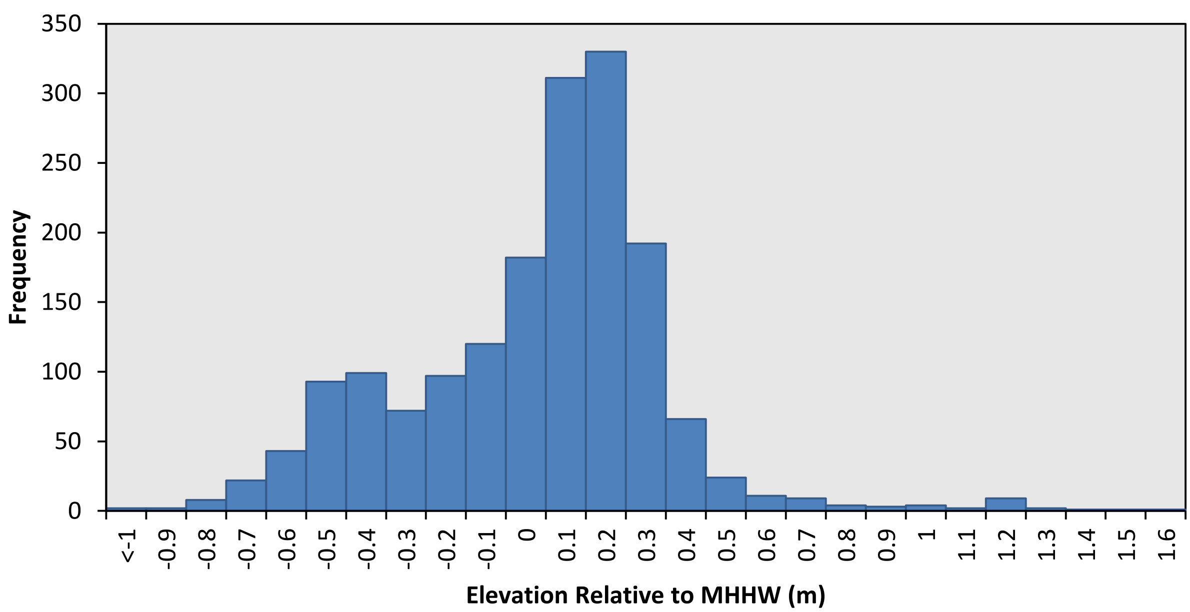

Figure I3. Frequency distribution of marsh surface elevation measurements relative to local mean higher high water (MHHW).

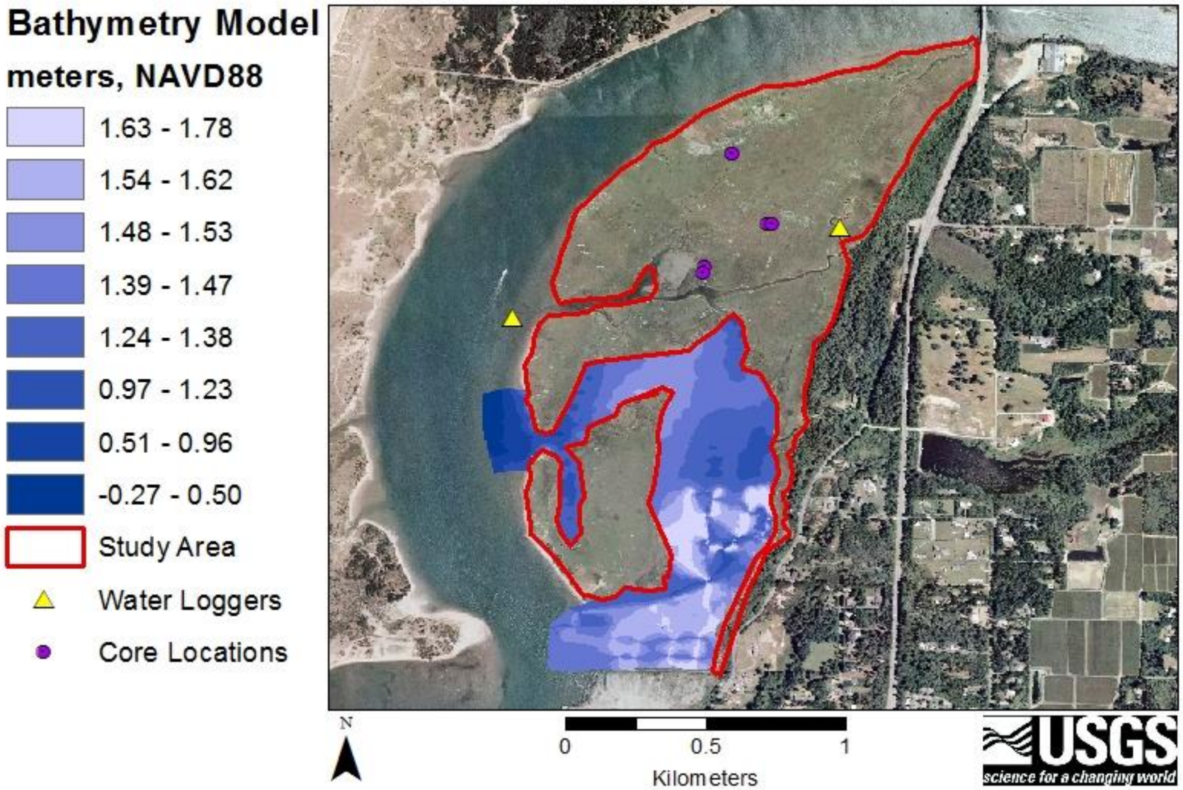

Figure I4. Near-shore bathymetry model at Bandon. Water level logger and core locations are shown within the marsh study site.

Table I1. Vascular plant species frequency of occurrence, percent cover, and height at Bandon.

Species	Species characteristics	Freq (%)	Mean cover (%)	Mean height (cm)
Sarcocornia perennis	Native perennial forb	65	21	30
Distichlis spicata	Native perennial grass	63	13	33
Jaumea carnosa	Native perennial forb	59	15	24
Deschampsia cespitosa	Native perennial grass	51	23	55
Carex lyngbyei	Native perennial sedge	34	7	52
Triglochin maritima	Native perennial forb	33	4	40
Juncus balticus	Native perennial rush	29	9	58
Agrostis stolonifera	Non-native perennial grass	25	10	52
Glaux maritima	Native perennial forb	21	2	29
Cuscuta pacifica	Native ann-perennial parasite	19	NA	NA
Potentilla anserina	Native ann-perennial forb	12	4	40
Schedonorus arundinaceus	Non-native perennial grass	8	2	52
Holcus lanatus	Non-native ann-perennial grass	6	1	66
Isolepis cernua	Native annual sedge	6	2	10
Atriplex sp.	Forb	5	1	32
Symphyotrichum subspicatum	Native perennial forb	3	1	78
Achillea millefolium	Native perennial forb	3	1	61
Vicia gigantea	Native perennial legume	3	1	60
Plantago maritima	Native perennial forb	3	0	18
Lilaeopsis occidentalis	Native perennial forb	2	0	10
Angelica lucida	Native perennial forb	1	0	50
Hordeum brachyantherum	Native perennial grass	1	0	51
Juncus breweri	Native perennial rush	1	0	52
Trifolium sp.	Legume	1	0	50
Tanacetum sp.	Forb	1	0	23
Spergularia canadiensis	Native annual forb	1	0	14
Grindelia stricta	Native perennial forb	1	0	49
Schedonorus arundinaceus	Perennial grass	1	0	155
Hordeum jubatum	Ann-perennial grass	1	0	41
Unknown Poaceae 3	Grass	0	0	37
Unknown Poaceae 5	Grass	0	0	37
Lotus corniculatus	Non-native perennial legume	0	0	26
Unknown Poaceae 1	Grass	0	0	55
Schoenoplectus tabernaemontani	Native perennial sedge	0	0	141
Phalaris arundinacea	Perennial grass	0	0	45
Carex pansa	Native perennial sedge	0	0	ND
Galium aparine	Native annual forb	0	0	95
Linum sp.	Forb	0	0	41
Unknown Poaceae 2	Grass	0	0	43
Galium trifidum	Native ann-perennial forb	0	0	47
Plantago lanceolata	Perennial forb	0	0	36
Unknown	NA	0	0	22
Eleocharis parvula	Native perennial sedge	0	0	1
Rumex sp.	Forb	0	0	10
Unknown Poaceae 4	Grass	0	0	51

Table I2. Mean percent cover of dominant plant species by marsh zone at Bandon. Zones were defined by degree of flooding. Atriplex = *Atriplex* sp(p); AgrSto = *Agrostis stolonifera*; CarLyn = *Carex lyngbyei*; DesCes = *Deschampsia cespitosa*; DisSpi = *Distichilis spicata;* JauCar = *Jaumea carnosa*; JunBal = *Juncus balticus*; SarPer = *Sarcocornia perennis*; VicGig = *Vicia gigantea*.

Marsh zone	% high tides reaching zone	MHHW range (m)	Sample size	Mean cover of top four dominant plants (%)
Transition	0.14-3	0.669 to 0.373	15	JunBal (13), Atriplex (12), SarPer (11), VicGig (11)
High	3-25	0.372 to 0.018	198	DesCes (28), SarPer (21), JunBal (16), AgrSto (14)
Middle	25-50	0.017 to -0.185	81	DesCes (35), SarPer (23), CarLyn (12), DisSpi (12)
Low	>50	-0.186 to -0.749	78	DisSpi (25), JauCar (24), SarPer (22), CarLyn (14)

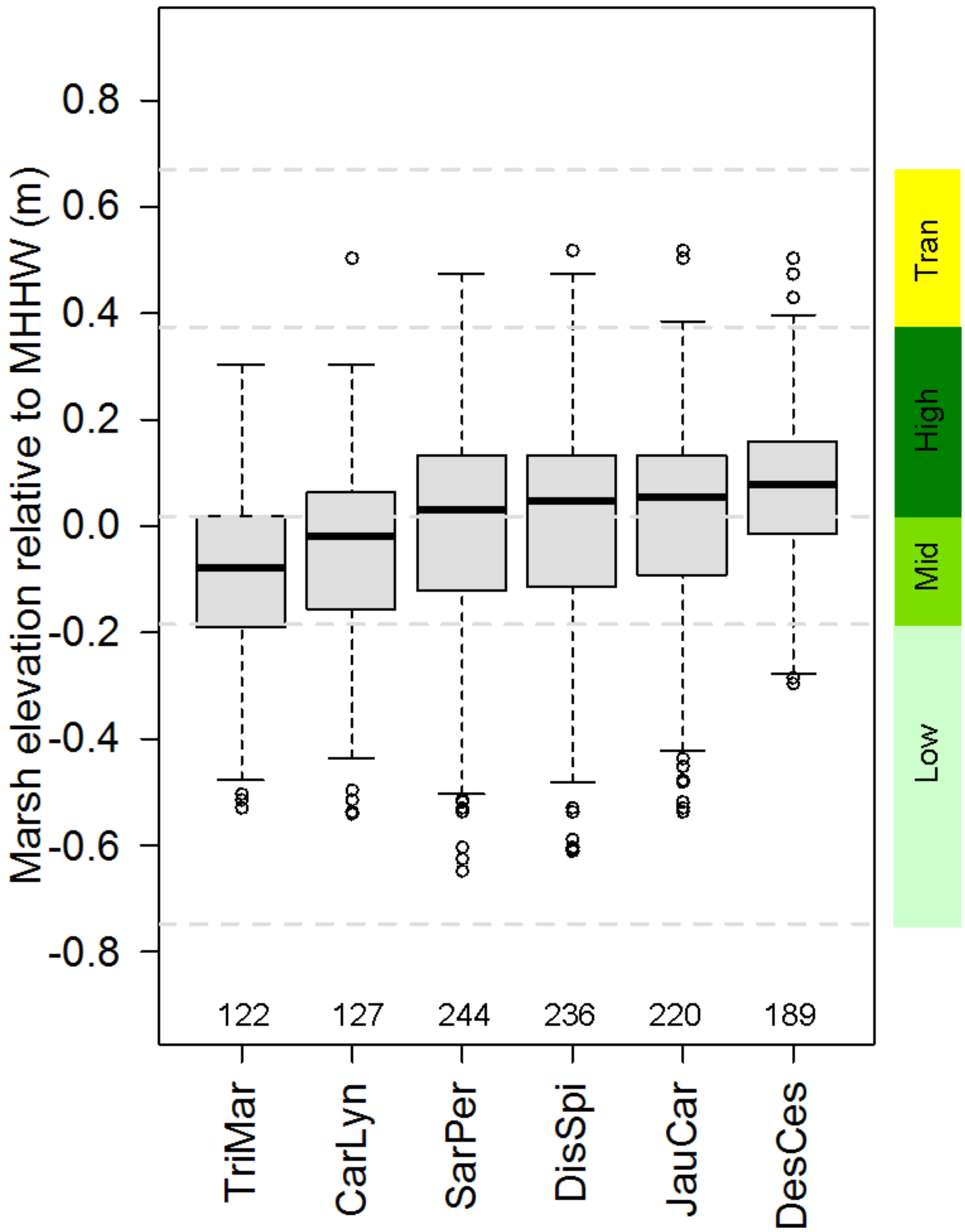

Figure I5. Elevation distribution of the six most common vascular plant species at Bandon. The black horizontal bars show the median elevation at which the species occurs; shaded boxes indicate the interquartile range; upper and lower whiskers encompass points no greater than 1.5x the length of the shaded box; and open circles indicate outliers. The number of plots in which the species occurred is indicated above the species codes (out of a total of 372 plots). Marsh elevation zones (low, middle, high and transition) are illustrated at right. CarLyn = *Carex lyngbyei;* DesCes = *Deschampsia cespitosa*; DisSpi = *Distichilis spicata;* JauCar = *Jaumea carnosa*; SarPer = *Sarcocornia perennis;* TriMar = *Triglochin maritima.*

Table I3. Location of water level loggers and deep sediment cores (UTM coordinates).

	Northing (m)	Easting (m)
Water level loggers	385283	4777000
	386142	4777309
Deep core locations	385870	4777581
	385789	4777178
	385955	4777328

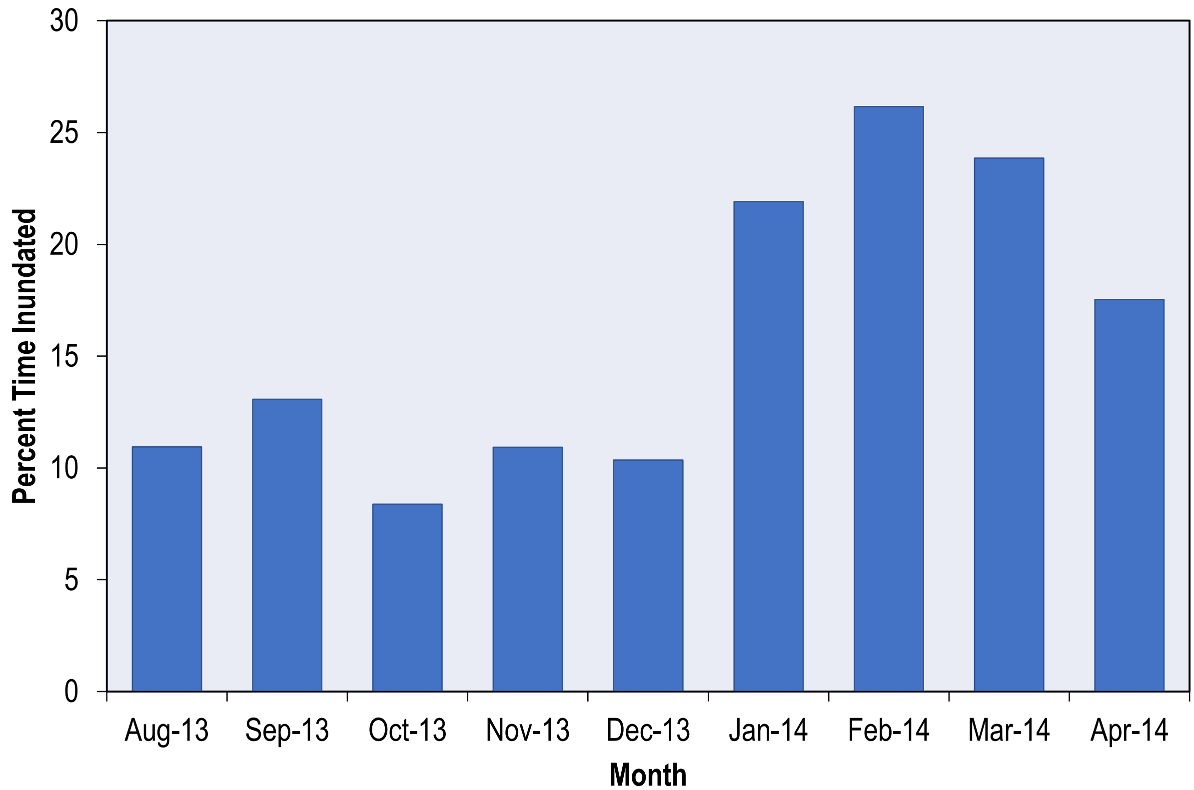

Figure I6. Variation in monthly inundation duration (at the average marsh elevation) at Bandon. Water levels were determined with a water level logger deployed at 0.25 m (NAVD88).

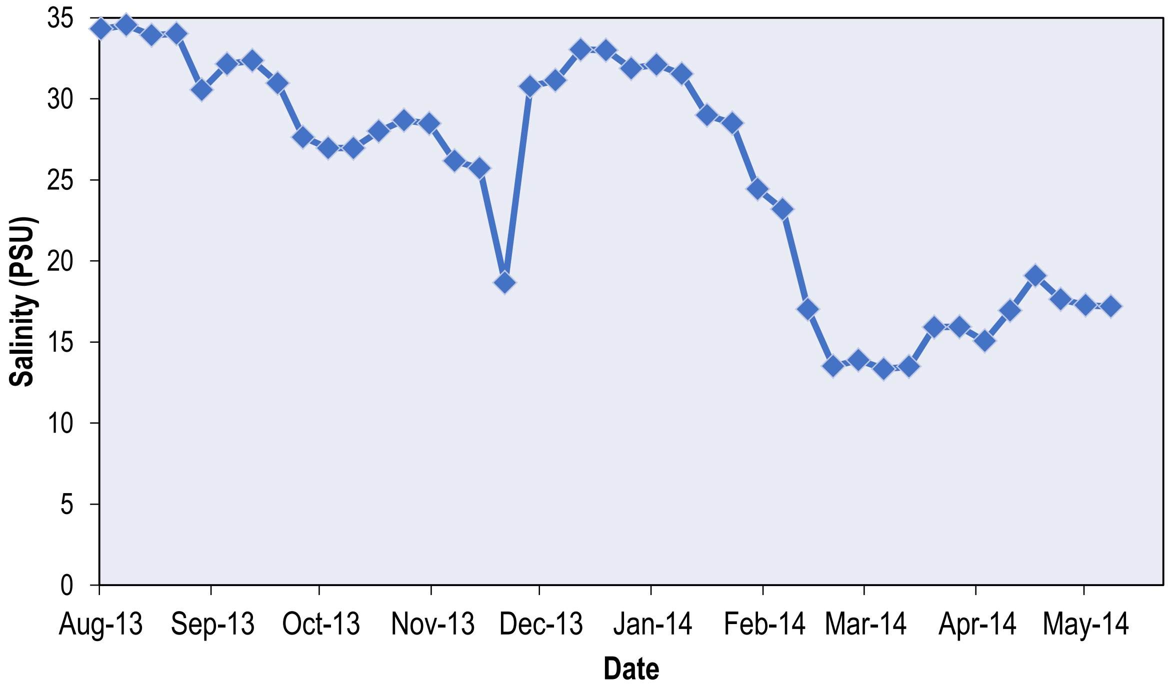

Figure I7. Average weekly maximum salinity from August 2013 – May 2014 at Bandon. Seawater is approximately 35 PSU.

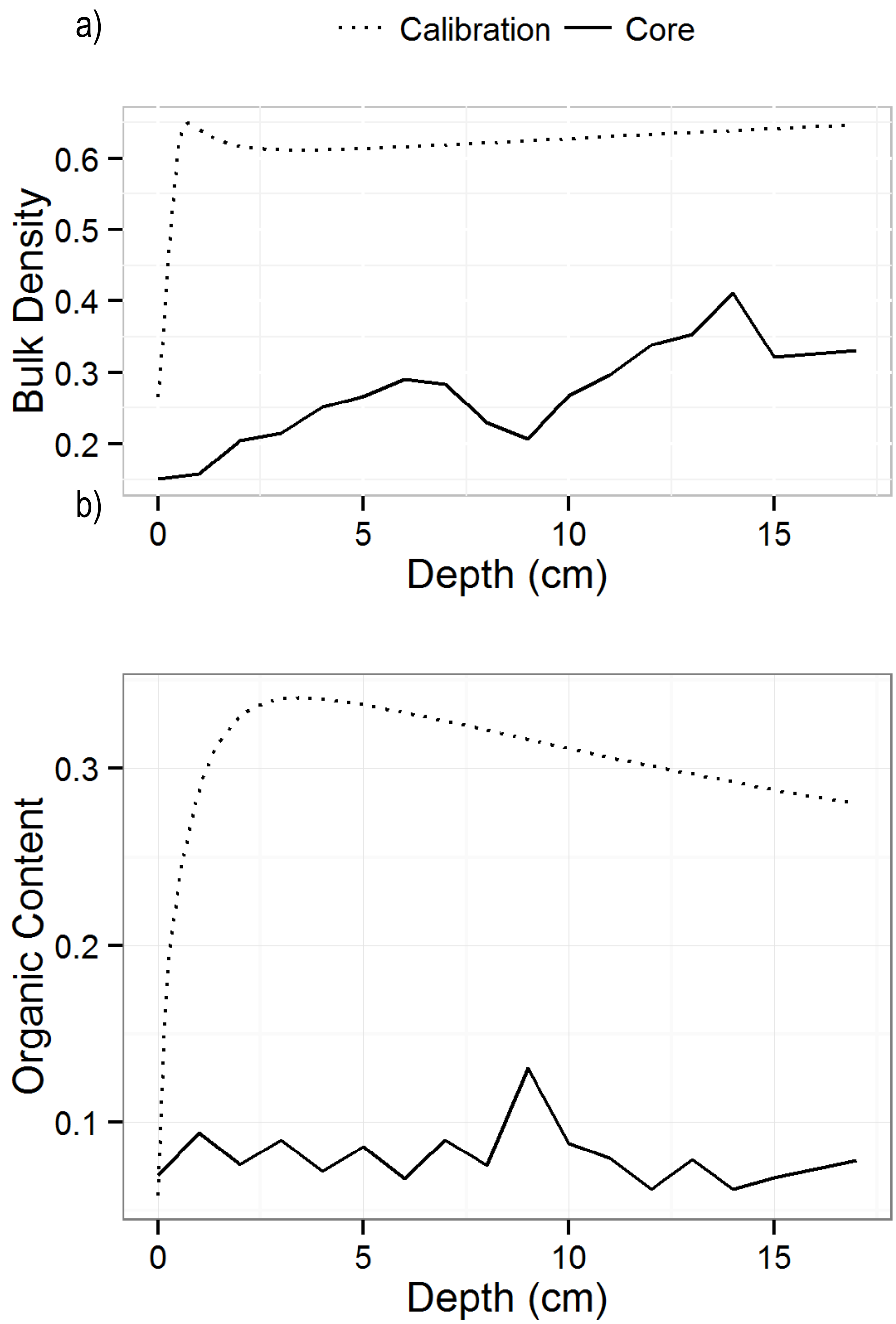

Figure I8. Deep core calibration of the WARMER model using depth profiles of (a) sediment bulk density (g cm^{-3}) and (b) sediment organic matter content (%).

Table I4. Model input parameters for Bandon. 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})	0.13	Core calibration
Elevation of peak biomass (cm, MSL)	123	NDVI from NAIP
Minimum elevation of vegetation (cm, MSL)	12	Field Surveys
Max. aboveground organic accumulation (g cm^{-2} yr^{-1})	0.0079	Core calibration
Root-to-shoot ratio	1.95	C. Janousek, unpub data
Porosity surface (%)	89	Core
Porosity depth (%)	66	Core
Refractory carbon (%)	28.1	Core
Maximum astronomical tide (cm, MSL)	183	CERCC water logger
Historic sea-level rise (mm yr^{-1})	0.59	Charleston tide gauge (NOAA, 9432780)
Organic matter density (g cm^{-3})	1.14	DeLaune 1983
Mineral density (g cm^{-3})	2.61	DeLaune 1983

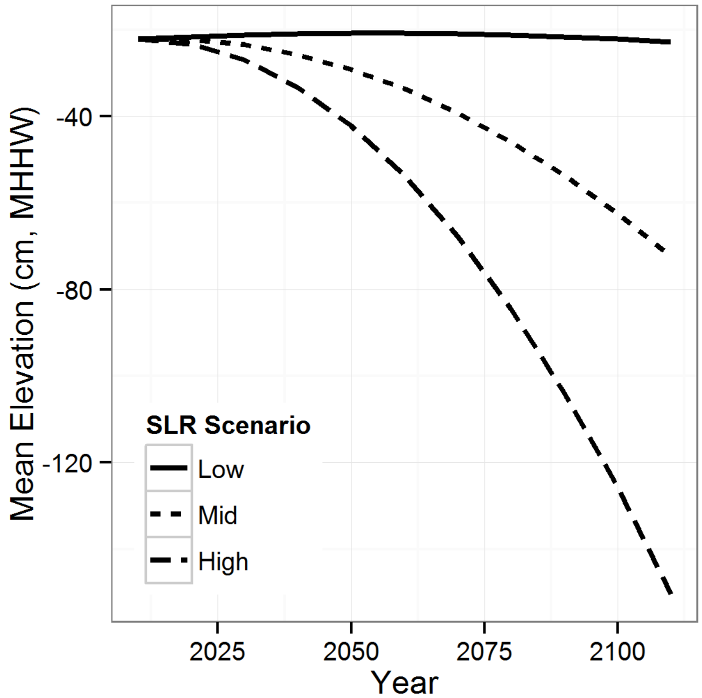

Figure I9. WARMER model projections for the change in average marsh elevation change at Bandon from 2010 to 2110 under low, mid, and high sea-level rise (SLR) scenarios.

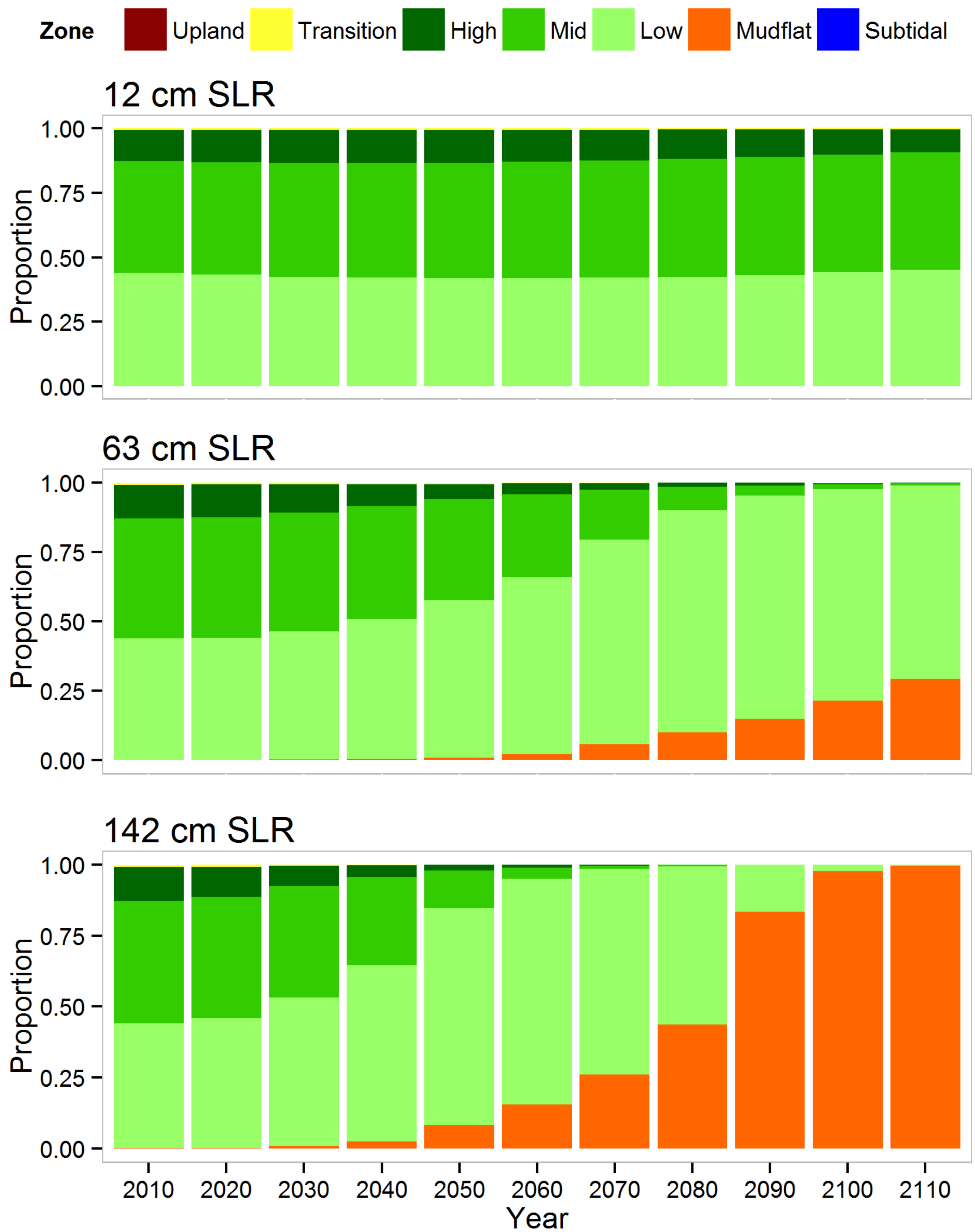

Figure I10. Model projections for change in the relative proportion of upland, transitional, high, mid, and low marsh habitat, and mudflat under low (12 cm), mid (63 cm), and high (142 cm) NRC sea-level rise scenarios from 2010 to 2110.

Table I5. Percentage of habitat area modeled for three sea-level rise scenarios for 2010, 2050, and 2110.

	Low SLR (12 cm)			Mid SLR (63 cm)			High SLR (142 cm)		
	2010	**2050**	**2110**	**2010**	**2050**	**2110**	**2010**	**2050**	**2110**
Upland	0	0	0	0	0	0	0	0	0
Transition	1	1	1	1	0	0	1	0	0
High	12	13	9	12	6	0	12	2	0
Mid	43	45	45	43	36	1	43	13	0
Low	44	42	45	44	57	70	44	77	0
Mudflat	0	0	0	0	1	29	0	8	100
Subtidal	0	0	0	0	0	0	0	0	0

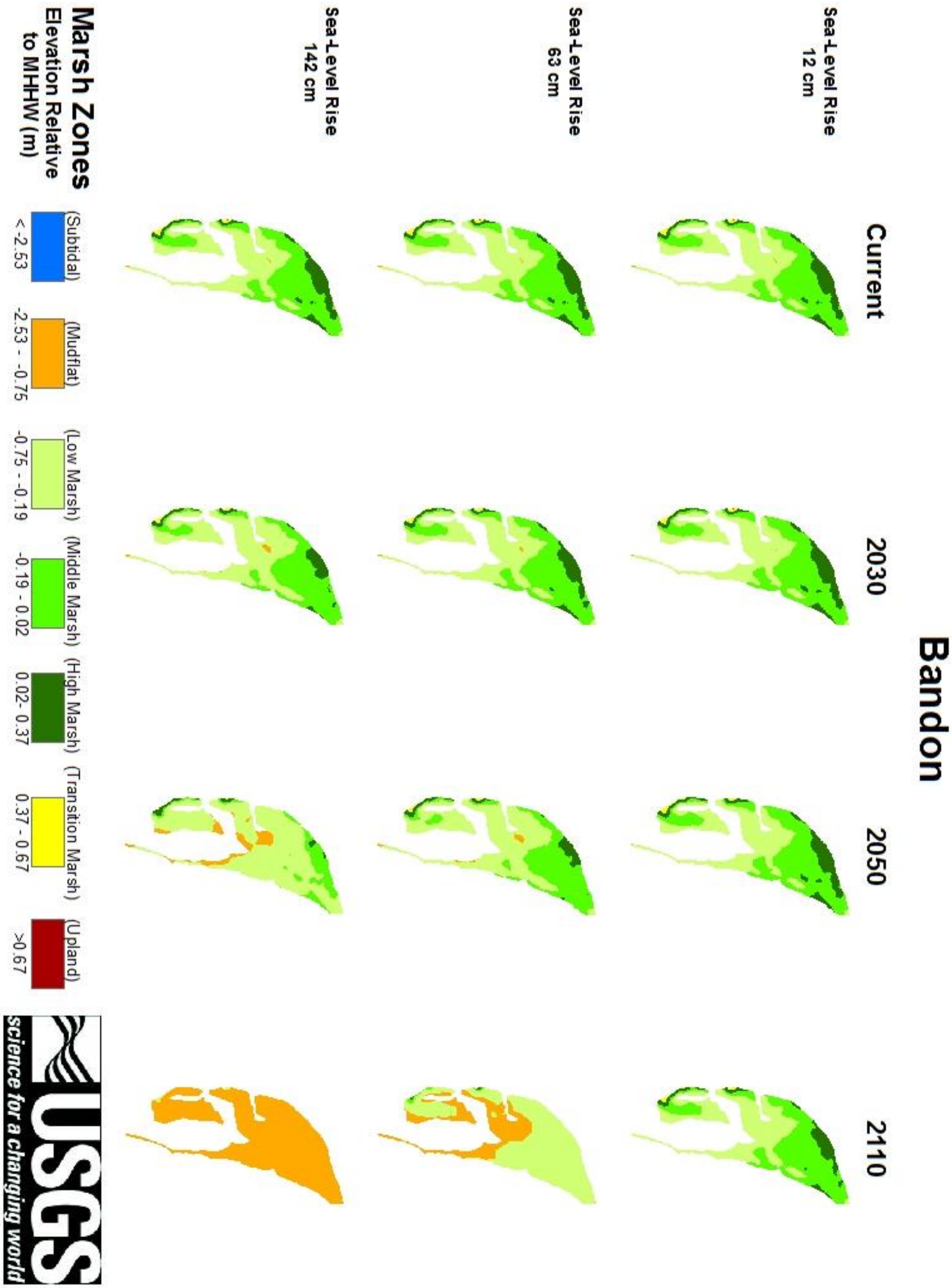

Figure I11. Projected habitat distribution at Bandon for 2030, 2050 and 2110 with the WARMER model under three NRC sea-level rise scenarios.

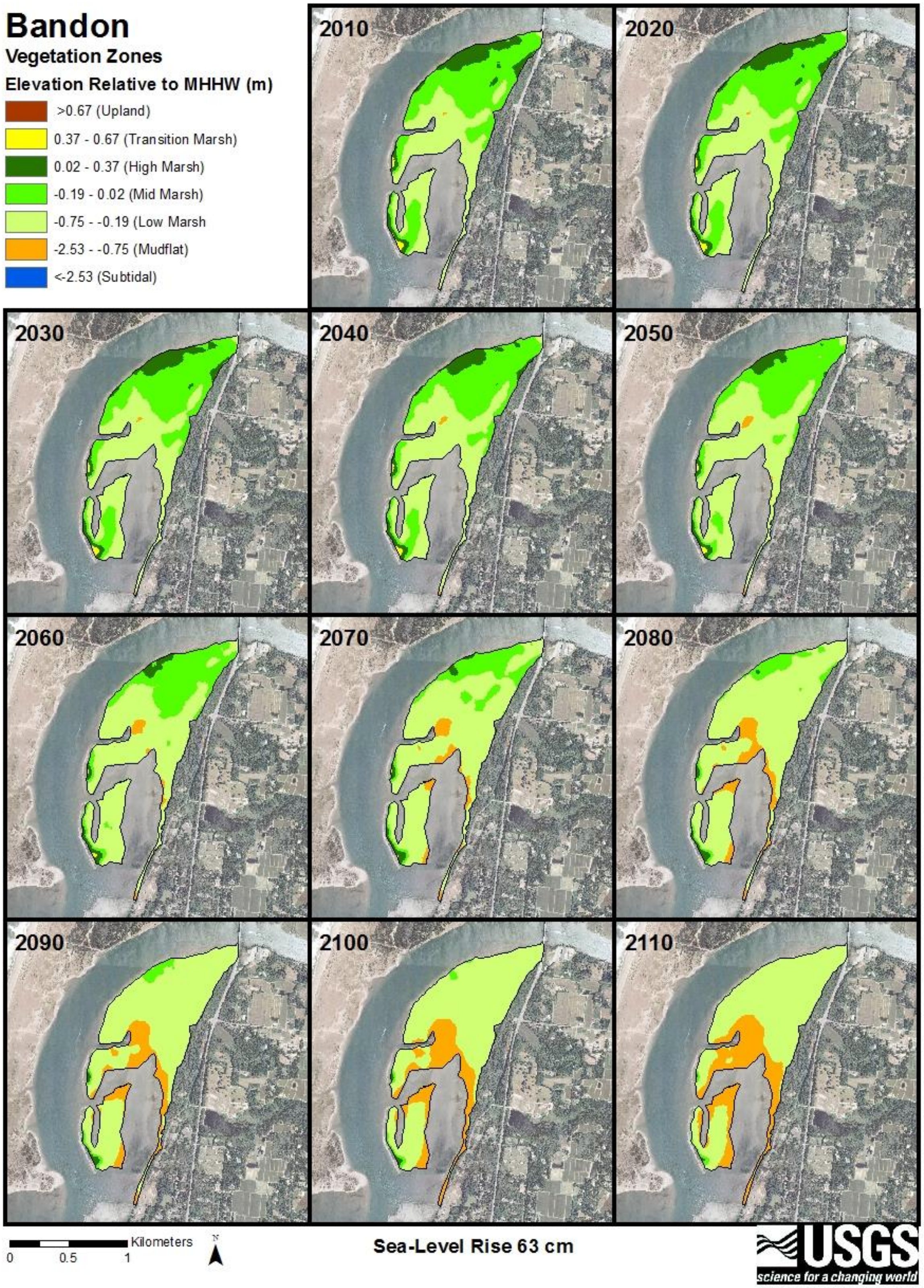

Figure I12. Projected changes in Bandon habitat zones under the mid NRC sea-level rise scenario (63 cm).