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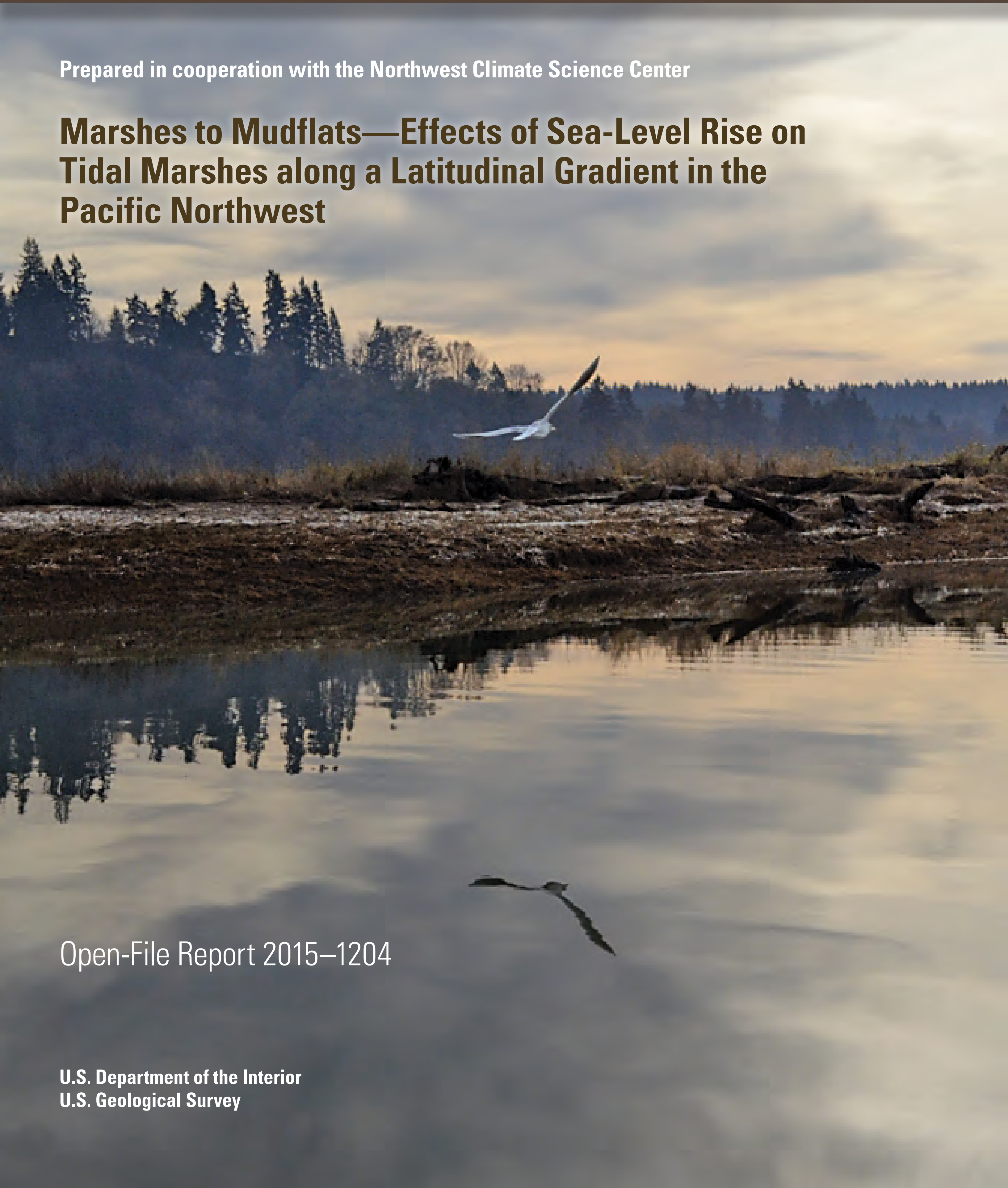
Marshes to Mudflats—Effects of Sea-Level Rise on Tidal Marshes along a Latitudinal Gradient in the Pacific Northwest



Open-File Report 2015–1204

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph showing sunset at Nisqually National Wildlife Refuge, Washington, 2015.
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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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Suggested citation:
Thorne, K.M., Dugger, B.D., Buffington, K.J., Freeman, C.M., Janousek, C.N., Powelson, K.W., Gutenspergen, G.R., and Takekawa, J.Y., 2015, Marshes to mudflats—Effects of sea-level rise on tidal marshes along a latitudinal gradient in the Pacific Northwest: U.S. Geological Survey Open-File Report 2015-1204, 54 p. plus appendixes, http://dx.doi.org/10.3133/ofr20151204.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
	Sediment accretion rate	
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Sediment accumulation rate	
gram per centimeter per year [(g/cm)/yr]	0.067196	pound per foot per year [(lb/ft)/yr]
	Density	
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Datums

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

CERCC program	Coastal Ecosystem Response to Climate Change program
GPS	Global Positioning System
DEM	digital elevation model
HOWL	highest observed water level
LCCs	Landscape Conservation Cooperatives
MHW	mean high water
MHHW	mean higher high water
MLLW	mean lower low water
MTL	mean tide level
NERR	National Estuarine Research Reserve
NGO	non-governmental organization
NRC	National Research Council
NOAA	National Oceanic and Atmospheric Administration
RMS	root-mean-square
RTK	Real Time Kinematic
SLR	sea-level rise
USGS	U.S. Geological Survey

Marshes to Mudflats—Effects of Sea-Level Rise on Tidal Marshes along a Latitudinal Gradient in the Pacific Northwest

By Karen M. Thorne[1], Bruce D. Dugger[2], Kevin J. Buffington[1], Chase M. Freeman[1], Christopher N. Janousek[1], Katherine W. Powelson[1], Glenn R. Gutenspergen[1], and John Y. Takekawa[1]

Section 1—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 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 between 2012 and 2015, 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, as well as recent and historical 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 communities of marsh plants or gradually increased proportions of middle-, high-, or transition-elevation zones of marsh vegetation. However, at most sites, mid sea-level rise projections led to loss of habitat of middle and high marshes and a gain of low marshes. Under a high sea-level rise scenario, marshes at most sites eventually converted to intertidal mudflats. Two sites (Grays Harbor and Willapa) seemed to have the most resilience to a high rate of rise in sea-level, persisting as low marsh until at least 2110. Our main model finding is that most tidal marsh study sites are resilient to sea-level rise over the next 50–70 years, but that sea-level rise will eventually outpace marsh accretion and drown most habitats of high and middle marshes by 2110.

[1]U.S. Geological Survey.
[2]Oregon State University.

Section 2—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 effects of climate change on coastal environments include sea-level rise (SLR), changes in freshwater delivery, saltwater intrusion, erosion, shifting mudflat profiles, and changing water temperature and ocean acidity. Climate change research often is 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 because of potential shifts in coastal inundation, salinity, storms, and other environmental factors. Integration of physical and ecological response models that project changes to tidal marsh ecosystems and habitats is required to assess the vulnerability of coastal climate change. 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?
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 (for example, 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 collected between 2012 and 2015 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 effect or a positive effect (increased proportions of middle- and high-elevation marsh zones) on the spatial extent or composition of future tidal marshes. However, middle-to-high SLR scenarios changed the composition of tidal marshes (high- and middle-elevation marsh zones usually became low-elevation marsh zones) 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 3—Purpose and Objectives

Climate change threatens the persistence and diversity of coastal ecosystems by altering physical and biological systems (Intergovernmental Panel on Climate Change, 2014). Effects on coastal environments include increased inundation from SLR and storms, saltwater intrusion, erosion, shifting beach and mudflat profiles, and changes in water temperature and acidification (Scavia and others, 2002; Huppert and others, 2009; National Research Council, 2012). Recent estimates of global SLR by the year 2100 range from 57 to 110 cm (Jevrejeva and others, 2012), 75 to 190 cm (Vermeer and Rahmstorf, 2009), and 54 to 71 cm (Slangen and others, 2014). In the Pacific Northwest, SLR rates are projected to be between 12 and 143 cm (National Research Council, 2012). Along the Pacific coast of the United States, local variations 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 and others, 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 effects 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-induced change (fig. 1). To understand climate effects on coastal ecosystems from site to regional scales, we established the Coastal Ecosystem Response to Climate Change (CERCC) program. To assess the scope of physical and biological climate-induced change 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 affect 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 (fig. 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 at Los Angeles, and local and regional management agencies.

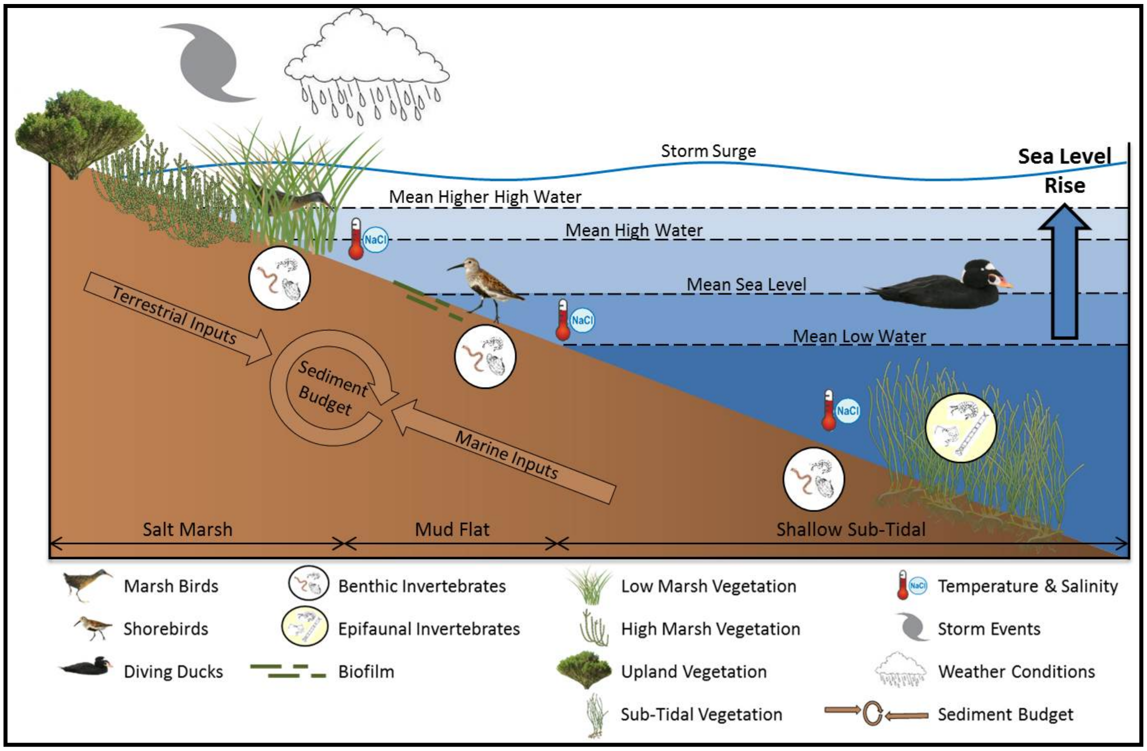

Figure 1. Conceptual model of linkages among physical and biological processes along the coast to assess climate-induced changes.

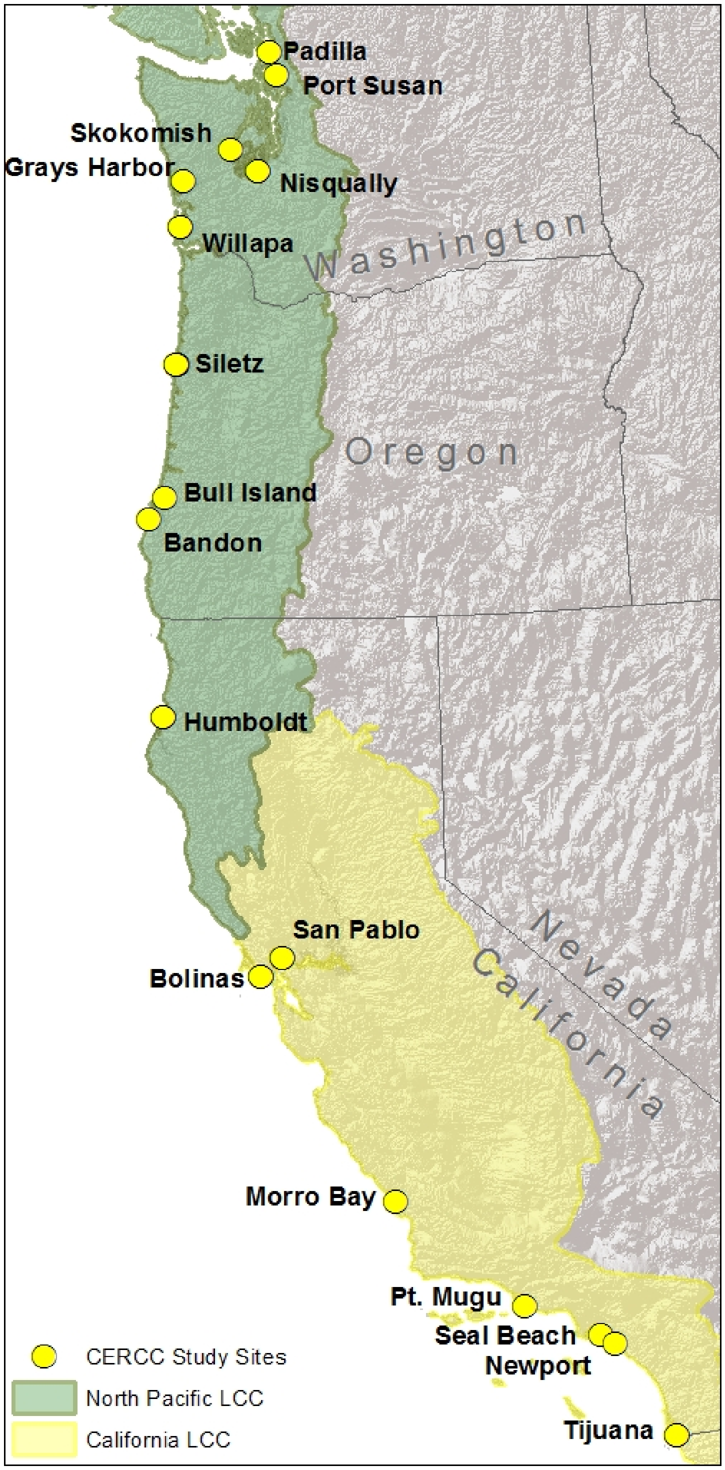

Figure 2. Seventeen project study sites that make up the Coastal Ecosystem Response to Climate Change (CERCC) program network, located within the boundaries of the North Pacific and California Landscape Conservation Cooperatives (LCCs).

Regional and local understanding of SLR effects 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—Strategic Plan for Responding to Accelerating Climate Change," developed by the U.S. Fish and Wildlife Service to establish their strategic climate change plan and to assist managers with development of adaptation and planning strategies (U.S. Fish and Wildlife Service, 2010). Additionally, our research helps meet one of the priority objectives in the U.S. Department of the Interior (National Fish, Wildlife and Plants Climate Adaptation Partnership, 2012), developed as a collaborative effort mandated by Congress (P.I. Thorne, oral commun., coastal development team member, June 2012). Our data provides information needed to increase preparedness of resource managers (for example, U.S. Fish and Wildlife Service, National Park Service, National Oceanic and Atmospheric Administration [NOAA] National Estuarine Research Reserve [NERR], and 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 (LCCs) in their strategic plans. Additionally, the CERCC program addresses the USGS Science Strategy (http://www.usgs.gov/start_with_science/), 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 potentially can be transferred to other coastal regions throughout the United States.

The overarching goal of our research was to use site-specific data to develop local and regional 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?
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 (for example, 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.

Section 4—Organization and Approach

4.1 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 at the mouth of the Coquille River in southern Oregon (fig. 3). These sites are managed by local non-governmental organizations (NGOs), Native American Tribes, and Federal or State agencies. The sites were located in Padilla National Estuarine Research Reserve (hereinafter Padilla), Port Susan Bay Preserve (hereinafter Port Susan), Skokomish Estuary on lands of the Skokomish Indian Tribe (hereinafter Skokomish), Nisqually National Wildlife Refuge in southern Puget Sound (hereinafter Nisqually), Grays Harbor National Wildlife Refuge (hereinafter Grays Harbor), Tartlatt Slough in Willapa Bay National Wildlife Refuge (hereinafter Willapa), Siletz National Wildlife Refuge (hereinafter Siletz), Bull Island in South Slough National Estuarine Research Reserve in Coos Bay (hereinafter Bull Island), and Bandon National Wildlife Refuge on the Coquille Estuary (hereinafter Bandon). Each study site comprised a part 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.

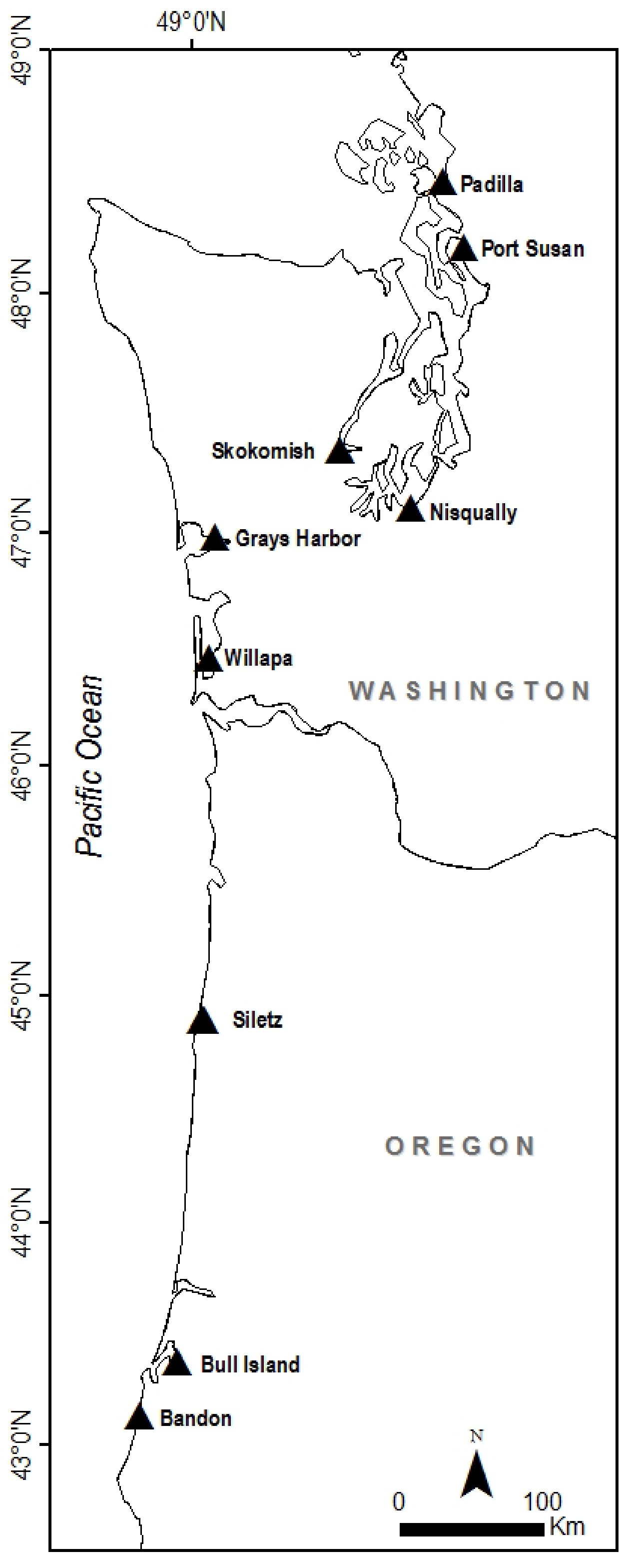

Figure 3. Pacific Northwest study sites in the Coastal Ecosystem Response to Climate Change (CERCC) network along a latitudinal and tidal gradient.

4.2 Elevation Surveys

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, Georgia; fig. 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 using a CDMA modem (http://www.leica-geosystems.us/en/index.htm). At sites without network coverage (Skokomish, Grays Harbor, and Willapa), rover positions were received in real time from a Leica GS10 antenna base station by 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 WGS 84 ellipsoid model for vertical and horizontal positioning and referenced positions to a local National Geodetic Survey benchmark or a benchmark established by a surveyor (fig. 4). Average measured vertical errors at benchmarks were 1–9 cm throughout the study, comparable to the stated error of the GPS (table 1).

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 (in meters, North American Vertical Datum of 1988 [NAVD 88]) and projected all points to North American Datum of 1983 [NAD 83] UTM zone 10 using Leica GeoOffice v7.0.1 (Leica Geosystems Incorporated, Norcross, Georgia).

Figure 4. U.S. Geological Survey technician collecting elevation data using a Real-Time Kinematic Global Positioning System at Bandon National Wildlife Refuge, southern Oregon. Photograph by Katherine Powelson, U.S. Geological Survey, 2012.

Table 1. National Geodetic Survey benchmarks used as references in elevation survey with associated measured error (published elevation minus average measured elevation).

[Sites are ordered from north to south. PID, Permanent Identifier]

Site	Benchmark PID	Latitude (N)	Longitude (W)	Average error (meters)	Survey methodology
Padilla	NERR[1]	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

[1]Benchmarks installed and surveyed by Skagit County, Washington.

4.3 Elevation Modeling

Using ArcGIS™ 10.2.1 Spatial Analyst (Environmental Systems Research Institute, Incorporated, 2013, Redlands, California), 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 (5×5-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 (NAVD 88) and local mean higher high water (MHHW), based on computation of site-specific MHHW from water-level data. 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-mean tide level or MTL)/(MHHW-MTL), as described in Swanson and others (2014). The lowest extent of tidal marsh generally occurs at approximately z* = 0.0 (MTL) while z*=1.0 (local MHHW) is approximately equal to the middle-high marsh boundary.

Table 2. Root-mean-square error (RMSE) for the digital elevation models of each site.

[Sites are ordered from north to south]

Site	RMS error (meters)
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

4.4 Vegetation Surveys

We conducted vegetation surveys concurrently with elevation surveys at every fourth elevation point (about 25 percent of the elevation points) (fig. 5). We visually assessed percentage of 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 percent because of vegetation layering. Vascular plant nomenclature generally follows Baldwin and others (2012) and Cook and others (2013).

4.5 Vegetation Zones

To consistently delineate habitat elevation zones for analyses and mapping across all study sites we used long-term 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 about at MTL). Higher in the intertidal zone, we defined four vegetated marsh zones based on long-term inundation data (low marsh, middle marsh, high marsh, and transitional marsh).

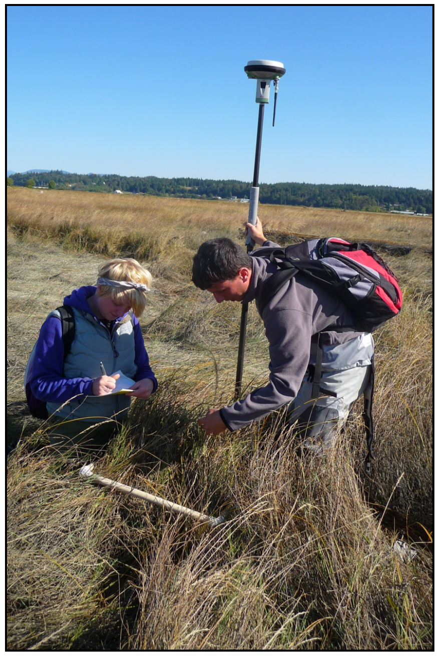

Figure 5. U.S. Geological Survey technicians collecting vegetation data at Port Susan, Washington. Photograph by Kelly Turner, U.S. Geological Survey, 2012.

To delineate elevation zones within vegetated tidal marsh, we compiled high-tide data from 2004 to 2013 at three NOAA tidal stations along the U.S. West Coast: Charleston, Oregon; Toke Point, Willapa Bay, Washington; and Seattle, Washington (http://tidesandcurrents.noaa.gov/) to assess the average inundation frequency in the upper intertidal zone. 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 percent of all high tides (inundated between once daily and once every 2 days), and high marsh included elevations flooded by 3–25 percent 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 percent 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, middle 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 (for example, Bandon was paired with Charleston NOAA records) and the local tidal datums to determine the local NAVD 88 and MHHW elevations that corresponded with each z* value defining zone boundaries. We used Charleston data for all Oregon sites, Toke Point data for outer-coast Washington sites, and Seattle data for all sites in Puget Sound.

4.6 Water Monitoring

To determine inundation patterns and to calculate site-specific tidal datums, we deployed water-level data loggers (Model 3001, Solinst Canada Limited, Georgetown, Ontario, and Model U-20-001-01-Ti, Onset Computer Corporation , Bourne, Massachusetts) at all sites, beginning in 2012 and continuing through 2015.(fig. 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 record high tides and to determine seasonal inundation patterns. Water loggers collected water-level readings every 6 minutes starting on the date of deployment and continuing to the present (2015). 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 Limited, Georgetown, Ontario); for Hobo water-level loggers, we used barometric pressure from local airports (distance <10 mi).

Figure 6. Water-level logger deployed in second-order tidal-marsh channels. Photograph by Katherine Powelson, U.S. Geological Survey, 2013.

Table 3. Water-level monitoring occurred at all Pacific Northwest study sites.

[Sites are ordered from north to south. Manufacturer information, number of loggers currently deployed, date of deployment, and source of barometric pressure data for compensation varied across sites]

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

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 United Nations Educational, Scientific and Cultural Organization (1983).

We used water-level data to estimate local tidal datums for all sites using procedures outlined in the NOAA Tidal Datums Handbook (National Oceanic and Atmospheric Administration, 2003). We only calculated local MHW and MHHW because the loggers were positioned in the intertidal zone, which is relatively high in the tidal frame, and, therefore, did not record 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 VDATUM 3.4 software (http://vdatum.noaa.gov/), except at Bandon where we used MTL directly from historical NOAA data. Many results in this report are reported relative to local MHHW calculated from local water data.

4.7 Bathymetry

We conducted bathymetric surveys using a shallow-water echo-sounding system (Takekawa and others, 2010; Brand and others, 2012) comprised of an acoustic profiler (Navisound 210, Reson, Incorporated, Slangerup, Denmark), Leica Viva RTK GPS, and laptop computer mounted on a shallow-draft, portable flat-bottom boat (fig. 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 were referenced to the same benchmark 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 greater than 10 cm of water. We recorded 20 depth readings and 1 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. U.S. Geological Survey technician conducting bathymetric surveys. Photograph by Katherine Powelson, U.S. Geological Survey, 2012.

4.8 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 (Environmental Systems Research Institute, Incorporated, 2013, Redlands, California) with exponential ordinary kriging methods (5×5-m cell size). We removed portions of the bathymetry data that overlapped with elevation surveys conducted on the tidal marsh. In this report, we present elevation data as local orthometric heights (NAVD 88). At Padilla, we mapped the nearshore area using the methodologies outlined in the sections 4.2 and 4.3 because the dense eelgrass beds would have increased the error in acoustic measurements.

4.9 Deep Sediment Coring

To parameterize accretion for SLR models, we measured historical rates of mineral and organic matter accumulation at each site by collecting deep soil cores with a Russian peat borer (fig. 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 laboratory, 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 550 ºC for 8 hr (Heiri and others, 2001).

Figure 8. Sediment core taken at a Coastal Ecosystem Response to Climate Change program study site. Photograph by Chase Freeman, U.S. Geological Survey, 2014.

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 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 one-half century.

4.10 Response Modeling of Tidal Marsh Ecosystems

We used WARMER, a one-dimensional cohort model of wetland accretion (Swanson and others, 2014), which is based on Callaway and others (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 mean sea level (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 (fig. 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.

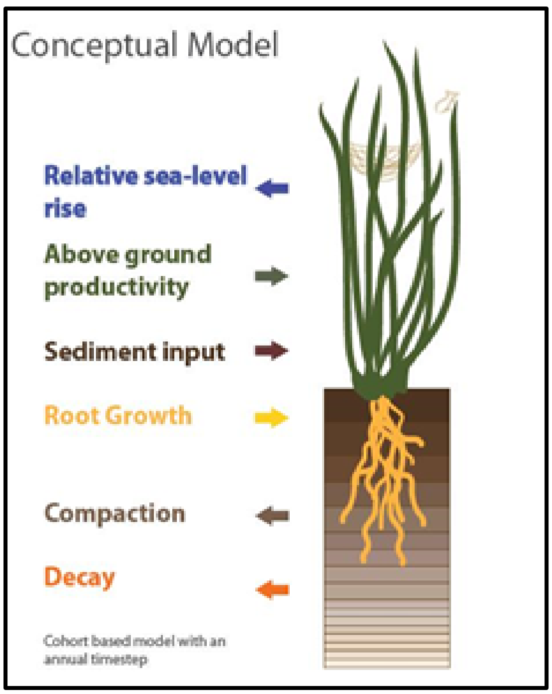

Figure 9. WARMER one-dimensional conceptual model that shows the input variable for the modeling approach (from Swanson and others, 2014).

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

$$E(t) = E(0) - SLR(t) + \sum_{i=0}^{t} V_i(t) \quad (1)$$

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.

Model Inputs

Sea-Level Rise Scenarios

In WARMER, we incorporated a recent forecast for the Pacific coast that projects low, mid, and high SLR scenarios of 12, 64, and 142 cm by 2110, respectively (National Research Council, 2012). We used the average annual SLR curve as the input function for the WARMER model. We assumed that 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 and others (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

$$M_s(z) = S * f(z) \quad (2)$$

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)/yr] (figs. 10–11).

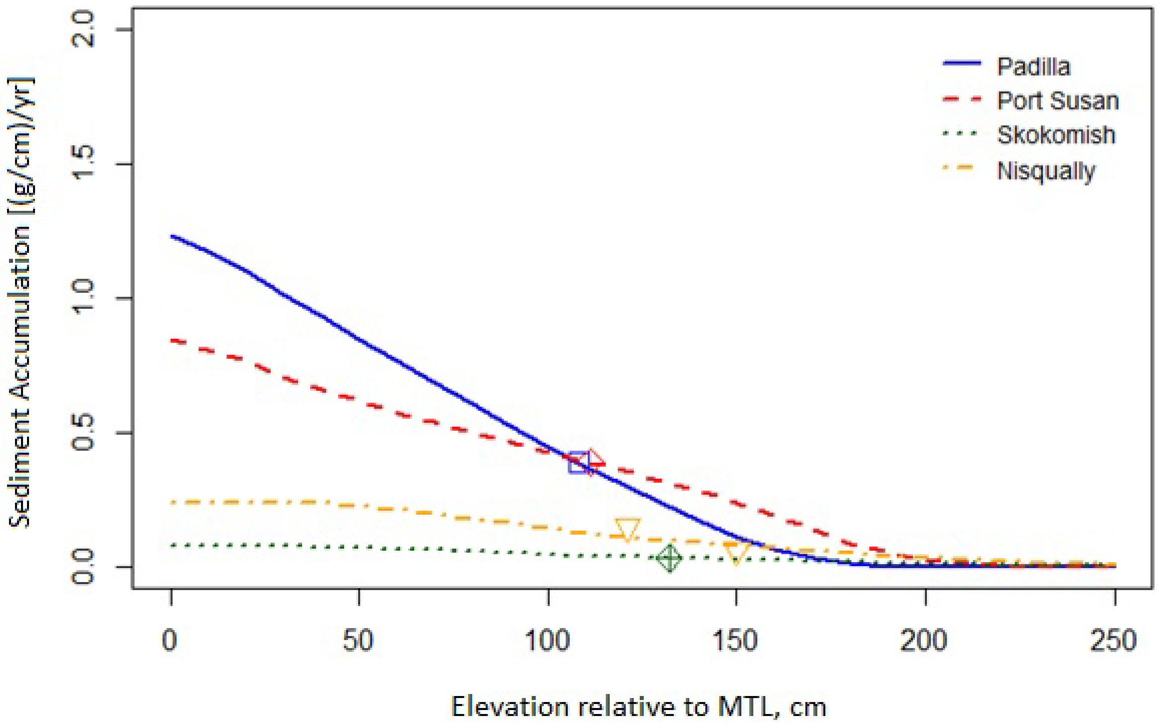

Figure 10. Calculated annual sediment accumulation curves (lines) and measured accumulation rates (points) for four study sites in Puget Sound, Washington. Padilla site values are based on core data from Port Susan.

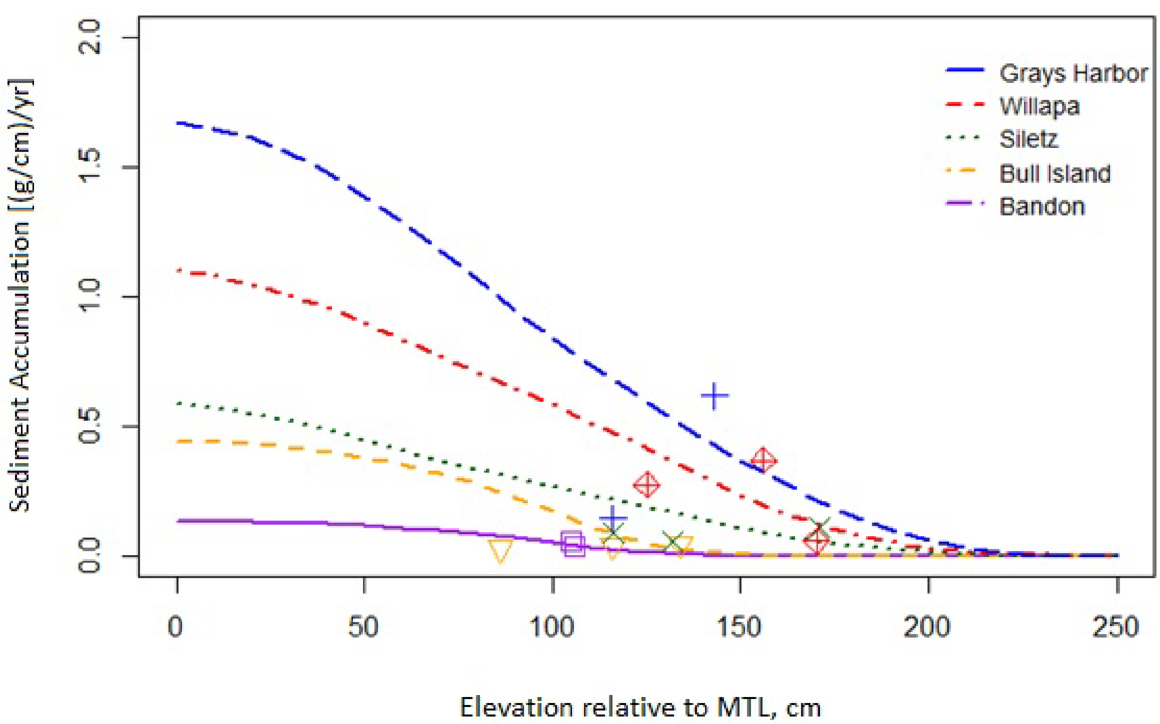

Figure 11. Calculated annual sediment accumulation curves (lines) and measured accumulation rates (points) for five study sites along the outer Pacific coast in Washington and Oregon.

Organic Matter

We used a unimodal functional shape to describe the relationship between elevation and organic matter (Morris and others, 2002), based on Atlantic coast work on Atlantic cordgrass (*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 at the low elevation by MTL and at the high elevation by the maximum observed water level from a nearby NOAA tide gauge. We determined the elevation of peak productivity by analyzing the Normalized Difference Vegetation Index (NDVI; [(NIR - Red)/(NIR + Red]) from 2011 National Agriculture Imagery Program 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 percentage of organic matter in the surface layer of the core) obtained from sediment cores across an elevation range at each site (figs. 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 (Christopher Janousek and others, U.S. Geological Survey, unpub. data, 2015). The mass of organic material generated belowground each year was distributed exponentially with depth and the coefficient of exponential decay, *kdist*, set equal to 1.0 (Deverel and others, 2008),

$$root\_prod = kdist * rs * om(x) * e^{-kdist*d} \tag{3}$$

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

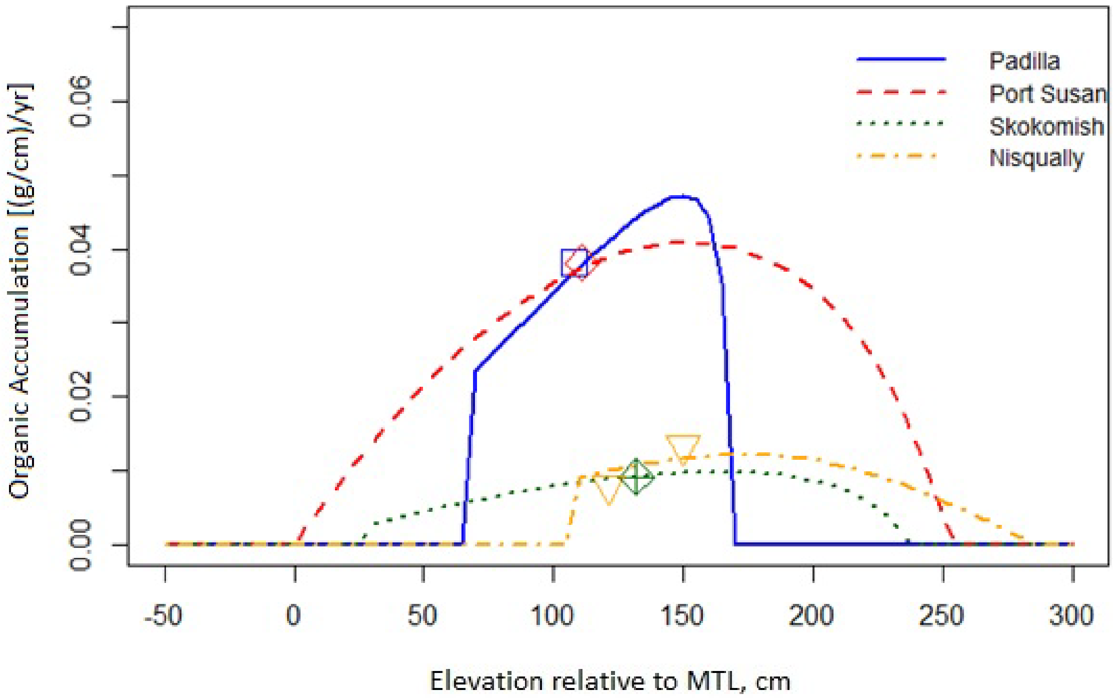

Figure 12. Calculated organic matter accumulation (lines) and measured accumulation rates (points) at four study sites across the Puget Sound, Washington. Site-specific elevations of minimum vegetation, maximum observed water level, and peak aboveground biomass were used to draw the curves. The amplitude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

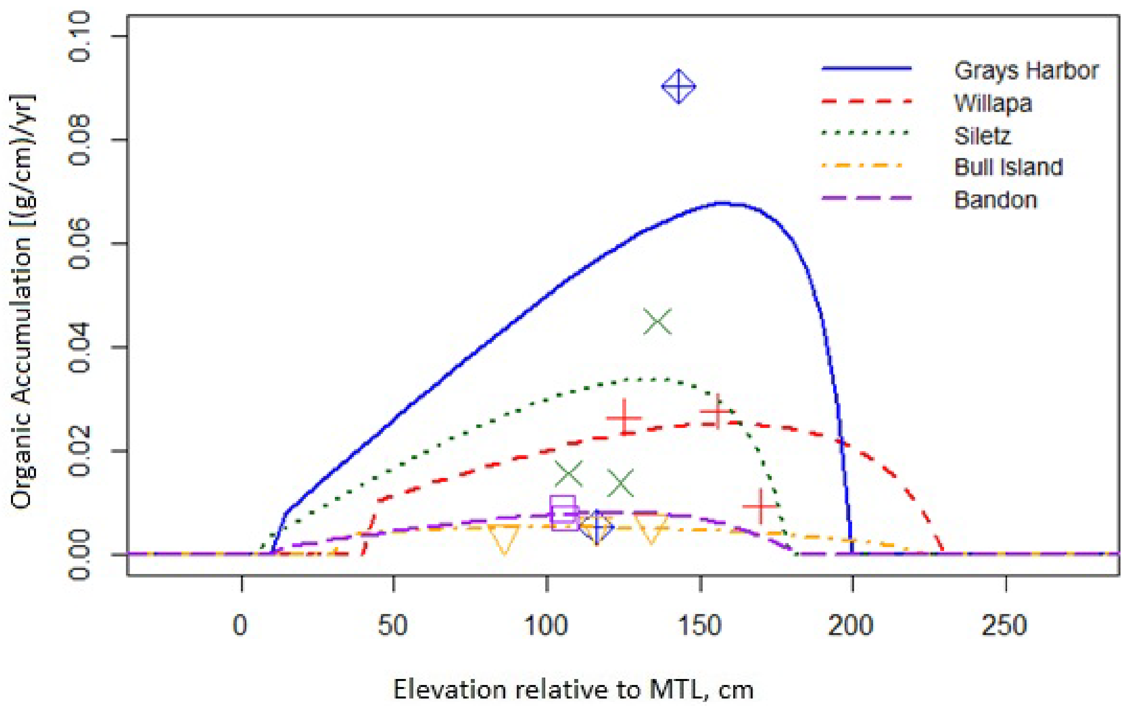

Figure 13. Calculated organic matter accumulation (lines) and measured accumulation rates (points) for five study sites along the outer Pacific coast, Washington and Oregon. Site-specific elevations of minimum vegetation, maximum observed water level, and peak aboveground biomass were used to draw the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

Compaction and Decomposition

Compaction and decomposition functions of WARMER followed Callaway and others (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:

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

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

Following Swanson and others (2014), we modeled decomposition as a three-tiered process where the youngest organic material, less than 1 year old, decomposed at the fastest rate; organic matter 1–2 years old decayed at a moderate rate; and organic matter greater than 2 years old decayed at the slowest rate. Decomposition also decreased exponentially with depth. 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 and others (2008). The decomposition rate was defined as,

$$decmp_i = m_i e^{-kdec_i * d} \quad (5)$$

where i is related to the age class 1, 2, or 3;
$kdec$ is set to 1.31, 0.57, or 0.1 respective of each age class;
m is 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, NAVD 88). A 200-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 so 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 for each site in the appendix tables A4–I4.

Section 5—Project Results

5.1 Tidal Wetland Elevations

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

Overall, the topographic range was large at most sites, indicating that a range of habitat types was present (fig. 18). Siletz, however, had a relatively more constrained elevation profile because it mostly consisted of high tidal marsh. Topographic profiles were significantly different at all sites (36 pair-wise Kolmogorov-Smirnov tests; all P<0.03; fig. 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 also were primarily comprised of high and middle tidal marsh, but had low marsh adjacent to open 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 primarily low marsh (fig. 18). Detailed site-specific results are shown in appendixes A–I.

Table 4. Metadata for each study site including area of study site; number of Real Time Kinematic Global Positioning System elevation points used in interpolation of digital elevation models ; and mean, maximum, minimum elevations and elevation range.

[Sites are ordered from north to south. Elevations are in meters above North American Vertical Datum of 1988]

Site	Area (hectares)	Elevation data points (number)	Mean elevation (meters)	Maximum elevation (meters)	Minimum elevation (meters)	Elevation range (meters)
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

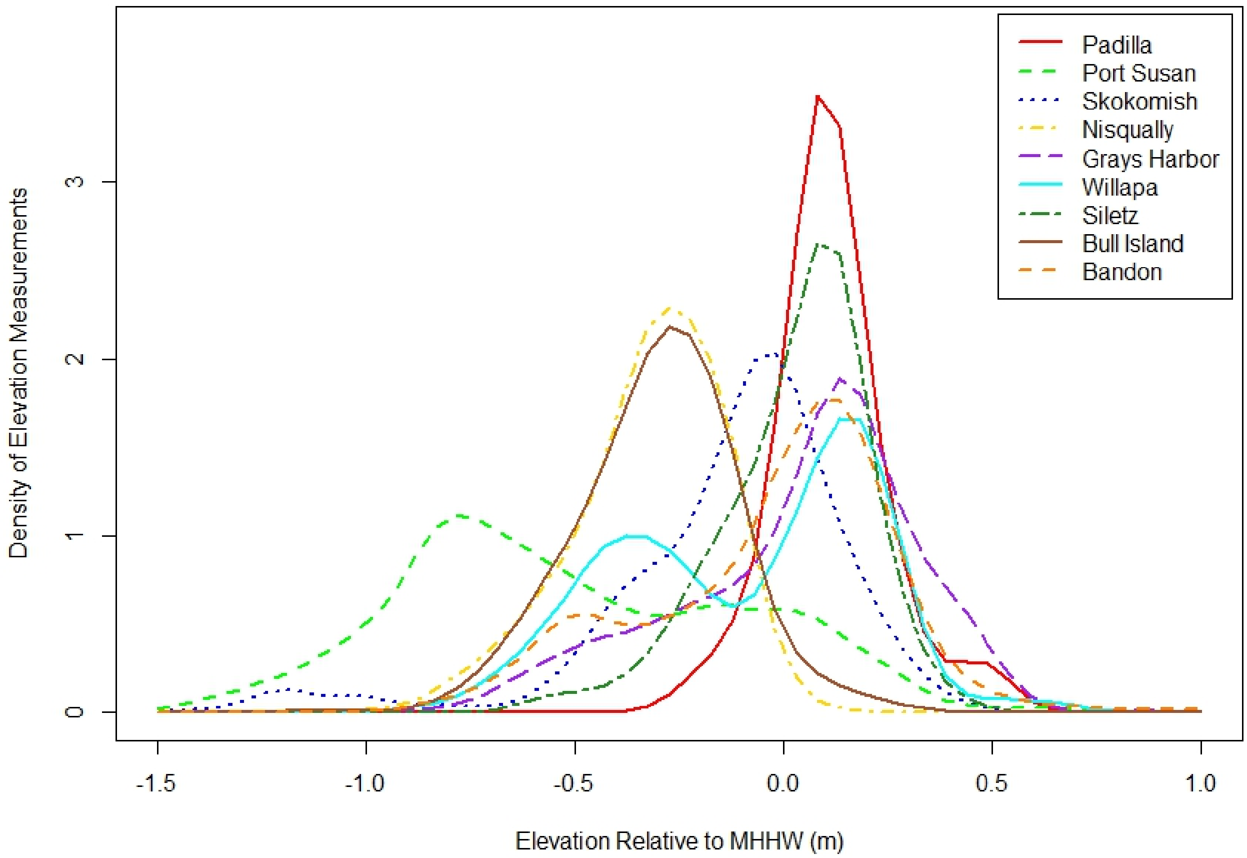

Figure 14. Density of elevation measurements relative to mean higher high water (MHHW), showing variability across the nine study sites, Oregon and Washington.

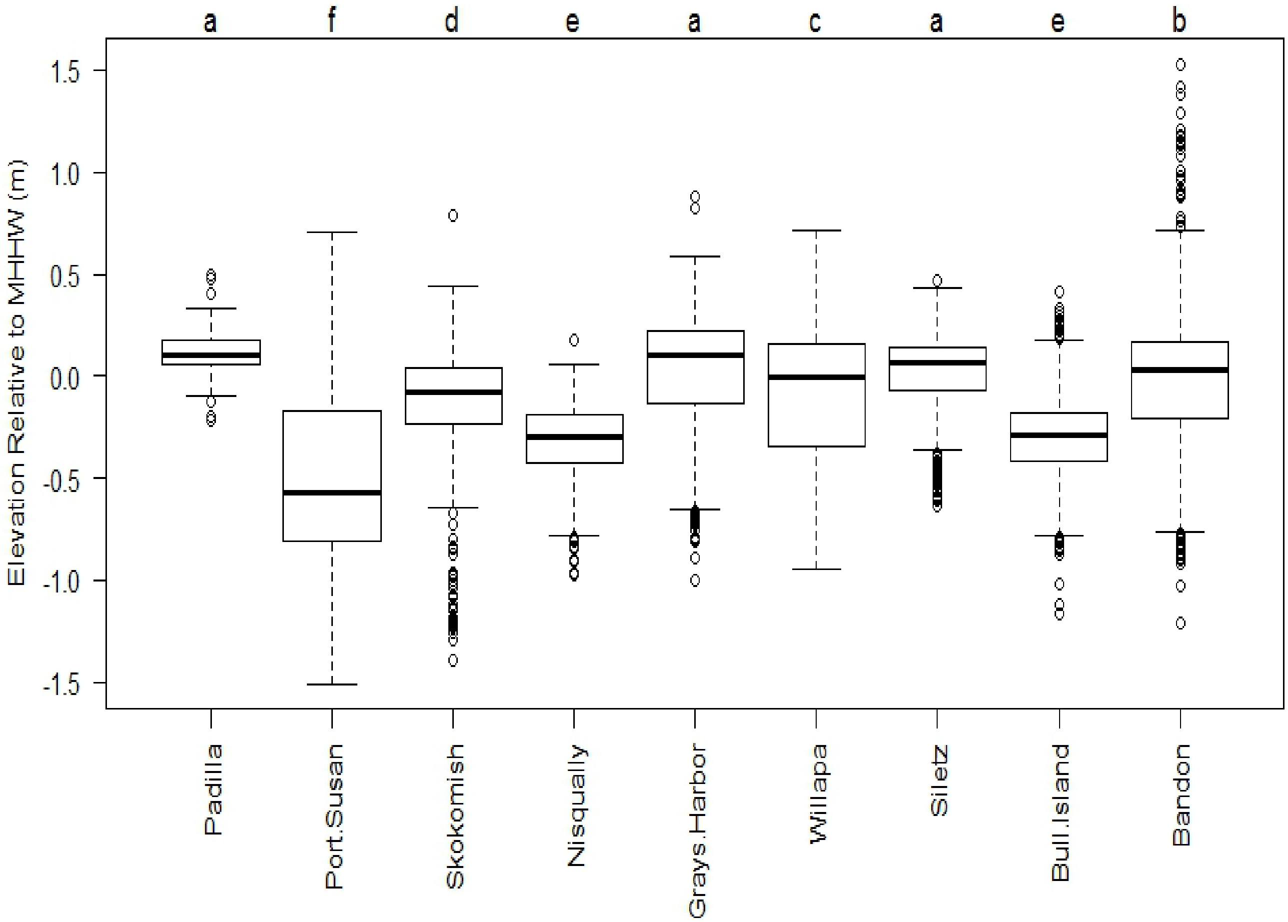

Figure 15. Distribution of elevation data points across all nine study sites from north to south (m, relative to mean higher high water [MHHW]).The black horizontal bars show the median elevation, boxes indicate the interquartile range, upper and lower whiskers encompass points no greater than 1.5 times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

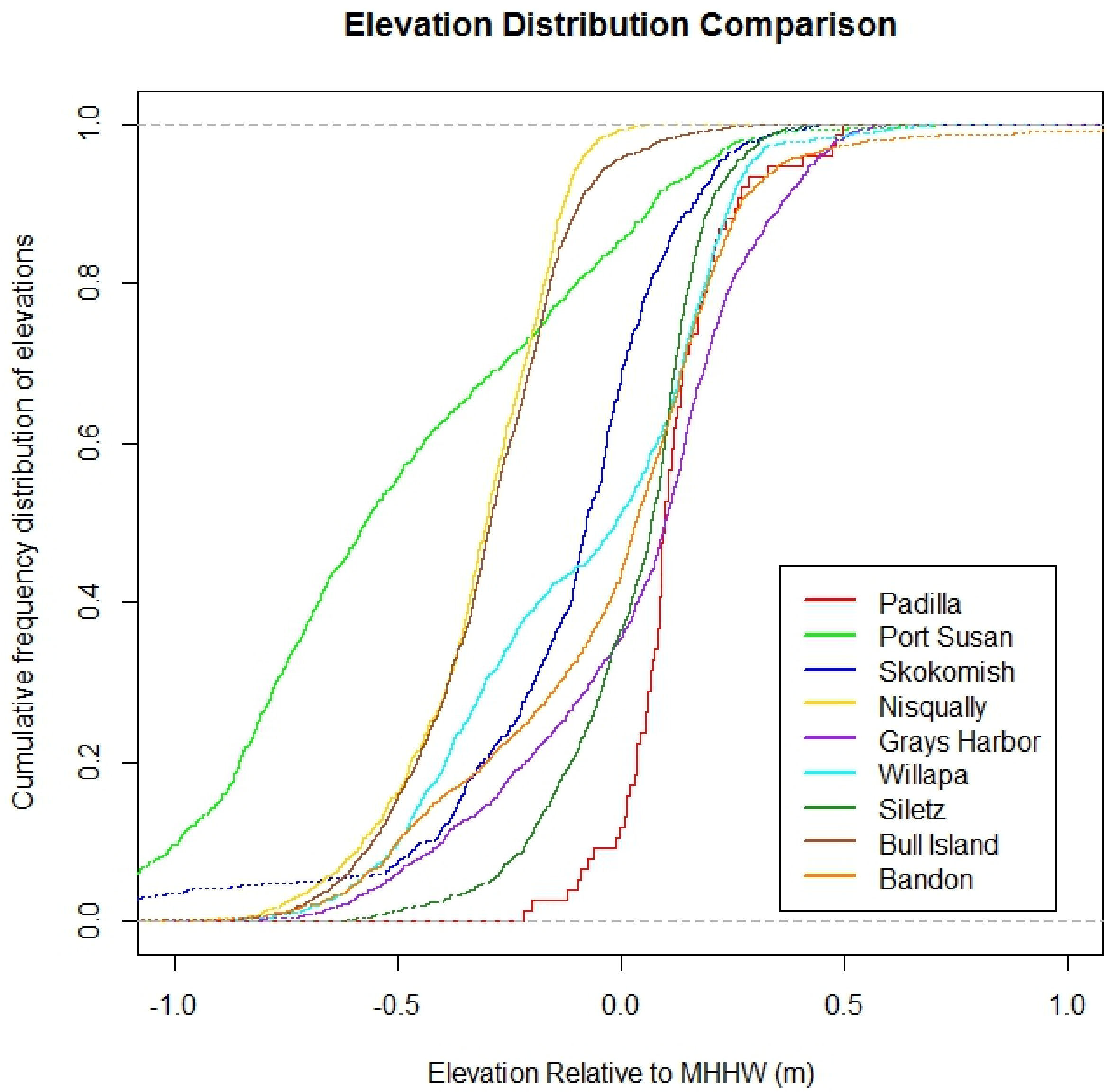

Figure 16. Cumulative frequency distribution of elevation data points relative to mean higher high water (MHHW, in meters [m]) across the nine study sites, Washington and Oregon. More steeply sloping curves indicate sites with more pronounced marsh platforms and less steeply sloping curves indicate marshes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

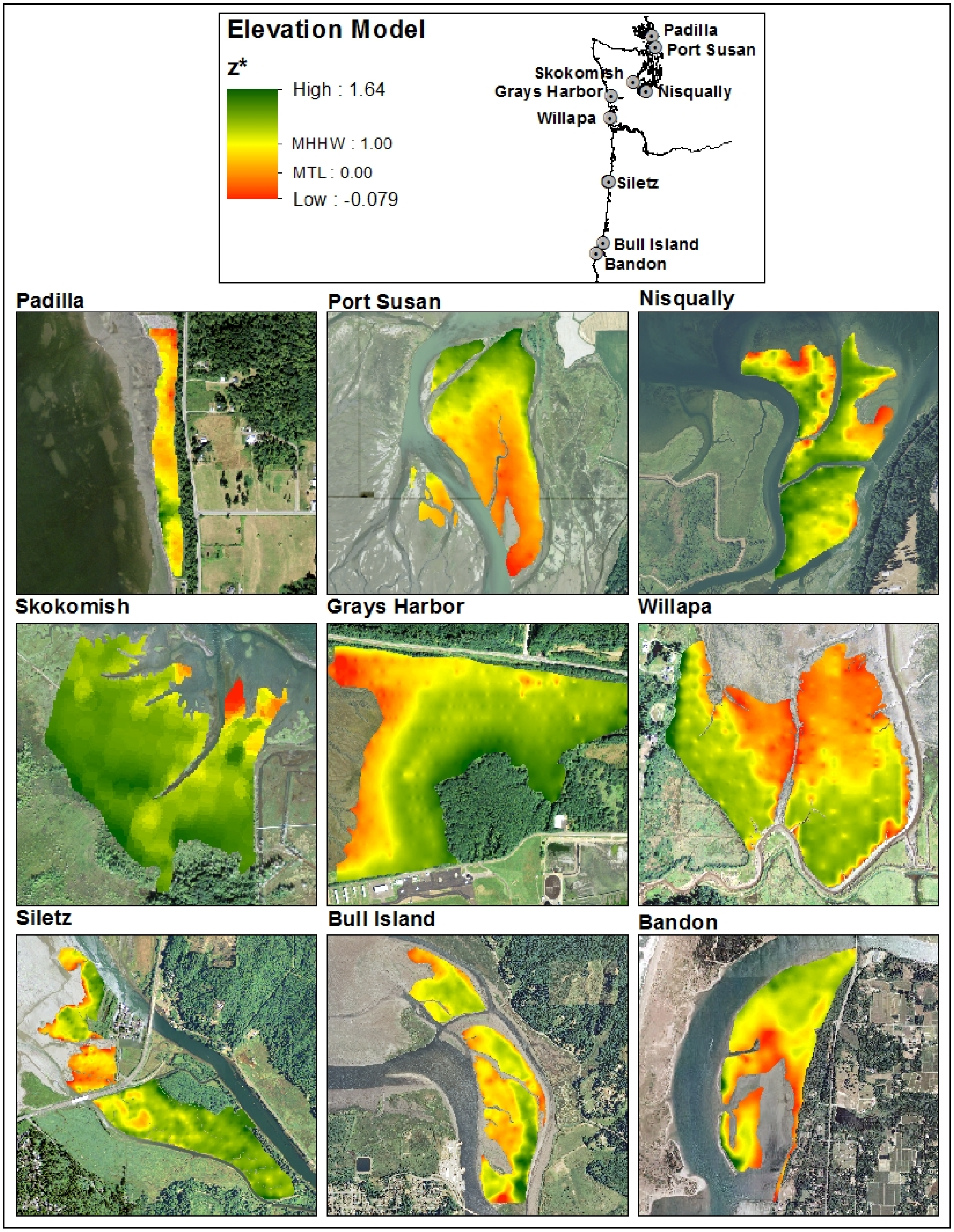

Figure 17. Digital elevations models presented in a standardized elevation (z*) across the nine study sites in the Coastal Ecosystem Response to Climate Change network, Washington and Oregon, showing that many of the sites have elevation gradients from high to low elevations.

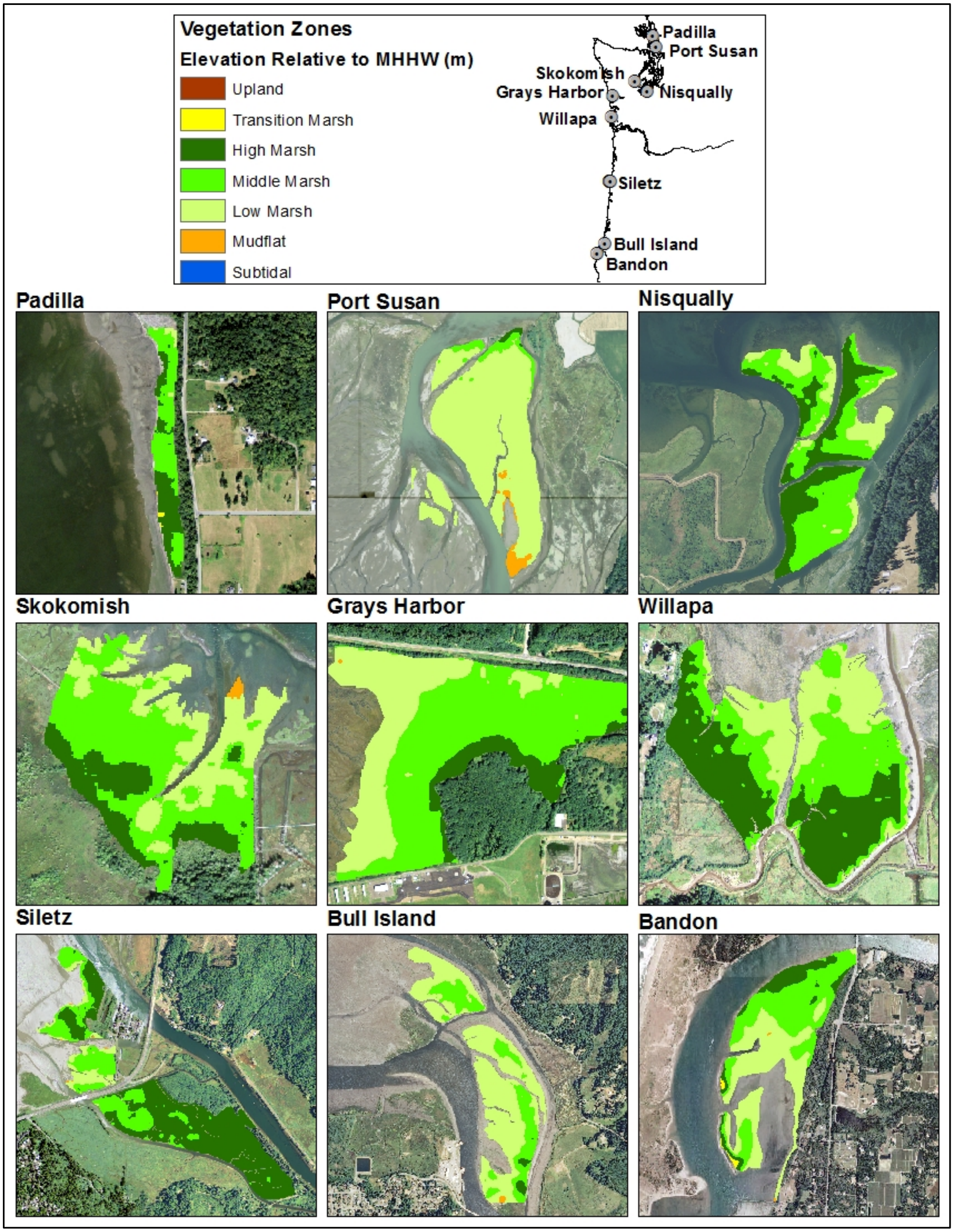

Figure 18. Distribution of tidal marsh vegetation zones across the nine study sites in the Coastal Ecosystem Response to Climate Change network, Washington and Oregon, illustrating that most sites have all the identified vegetation zones. Vegetation zones were defined by tidal flooding extent.

5.2 Bathymetry

We collected bathymetry data in the adjacent nearshore habitat at all sites (except for Siletz) for a total of 984.4 ha surveyed (fig. 19, table 5). Bathymetry greatly varied 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 because of inclusion of offshore areas of Puget Sound. Detailed site-specific results are shown in appendixes A–I.

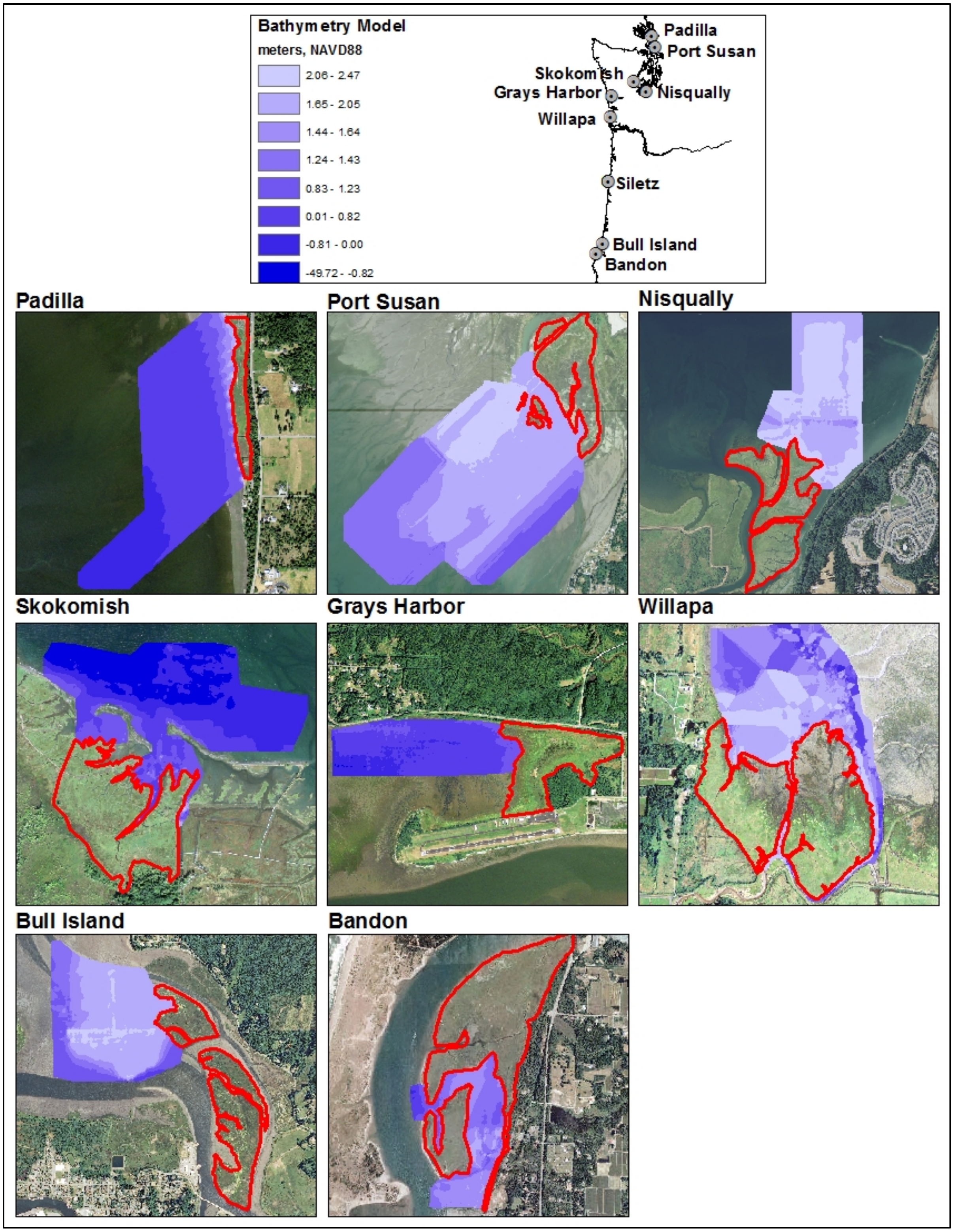

Figure 19. Bathymetry coverage across eight study sites in Washington and Oregon, showing that nearshore mudflat habitats have shallow ranges at most sites. Bathymetric data were not collected at Siletz.

Table 5. Area and maximum and minimum elevations and elevation range of nearshore habitat for eight study sites, Washington and Oregon.

[Sites are ordered from north to south. Bathymetry surveys were not conducted at Siletz. Elevations are in meters above North American Vertical Datum of 1988]

Site	Area (hectares)	Mean elevation (meters)	Maximum elevation (meters)	Minimum elevation (meters)	Elevation range (meters)
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

5.3 Sediment Characteristics

Net accretion rates greatly varied across the study sites (table 6). Among cores taken from mid-elevation marsh habitat, net accretion rates were highest at Grays Harbor and Willapa (8.7 and 8.9 mm/yr, respectively), and lowest at Bandon and Skokomish (2.5 and 1.7 mm/yr, 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). Mean organic matter content was highest across the elevation gradient at sites Siletz and Skokomish and lowest at sites Grays Harbor and Port Susan. Sediment bulk density was highest at Port Susan and Nisqually, and lowest at Grays Harbor and Bull Island. Detailed site-specific results are shown in appendixes A–I.

Table 6. Net accretion rates from soil cores sampled at low-, middle-, and high-elevation marsh zones across the study sites (n=1), Washington and Oregon.

[Sites are ordered from north to south. A subset of the cores has not yet been dated, and, therefore, has no accretion rate value (NA). Padilla was not cored. mm/yr, millimeter per year]

Site	Marsh elevation zone		
	Low	Middle	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 organic matter content and bulk density of sediments from the top 20 centimeters of cores at low, middle, and high marsh locations across the study sites (n=1), Washington and Oregon.

[Sites are ordered from north to south . Analysis on a subset of the cores has not yet been completed (NA). g/cm^3, grams per cubic centimeter]

Site	Organic matter (percent)			Bulk density (g/cm^3)		
	Low	Middle	High	Low	Middle	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

5.4 Water Monitoring

Water-level loggers deployed within marsh channels recorded variation in water levels and salinity starting 2012 and continuing through 2015. Loggers often did not record lower parts 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 (mean high water [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 (http://tidesandcurrents.noaa.gov). Differences likely reflect site-specific tidal and bathymetric conditions in local estuarine hydrology.

We collected salinity data at all sites; however, because of equipment recalls and failure, we do not have salinity data for the duration of the study. We report weekly maximum salinities because many of our salinity loggers were not submerged during the entire tidal cycle at all sites, except for Grays Harbor, owing to recalled loggers and loggers being washed away during storm events. We observed a high level of variation in salinity between and within sites (fig. 20). Variation in salinity during the study period was highest at site Siletz, ranging from 0.8 to 32 practical salinity units (PSU). Willapa was the freshest system, ranging from 12 to 15 PSU, and had very little temporal variation. Variation in salinity was high at most sites from September through December. Salinity was less than 35 PSU for all sites throughout most of the year; however, the salinities were highest in August. Detailed site-specific results are shown in appendixes A–I.

Table 8. Tidal datums (in meters, North American Vertical Datum of 1988) calculated from water-level loggers deployed at each study site in Washington and Oregon, except as noted.

[Sites are ordered from north to south. HOWL, highest observed water level; MHHW, mean higher high water; MHW, mean high water; MTL, mean tide level]

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

[1]Values estimated from VDATUM model.

[2]Values are from Brophy and others (2011).

[3]Value from National Oceanic and Atmospheric Administration historical station at Bandon, .

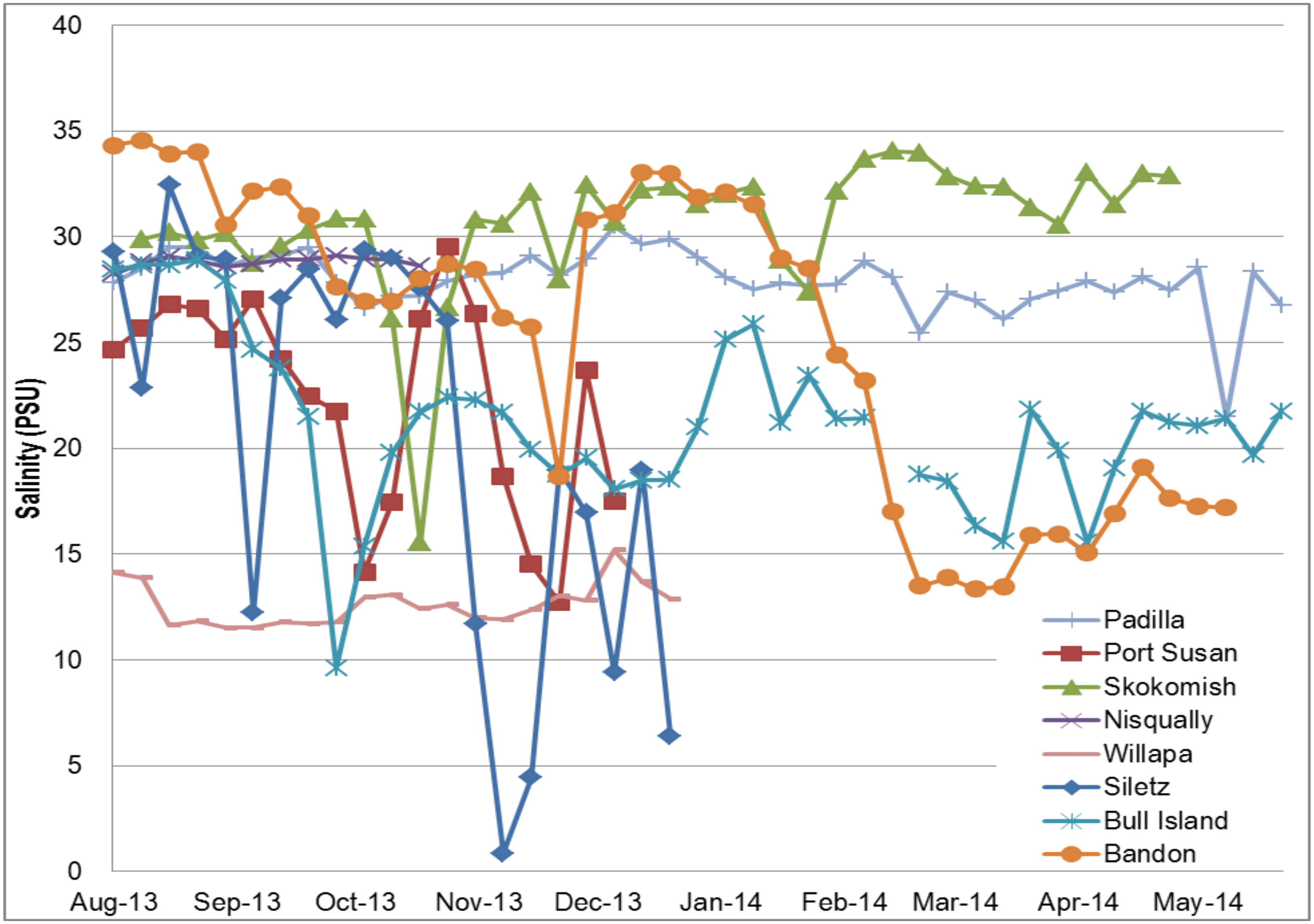

Figure 20. Weekly maximum salinity at eight study sites, Washington and Oregon, August 2013–May 2014.

5.5 Vegetation

We located 69 tidal wetland species in 2,027 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 (fig. 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 was much less common in Puget Sound marshes. The high marsh rush, *Juncus balticus*, was most frequent at site Siletz and absent or rare at sites Willapa and Padilla. The occurrence of *Carex lyngbyei* varied regionally, ranging from greater than 75-percent 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). Detailed site-specific results are shown in appendixes A–I.

Table 9. Number of vegetation plots sampled and total plant richness at the nine study sites in the Pacific Northwest.

[Sites are ordered from north to south]

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

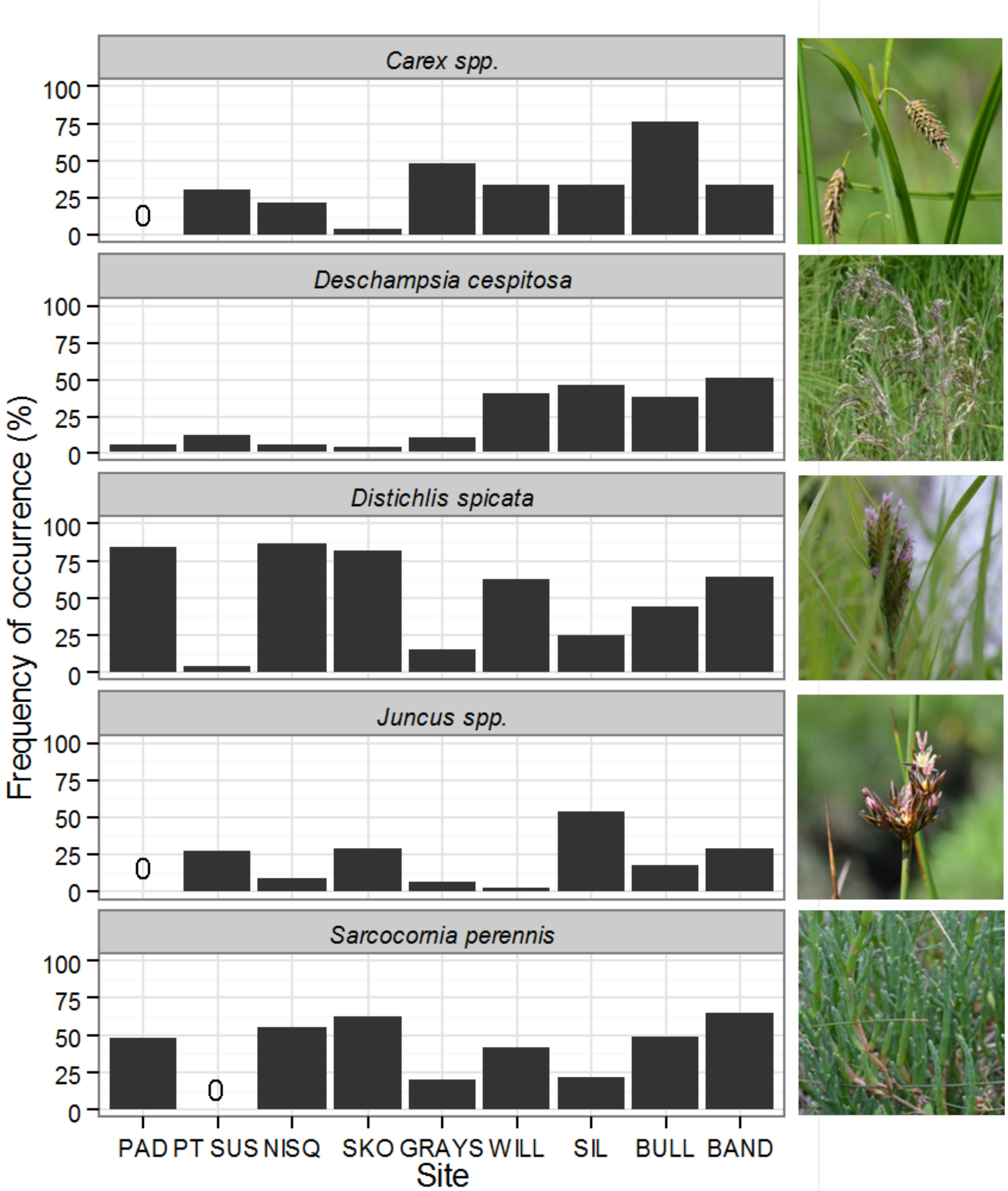

Figure 21. Differences in the frequency of occurrence of five common Pacific Northwest tidal wetland species across sites in Washington and Oregon. PAD, Padilla; PT SUS, Port Susan; NISQ, Nisqually; SKO, Skokomish; GRAYS, Grays Harbor; WILL, Willapa; SIL, Siletz; BULL, Bull Island; BAND, Bandon. *Carex* 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 photographs taken by Christopher Janousek, U.S. Geological Survey, 2014.

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 (appendix tables A2–I2). For instance, at Bandon, *Deschampsia cespitosa* was the most abundant high and middle marsh species (with *Distichilis spicata* most abundant in low marsh), whereas *S. perennis* was the most abundant plant in low marsh at Grays Harbor (*Carex* spp. dominated the middle marsh and high marsh). Vertical zonation of plant assemblages was less pronounced at other sites, including Nisqually where *Distichlis spicata* had the highest mean cover in low and middle 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 the sites and was 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 is indicated in the respective appendixes (appendix figs. B5, C5, D5, E5, F5, G4 H5, and I5).

Our data suggest that most Pacific Northwest vegetation communities are dominated by native species. The major exception is creeping bentgrass (*Agrostis stolonifera*), a likely non-native species, which can be locally common at many sites in the region. At Siletz, *A. stolonifera* was the most frequently occurring taxon (found in 84 percent of all surveyed plots) and had a mean cover of 59 percent across the site (appendix table G1). 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 non-native species, occurred commonly across sites in the region, but never attained greater than 6 percent 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 percent mean cover). Willapa Bay also was relatively uninvaded, with only three non-native species in relatively low abundance: *A. stolonifera* (3 percent mean cover), *A. prostrata* (0.2 percent mean cover), and *Cotula coronopifolia* (0.1 percent).

Aside from *A. stolonifera* and *A. prostrata*, most non-native species occurred only infrequently at the sites we studied. Other non-native species included 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 cordgrass (*Spartina*) hybrid and common reed (*Phragmites australis*) were observed in Grays Harbor in late 2014, but were not found in any surveyed plots during 2012. Total 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 compared to Bull Island in nearby Coos Bay despite similar sample sizes. At the plot level, Bandon, Siletz, Nisqually, and Skokomish had the highest plant richness (fig. 22). Each of these sites is affected relatively heavily by freshwater flow (Nisqually and Skokomish are located next to major river deltas), suggesting the role of freshwater in affecting overall richness. Padilla and Bull Island 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 rare taxa seem to contribute to the high diversity of tidal wetland plant assemblages in the Pacific Northwest. Unlike many California marshes, Pacific Northwest marshes support several dominant species. For instance, at Bandon, nine species occurred in at least 20 percent of plots at the site (appendix table I1). Similarly, at Nisqually and Siletz, eight species occurred in at least 20 percent of plots (appendix tables D1 and G1). However, rare taxa also contribute to the high richness of Pacific Northwest marshes. At Bandon, 30 taxa occurred in less than 5 percent of the plots. Detailed site-specific results are shown in appendixes A–I.

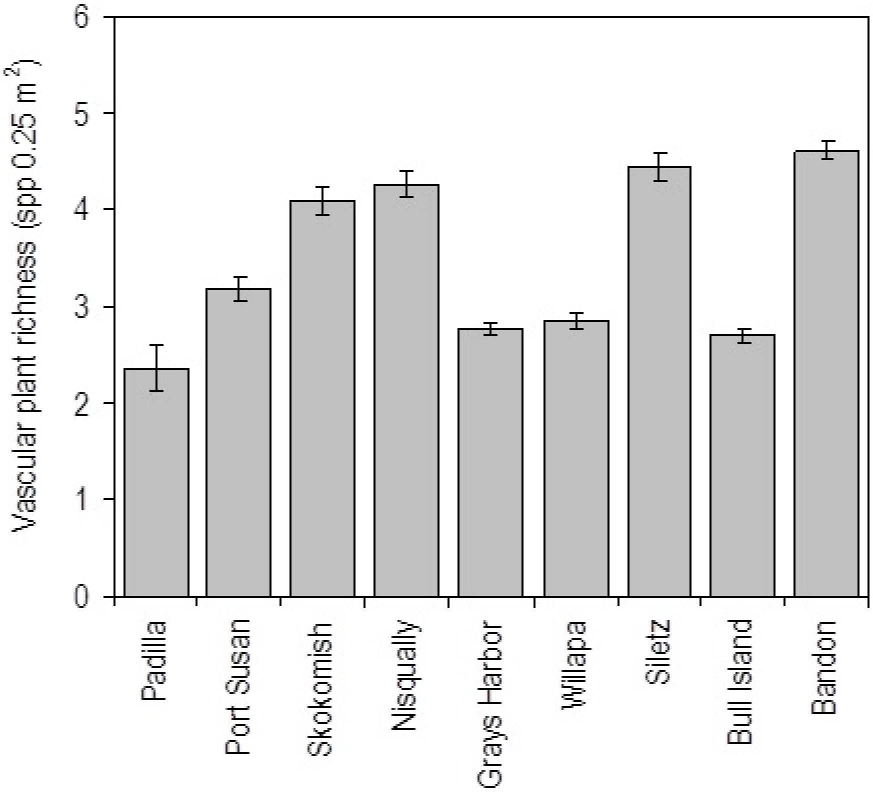

Figure 22. Mean (± standard error) vascular plant richness (species [spp.] per 0.25 square meters [m²]) in vegetation plots at the nine study sites, Washington and Oregon. Sites are ordered from north to south.

5.6 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 (fig. 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 National Research Council (NRC) low (+12 cm/100 yr) SLR rate, with mean elevation increasing or remaining unchanged over the coming century, indicating tidal marsh resiliency to low SLR rates (fig. 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 elevations 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. Detailed site-specific results are shown in appendixes A–I.

WARMER results also showed state changes in vegetation zones and their spatial distribution (fig. 25; appendix figs. A8, A10, B10, B12, C10, C12, D10, D12, E10, E12, F10, F12, G9, G11, H10, H12, I10, I12) under mid-SLR scenarios for most sites. For instance, at Willapa, which has a relatively high proportion of high marsh, 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 changes at Willapa. A mixture of high, middle and low marsh remains until 2090, but the site is modeled to be 86 percent 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 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 high SLR scenario, during the coming century, all study sites in the Pacific Northwest are projected to undergo substantial changes in elevation profiles that are expected to result in changes in the composition of tidal marsh plant communities and available habitat (fig. 26). At all study sites except Grays Harbor, Willapa, and Siletz, high marsh is essentially lost between about 2040 and 2060. These three sites lose high marsh by 2080–2090. WARMER projections suggest that all sites will lose all middle 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 will be comprised largely of unvegetated mudflat (fig. 26). Detailed site-specific results are shown in appendixes A–I.

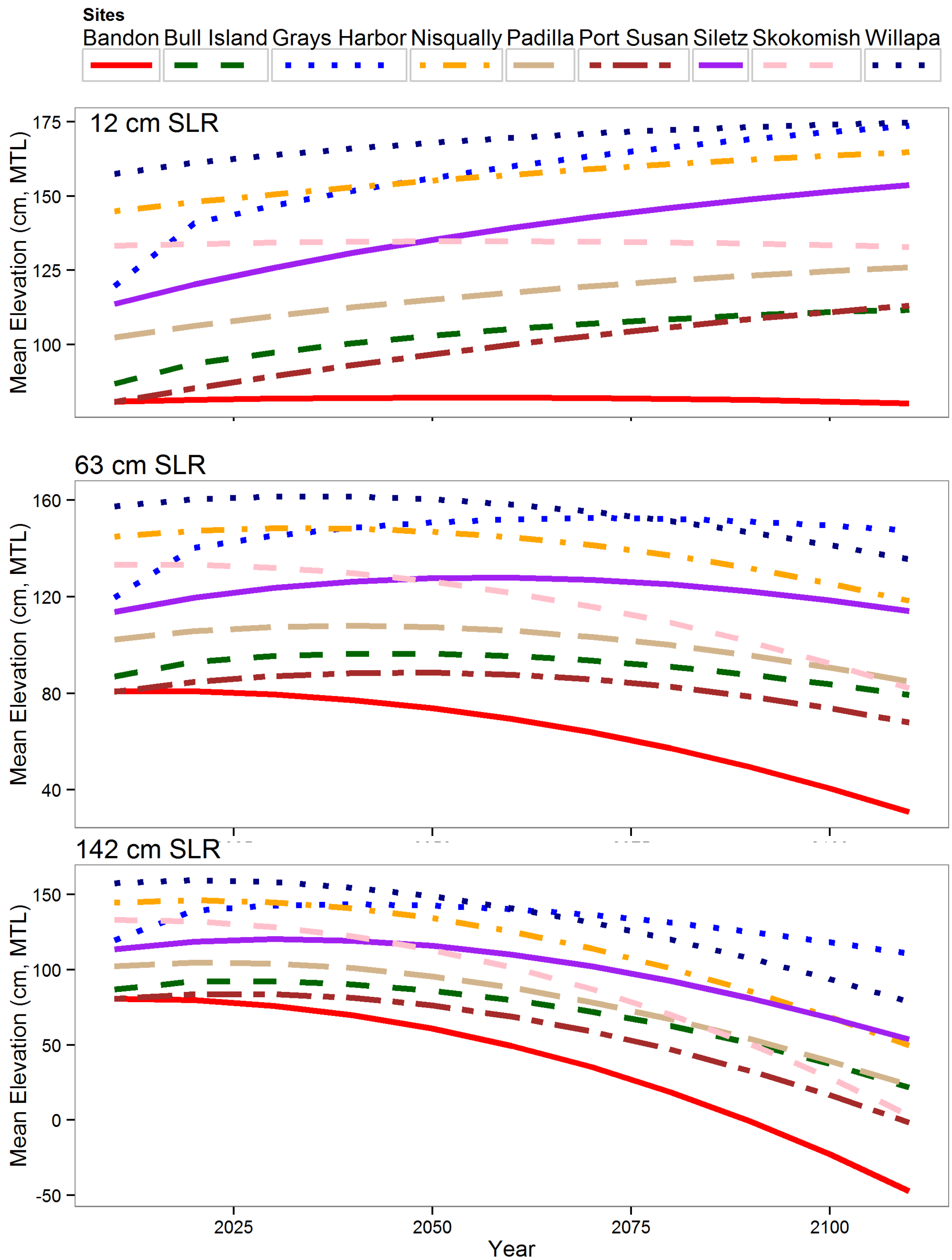

Figure 23. Projected changes in mean site elevation to 2110 using the WARMER model. Low, mid and high sea-level rise (SLR) scenarios are +12, +63, and +142 centimeters (cm) relative to mean tide level (MTL)by 2110, respectively.

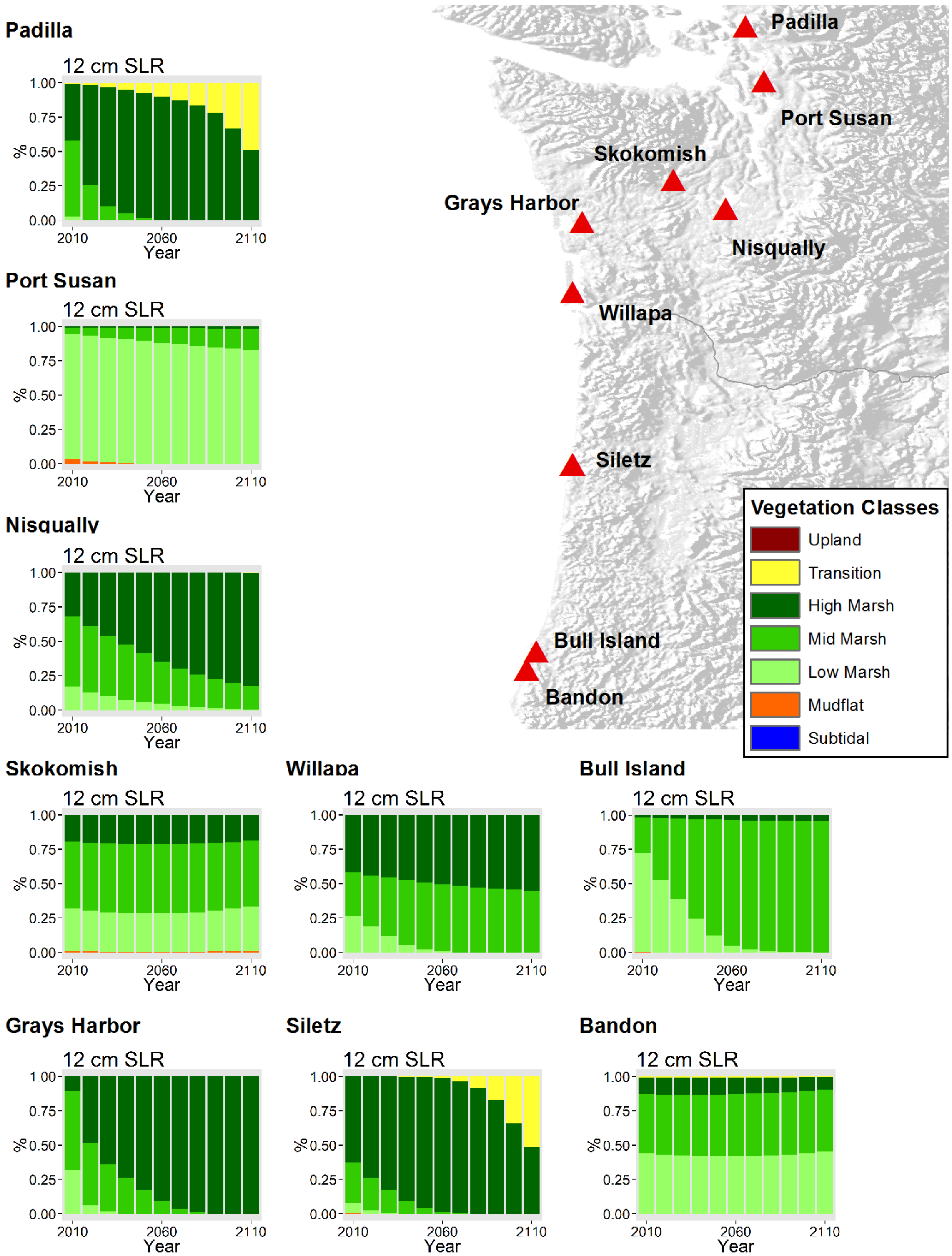

Figure 24. Projected changes to the relative abundance of marsh vegetation zones under the National Research Council low sea-level rise (SLR) scenario (+12 centimeters [cm] by 2110). The composition of all marsh vegetation remains unchanged or shows increases in proportions of middle, high and transition marsh vegetation zones. No marsh transgression was assumed upslope at all sites. Site-specific results are available in the appendixes.

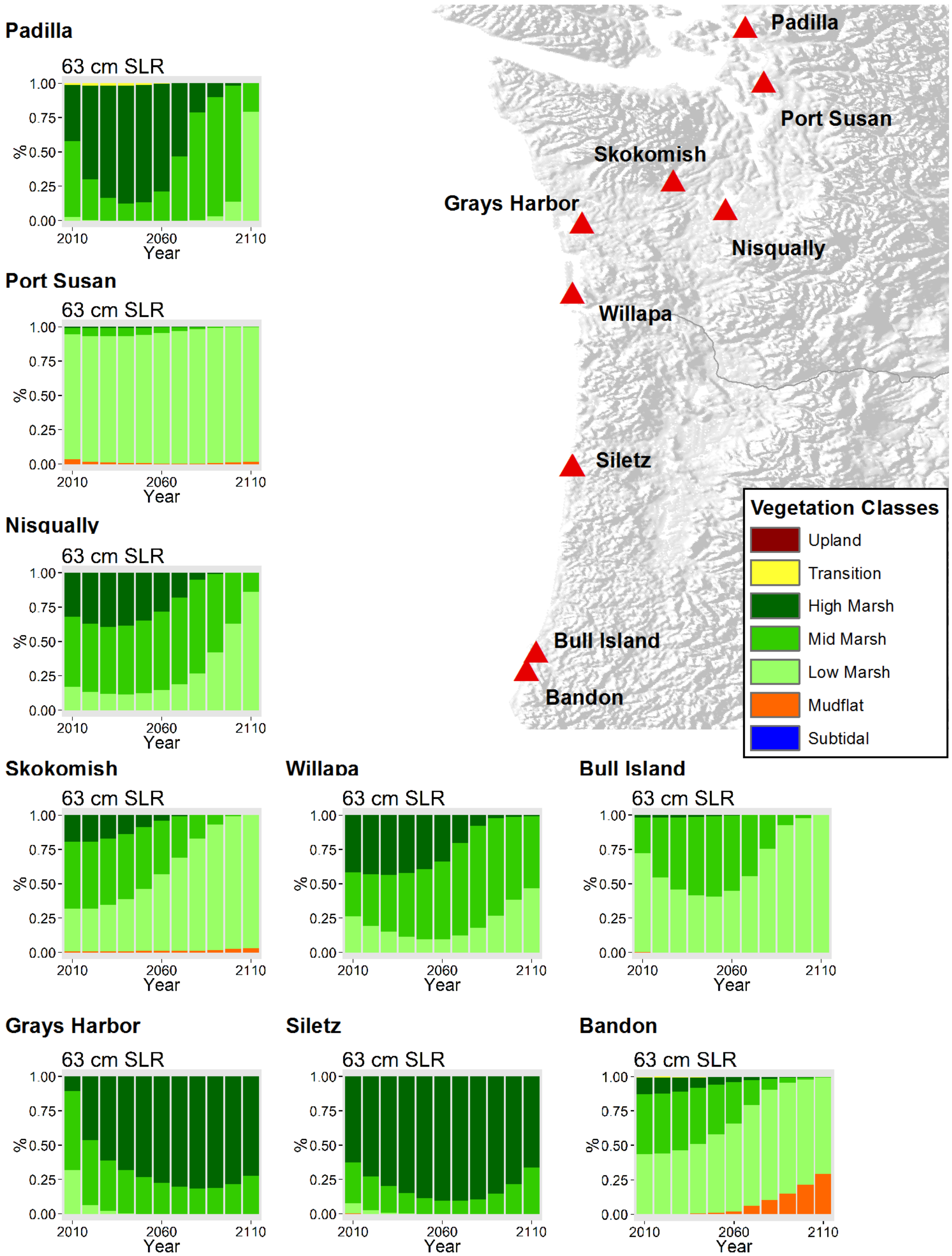

Figure 25. Projected changes to the relative abundance of marsh vegetation zones under the National Research Council mid sea-level rise (SLR) scenario (+63 centimeters [cm] by 2110). The composition of most of the marsh vegetation shows gradual decreases in proportions of middle and high marsh vegetation zones. No marsh transgression was assumed upslope at all sites. Site-specific results are available in the appendixes.

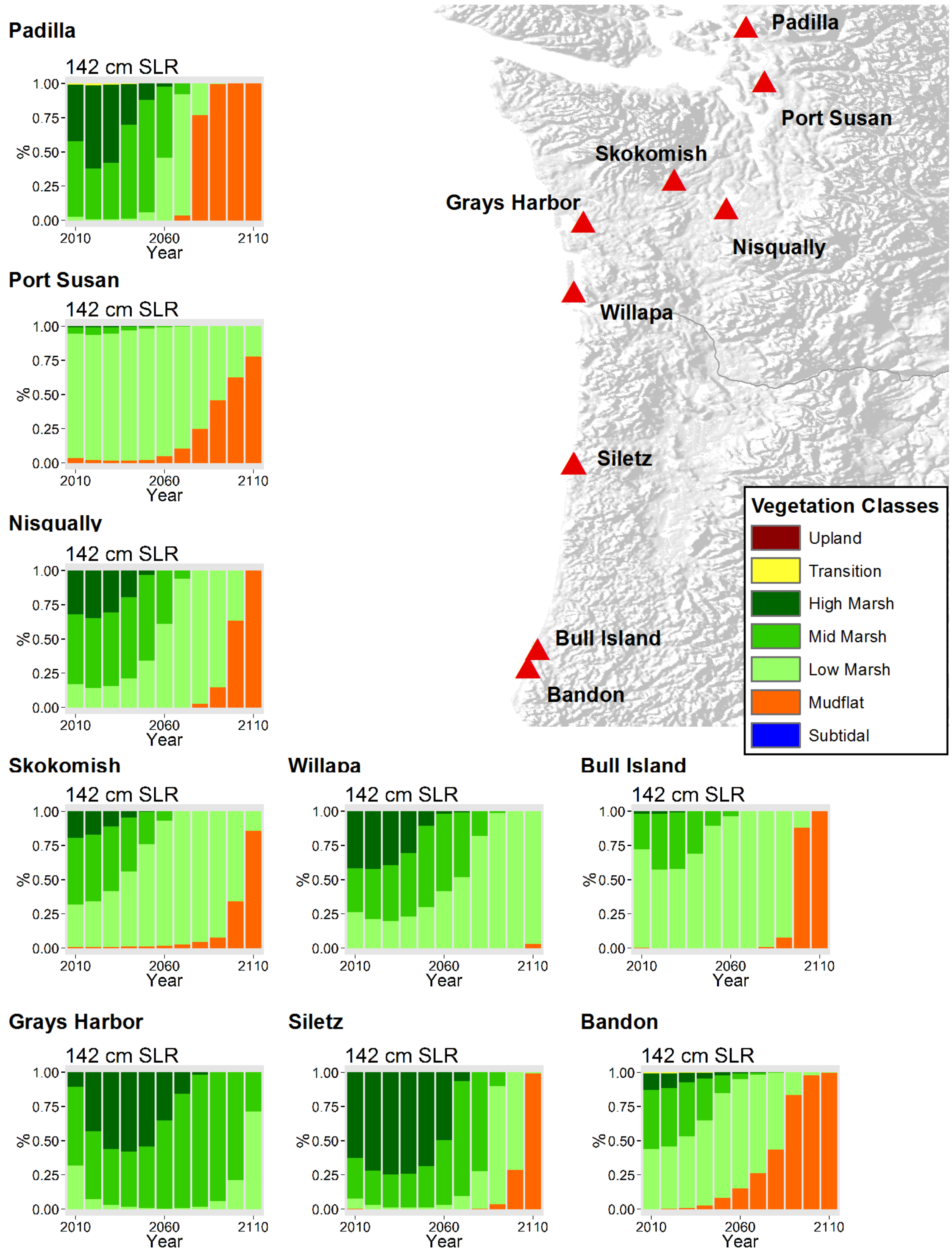

Figure 26. Projected changes to the relative abundance of marsh vegetation zones under the National Research Council high \ sea-level rise (SLR) scenario (+142 centimeters [cm] by 2110). All marsh vegetation is presumed to be lost once the area transitions to mudflat. No marsh transgression was assumed upslope at all sites. Site-specific results are available in the appendixes.

Section 6—Analysis and Findings

Our SLR modeling results suggests that Pacific Northwest tidal marshes are at risk of transitioning to unvegetated mudflat under the NRC mid and high SLR scenarios; however, there is substantial variation in vulnerability across sites (figs. 24–26). At all sites under mid and high SLR rates, most high and middle 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 (figs. 24 and 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 (Enderlin and others, 2014; McMillian and others, 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 (for example, 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. Additionally, the results indicated that not only is the magnitude of SLR over the next century important, but the acceleration of SLR in the latter one-half of the century also is critical for understanding marsh sustainability. SLR, initial elevation, and inorganic sediment accumulation are all dominant factors that determine tidal marsh sustainability.

Initial tidal marsh elevation (0–360 cm in 10-cm increments) had the second greatest relative effect on the final output of the elevation model. 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 percent of variance in the final model output, with inorganic matter accumulation rates having a greater effect on final elevation than organic sediment contributions. SLR, initial elevation, sediment accumulation, and organic matter input accounted for 95 percent 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 percent of the variance. The factors that resource managers may have the ability to manage (initial elevation and sediment accumulation rate) accounted for about 50 percent of the total variance.

Table 10. Relative influence of major model parameters in elevation change by 2110.

[We calculated the importance of variables 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. MTL, mean tide level]

Variable	Relative influence (percent)
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 7—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 determined that Pacific Northwest tidal marshes had variable historical accretion rates, which also varied between high and low marsh zones. Integrating the elevation, vegetation, and accretion data into elevation modeling (WARMER) under the National Research Council sea-level rise (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. The timing and degree of projected effects varied among sites. Under mid SLR projections, all sites lost high marsh habitat by 2110, and most became entirely low marsh habitat. 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 affect various 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 middle and high marsh habitat across the region could have negative effects 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, 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 more than one-half of our study sites, the high SLR scenario resulted in transition from tidal marsh to mudflat habitat, suggesting that historical rates of net accretion are less than what is needed to keep pace with rising sea levels. Our preliminary findings suggest that the persistence of Washington and Oregon tidal marshes 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. Additionally, integrating marsh transgression processes into modeling can help identify areas where marsh migration upslope could occur, which could prevent complete loss of marshes.

To promote habitat persistence (especially in transitional, high, and middle 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. Management options for marsh elevation augmentation and adapting marshes to SLR needs further exploration.

This project was successful in evaluating SLR vulnerability across a range of estuary types in the Pacific Northwest. Our results inform 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 of changes in marsh function owing to SLR, including vegetation responses to inundation
- Assessment of delivery of suspended sediment to river-dominated estuaries and how this contributes seasonally to tidal marsh accretion 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; and
- Integration of site-specific results with landscape-scale sea-level rise modeling to assess estuary-wide effects.

Success of a regional project such as the Coastal Ecosystem Response to Climate Change 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 (for example, mudflats and uplands) would improve the scope of the results to the broader estuarine environment. Additionally, although 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 8—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 (for example, USGS Open-File Report) to the USGS Climate Science Centers (CSCs), North Pacific LCC, U.S. Fish and Wildlife Service national wildlife refuges, National Oceanic and Atmospheric Administration National Estuarine Research Reserve (NOAA NERR), Washington State Parks, Oregon State Parks, and other interested land managers. Our study complements regional climate change programs, including the California LCC, U.S. Fish and Wildlife Service Inventory and Monitoring initiative, and NOAA NERR climate change programs, as well as ongoing wetland restoration projects at Nisqually, Port Susan, and Willapa sites.

We conducted three science delivery workshops in the Pacific Northwest within the Northwest CSC region, funded by the North Pacific 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 in habitat conservation, planning, and adaptation strategies; and
3. Develop a coast wide climate change science needs assessment to inform the North Pacific and California LCCs.

A total of 40 individuals from State, Federal, local, nongovernmental organizations, and Tribes attended the workshops. A final report will be compiled and provided to the Northwest CSC and North Pacific LCC. 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 around the results presented in this report. The establishment of this dialog has led to fruitful relationships with partners that will improve management understanding about climate change and effects on their respective estuaries. For example, these modeling results are being used by Region 1 U.S. Fish and Wildlife Service-managed refuges in identifying areas for future planning, research projects, and restoration. In particular, at Willapa Bay National Wildlife Refuge, these modeling results showed that a part of the refuge would persist with SLR to 2110. However, it was identified at the workshop that an important next step would be to expand modeling to include other refuge parcels and adjacent habitat types (for example, eelgrass beds, mudflats, and beaches) to determine if vulnerability to SLR varied across these key resources, which would help inform management actions. The modeling results are being used by the North Pacific and California LCCs to identify and prioritize areas for new research and coordination projects that include vulnerability assessments.

Table 11. Three workshops to disseminate site-specific sea-level rise modeling results held by the U.S. Geological Survey to engage resource managers and their partners, Washington and Oregon, 2014.

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

Acknowledgments

We would like to thank the resource management staff of numerous agencies for providing assistance and site access, including Marian Bailey (USFWS), Heath Bohlmann (NERR), Bill Bridgeland (USFWS), Craig Cornu (NERR), Jolene Boyd (TNC), Shannon Kirby (Skokomish Tribe), Glynnis Nakai (USFWS), Susanna Pearlstein (UA), William Ritchie (USFWS), Doug Roster (USFWS), and Shawn Stephensen (USFWS). Thanks to Arianna Goodman (USGS) for your important assistance in water data processing and leadership. Additionally, we thank USGS staff Lisa Belleveau, Sierra Blakely, Melanie Davis, Tristan Edgarian, Matt Holt, Sam Kaviar, Katharine Lovett, Mee-ya Monnin, Lennah Shakeri, Greg Salwin, Karl Schmidt, and Kelly Turner, who assisted with data collection or analyses. We would also like to thank Sam Veloz (Pt. Blue) and Julie Yee (USGS) for their peer-review. Also we would like to thank the USGS Western Ecological Research Center and North Pacific Landscape Conservation Cooperative for their support.

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Appendixes. Detailed Site-Specific Results

Appendixes A-I are available for download in PDF format from http://dx.doi.org/10.3133/ofr20151204.

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Publishing support provided by the U.S. Geological Survey
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Thorne and others—**Effects of Sea-Level Rise on Tidal Marshes along a Latitudinal Gradient in the Pacific Northwest**—Open-File Report 2015–1204

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20151204