Implications of climate change for strategic conservation and restoration of tidal wetlands in the U.S. portion of the Salish Sea

Brittany Robinson Jones

A thesis

submitted in partial fulfilment of the

requirements for the degree of

Master of Science

University of Washington

2015

Committee:

Charles A. Simenstad

Miles G. Logsdon

Julian D. Olden

Amy K. Snover

Program Authorized to Offer Degree:

Aquatic and Fishery Sciences

University of Washington

Abstract

Implications of climate change for strategic conservation and restoration of tidal wetlands in the U.S. portion of the Salish Sea

Brittany Robinson Jones

Chair of Supervisory Committee:

Research Professor Charles A. Simenstad

Aquatic and Fishery Sciences

Coastal ecosystems are potentially at risk of sea level rise and other accelerated changes in climate. The overall goal of this thesis was to explore the potential influences of spatially varied climate change impacts on tidal wetlands in the U.S. portion of the Salish Sea and discuss implications for strategic conservation and restoration of current and future wetland areas. Since sediment accretion is a vital mechanism for tidal wetland persistence under sea level rise, the overall objective of Chapter 1 was to determine the relationship between sediment accretion rate and surface elevation in a restored and a natural tidal wetland in the Stillaguamish River delta. In the restored zone, there was a negative linear relationship between sediment accretion rates and surface elevation but a quadratic relationship in the reference zone. Vegetation, including dominant vegetation species and vegetation height, also helped explain the pattern of sediment

accretion rates. The objective of Chapter 2 was to conduct a spatial analysis of potential tidal wetland responses to future climate change in the U.S. portion of the Salish Sea in order to simulate the (1) overall change in wetland area, (2) potential for tidal wetlands to persist locally, and (3) opportunity for transgressive migration between initial conditions and 2025, 2050, 2075, and 2100 under a low (0.5 m between 2000 and 2100) and high (1.4 m between 2000 and 2100) sea level rise scenario. Total tidal wetland area was projected to decline under both sea level rise scenarios, but some wetland types (e.g., emergent marsh) were projected to expand. Projected local persistence was greater for tidal flat and emergent marsh compared to transitional scrub-shrub and tidal swamp. While the projected area for transgressive migration was small, this process may serve as a buffer for wetland loss by providing dry land for the establishment of new wetland areas. Identifying variability in the adaptive capacity and opportunity for transgressive migration of tidal wetlands to climate change impacts is an important tool for prioritizing sites in order to protect wetlands and enhance their persistence and health into the future along with the ecosystem services they provide. The objectives of Chapter 3 were to model the projected changes in tidal wetlands in the U.S. portion of the Salish Sea without levee protection and to apply the findings of Chapter 2 to a framework of strategic conservation and restoration of tidal wetlands. The projected change in total wetland area between initial conditions and 2100 switched from a decline with levee protection to an expansion without levee protection in the San Juan and Whidbey sub-basins and the Skagit and Stillaguamish River deltas under both sea level rise scenarios. The Skagit, Stillaguamish, and Snohomish river deltas were identified as high priority for conservation and restoration based on historical potential and degradation level under a climate change context, followed by the Nooksack and Samish. In order for conservation and restoration efforts of tidal wetlands to be successful and persist into

the future, this study shows that climate change should be considered to identify current and future tidal wetland areas that are projected to exist under the influence of accelerated sea level rise. Identifying priority deltas for tidal wetland conservation and restoration under a climate change framework will be beneficial for the allocation of resources in the short- and long-term.

Key words: tidal wetlands, sea level rise, sediment accretion, transgressive migration, conservation, restoration

Introduction

Coastal ecosystems, such as tidal wetlands, are now at risk of sea level rise and other accelerated changes in climate (Desantis et al. 2007; Swanson et al. 2014). Many processes that naturally sustain tidal wetlands and other coastal ecosystems may allow natural adaption, depending on the pace of climate change. Tidal wetlands are important nearshore ecosystems providing valuable ecologic, economic, and social services (Costanza et al. 1997; Martínez et al. 2007). Historically, however, humans have often viewed wetlands negatively and have attempted to reclaim these wastelands by converting them into usable dry land (Valiela 2006). The accumulation of scientific evidence (Hopkinson 1985; Robertson and Duke 1987; van der Velde et al 1992; Turner 1992; Brampton 1992) has recently altered this negative point of view and motivated an increase in wetland conservation and restoration. Many of these restoration efforts, however, often fail to consider the projected impacts of future climate change. Therefore, strategic conservation and restoration of tidal wetlands should consider the potential influences of future climate change on the success of local and regional management strategies.

Contemporary development and equilibrium of tidal wetlands

Coastal wetlands are defined as areas in which water saturation dominantly influences soil development and the establishment of plant and animal communities (Cowardin et al. 1979). For the purposes of this study, tidal wetlands are considered estuarine and coastal wetlands that are tidally influenced (Wolanski et al. 2011), including tidal flats, regularly flooded emergent marsh, irregularly flooded emergent marsh, transitional scrub-shrub, and freshwater tidal swamps (Simenstad et al. 2011).

Most tidal wetlands in existence around the world today have developed in recent geological time. Based on isotopic dating, contemporary tidal wetlands developed after the rapid sea level rise associated with the deglaciation that concluded the last glacial maximum (Redfield 1965; Redfield 1972; Rampino and Sanders 1981). The areal extent and distribution of these wetlands have not been static, but have constantly changed, expanding and contracting as environmental conditions have been naturally altered (Valiela 2006).

Tidal wetlands can migrate landward in response to sea level rise in a process known as transgressive migration (Brinson et al. 1995; Glick et al. 2007; Feagin et al. 2010; Schile et al. 2014). As sea level increases, previously exposed land is inundated and submerged. In response, the wetlands may migrate landward if they can propagate at a rate comparable to sea level rise (Brinson et al. 1995).

The surface elevation of tidal wetlands is controlled by a combination of surface processes, such as sediment deposition, organic matter accumulation, and sediment erosion; and subsurface processes, such as root and rhizome growth, decomposition, and compaction (Reed 1995; Nyman et al. 1993; USGS 2010). Sediment accretion and surface elevation change rates are not constant, but vary spatially and temporally across the landscape due to the interaction of these controlling processes, many of which are projected to be affected by climate change (Costanza et al.1985). When surface elevation increases at a rate comparable to sea level rise, wetlands are able to persist locally due to the ecogeomorphic feedbacks between water depth, plant growth, and sediment accretion (Stevenson et al. 1986, Reed 1990).

Anthropogenic modifications

Anthropogenic-induced environmental changes have continually stressed and altered natural wetland dynamics. Throughout history, there have been many cycles of anthropogenic changes made upon wetlands, including aquaculture development, deforestation of uplands, damming of rivers, the physical conversion of wetlands to dry land, the construction of levees, and the formation of shoreline armoring (Valiela 2006).

Humans have directly modified wetlands by filling and converting wetlands to dry land in order to construct urban centers, industrial complexes, and agricultural fields (Dahl 1990). Humans have also often indirectly modified wetlands by altering sediment supply in several ways and with differing results. For instance, after European settlement of North America, wide-spread deforestation of uplands, particularly to clear land for agriculture, increased surface erosion and led to an increase in sediment laden runoff and river sediment supply (Trimble 1977; Kirwan et al. 2011). Once the sediment load reached the river deltas, the suspended sediment accreted onto the wetland surface and onto the seaward edge of the wetland platforms, which resulted in progradation, or the seaward expansion of wetlands (Kirwan et al. 2011). In contrast, damming of rivers reduced sediment supply by trapping large amounts of sediment behind the dams, which resulted in a contraction of deltaic wetlands (Yang et al. 2003, Yang et al. 2005).

Historical change, restoration, and conservation

Anthropogenic modifications of tidal wetlands have been pervasive in the Pacific Northwest region of the United States. For instance, during the last ~150 years, 90% of tidal freshwater forested wetlands, 98.5% of transitional scrub-shrub, 46% of emergent marsh, and 24% of tidal flats have been lost in the 16 largest deltas throughout the U.S. portion of the Salish Sea, Washington (hereafter referred to as the Salish Sea) (Simenstad et al. 2011).

Each year, billions of dollars are invested in aquatic ecosystem restoration throughout the United States (Bernhardt et al. 2005), a portion of which is allocated toward tidal wetland restoration. Recently, there have been many tidal wetland restoration projects completed around the Salish Sea and more in the planning stages. For instance, the Estuary and Salmon Restoration Program provides around $5 million each year to protect and restore the Puget Sound Nearshore (WARCO 2010). In the Nisqually River delta, 3.6 ha were restored in 1996, 8.5 ha in 2002, 40.5 ha acres in 2006, and 308.4 ha acres in 2009 (Nisqually Delta Restoration 2011). In the Stillaguamish River delta, a 150-ha site was restored by reducing the height of the levee and breaching the levee footprint in two locations in 2012 (Nature Conservancy 2015). Additionally, in the Snohomish River estuary, there are 17 restoration project sites that have been completed or are in the planning stages (Tulalip Tribes 2015).

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) developed a strategic framework for nearshore conservation and restoration in order to promote the use of strategic management in the Salish Sea but did not incorporate potential effects of future climate change (Cereghino et al. 2012). The framework was designed to determine where conservation, restoration, or enhancement of nearshore ecosystems would meet local and regional recovery goals of river deltas, beaches, barrier embayments, and coastal inlets based on the level of degradation and historical potential to provide ecosystem services (Cereghino et al. 2012). Although there are many restoration efforts attempting to revive lost and degraded tidal wetland ecosystems, efforts often fail to consider the projected impacts of future climate change.

Sea level rise and other climate change projections

Between 1901 and 2010, global sea level increased at a rate of 1.5-1.9 mm yr^{-1} (IPCC 2014). Recently, between 1993 and 2010, the rate of sea level rise increased to 2.8-3.6 mm yr^{-1}. Based on a range of climate change scenarios, global sea level is projected to rise at an even more accelerated rate of 8-16 mm yr^{-1} between the period 2081 and 2100 (IPCC 2014). The National Research Council Committee on Sea Level Rise in California, Oregon, and Washington generated sea level rise projections that incorporate glacier and ice sheet dynamics and local circulation changes (NRC 2012). Under the low NRC (2012) projections, sea level is projected to increase at a rate of 5 mm yr^{-1} between 2000 and 2100, and under the high climate change scenario, sea level is projected to increase at a rate of 14 mm yr^{-1} between 2000 and 2100 (NRC 2012).

In addition to sea level rise, precipitation patterns, but not necessarily the total annual amount of precipitation, are projected to change under future climate conditions in the Pacific Northwest (CIG 2009). Annual temperatures in the Pacific Northwest are projected to increase by 2.8ºF to 9.7ºF by the 2080s relative to 1970-1999. These increased temperatures are expected to result in lower proportions of precipitation falling as snow compared to rain, leading to earlier snowmelt and a transition from spring to winter runoff (CIG 2009). These changes in temperature and precipitation alter the hydrology of rivers, such as the timing and magnitude of peak and low flows (Hamlet et al. 2005), which are important influences on fluvial sediment delivery to tidal wetlands (Czuba et al. 2011).

Modeling approaches to assessing climate impacts

Recent studies have employed projection models to assess the future impacts of climate change on coastal ecosystems and explore their implications for conservation and restoration. These modeling approaches include bathtub sea level rise studies, the Marsh Equilibrium Model (Morris and Bowden 1986), the Wetland Accretion Rate Model of Ecosystem Resilience (Swanson et al. 2014), the Sea Level Affecting Marshes Model (Park et al. 1986), and others.

First developed in the 1980s, the Sea Level Affecting Marshes Model (SLAMM) simulates processes involved in wetland conversion under long-term sea level rise, such as inundation, accretion, erosion, and soil saturation (Park et al. 1986). Since then, SLAMM has been applied to regions throughout the United States, including Louisiana (Glick et al. 2013), Florida (Glick and Clough 2006), Georgia (Craft et al. 2009), and Washington (Park et al. 1993; Glick et al. 2007).

In southeastern Louisiana, SLAMM results indicated that wetland responses to sea level rise varied from a loss of around 2,000 km^2 by 2100 (9% of 2007 wetland area) under a low sea level rise scenario (0.34 m between 2007 and 2100) to a loss of almost 6,000 km^2 (24% of 2007 wetland area) under a high sea level rise scenario (0.19 m between 2007 and 2100) (Glick et al. 2013). Along the Georgia coast, the areal extent of salt marsh was projected to decrease by 20% under a 39 cm increase in sea level and decrease by 45% under a 69 cm sea level increase by 2100 relative to 1999 (Craft et al. 2009). In nine areas in Florida, SLAMM simulations projected that salt marsh would decrease by almost 50% and tidal flat would decrease by 84%, while brackish marsh was projected to increase by 40-fold under a mid-range sea level rise scenario (36 cm by 2100) (Glick and Clough 2006).

SLAMM simulations were conducted for 11 sites in Washington and Oregon in 2007 (Glick et al. 2007). Changes in wetland area were projected between initial conditions (the initial conditions ranged from 1972 and 2000) and 2100 under a sea level rise of +0.69 m (IPCC 2001 A1B maximum scenario). In total, transitional marsh was projected to expand by 12,832% and saltmarsh by 52%, while tidal flat was estimated to decrease by 44%, brackish marsh by 52%, and tidal swamp by 61% between initial conditions and 2100 (Glick et al. 2007). In Padilla Bay, Skagit Bay, and Port Susan Bay, transitional marsh was projected to expand by 1,531%, salt marsh by 96%, and tidal flat by 613%, while brackish marsh decreased by 77% and tidal swamp by 89% between initial conditions and 2100 (Glick et al. 2007). With no levee protection in Padilla Bay, Skagit Bay, and Port Susan Bay, transitional marsh was projected to expand by 14,346%, salt marsh by 1,115%, and tidal flat by 1,559%, while brackish marsh decreased by 77% and tidal swamp by 89% (Glick et al. 2007).

Problem statement

The Salish Sea is a fjord-like estuary with tidal range varying from 2.1 m to 4.4 m (NOAA CO-OPS 2015). The Salish Sea is approximately 8,000 km^2, encompasses nearly 4,000 km of crenulated shoreline, and drains a combined 36,000 km^2 catchment area (Simenstad et al. 2011). Estimates suggest that in the Salish Sea in 2000-2006 there were 125 km^2 of deltaic tidal flats, 78 km^2 of emergent wetland, 1.5 km^2 of transitional scrub-shrub, and 11.9 km^2 freshwater tidal (Simenstad et al. 2011). Much of the variability in oceanography, tidal hydrology, riverine inputs, and shoreline geomorphology across the Salish Sea is captured in the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) definition of seven basins: Hood Canal, San Juan Islands – Georgia Strait, Strait of Juan de Fuca, North Central Puget Sound, South Puget Sound, South Central Puget Sound, and Whidbey.

There are 16 large river deltas in the Salish Sea: five within the Hood Canal sub-basin (Dosewallips, Duckabush, Hamma Hamma, Quilcence, and Skokomish), two within the Juan de Fuca sub-basin (Dungeness and Elwha), none within the North Central sub-basin, two within the San Juan sub-basin (Nooksack and Samish), two within the South Puget Sound sub-basin (Deschutes and Nisqually), two within the South Central sub-basin (Duwamish and Puyallup), and three in the Whidbey sub-basin (Skagit, Snohomish, and Stillaguamish).

The Salish Sea is a dynamic system in which estuarine and nearshore ecosystem processes vary spatially and temporally. Many of these ecosystem processes affect the ability of tidal wetlands to respond to future climate change. Tidal wetlands throughout the world, not just in the Pacific Northwest, are at risk of future climate change impacts, such as hydrologic alterations and submergence due to accelerated sea level rise.

Consequently, in order for conservation and restoration efforts of existing tidal wetlands to be successful and persist into the future, climate change must be considered. In addition, climate change may offer new opportunities for tidal wetland expansion by inundating uplands and facilitating transgressive migration into formally dry land. Although there have been various delta-scale studies of climate change impacts on wetland systems, there has yet to be a study conducted to assess variation in the adaptive capacity and transgressive migration potential of tidal wetlands across the entire U.S. Salish Sea region.

Thesis goal and objectives

The overall goal of this thesis was to explore potential influences of spatially varied climate change impacts on tidal wetlands and discuss implications for strategic conservation and restoration of current and future wetland areas. Since sediment accretion is a vital mechanism for tidal wetland persistence under sea level rise, the overall objective of Chapter 1 was to determine the relationship between sediment accretion and surface elevation in a restored and a natural wetland in a case study in the Stillaguamish River delta. The objective of Chapter 2 was to conduct a spatial analysis of potential tidal wetland responses to future climate change in the U.S. portion of the Salish Sea in order to simulate the (1) overall change in wetland area, (2) potential for tidal wetlands to persist locally, and (3) opportunity for transgressive migration under accelerated sea level rise. The objectives of Chapter 3 were to model the projected changes in tidal wetland without levee protection and to apply the findings of Chapter 2 to a framework of strategic conservation and restoration of tidal wetlands.

Thesis approach

In Chapter 1, sediment accretion was measured along elevation gradients in a restored and reference tidal wetland in the Nature Conservancy's Port Susan Bay Preserve in the Stillaguamish River delta, Puget Sound, Washington. Sediment accretion is an important component of surface elevation change, which is one of the main processes by which tidal wetlands can adapt to sea level rise. The goal of this chapter was to analyze the interacting effects of biological and physical wetland characteristics on sediment accretion rates.

In Chapter 2, the Sea Level Effecting Marshes Model (SLAMM, Warren Pinnacle Consulting 2015) was utilized to simulate potential changes to tidal wetland distributions in the U.S. portion of the Salish Sea under the influence of accelerated sea level rise and other changes in climate given the spatial variability in the various factors that influence tidal wetland adaptability and development. The current study expanded previous studies by taking into account documented spatial variability in wetland processes throughout the Salish Sea and utilizing the Puget Sound Nearshore Ecosystem Project (PSNERP) geodatabase of current tidal wetland distribution.

In Chapter 3, the simulation outputs from the SLAMM analysis were additionally run without levee protection and then applied to an assessment of tidal wetland conservation and restoration potential based in part on the PSNERP strategic framework. The PSNERP strategic framework was expanded upon by adding climate change impact metrics into the analysis.

The insights gained by Chapter 2 and 3 are intended to aid wetland managers and restoration practitioners by identifying wetland areas in which strategic planning and investment in conservation and restoration efforts will be most beneficial under a range of potential future climate conditions. These analyses can be used to identify targets for strategic conservation and restoration in order to maximize feasibility and success under the burdens of climate change and to project areas in which there may be future restoration opportunities.

The concluding chapter synthesizes the major findings and implications from each research chapter, identifies data gaps and limitations, and discusses opportunities and needs for future research.

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Chapter 1: Varying effects of surface elevation, restoration, and other biophysical processes on tidal wetland sediment accretion rates

Abstract

Sediment accretion is vital for the persistence of tidal wetlands under the influence of future climate change impacts, especially accelerated sea level rise. Tidal wetlands have often historically maintained relative surface elevation through accumulation of mineral and organic matter, a process known as accretion. An assumption is often made that tidal wetland surface elevation is an adequate predictor of sediment accretion rate. Sediment accretion, however, is influenced by the interaction of many biological, physical, and hydrological processes. Sediment accretion rates were measured for 1 year using sediment pins along elevation gradients in a restored zone and a reference zone in the Stillaguamish River delta, Washington. In the restored zone, there was a negative linear relationship between sediment accretion rates and surface elevation but a quadratic relationship in the reference zone. Vegetation, including dominant vegetation species and vegetation height, also helped explain the pattern of sediment accretion rates. These results support that sediment accretion is controlled by many interacting and compounding factors, including surface elevation and vegetation. These relationships can be used to model the potential adaptive capacity of tidal wetlands to future accelerated sea level rise.

Keywords tidal wetlands, sediment accretion, surface elevation, marsh vegetation

Introduction

Tidal wetlands have often been able to maintain relative surface elevation with gradual sea level rise through the accumulation of mineral and organic matter (Redfield 1972; Thom 1992; Brinson et al. 1995; Clancy et al. 2009). However, tidal wetlands are now at risk of submergence due to the acceleration of sea level rise under the influence of climate change if processes, such as sediment accretion, do not compensate rapidly enough (Glick et al. 2007; Craft et al. 2009). Between 1901 and 2010, global sea level increased at a rate of 1.5-1.9 mm yr^{-1} (IPCC 2014). Based on a range of climate change scenarios, global sea level is projected to rise at an accelerated rate of 8-16 mm yr^{-1} between the period 2081 and 2100 (IPCC 2014).

The sediment surface elevation of tidal wetlands is controlled by a combination of surface and subsurface processes (Figure 1). Surface processes include sediment deposition, organic matter accumulation, and erosion. Subsurface processes include root and rhizome growth, decomposition, and compaction (USGS 2010). Sediment accretion is an important component of surface elevation change that is widely measured and studied (Nolte et al. 2013). In this study, sediment accretion is defined as the vertical increase in surface elevation relative to a baseline soil layer, a process that combines sediment deposition, biomass accumulation, and erosion (Cahoon et al. 1995; Nolte et al. 2013).

Tidal wetland sediment accretion rates are controlled by a combination of interacting and interrelated processes, including biological characteristics, such as vegetation community structure, height, and density; physical properties, such as surface elevation and salinity; and hydrological processes, such as proximity to tidal channels (Reed 1995). Sediment is delivered to tidal wetlands during inundation through fluvial river inputs and resuspended deltaic sediment.

The relative surface elevation of a tidal wetland determines the duration and frequency of inundation (Morris et al. 2002). As the wetland is inundated, many other factors, such as vegetation structure, may enhance and increase sediment accretion (Knujston et al. 1982; Gedan et al. 2011).

When surface elevation increases at a rate comparable to sea level rise, wetlands are able to persist locally (Stevenson et al. 1986; Reed 1999). In the past, wetlands have often been able to vertically keep pace with gradual sea level rise if they had adequate sediment supply and plant growth requirements (Baumann et al. 1984; Stevenson et al. 1986; Thom 1992; Brinson et al. 1995; Clancy et al. 2009). However, these existing wetlands are now at risk of submergence due to the acceleration in the rate of sea level rise under the influence of climate change if sedimentation processes do not compensate (Glick et al. 2007; Craft et al. 2009; Swanson et al. 2014).

The persistence of tidal wetlands under the influence of future climate change impacts is important because tidal wetlands are vital nearshore ecosystems providing valuable ecosystem services, such as coastal protection from sea level rise and storm surges; water quality maintenance; carbon sequestration; and habitat provision for economically important bivalves, crustaceans, and fish (Costanza et al. 1997, Martínez et al. 2007). Despite their ecological and economic benefits, tidal wetlands have historically been extensively altered by human activity. For example, in Puget Sound, Washington, 57.7% to 94.0% of tidal wetlands (depending on specific tidal wetland type) have been lost since the mid-1800s (Simenstad et al. 2011).

There are currently many tidal wetland restoration efforts in the Salish Sea in an attempt to revive these lost and degraded ecosystems. Yet, many restoration efforts do not consider future climate change impacts. Studies, however, have shown the increasing need to assess potential climate change impacts on nearshore systems, especially tidal wetlands (Weiss et al. 2001).

Many studies have employed projection models to assess the impacts of climate change on coastal ecosystems and explore the implications for conservation and restoration. Some studies have attempted to capture the interaction between elevation and vegetation in controlling surface elevation change (e.g., Morris et al. 2002), which can be used in modeling potential adaptive capacity of tidal wetlands to accelerated sea level rise. However, there have been no studies published on the relationship between sediment accretion rate and surface elevation in the U.S. portion of the Salish Sea.

This study examined the effects of surface elevation and vegetation in a restored and reference tidal wetland in the Stillaguamish River delta in Port Susan Bay, Washington, by addressing the following questions:

(1) Is there a relationship between tidal wetland sediment accretion rate and surface elevation in the restored zone and in the reference zone?

(2) Is there a relationship between sediment accretion rate and vegetation structure?

This study provides additional insight on the interaction of biological and physical tidal wetland characteristics on controlling sediment accretion rates, which can be used to model the adaptive capacity of tidal wetlands to future accelerated sea level rise.

Methods

Study site

The field study was conducted in the Nature Conservancy's Port Susan Bay Preserve, a 1,664 ha preserve in Port Susan Bay, Washington, including the Stillaguamish River delta (Figure 2). Port Susan Bay historically contained 1,120 ha of emergent wetlands, 1,190 ha of scrub-shrub wetlands, and 2,010 ha of floodplain forests in ~1870 (Collins 1997). Almost 85% of the emergent wetlands had been converted to agricultural land by the mid-1990s (Collins 1997). In 2012, a 150 ha site was restored by reducing the height of the levee and breaching the levee footprint in two locations (Figure 2).

The wetland area below mean high water (~2.5 m above mean tidal level) is dominated by *Schoenoplectus americanus* (American threesquare bulrush) and *Bolboschoenus maritimus* (maritime bulrush). In wetland areas ~2.0 m and higher, other vegetation species become dominant, such as *Agrostis alba* (creeping bentgrass), *Schoenoplectus tabernaemontani* (softstem bulrush), *Typha latifolia* (broad-leaved cattail), and *Symphyotrichum subspicatum* (Douglas aster).

Study design

The Port Susan Bay Restoration Monitoring Project divided the Port Susan Bay Preserve into 5 zones (the 150 ha restored site and four natural zones) for extensive physical and biological monitoring. This project used the Monitoring Project division of zones by measuring sediment accretion rates in Zone 2, the restored zone, and Zone 3, which served as a reference zone.

A total of 50 sampling stations were established in a randomized block design, 14 in Zone 2 (hereafter called the restored zone) and 36 in Zone 3 (hereafter called the reference zone; Figure 2). Sampling stations were installed along elevation gradients: 7 bins in the restored zone and 8 bins in the reference zone. In the restored zone, each bin had 2 sampling stations. In the reference zone, the highest elevation and lowest elevation bins had 3 sampling stations while the middle elevation bins had 5 sampling stations each. The number of sampling stations was determined based on the uniformity of the vegetation, and fewer stations were installed in bins with more uniform vegetation.

Elevation data were derived in 2013 from the Watershed Sciences, Inc. Stillaguamish LiDAR Project, contracted by the United States Geological Survey (USGS) and the Nature Conservancy. The LiDAR had a vertical absolute accuracy of 0.005 ± 0.017 m, a relative accuracy of 0.020 ± 0.003 m, and a raster cell size of 1 m by 1 m (WSI 2013). The LiDAR was sampled in ArcGIS at each sampling station GPS location to determine the corresponding elevation.

Sediment accretion measurements

Sediment accretion was measured using sediment pins, which were 3.05 m long, 7.62 cm diameter PVC pipes pounded about 2 m into the sediment and capped (modified method from Takekawa et al. 2002). The distance between the sediment surface and the top of the cap was measured in the four ordinal directions and averaged. Baseline measurements were taken from

November to December in 2013. Subsequent measurements were then subtracted from the baseline distance to determine the amount of accreted sediment. Pin measurements were recorded in April, June, and September 2014 and April 2015. Rates of sediment accretion were then calculated between April 2014 and April 2015. Sampling stations with missing data were removed from the analyses. For instance, one station had been disturbed, likely swept by a log; and the pin was bent and the cap had been removed.

Vegetation surveys

At each sampling station, estimates of vegetation community structure were recorded in conjunction with sediment sampling events within a 4 m by 4 m plot in June 2014. Vegetation height was categorized as bare sediment, grass mat, low (<0.5 m), low-medium (0.5-1.0 m), medium (1.0-1.5 m), high-medium (1.5-2.0 m), or high (>2.0). Vegetation density was also categorically estimated as bare, grass mat, low (< 100 stems/0.25m^2), medium (100-200 stems), or high (>300 stems). The presence of all vegetation species was noted and the dominant or co-dominate species were determined.

Data analysis

The Shapiro-Wilk test was conducted to test for normality of the accretion rate data. Accretion rates were normally distributed in the restored zone (W = 0.98, p-value = 0.99) and the reference zone (W = 0.99, p-value = 0.99).

A forward-sequential polynomial regression analysis was conducted to determine the model that best fit the relationship between sediment accretion rate and surface elevation in the restored and reference zone.

A forward-sequential regression analysis was conducted to determine the model that best fit the relationship between sediment accretion, surface elevation, and vegetation in the restored and reference zone. Vegetation parameters tested included the dominant vegetation species, the estimated vegetation height, and estimated vegetation density.

Results

Is there a relationship between sediment accretion rate and tidal wetland surface elevation?

In the restored zone, the linear model was the best model describing the relationship between sediment accretion rate and surface elevation (Table 1). The linear parameter had the highest F-value (8.1) and the lowest p-value (0.02) of the models tested and a delta AIC of only 2. The fitted linear model was $y = -56x + 209$ where y = sediment accretion rate and x = surface elevation (Figure 3a).

In the reference zone, the best model that described the relationship between sediment accretion rate and surface elevation was the quadratic model (Table 2). The quadratic parameter had the highest F-value (30.8) and the lowest p-value (<0.01) among the models tested and a delta AIC of only 3. The fitted quadratic model was $y = 931x – 143x^2 – 1466$ where y = sediment accretion rate and x = surface elevation (Figure 3b).

Is there a relationship between sediment accretion and vegetation structure?

In the restored zone, the best model contained surface elevation and vegetation height (R^2 = 0.99, model p-value <0.01) (Table 3). The delta AIC was 0 and the model had one fewer parameters compared to the model with surface elevation, vegetation height, and vegetation density, which also had a delta AIC of 0.

In the reference zone, the best model was still the quadratic relationship with surface elevation, which had a delta AIC of 0 (R^2 = 0.52, p-value <0.01) (Table 4). However, in the single-variable regressions, the dominant vegetation (p-value = <0.01) and vegetation height (0.01) parameters both had significant p-values.

Discussion

Sediment accretion rates were measured along elevation gradients in a restored and reference tidal wetland in Port Susan Bay. There was a negative linear relationship between sediment accretion rates and surface elevation in the restored zone. As surface elevation of the tidal wetland increases, the tidal inundation frequency and duration decreases. As inundation frequency and duration decreases, the wetland is under water for a shorter amount of time. This submergence constraint limits the amount of time that sediment can settle out of suspension and deposit onto the surface of the wetland (French 1993; Kirwan and Murray 2007), potentially resulting in a negative relationship between surface elevation and sediment accretion rates as seen in the restored zone. This relationship, however, was not the same for the reference zone.

There was a quadratic relationship between elevation and sediment accretion rate in the reference zone. A possible explanation for this parabolic relationship in the reference zone compared to the restored zone is the influence of the vegetation community structure.

In the restored zone, the vegetation community structure, including species composition, vegetation height, and vegetation density, was relatively uniform throughout the elevation gradient. The estimated vegetation height was shown to help explain the pattern of sediment accretion rates in the restored zone, and this is likely attributed to the differences in vegetation in the highest and lowest elevation sites. The high elevation sites were dominated by grass mats while the low elevation sites were mostly bare sediment. Since the low elevation sites were bare, it would be expected that sediment accretion was reduced at these sites since there is no vegetation structure to trap sediment (Bouma et al. 2005). Future research could analyze the influence of other factors on the high sediment accretion rates at these bare sites, such as the distance to tidal channel (Reed et al. 1999).

The vegetation community structure in the reference zone was much more complex, diverse, and varied compared to the restored zone. While the best fit model explaining the pattern of sediment accretion rates in the reference zone did not include vegetation, dominant vegetation and vegetation height were significant parameters when considered in the single-variable regressions.

In the reference zone in winter, the low elevation *Schoenoplectus americanus* vegetation dies and is washed away, leaving bare sediment exposed to winter storms, current, and erosion. In contrast, the structure of *Bolboschoenus maritimus* and *Schoenoplectus tabernaemontani* vegetation remains partially intact throughout winter, although definitely reduced from the vegetation summer peak. In the Pacific Northwest of the United States, suspended sediment concentration in rivers is high in winter due to frequent rain events (Hamlet and Lettenmaier 1999) and increased runoff (Czuba et al. 2011). This high suspended sediment concentration in rivers results in high sediment supply to tidal wetlands that are fed by rivers (Campbell and Bauder 1940; Asselman 2000), such as the tidal wetland in Port Susan Bay that is fed by the Stillaguamish River. Although sediment supply may be high in winter, vegetation is not at its peak, so sediment trapping and deposition may not be proportionally enhanced by the increase in sediment supply. When low elevation tidal wetland areas are dominated by *Schoenoplectus americanus*, sediment trapping and deposition is going to be even more reduced (Bouma et al. 2005) since the vegetation is completely washed away in winter. This variation in winter deposition and trapping may be another mechanism compounding the control of sediment accretion rates. Surface elevation may be the major controlling factor on sediment accretion rates when vegetation structure is uniform, but when vegetation structure is complex and varied, an interaction of vegetation structure, surface elevation, and other factors control sediment accretion rates.

Studies have found parabolic relationship between other tidal wetland processes and surface elevation. For instance, there can be a parabolic relationship between wetland biomass, or productivity, and relative surface elevation (Morris et al. 2002). This parabolic relationship between biomass and surface elevation suggests that there is an optimal elevation range for tidal wetland productivity (Morris et al. 2002).

Accretion rates in this study may be high compared to previous studies in the region in part due to the increased sediment load associated with the SR530 (Oso) landslide that occurred upstream of the delta on the North Fork Stillaguamish River in March 2014 (USGS 2015) after baseline sediment measurements were recorded.

There are limitations and constraints associated with measuring short-term (i.e., 1-year) sediment accretion rates in tidal wetlands. For instance, sediment pins protrude above the surface, altering current patterns and possibly affecting sediment deposition and erosion. Additionally, the height of the sediment surface is not consistent throughout the tidal cycle. When the sediment contains subsurface pore water, the sediment expands and increases the height of the surface (Nuttle et al. 2006). If the height of low tide is different between measurements or measurements are taken at different stages of the low tide cycle, the sediment accretion measurement may be altered by the amount of pore water still present.

There are many gaps in the knowledge of sediment accretion rates in tidal wetlands throughout the Salish Sea (except see Thom 1992) even though sediment accretion is one of the key processes in maintaining the structure and function of healthy tidal wetlands. Additionally, knowledge of sediment accretion is vital to understanding the potential responses of tidal wetlands to environmental changes and to projecting the adaptive capacity of wetlands to climate change impacts, especially sea level rise (Craft et al. 2009). This study shows that the relationship between sediment accretion rate and surface elevation differed between a restored and reference zone, partially influenced by vegetation compositions.

Sediment accretion is controlled by many interacting and compounding factors, including surface elevation and vegetation. Site-specific studies are useful in determining the relationship between sediment accretion rates and the physical and biological characteristics of the wetland. Since sediment accretion is a vital process for the persistence of tidal wetlands into the future, it is important to continue to study the mechanisms influencing sediment accretion, especially as the threat of accelerated sea level rise becomes stronger.

Acknowledgments Funding was provided by the Nature Conservancy; the Northwest Climate Science Center; and the School of Aquatic and Fishery Sciences, College of the Environment, University of Washington. I would like to thank Roger Fuller and John Rybczyk for their advice, and I would also like to thank Alec Barber, Andrew Cortese, Katy Hancock, James McArdle, Katrina Poppe, and Sarah Thomas for help in the field.

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Tables

Table 1: Restored zone (a) sequential ANOVA (b) model summary. The parameter, x, represents elevation.

(a)

Source	DF	SS	MS	F	P
$Total_{cor}$	11				
x	1	1967.9	1967.9	8.1	0.02
Residuals	10	2419.1	241.9		
x^2	1	626.9	626.9	3.1	0.11
Residuals	9	1792.2	199.1		

(b)

Model	R^2	Adjusted R^2	Model p-value	Parameter p-value	AIC	Delta AIC
x	0.45	0.39	0.02	0.02	104	2
x^2	0.59	0.50	0.02	0.11	102	0

Table 2: Reference zone (a) sequential ANOVA (b) model summary. The parameter, x, represents elevation.

(a)

Source	**DF**	**SS**	**MS**	**F**	**P**
Total$_{cor}$	30				
x	1	2.7	2.7	0.01	0.92
Residuals	29	7467.2	257.5		
x^2	1	3909.4	3909.4	30.8	<0.01
Residuals	28	3557.8	127.1		
x^3	1	520.0	520.0	4.6	0.04
Residuals	27	3037.8	112.5		

(b)

Model	**R^2**	**Adjusted R^2**	**Model p-value**	**Parameter p-value**	**AIC**	**Delta AIC**
x	<0.01	-0.03	0.92	0.92	264	24
x^2	0.52	0.49	<0.01	<0.01	243	3
x^3	0.59	0.55	<0.01	0.04	240	0

Table 3: Forward-sequential regression selection in the restored zone. (a) Single-variable regressions. Elevation had the lowest p-value and was the selected variable. (b) Two-variable regressions. Given elevation, height had the lowest p-value and was the selected variable. (c) Three-variable regressions. Given elevation and height, dominant vegetation had the lowest p-value and was the variable selected. (d) Four-variable regressions. (e) Model summaries. The model with elevation and height had a delta AIC of 0 and contained only 2 parameters.

(a) Single-variable regression

Source	DF	SS	MS	F	p-value
Total	11				
Elevation	1	1967.9	1967.9	8.1	0.02
Residuals	10	2419.1	241.9		
Dominant	2	1383.7	691.9	2.1	0.18
Residuals	9	3003.3	333.7		
Height	7	3626.0	518.0	2.7	0.18
Residuals	4	761.0	190.3		
Density	4	2106.4	526.6	1.6	0.27
Residuals	7	2280.6	325.8		

(b) Two-variable regression

Source	DF	SS	MS	F	p-value
Total	11				
Elevation	1	1967.9	1967.9	8.1	0.02
Dominant | Elevation	2	1324.1	662.0	4.8	0.04
Residuals	8	1095.0	136.9		
Height | Elevation	7	2390.8	341.5	36.1	0.01
Residuals	3	28.4	9.5		
Density | Elevation	4	1341.8	335.4	1.9	0.24
Residuals	6	1077.3	179.6		

(c) Three-variable regression

Source	DF	SS	MS	F	p-value
Total	11				
Elevation + Height	8	5593.9	699.2	54.7	<0.01
Dominant | Elevation + Height	2	1324.1	662.0	70.1	>0.01
Residuals	3	28.4	9.5		
Density | Elevation + Height	4	1341.8	335.4	73.4	0.09
Residuals	1	4.6	4.6		

(d) Four-variable regression

Source	DF	SS	MS	F	p-value
Total	11				
Elevation + Height +Dominant	10	6977.6	697.8	57.7	<0.01
Density | Elevation + Height +Dominant	2	23.8	11.9	2.6	0.40
Residuals	1	4.6	4.6		

(e) Model summary

Model	R^2	Adjusted R^2	Model p-value	Parameter p-value	AIC	Delta AIC
Elevation	0.45	0.39	0.02	0.02	104	40
Elevation + Height	0.99	0.98	<0.01	0.01	64	0
Elevation + Height + Dominant	0.99	0.98	<0.01	<0.01	64	0

Table 4: Forward-sequential regression selection for the reference zone. (a) Single-variable regressions. The quadratic elevation term had the lowest p-value and was the term selected. (b) Two-variable regression. Given the quadratic elevation term, dominant vegetation had the lowest p-value and was the parameter selected. (c) Model summaries. The quadratic elevation model had a delta AIC of 0.

(a) Single-variable regression

Source	DF	SS	MS	F	P
Total	30				
Elevation + Elevation²	2	3912.1	1956.1	15.4	<0.01
Residuals	28	3557.8	127.1		
Dominant	8	4610.1	576.3	4.4	<0.01
Residuals	22	2859.5	130.0		
Height	8	4039.6	505.0	3.2	0.01
Residuals	22	3430.2	155.9		
Density	5	1894.4	378.9	1.7	0.17
Residuals	25	5575.5	223.0		

(b) Two-variable regression

Source	DF	SS	MS	F	P
Total	30				
Elevation + Elevation²	2	3912.1	1956.1	15.4	<0.01
Dominant | Elevation + Elevation²	8	1282.9	160.4	1.4	0.25
Residuals	20	2274.9	113.7		
Height | Elevation + Elevation²	8	915.5	114.4	0.9	0.56
Residuals	20	2642.2	132.1		
Density | Elevation + Elevation²	5	384.1	76.8	0.56	0.73
Residuals	23	3173.7	138.0		

(c) Model summary

Model	R²	Adjusted R²	Model p-value	Parameter p-value	AIC	Delta AIC
Elevation + Elevation²	0.52	0.49	<0.01	<0.01	243	0
Elevation + Elevation² + Dominant	0.79	0.54	<0.01	0.25	245	2

Figures

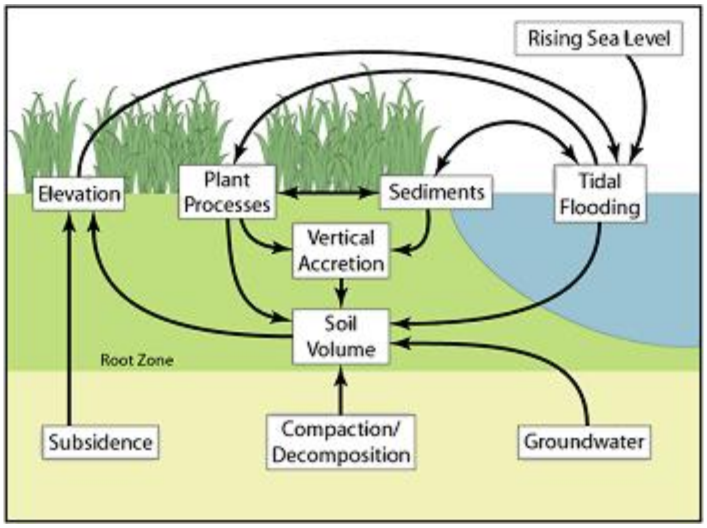


Figure 1: Surface and subsurface processes controlling tidal wetland surface elevation. From Defense Coastal/Estuarine Research Program.

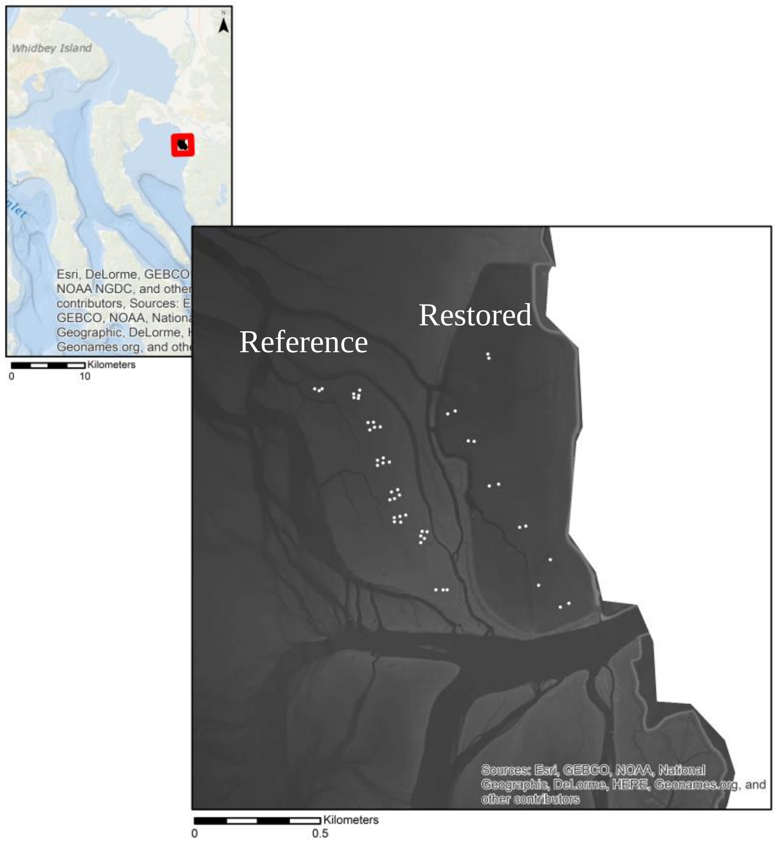
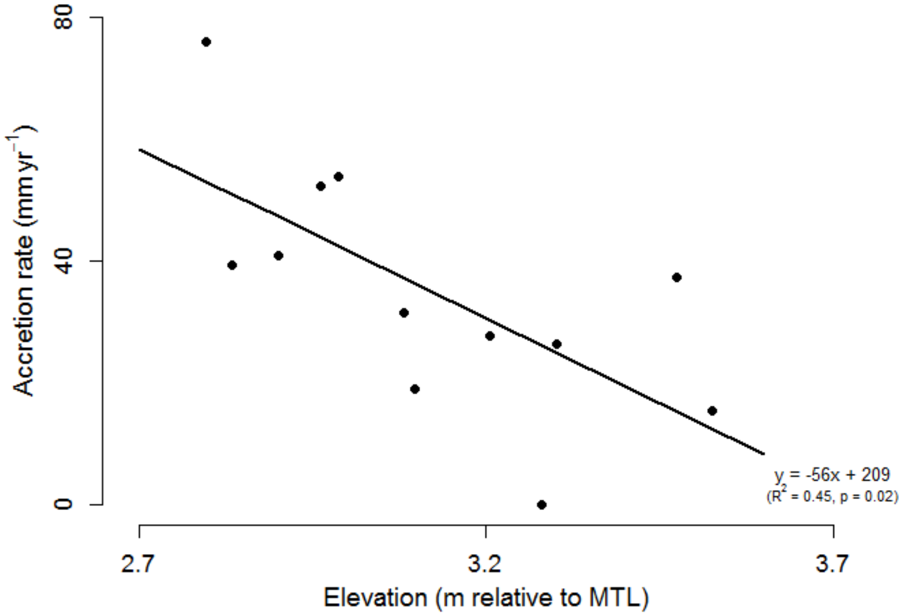


Figure 2: Study site in the Stillaguamish River delta in Port Susan Bay, Washington. White dots represent sampling stations in the restored and reference zone.

(a)



(b)

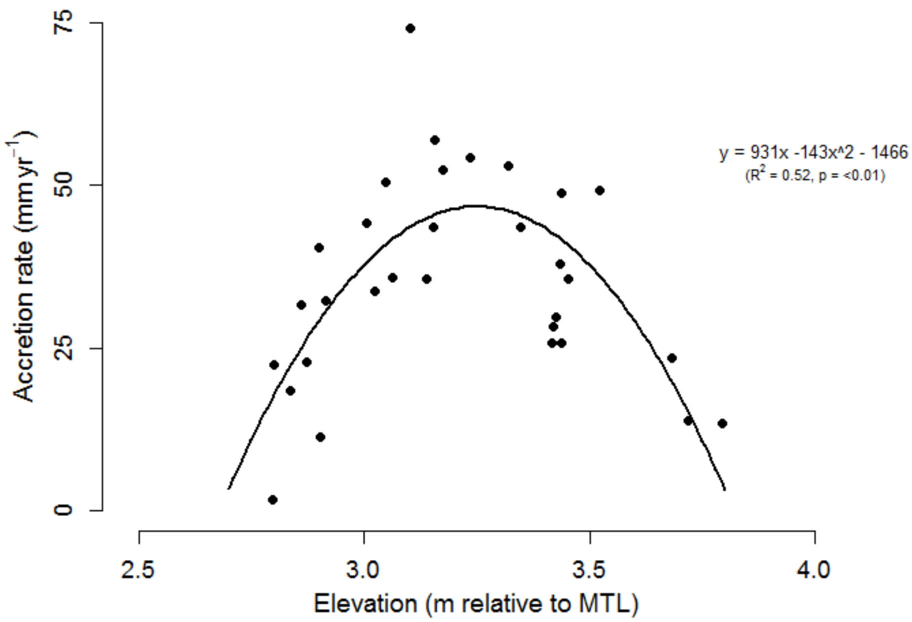


Figure: Sediment accretion rates measured between April 2014 and 2015 versus surface elevation. (a) Sediment accretion rates for the restored zone. Solid black line represents the linear regressions of pin measurements (R-squared = 0.45, p-value = 0.02). (b) Sediment accretion rates for the reference zone. Solid black line is the quadratic regression (R-squared = 0.52, p-value = <0.01).

Chapter 2: Potential effects of sea level rise and other accelerated climate changes on tidal wetland distribution in the U.S. portion of the Salish Sea

Abstract

Tidal wetlands are one type of coastal ecosystem potentially threatened by accelerated sea level rise. Modeling potential tidal wetland responses to future climate change is important for the development of strategic conservation, restoration, and management of these degraded and lost ecosystems. The Sea Level Affecting Marshes Model was utilized to simulate tidal wetland conversion in the U.S. portion of the Salish Sea under a low and high sea level rise scenario. Total tidal wetland area was projected to decline under both sea level rise scenarios, but some wetland types (e.g., emergent marsh) were projected to expand. Projected local persistence was greater for tidal flat and emergent marsh compared to transitional scrub-shrub and tidal swamp. Although the projected area for transgressive migration was small, this process may serve as a buffer for wetland loss by providing dry land for the establishment of new wetland areas. The spatial distribution of potential tidal wetland responses to climate change can help identify priority needs for the restoration of lost wetland area, conservation of persistent tidal wetlands, and conservation of dry land to preserve areas for future tidal wetland migration.

Keywords sea level rise, tidal wetlands, sediment accretion, transgressive migration

Introduction

Coastal ecosystems are potentially at risk of sea level rise and other accelerated changes in climate (Desantis et al. 2007; Swanson et al. 2014). Many processes that sustain coastal ecosystems may allow natural adaption, depending on the pace of climate change. Between 1901 and 2010, global sea level increased at a rate of 1.5-1.9 mm yr^{-1} (IPCC 2014). Based on a range of climate change scenarios, however, global sea level is projected to rise at an accelerated rate of 8-16 mm yr^{-1} between 2081 and 2100 (IPCC 2014). Due to projected acceleration in climate change impacts, strategic conservation, restoration, and management may be required in addition to natural adaptation to facilitate persistence into the future (Pressey et al. 2007).

Tidal wetlands are important nearshore ecosystems providing valuable ecological, economic, and social services, such as coastal protection from sea level rise and storm surges; water quality maintenance; carbon sequestration; and habitat provision for economically important bivalves, crustaceans, and fish (Costanza et al. 1997; Martínez et al. 2007). However, tidal wetlands have historically been drained and converted into dry land (Dahl 1990) for agriculture (Bortleson et al. 1980), industry (Boule et al. 1983), and housing and have been extensively altered with levees to protect against coastal threats. During the last ~150 years, 90% of tidal freshwater wetlands, 98.5% of transitional scrub-shrub, 46% of emergent marsh, and 24% of tidal flats have been lost in the 16 largest deltas throughout the U.S. portion of the Salish Sea, Washington (Simenstad et al. 2011).

In addition to losses from direct human modification, tidal wetlands are now at risk of future losses due to potential submergence under the influence of accelerated sea level rise and other changes in climate (Desantis et al. 2007; Swanson et al. 2014). For instance, changes to regional and local precipitation patterns and temperature (CIG 2009) and increases in storm frequency and magnitude are mechanisms that may alter future tidal wetland persistence into the future.

Modeling potential tidal wetland responses to future climate change is important for the development of strategic conservation, restoration, and management of these degraded and lost ecosystems. There are two main non-mutually exclusive processes by which tidal wetlands can adapt to rising sea level and which can be modeled under future climate change scenarios: (1) surface elevation increase (Thom 1992); and, (2) transgressive migration (Brinson et al. 1995).

The surface elevation of tidal wetlands is controlled by a combination of surface processes, such as sediment deposition, organic matter accumulation, and sediment erosion; and subsurface processes, such as root and rhizome growth, decomposition, and compaction (Nyman et al. 1993; Reed 1995). Sediment accretion and surface elevation change rates are not constant but vary spatially and temporally across the landscape due to the interaction of these controlling processes, many of which are projected to be affected by climate change (Costanza et al.1985). When surface elevation increases at a rate comparable to sea level rise, wetlands are able to persist locally (Stevenson et al. 1986; Reed 1990). In the past, wetlands have often been able to vertically keep pace with gradual sea level rise if they had adequate sediment supply, accretion, and surface elevation increase (Baumann et al. 1984; Stevenson et al. 1986; Thom 1992; Brinson et al. 1995; Clancy et al. 2009). However, these existing wetlands are now at risk of submergence due to the acceleration in the rate of sea level rise under the influence of climate change if sedimentation processes do not compensate (Puget Sound, Glick et al. 2007; Georgia, Craft et al. 2009; San Francisco Estuary, Swanson et al. 2014).

Transgressive migration, the second process by which tidal wetlands can adapt to climate change impacts, is the natural process by which tidal wetlands migrate landward in response to sea level rise (Brinson et al. 1995; Glick et al. 2007; Feagin et al. 2010; Schile et al. 2014). As sea level increases, succession occurs as high tidal vegetation communities are converted to low elevation vegetation communities (Donnelly and Bertness 2001). Additionally, dry land is inundated and submerged, which in some cases may actually result in an increase in tidal wetland area (Park et al. 1993). Shoreline modifications, however, such as levees, reduce the ability of tidal wetlands to transgressively migrate by barricading access to the adjacent upland and, consequently, drowning the wetlands (Feagin et al. 2005; Feagin et al. 2010). Transgressive migration of tidal wetlands can also be naturally blocked by shoreline geologic formations, such as bluffs and cliffs.

In addition to eustatic sea level rise projections, regional and local variability in tidal wetland processes, such as sediment delivery, sediment accretion, vertical land movement, and upland availability for transgressive migration needs to be incorporated into tidal wetland modeling. Therefore, it is important to examine these processes at the scale of variability that will affect natural adaption of existing tidal wetlands and the transgression of new wetlands.

Given the extensive spatial variability in many of the factors influencing tidal wetland vulnerability to climate change, regional risk mapping is an important tool for prioritizing strategic conservation and restoration. Spatial display of the projected locations and amount of tidal wetland change, local persistence, and opportunity for transgressive migration can help identify needs of restoration of lost wetland area, conservation of persistent tidal wetlands, and conservation of dry land to preserve areas for future migration.

The objective in this study was to conduct a spatial analysis of potential responses by existing and future tidal wetlands to accelerated climate change in the U.S. portion of the Salish Sea by addressing the following questions:

(1) What is the projected change in overall wetland area due to sea level rise?
(2) What is the potential for tidal wetlands to increase surface elevation at a rate comparable to sea level rise and persist locally? and,
(3) What are the wetland and land cover transitions that are projected to occur, and what is the potential for transgressive migration?

By addressing these questions, this study will assess variation in the adaptive capacity and opportunities for transgressive migration of tidal wetlands in response to climate change across the U.S. portion of the Salish Sea in order to help inform strategic conservation and restoration of tidal wetlands and adjacent upland.

Methods

Study site

A spatial analysis was conducted over the extent of U.S. portion of the Salish Sea (hereafter referred to as the Salish Sea) (Figure 1). The Salish Sea is a fjord-like estuary with tidal range varying from 2.1 m to 4.4 m (NOAA CO-OPS 2015). The Salish Sea is approximately 8,000 km^2, encompasses nearly 4,000 km of crenulated shoreline, and drains a combined 36,000 km^2 catchment area (Simenstad et al. 2011). Estimates suggest that in the Salish Sea in 2000-2006 there were 125 km^2 of deltaic tidal flats, 78 km^2 of emergent wetland, 1.5 km^2 of transitional scrub-shrub, and 11.9 km^2 freshwater tidal (Simenstad et al. 2011). Much of the variability in oceanography, tidal hydrology, riverine inputs, and shoreline geomorphology across the Salish Sea is captured in the PSNERP definition of seven basins: Hood Canal, San Juan Islands – Georgia Strait, Strait of Juan de Fuca, North Central Puget Sound, South Puget Sound, South Central Puget Sound, and Whidbey (Figure 1). Due to computing processing capabilities, model simulations were conducted for each basin separately, which may result in an edge effect during model simulations.

There are 16 large river deltas in the Salish Sea: five within the Hood Canal sub-basin (Dosewallips, Duckabush, Hamma Hamma, Quilcence, and Skokomish), two within the Juan de Fuca sub-basin (Dungeness and Elwha), none within the North Central sub-basin, two within the San Juan sub-basin (Nooksack and Samish), two within the South Puget Sound sub-basin (Deschutes and Nisqually), two within the South Central sub-basin (Duwamish and Puyallup), and three in the Whidbey sub-basin (Skagit, Snohomish, and Stillaguamish) (Figure 2).

Model

The Sea Level Affecting Marshes Model (SLAMM 6.2, open-source, Warren Pinnacle Consulting 2015) was used to simulate potential changes in tidal wetland area, distribution, and wetland type under the influence of accelerated sea level rise (Figure 2). SLAMM simulates processes involved in wetland conversion under long-term sea level rise, such as inundation, accretion, erosion, and soil saturation (Park et al. 1989). Conversions among wetland and land cover types are determined based on a decision tree composed of geometric and qualitative relationships. The relative change in sea level is computed for each grid cell for each time-step as the sum of projected sea level rise, local vertical land movement, and local sedimentation. Wetland and land cover conversions are based on specific elevation ranges for each wetland or land cover type, salinity, and water saturation of dry land. Model inputs included current distribution of wetland and other land cover types, elevation, slope, historical sea level trend, tidal range, accretion rates, erosions rates, and river discharge. These inputs and others are discussed in the sections below.

Wetland and land cover

The PSNERP geodatabase delineates four main tidal wetland classes: (1) tidal freshwater, predominantly forested swamps; (2) oligohaline transition, characterized by scrub-shrub woody vegetation; (3) estuarine mixing, characterized by emergent marsh vegetation; and (4) euryhaline unvegetated, such as mudflats (Simenstad et al. 2011). Estuarine mixing wetlands were further divided into high elevation estuarine mixing and low elevation estuarine mixing wetlands based on mean higher high water (MHHW). Additional categories of tidal wetlands, inland wetlands, and open water were used in the analysis as defined and delineated by the National Wetland Inventory (NWI) (USFWS 2014).

For the PSNERP wetland classes to be compatible with SLAMM, tidal freshwater wetlands were categorized as tidal swamp, oligohaline transition wetlands were categorized as transitional salt marsh, high estuarine mixing wetlands were categorized as irregularly flooded marsh, low estuarine mixing wetlands were classified as regularly flooded marsh, and euyhaline unvegetated were classified as tidal flat (Table 1). The NWI wetland classifications were converted to SLAMM categories using the NWI classes to SLAMM 6 categories table provided in the SLAMM Technical documentation (Warren Pinnacle Consulting 2015).

The 2001 National Land Class Database (NLCD) was used to categorize developed land cover. Grid cells with greater or equal to 20% impervious surface (i.e., NLCD low, medium, and high intensity developed land classes) were considered developed for this analysis (Table 1). Throughout model simulations, developed land was assumed to be protected and excluded from inundation and other model processes.

The SLAMM-categorized PSNERP current wetlands data layer (with high and low estuarine mixing classes separated), the SLAMM-categorized NWI layer, and the NLCD developed land layer were unioned and extracted to a 20 km smoothed buffer around the PSNERP current wetlands. All unclassified land was categorized as undeveloped dry land. The final wetland and land cover dataset was then extracted to each of the seven PSNERP sub-basins.

Spatial data

In order to maximize the spatial extent of the study area, a spatial union of bathymetry and elevation data was conducted to combine the Puget Sound LiDAR Consortium 6-foot 2010 supermosaic (PSLC 2010), the 2005 Puget Sound Digital Elevation Model (DEM; Finlayson 2005), and the 2000 Puget Sound DEM (Finlayson et al. 2000). All elevation data were projected into North American Datum 1983 Universal Transverse Mercator Zone 10 North, referenced to the North American Vertical Datum 1988 (NAVD88), and converted to meters. Slope was derived from the final unioned DEM. The National Oceanic and Atmospheric Administration

(NOAA) Vertical Datum Transformation Tool (VDatum, Version 1.01, 2012) was used to calculate the conversion between NAVD88 and mean tidal level (MTL).

The PSNERP tidal barriers data layer was used to represent the location of the levees throughout the Salish Sea. Since much of the agricultural land in the Salish Sea, particularly in the Skagit Valley, is protected by levees (Collins and Montgomery 2001), land cover in the NLCD that was categorized as Pasture/Hay or Cultivated Crops was used to represent land protected by levees. The tidal barrier and agricultural land datasets were combined in order to form one comprehensive levee layer.

All spatial data layers were resampled to a cell size of 9.14 m by 9.14 m for model simulations, which was the lowest resolution of the unioned DEMs, extracted to the 20 km buffer, and then extracted to each sub-basin.

Model parameters

NOAA tide gauges throughout the study area were used for SLAMM input tidal parameters established uniquely for each sub-basin, including historical sea level trend (mm yr^{-1}; Table 2), great diurnal tide range (GT; m; Table 3), and mean higher high water (MHHW; m; Table 4). Historical sea level trend and GT are SLAMM input parameters, while MHHW was used to distinguish regularly and irregularly flooded marsh as described above (see Wetland type and land cover). The local historical sea level trend is subtracted from the global historical sea level trend of 1.7 mm yr^{-1} (IPCC 2007) to represent local vertical land movement. The NOAA Inundation Analysis Tool (NOAA NOS 2013) was used to calculate the salt elevation (Table 5), which is defined as the elevation that is inundated by salt water less than every 30 days.

SLAMM default values were used for marsh (2 m yr^{-1}) and swamp (1 m yr^{-1}) erosion rates due to limited information in peer-reviewed literature. A tidal flat erosion rate of 0.15 m yr^{-1} was used (determined from Keuler 1988 and Shipman 2004). Erosion is only simulated when average fetch is greater than 9 km (Knutson et al. 1981). Accretion rates were taken from peer-reviewed literature from studies in the Salish Sea when possible or from other coastal regions (Table 6). Regularly and irregularly flooded marsh accretion rates were allowed to vary around the mean over a range of accretion rates depending on a parabolic relationship with wetland surface elevation similar to that found in the reference zone in Chapter 1. In major river deltas, regularly and irregularly flooded marsh average and maximum accretion rates were increased by 0.5 mm yr^{-1}. Mean annual discharge of major rivers was taken from Czuba et al. (2011) (Table 7).

Sea level rise scenarios

The model was simulated under two future sea level rise (SLR) scenarios. SLAMM uses the 2001 Intergovernmental Panel on Climate Change (IPCC) climate change scenarios by default. The IPCC 2001 scenarios were generated using ocean-atmosphere models based on the responses of physical processes to greenhouse gas emission scenarios. These types of models, however, fail to incorporate ice dynamics, such as rapid changes in ice sheets and glaciers due to melt feedbacks (NRC 2012). The National Research Council Committee on Sea Level Rise in California, Oregon, and Washington generated sea level rise projections that incorporate glacier and ice sheet dynamics and local circulation changes (NRC 2012). Accordingly, the low and high NRC (2012) projections were used. Sea level is projected to increase by 0.5 m between

2000 and 2100 under the low scenario and by 1.4 m under the high scenario (NRC 2102). In SLAMM, the maximum A1B scenario is scaled up to produce the custom sea level rise projection by 2100 for the low and high NRC scenarios.

Sensitivity analysis

SLAMM has a built-in nominal range sensitivity analysis (Critchfield and Willard 1986; Cullen and Frey 1999) to examine the sensitivity of the wetland and land cover outputs to the input parameters, including the historical rate of local SLR, GT, salt elevation, erosion rates, and accretion rates. The sensitivity analysis was conducted by varying each parameter by 15% of input value under the high SLR scenario for 2100 while all other parameters were held constant. Results are presented for the Hood Canal sub-basin.

Results

The amount of initial tidal wetland area varied among sub-basins and large river deltas (Table 9). The initial area of transitional scrub-shrub and tidal swamp was low compared to tidal flat and emergent marsh.

What is the projected change in overall wetland area?

Total wetland area over the entire Salish Sea study area was projected to decline between initial conditions and each time-step (i.e., 2025, 2050, 2075, 2100) under both SLR scenarios (projected declines in 2025 were <1% of initial wetland area). Changes of individual wetland types (i.e., tidal flat, emergent marsh, transitional scrub-shrub, tidal swamp) were projected to vary and some were even projected to expand (Table 10). Emergent marsh was projected to expand, while tidal flat (except in 2050 under the low scenario), transitional scrub-shrub (except in 2075 under the high scenario), and tidal swamp were projected to decline between initial conditions and each time-step under both SLR scenarios over the Salish Sea study area, although some declines were <1% of initial wetland area (Table 10).

The total wetland area was also projected to decline in all sub-basins between initial conditions and 2100 under both SLR scenarios (Figure 2), while projected changes in individual wetland types varied. Emergent marsh was projected to expand (except in the South Central sub-basin under the high SLR scenario), tidal flat was projected to decline, while transitional scrub-shrub and tidal swamp changes were projected to vary between initial conditions and 2100 under both SLR scenarios (Table 10d). The greatest absolute changes for tidal flat and emergent marsh were projected for the Whidbey sub-basin. Tidal flat was projected to decline by one-third, while emergent marsh was projected to expand by one-half between initial conditions and 2100 under the high SLR scenario.

The projected changes in tidal wetland area in river deltas varied for total wetland area, tidal flat, emergent marsh, transitional scrub-shrub, and tidal swamp, with wetland area expanding, declining, and remaining the same depending on river delta, time-step, and SLR scenario (Table 10). The greatest decline of total wetland area was projected to occur in the Skagit (Figure 6-7), while the greatest expansion was projected to occur in the Snohomish.

The projected changes in wetland area are also temporally variable (Figure 4). Some wetland types continually increase or decrease through time in some sub-basins. Emergent marsh sometimes increases initially and then decreases. Conversely, transitional scrub-shrub often decline early and then expands.

What is the projected potential for tidal wetlands to persist locally?

Projected local persistence of total tidal wetland area was 92% and 79% for all of the Salish Sea between initial conditions and 2100 under the low and high SLR scenarios, respectively (Table 11d). The percentage of the initial wetland area that was projected to locally persist was often higher for tidal flat and emergent marsh compared to transitional scrub-shrub and tidal swamp between initial conditions and 2100, but the amount of transitional scrub-shrub and tidal swamp was small to start (i.e., small change in wetland area results in a large change in the percentage). Local persistence was projected to be mostly higher under the low SLR scenario and early time-steps (e.g., 2025, 2050) compared to the high SLR scenario and late time-steps (e.g., 2075, 2100). Local persistence varied among sub-basins and river deltas. Local persistence was projected to be 100% for some wetland types, such as emergent marsh in the Nooksack and Samish River deltas and tidal swamp in the Hamma Hamma and Skokomish River deltas (Table 11). By contrast, the projected local persistence of transitional scrub-shrub in the Snohomish River delta was 0%.

What is the projected opportunity for transgressive migration?

The projected opportunity for transgressive migration into undeveloped dry land often increased with time and was larger under high SLR scenario compared to the low SLR scenario (Table 11).

Emergent marsh and transitional scrub-shrub were projected to have larger opportunities for transgressive migration compared to tidal flat and tidal swamp. The largest areas of dry land for transgressive migration were projected for river basins in the San Juan and Whidbey sub-basins, while very little to none occurred in river deltas in the Hood Canal sub-basin. For example, as much as ~300 ha of emergent marsh and ~150 ha of transitional scrub-shrub transgressive migration was projected for the Snohomish River delta by 2100 under the high SLR scenario (Table 11d).

Many transitions are also projected to occur between wetland types (Table 13). Most of these transitions are high elevation wetland classes converting into low elevation classes. The number, extent, structure, and timing of transitions were highly variable. More transitions tend to occur in late time-steps and under the high SLR scenario compared to early time-steps and the low SLR scenario.

Sensitivity analysis

SLAMM tended to overestimate the amount of transitional scrub-shrub compared to the input wetland and land cover data layer (Table 9). The modeled amount of wetland in river deltas was generally similar to the input data.

Under the high SLR scenario, model results (i.e., amount of wetland area) in the Hood Canal sub-basin were sensitive to historical sea level trend, GT, and salt elevation (Table 14). Model results were most sensitive to GT and salt elevation. Increasing GT by 15% resulted in a 2% increase in tidal flat, a 1% decline in transitional scrub-shrub, and a 1% increase in total wetland area. Increasing salt elevation by 15% resulted in a 1% increase in emergent marsh, an

18% increase in transitional scrub-shrub, a 2% decline in tidal swamp, and a 1% increase in total wetland area. Model results were also sensitive to accretion and erosion parameters depending on wetland type.

Discussion

This study is among the first to assess variation in projected adaptive capacity of tidal wetlands and opportunities for transgressive migration in response to climate change across the U.S. Salish Sea region. The Sea Level Affecting Marshes Model (SLAMM) was utilized to quantify the projected change, local persistence, and opportunity for transgressive migration of tidal wetlands in 7 sub-basins, which contain 16 large river deltas.

The total wetland area was projected to consistently decline over the entire Salish Sea study area and in all sub-basins (except in the Juan de Fuca sub-basin in 2025 under the high SLR scenario), while the projected changes for each wetland type (i.e., tidal flat, emergent marsh, transitional scrub-shrub, tidal swamp) spatially and temporally varied. For instance, emergent marsh was projected to expand between initial conditions and 2100 under both SLR scenarios (except in the South Central sub-basin under the high SLR scenario), tidal flat was projected to decline, and the projected changes in transitional scrub-shrub and tidal swamp varied among sub-basins, time-steps, and SLR scenarios

Emergent marsh has a wide elevation tolerance (i.e., MTL to the salt elevation) (Weinmann et al. 1984)), which helps buffer against changes in sea level. Tidal flat (Ball 2004) and tidal swamp (Kroes and Hupp 2010; Craft 2012) accretion rates are low compared to emergent marsh accretion rates (Thom 1992; Craft et al. 1993), which is a vital component of surface elevation change (Nyman et al. 1993; Reed 1995). The rate of sediment accretion and surface elevation changes needs to be comparable to local sea level rise (i.e., global SLR and local vertical land movement) in order to locally persist (Stevenson et al. 1986; Reed 1995).

Additionally, freshwater forested tidal swamps are sensitive to saltwater intrusion (Williams et al. 1998; Desantis et al. 2007). Saltwater can stress or kill tidal swamp vegetation (Williams et al. 1999). Consequently, as sea level rise and salt inundation occur, the conversion of tidal swamp to other wetland types may occur (Williams et al. 1999), even if the frequency of inundation (i.e., surface elevation) has not surpassed the elevation range for tidal swamp.

Overall, local persistence was relatively high for tidal flats and emergent marsh, but low and more variable for transitional scrub-shrub and tidal swamp. Local persistence of tidal wetlands has important ecological implications for the establishment of wetland structure and function (Moreno-Mateos et al. 2012). Particularly for wetland classes containing woody vegetation, development of a healthy and robust system needs time even though physical and hydrological requirements, such as surface elevation, inundation frequency, and salinity are met (Mathews et al. 2009; Moreno-Mateos et al. 2012).

While the high SLR scenario reduced the local persistence of tidal wetlands, it provided more opportunity for tidal wetland transgressive migration into undeveloped dry land. Transgressive migration is an important process by which new tidal wetlands form as the sea level rises (Brinson et al. 1995; Feagin et al. 2010; Schile et al. 2014). The projected amount of transgressive migration was high for the Whidbey and San Juan sub-basins, particularly for emergent marsh and transitional scrub-shrub.

Salish Sea is a dynamic system with great regional variability of hydrological and geological processes, many of which control tidal wetland dynamics, and variability among sub-basins is partly due to a combination of these factors. For instance, large declines in total wetland area were projected in the Juan de Fuca and Whidbey sub-basins compared to other sub-basins. Local persistence of transitional scrub-shrub, tidal swamp, and tidal flat was low in the Juan de Fuca and Whidbey sub-basins under the high SLR scenario. While there are large opportunities for transgressive migration in both sub-basins, these opportunities level off and even start to decline for transitional scrub-shrub as sea level continues to rise at high levels. The Juan de Fuca sub-basin contains a large area of non-deltaic wetlands, which have lower accretion rates for emergent marsh and transitional scrub-shrub compared to deltaic wetlands. In the Whidbey sub-basin, there is an extensive network of levees to protect agriculture, shoreline armoring, and cliffs along Whidbey basin. In contrast to these sub-basins, the Hood Canal sub-basin is projected to have small losses in wetland area and high local persistence.

Tidal wetlands in large river deltas were projected to have a higher adaptive capacity compared to non-deltaic wetlands. In this analysis, tidal wetlands in the 16 largest river deltas in the Salish Sea were assumed to have higher sediment accretion rates compared to non-deltaic tidal wetlands, since rivers are large sources of sediment supply (Campbell and Bauder 1940; Asselman 2000). While input accretion rates in the model did not vary among river deltas, river discharge was specified. The amount of sediment load and, consequently, delivery and accretion is related to the amount of river discharge (Campbell and Bauder 1940; Asselman 2000). River discharge and sediment delivery is highly variable among river deltas. River discharge ranges from around 6 m^3 yr^{-1} in the Samish River to around 210 m^3 yr^{-1} in the Skagit River (Czuba et al. 2011). The variability in river discharge contributes to variation in projected wetland responses among river deltas. For example, the Snohomish, Puyallip, Duwamish, Nooksak, Skokomish, and Elwha Rivers have relatively high discharge, and total wetland was projected to expand in these deltas under the high SLR scenario.

The wetland area was also projected to expand in the Quilcene and Skokomish between initial conditions and 2100 under the high SLR scenario. Although local persistence in these river deltas was relative low at 85 and 89%, respectively, both had opportunities for transgressive migration.

Total wetland area was projected to decline by almost 240 ha in the Stillaguamish River delta and over 1,300 ha in the Skagit River delta under the high SLR scenario by 2100. Total persistence was 93% in the Stillaguamish and only 73% in the Skagit. Opportunities for transgressive migration were also low in these deltas, at 15 ha in the Stillaguamish and 72 ha in the Skagit. These River deltas are both highly altered by levees and agriculture (Collins and Montgomery 2001).

The projected responses of tidal wetland to future climate change and accelerated sea level rise also varied temporally. Topographic variation may contribute to temporal variation in wetland responses as the rate and extent of sea level rise differs over steep or gradual slopes (Castaneda and Putz 2007). Some wetlands consistently expanded or contracted, but the direction of change in other wetlands varied through time. For instance, transitional scrub-shrub often declined early and later expanded. Wetlands have optimal elevations for maximum accretion (Morris 2002). As sea level rises, wetland elevation may fall in and out of this optimal range, contributing to temporal changes in adaptive capacity. Additionally, as sea level rise and transgressive migration of dry land and transitions between wetland types occur, wetland area may remain constant, increase, or decrease. If sea level rise reaches a tidal barrier, such as a cliff or levee, coastal squeeze may occur and the wetland area will decline.

There are still many data gaps that must be addressed when conducting future analyses in the Salish Sea. While the PSNERP geodatabase contains the most extensive database of current wetland distributions, it has not been updated since 2006 (Simenstad et al. 2011). Additionally, the PSNERP geodatabase only included the location and extent of tidal wetlands. The distribution and extent of freshwater wetlands had to be taken from the National Wetland Inventory (NWI 2014), which contains its own errors and uncertainties. There is also no sufficient database of levee locations and heights throughout the Salish Sea. The spatial resolution of this analysis is limited by the lowest elevation resolution used in the unioned DEM (9.1 m by 9.1 m), which dictated the resolution of the sample cell size. Many tidal wetland structures and processes occur at spatial scales smaller than this resolution and are, therefore, excluded from this analysis. Particularly, tidal creeks often occur at small spatial scales but have strong influences on tidal wetland sediment dynamics (Hood 2007).

The model results (i.e., amount of wetland area) are most sensitive to the tidal parameters, including historical SL trend, GT, and salt elevation. These parameters are based on 8 to16 NOAA stations throughout the Salish Sea. Since there are so few, parameters for each sub-basin were averaged from the stations within the sub-basin. In some cases, sub-basins did not contain a NOAA station so the parameter was used from nearby stations (see Tables 2-7).

Additionally, projected changes in temperature and precipitation will likely alter the hydrology of rivers, such as the timing and magnitude of peak and low flows (Hamlet et al. 2005), which are important influences on sediment delivery to tidal wetlands. The projected changes in river discharge and sediment load were not incorporated into this analysis, but could be an avenue for future research. This study has highlighted research needs that will increase the understanding of current tidal wetland dynamics, which will enhance the scientific ability to provide reasonable and accurate future projections.

Even with the current data limitations and uncertainties, the results of this analysis have important implications for creating conservation and restoration strategies that are individualized based on local and regional variability. This variability can be utilized to prioritize sites under plausible SLR scenarios and ranges of wetland responses for which restoration and conservation planners and managers may need to prepare.

Extensive areas of tidal wetlands have been historically lost throughout the Salish Sea (Simenstad et al. 2011). Tidal wetland area is projected to continue to decline under climate change and accelerated sea level rise. An overall projected reduction of total wetland area and most wetland types supports the need for restoration. Under a climate change context, restoration will aid in the recovery of historically lost wetland area as well as buffer against future losses due to accelerated sea level rise. The combined losses of historical and projected tidal wetland losses suggests a need for more restoration than has been completed or is currently in the planning stages if wetland area is going to recover toward historical extent.

Sites where large areas of tidal wetland are projected to locally persist can be identified as ideal sites for wetland conservation. For instance, the river deltas on the Hood Canal and San Juan sub-basins have high projected local persistence, particularly emergent marsh and tidal swamp. These river deltas are also relatively pristine with low degradation compared to other river deltas in the Salish Sea (Cereghino et al. 2012). Protecting these river deltas from future degradation may provide important buffers against total wetland loss in the region and may offer vital refugia for organisms, such as salmon and waterfowl.

Potential future gains in transitional scrub-shrub and tidal swamp from transgressive migration have important ecological implications since these are the two wetland classes that experienced the greatest historical losses throughout the Salish Sea, losses of 98.5% and 90%, respectively (Simenstad et al. 2011). For instance, transitional scrub-shrub was projected to expand in the Skagit, Snohomish, and Nisqually River deltas under both SLR scenarios, and tidal swamp was projected to expand in the Skokomish and Nisqually River deltas under the high SLR scenario. While transgressive migration into undeveloped dry land may provide opportunity for wetland gains, or at least buffer wetland loss, the social availability of upland must be considered. Some of the undeveloped dry land naturally inundated during simulations may be developed in the future or tidal inundation may be blocked by new barriers, such as the construction of new levees or shoreline armoring. This analysis identified particular locations of currently dry land that may provide opportunity of tidal wetland transgressive migration in the future. These projected locations can be utilized to create areas of preservation to prevent future development so that these areas may continue to be available for wetland transgression as sea level rises (Pearsall 2005).

Large areas of projected local persistence or transgressive migration can be identified as priority areas for conservation. The overall change in wetland area and the amount of wetland projected to exist at a particular site can be used to determine the potential trade-offs between the amount of conservation and restoration effort and the amount of ecosystem service return. Identifying variability in the adaptive capacity and opportunity for transgressive migration of tidal wetlands to climate change impacts is an important tool for prioritizing sites in order to protect wetlands and enhance their persistence and health into the future along with the ecosystem services they provide.

Acknowledgments Funding was provided by the Northwest Climate Science Center Fellowship and from the School of Aquatic and Fishery Sciences, College of the Environment, University of Washington.

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Tables

Table 1: Wetland and land cover data were unioned from multiple sources. Wetland data were taken from the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and the National Wetland Inventory (NWI). Land cover data were taken from that National Land Cover Dataset (NLCD). Source wetland categories were reclassified to match SLAMM categories. The SLAMM descriptive names are the wetland and land cover names used in text.

Source	Source category	SLAMM category	SLAMM descriptive name
PSNERP	Euyhaline unvegetated	Tidal flat	Tidal flat
PSNERP	Low estuarine mixing	Regularly flooded marsh	Emergent marsh
PSNERP	High estuarine mixing	Irregularly flooded marsh	Emergent marsh
PSNERP	Oligohaline transition	Transitional salt marsh	Transitional scrub-shrub
PSNERP	Tidal freshwater	Tidal swamp	Tidal swamp
NWI	See Technical Documentation	See Technical Documentation	See Technical Documentation
NLCD	Low intensity developed	Developed dry land	Developed land
NLCD	Medium intensity developed	Developed dry land	Developed land
NLCD	High intensity developed	Developed dry land	Developed land

Table 2: Parameter values for historical sea level trends, averaged from NOAA stations within or near each sub-basin. Historical sea level trend measured in mm yr^{-1} based on monthly mean sea level data. Years of data collection in parentheses under station name. Data from NOAA CO-OPS (2015).

Sub-basin	Parameter input	NOAA Station	Value
Hood Canal	1.71	Port Townsend (1972-2013)	1.45
		Seattle (1899-2013)	1.97
Juan de Fuca	-1.08	Neah Bay (1934-2013)	-1.81
		Port Angeles (1975-2013)	-0.35
North Central	1.45	Port Townsend (1972-2013)	1.45
San Juan Islands – Georgia Strait	0.455	Cherry Point (1973-2014)	-0.11
		Friday Harbor (1934-2013)	1.02
South	1.97	Seattle (1899-2013)	1.97
South Central	1.97	Seattle (1899-2013)	1.97
Whidbey	1.48	Friday Harbor (1934-2013)	1.02
		Port Townsend (1972-2013)	1.45
		Seattle (1899-2013)	1.97

Table 3: Parameter values for great diurnal tide (GT), averaged from NOAA stations within or near each sub-basin. GT measured in meters. Data from NOAA CO-OPS (2015).

Sub-basin	Parameter	NOAA Station	Value
Hood Canal	3.374	Bangor	3.374
Juan de Fuca	2.238	Ediz Hood	2.136
		Port Angeles	2.153
		Neah Bay	2.425
North Central	2.597	Port Townsend	2.597
San Juan Islands – Georgia Strait	2.607	Armitage	2.391
		Bellingham	2.595
		Bowman	2.352
		Cherry Point	2.788
		Friday Harbor	2.364
		Richardson	3.15
South	4.0165	Olympia	4.438
		Tacoma	3.595
South Central	3.5255	Lockhead	3.47
		Poulsbo	3.575
		Seattle	3.462
		Tacoma	3.595
Whidbey	2.6938	Bowman	2.353
		Friday Harbor	2.3938
		Port Townsend	2.597
		Seattle	3.462

Table 4: Values for mean lower low water (MLLW), averaged from NOAA stations within or near each sub-basin. MLLW measured in meters above mean tidal level (MTL). Data from NOAA CO-OPS (2015).

Sub-basin	Parameter	NOAA Station	Value
Hood Canal	-1.99	Bangor	-1.990
Juan de Fuca	-1.306	Ediz Hood	-1.305
		Port Angeles	-1.286
		Neah Bay	-1.327
North Central	-1.574	Port Townsend	-1.574
San Juan Islands – Georgia Strait	-1.480	Armitage	-1.456
		Bellingham	-1.546
		Bowman	-1.450
		Cherry Point	-1.666
		Friday Harbor	-1.433
		Richardson	-1.330
South	-2.316	Olympia	-2.532
		Tacoma	-2.099
South Central	-2.064	Lockhead	-2.037
		Poulsbo	-2.089
		Seattle	-2.032
		Tacoma	-2.099
Whidbey	-1.622	Bowman	-1.450
		Friday Harbor	-1.433
		Port Townsend	-1.574
		Seattle	-2.032

Table 5: Mean higher high water (MHHW), averaged from NOAA station values from within or near each sub-basin. MHHW levels in meters above mean tidal level (MTL). Data from NOAA CO-OPS (2015).

Sub-basin	Parameter	NOAA Station	Value
Hood Canal	1.384	Bangor	1.384
Juan de Fuca	0.932	Ediz Hood	0.83
		Port Angeles	0.867
		Neah Bay	1.098
North Central	1.022	Port Townsend	1.022
San Juan Islands – Georgia Strait	0.966	Armitage	0.935
		Bellingham	1.048
		Bowman	0.902
		Cherry Point	1.122
		Friday Harbor	0.931
		Richardson	0.855
South	1.701	Olympia	1.905
		Tacoma	1.497
South Central	1.462	Lockhead	1.433
		Poulsbo	1.486
		Seattle	1.431
		Tacoma	1.497
Whidbey	1.072	Bowman	0.902
		Friday Harbor	0.931
		Port Townsend	1.022
		Seattle	1.431

Table 6: Parameter values for salt elevation calculated using the NOAA Inundation Analysis Tool (NOAA NOS 2013) and averaged from NOAA stations within or near each sub-basin. Salt elevation measured in meters above mean tidal level (MTL).

Sub-basin	Parameter	NOAA Station	Value
Hood Canal	1.679	Port Townsend	1.515
		Seattle	1.843
Juan de Fuca	1.443	Port Angeles	1.289
		Neah Bay	1.596
North Central	1.515	Port Townsend	1.515
San Juan Islands – Georgia Strait	1.399	Cherry Point	1.487
		Friday Harbor	1.311
South	1.917	Tacoma	1.917
South Central	1.880	Seattle	1.843
		Tacoma	1.917
Whidbey	1.556	Friday Harbor	1.311
		Seattle	1.843
		Port Townsend	1.515

Table 7: Mean annual discharge in $m^3\ yr^{-1}$ of major rivers draining into the U.S. portion of the Salish Sea. Discharge values converted from Czuba et al. (2001) with data from Williams (1981).

Sub-basin	River	Mean annual discharge ($m^3\ yr^{-1}$)
Hood Canal	Dosewallips	19.0
	Hamma Hamma	14.2
	Skokomish	36.8
Juan de Fuca	Dungeness	13.0
	Elwha	56.6
San Juan Islands – Georgia Strait	Nooksack	90.6
	Samish	5.7
South	Deschutes	11.6
	Nisqually	59.5
South Central	Duwamish	39.6
	Lake Washington Ship Canal	39.6
	Puyallup	101.9
	Snohomish	283.2
Whidbey	Skagit	509.7
	Snohomish	283.2
	Stillaguamish	76.5

Table 8: Parameter values for accretion rates for each wetland type measured in mm yr^{-1}.

Wetland type	Accretion rate (mm yr^{-1})	Data source
Regularly flooded marsh	3.16	Thom (1992)
Irregularly flooded marsh	3.6	Craft et al. (1993)
Tidal fresh marsh	8.4	Neubauer et al (2002)
Inland fresh marsh	5.35	Hansen and Nestlerode (2014)
Tidal swamp	2.26	Craft (2012); Kroes and Hupp (2010); Noe and Hupp (2009); Rybczyk et al. (2002);
Swamp	3.65	Conner and Day (1991); Hansen and Nestlerode (2014)
Beach	2.1167	Ball (2004)

Table 9: Amount of initial wetland area (hectares) in each sub-basin, large river delta, and the Salish Sea study area. The input value is the wetland area from the combined PSNERP and NWI dataset. The modeled value is the initial wetland area as modeled by SLAMM.

	Tidal flat		**Emergent marsh**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Input	Modeled	Input	Modeled	Input	Modeled	Input	Modeled	Input	Modeled
Hood Canal	**3,132**	**3,362**	**785**	**1,115**	**29**	**113**	**104**	**104**	**4,050**	**4,694**
Dosewallips	140	140	47	47	3	3	4	3	194	194
Duckabush	118	118	31	31	1	1	7	7	157	157
Hamma Hamma	130	126	23	23	1	1	9	9	164	159
Quilcene	46	66	246	227	1	2	17	16	310	311
Skokomish	56	456	673	268	1	1	59	59	789	784
Juan de Fuca	**3,630**	**3,142**	**321**	**324**	**14**	**1,073**	**78**	**70**	**4,042**	**4,609**
Dungeness	600	583	74	74	0	0	11	11	685	668
Elwha	42	36	11	11	0	0	40	40	92	87
North Central	**2,258**	**1,992**	**455**	**455**	**5**	**38**	**17**	**17**	**2,735**	**2,502**
San Juan	**12,736**	**11,629**	**988**	**985**	**20**	**173**	**84**	**109**	**13,828**	**12,896**
Nooksack	1,467	1,466	485	485	9	9	58	84	2,019	2,044
Samish	1,527	1,525	38	38	4	4	11	11	1,580	1,578
South	**5,775**	**5,688**	**669**	**777**	**11**	**54**	**53**	**51**	**6,508**	**6,570**
Deschutes	88	87	109	108	0	2	0	0	196	197
Nisqually	659	659	225	225	1	1	23	23	908	908
South Central	**4,522**	**3,812**	**311**	**256**	**6**	**102**	**7**	**23**	**4,846**	**4,193**
Duwamish	14	14	2	2	0	5	1	1	17	22
Puyallup	31	28	4	3	0	0	6	6	41	37
Whidbey	**11,652**	**11,171**	**2,930**	**3,009**	**56**	**101**	**970**	**873**	**15,608**	**15,154**
Skagit	4,294	4,230	1,700	1,678	47	47	309	315	6,350	6,270
Snohomish	1,018	927	296	390	0	20	560	461	1,875	1,798
Stillaguamish	2,720	2,677	817	823	10	10	84	84	6,631	3,594
Salish Sea	**42,090**	**39,299**	**7,307**	**6,682**	**140**	**1,636**	**1,306**	**1,234**	**50,843**	**48,851**

Table 10: The projected amount of wetland change (hectares) between initial conditions and (a) 2025, (b) 2050, (c) 2075, and (d) 2100 under the low and high SLR scenarios for each sub-basin, large river delta, and the Salish Sea study area. Relative changes (percent change) included in parentheses. The percent change could not be calculated when the initial areas was 0 ha and is symbolized by (-).

(a) 2025

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**-29 (-1)**	**-27 (-1)**	**82 (7)**	**73 (7)**	**-83 (-73)**	**-80 (-71)**	**0 (0)**	**-1 (-1)**	**-30 (-1)**	**-35 (-1)**
Dosewallips	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Duckabush	0 (0)	0 (0)	0 (0)	(0) (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Hamma Hamma	0 (0)	-1 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-1 (-1)
Quilcene	0 (0)	0 (0)	0 (0)	-1 (0)	-1 (-50)	-1 (-50)	0 (0)	-1 (-6)	-1 (0)	-3 (-1)
Skokomish	-7 (-2)	-3 (-1)	-1 (0)	-8 (-3)	0 (0)	0 (0)	0 (0)	0 (0)	-8 (-1)	-11 (-1)
Juan de Fuca	**-26 (-1)**	**-24 (-1)**	**1,045 (323)**	**7 (2)**	**-1,045 (-97)**	**43 (4)**	**0 (0)**	**-13 (-19)**	**-26 (-1)**	**13 (0)**
Dungeness	-1 (0)	-3 (-1)	0 (0)	0 (0)	0 (-)	1 (100)	0 (0)	0 (0)	0 (0)	-2 (0)
Elwha	0 (0)	0 (0)	0 (0)	6 (55)	0 (0)	4 (-)	0 (0)	-12 (-30)	0 (0)	-2 (-2)
North Central	**-23 (-1)**	**-38 (-2)**	**25 (5)**	**47 (10)**	**-24 (-63)**	**-32 (-80)**	**0 (0)**	**0 (0)**	**-22 (-1)**	**-23 (-1)**
San Juan	**-28 (0)**	**-80 (-1)**	**147 (15)**	**51 (5)**	**-152 (-88)**	**-151 (-87)**	**0 (0)**	**0 (0)**	**-33 (0)**	**-80 (-1)**
Nooksack	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Samish	0 (0)	-1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-1 (0)
South	**-14 (0)**	**14 (0)**	**41 (5)**	**-28 (-4)**	**-45 (-83)**	**6 (11)**	**0 (0)**	**0 (0)**	**-18 (0)**	**-8 (0)**
Deschutes	0 (0)	27 (31)	2 (2)	-27 (-25)	-2 (-)	2 (100)	0 (-)	0 (-)	0 (0)	2 (1)

Nisqually	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
South Central	**-47 (-1)**	**-74 (-2)**	**89 (35)**	**96 (38)**	**-90 (-88)**	**-87 (-84)**	**-16 (-70)**	**-15 (-65)**	**-64 (-2)**	**-80 (-2)**
Duwamish	0 (0)	0 (0)	5 (250)	5 (250)	-4 (-80)	-3 (-60)	-4 (-80)	-4 (-80)	-3 (-12)	-2 (-8)
Puyallup	0 (0)	0 (0)	0 (0)	0 (0)	0 (-)	0 (-)	-8 (-57)	-8 (-57)	-8 (-18)	-8 (-18)
Whidbey	**-27 (0)**	**-91 (-1)**	**33 (1)**	**83 (3)**	**-28 (-28)**	**30 (30)**	**-8 (-1)**	**-62 (-7)**	**-30 (0)**	**-40 (0)**
Skagit	0 (0)	-11 (0)	3 (0)	4 (0)	1 (2)	3 (7)	-4 (-1)	-13 (-4)	0 (0)	-17 (0)
Snohomish	-4 (0)	-32 (-3)	10 (3)	58 (15)	-6 (-30)	43 (205)	-7 (-2)	-49 (-11)	-7 (0)	20 (1)
Stillaguamish	0 (0)	0 (0)	0 (0)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (0)
Salish Sea	**-177 (0)**	**-286 (-1)**	**1,1448 (22)**	**391 (6)**	**-1,451 (-89)**	**-237 (-14)**	**-18 (-1)**	**-85 (-7)**	**-198 (0)**	**-217 (0)**

(b) 2050

	Tidal flat		**Emergent marsh**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**-90 (-3)**	**-76 (-2)**	**48 (4)**	**19 (2)**	**-81 (-72)**	**-64 (-57)**	**-1 (-1)**	**-4 (-4)**	**-124 (-3)**	**-125 (-3)**
Dosewallips	-2 (-1)	-2 (-1)	(0) (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-2 (-1)	-2 (-1)
Duckabush	-1 (-1)	-1 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-1 (0)	-1 (-1)
Hamma Hamma	-2 (-2)	-2 (-2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-2 (-1)	-2 (-1)
Quilcene	2 (3)	10 (15)	-1 (0)	-5 (-2)	-1 (-50)	-2 (-100)	-1 (-6)	-4 (-24)	-1 (0)	-1 (0)
Skokomish	-7 (-2)	10 (2)	0 (0)	-23 (-9)	0 (0)	0 (0)	0 (0)	0 (0)	-11 (-1)	-13 (-2)
Juan de Fuca	**888 (28)**	**819 (26)**	**6 (2)**	**32 (10)**	**-1,039 (-97)**	**-961 (-90)**	**0 (0)**	**-21 (-30)**	**-145 (-3)**	**-131 (-3)**

Dungeness	-7 (-1)	-18 (-3)	0 (0)	0 (0)	0 (-)	19 (-)	0 (0)	-1 (-9)	-7 (-1)	-1 (0)
Elwha	-2 (-6)	-3 (-8)	0 (0)	14 (140)	3 (-)	14 (-)	0 (0)	-17 (-43)	1 (1)	8 (9)
North Central	**-114 (-6)**	**-162 (-8)**	**24 (5)**	**49 (11)**	**-12 (-31)**	**23 (58)**	**0 (0)**	**0 (0)**	**-102 (-4)**	**-90 (-4)**
San Juan	**-74 (-1)**	**-294 (-3)**	**18 (2)**	**26 (3)**	**-151 (-87)**	**-85 (-49)**	**0 (0)**	**-43 (-39)**	**-207 (-2)**	**-395 (-3)**
Nooksack	-6 (0)	-7 (0)	0 (0)	4 (1)	0 (0)	20 (222)	0 (0)	-43 (-51)	-6 (0)	-26 (-1)
Samish	-9 (-1)	-14 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-9 (-1)	-14 (-1)
South	**-247 (-4)**	**-258 (-5)**	**6 (1)**	**4 (1)**	**-44 (-80)**	**-42 (-76)**	**0 (0)**	**0 (0)**	**-285 (-4)**	**-296 (-5)**
Deschutes	27 (31)	29 (33)	-26 (-24)	-26 (-24)	0 (0)	-2 (-100)	0 (-)	0 (-)	1 (1)	1 (1)
Nisqually	-9 (-1)	-9 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-9 (-1)	-9 (-1)
South Central	**-200 (-5)**	**-279 (-7)**	**68 (2)**	**77 (30)**	**-83 (-81)**	**-22 (-22)**	**-15 (-65)**	**-11 (-50)**	**-230 (-5)**	**-235 (-6)**
Duwamish	2 (13)	3 (20)	6 (300)	8 (400)	-3 (-60)	8 (133)	-4 (-80)	-1 (-20)	1 (4)	18 (64)
Puyallup	6 (21)	5 (17)	1 (33)	1 (33)	0 (-)	0 (-)	-8 (-57)	-7 (-50)	-1 (-2)	-1 (-2)
Whidbey	**-223 (-2)**	**-504 (-5)**	**28 (1)**	**210 (7)**	**30 (30)**	**85 (84)**	**-14 (-2)**	**-133 (-15)**	**-179 (-1)**	**-342 (-2)**
Skagit	-20 (0)	-74 (-2)	4 (0)	35 (2)	4 (9)	14 (30)	-3 (-1)	-150 (-48)	-15 (0)	-175 (-3)
Snohomish	-13 (-1)	-141 (-15)	15 (4)	147 (38)	41 (195)	59 (281)	-12 (-3)	-78 (-17)	31 (2)	-13 (-1)
Stillaguamish	-16 (-1)	-17 (-1)	1 (0)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-15 (0)	-16 (0)
Salish Sea	**18 (0)**	**-582 (-1)**	**188 (3)**	**403 (6)**	**-1,362 (-83)**	**-1,067 (-65)**	**-24 (-2)**	**-210 (-17)**	**-1,180 (-2)**	**-1,456 (-3)**

(c) 2075

	Tidal flat		**Emergent marsh**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**-121 (-4)**	**-97 (-3)**	**49 (4)**	**7 (1)**	**-78 (-70)**	**-51 (-45)**	**-2 (-2)**	**-9 (-9)**	**-152 (-3)**	**-150 (-3)**
Dosewallips	-2 (-1)	-2 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-2 (-1)	-2 (-1)
Duckabush	-1 (-1)	-1 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-1 (-1)	-1 (-1)
Hamma Hamma	-2 (-2)	-3 (-2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-2 (-1)	-3 (-2)
Quilcene	3 (5)	20 (30)	-2 (-1)	-9 (-4)	-1 (-50)	6 (300)	-1 (-6)	-9 (-53)	-1 (0)	8 (3)
Skokomish	-4 (-1)	26 (6)	-9 (-3)	-42 (-16)	0 (0)	0 (0)	0 (0)	0 (0)	-13 (-2)	-16 (-2)
Juan de Fuca	**-171 (-5)**	**-356 (-11)**	**6 (2)**	**137 (42)**	**-1,005 (-94)**	**-996 (-93)**	**0 (0)**	**-31 (-44)**	**-1,170 (-25)**	**-1,246 (-27)**
Dungeness	-8 (-1)	-41 (-7)	0 (0)	20 (27)	1 (-)	27 (2,700)	0 (0)	-4 (-36)	-7 (-1)	2 (0)
Elwha	-2 (-6)	-5 (-14)	0 (0)	44 (440)	5 (-)	10 (-)	0 (0)	-21 (-54)	3 (3)	28 (33)
North Central	**-146 (-7)**	**-307 (-15)**	**26 (6)**	**109 (24)**	**9 (23)**	**131 (336)**	**0 (0)**	**0 (0)**	**-111 (-4)**	**-68 (-3)**
San Juan	**-259 (-2)**	**-817 (-7)**	**22 (2)**	**18 (2)**	**-148 (-86)**	**402 (231)**	**0 (0)**	**-29 (-26)**	**-385 (-3)**	**-426 (-3)**
Nooksack	-6 (0)	-18 (-1)	0 (0)	16 (3)	1 (11)	88 (978)	0 (0)	-32 (-38)	-5 (0)	54 (3)
Samish	-10 (-1)	-23 (-2)	0 (0)	2 (5)	0 (0)	57 (1,425)	0 (0)	4 (36)	-10 (-1)	40 (3)
South	**-269 (-5)**	**-296 (-5)**	**10 (1)**	**14 (2)**	**-45 (-83)**	**-15 (-27)**	**0 (0)**	**0 (0)**	**-304 (-5)**	**-297 (-5)**
Deschutes	27 (31)	31 (36)	-24 (-22)	-28 (-26)	-2 (-100)	-1 (-50)	0 (-)	0 (-)	1 (1)	2 (1)
Nisqually	-9 (-1)	-9 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-9 (-1)	-9 (-1)
South Central	**-288**	**-508**	**80**	**150**	**-76**	**-26**	**-15**	**-8**	**-299**	**-392**

	(-8)	**(-13)**	**(31)**	**(59)**	**(-75)**	**(-25)**	**(-68)**	**(-36)**	**(-7)**	**(-9)**
Duwamish	0 (0)	0 (0)	7 (350)	21 (1,050)	-1 (-20)	14 (280)	-4 (-80)	-1 (-17)	2 (7)	34 (121)
Puyallup	1 (4)	0 (0)	1 (33)	1 (33)	0 (-)	0 (-)	-8 (-57)	-5 (-36)	-6 (-13)	-4 (-9)
Whidbey	**-314 (-3)**	**-1,365 (-12)**	**86 (3)**	**546 (18)**	**53 (52)**	**768 (768)**	**-74 (-8)**	**-329 (-38)**	**-249 (-2)**	**-380 (-3)**
Skagit	-32 (-1)	-335 (-8)	5 (0)	162 (10)	12 (26)	7 (16)	-18 (-6)	-180 (-58)	-33 (-1)	-346 (-6)
Snohomish	-50 (-5)	-404 (-44)	64 (16)	316 (81)	50 (250)	700 (3,500)	-54 (-12)	-142 (-31)	10 (1)	470 (26)
Stillaguamish	-16 (-1)	-44 (-2)	1 (0)	5 (1)	0 (0)	4 (36)	0 (0)	1 (1)	-15 (0)	-34 (-1)
Salish Sea	**-1,457 (-4)**	**-3,383 (-9)**	**265 (4)**	**959 (14)**	**-1,276 (-78)**	**163 (10)**	**-86 (-7)**	**-426 (-34)**	**-2,554 (-5)**	**-2,687 (-6)**

(d) 2100

	Tidal flat		**Regularly flooded emergent**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**-195 (-6)**	**-159 (-5)**	**54 (5)**	**10 (1)**	**-77 (-68)**	**-40 (-36)**	**-3 (-3)**	**10 (10)**	**-221 (-5)**	**-179 (-4)**
Dosewallips	-4 (-3)	-4 (-3)	0 (0)	0 (0)	0 (0)	1 (50)	0 (0)	-1 (-25)	-4 (-2)	-4 (-2)
Duckabush	-2 (-2)	-2 (-2)	-1 (-3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-3 (-2)	-2 (-1)
Hamma Hamma	-4 (-3)	-5 (-4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	-4 (-3)	-5 (-3)
Quilcene	5 (8)	33 (50)	-1 (0)	-12 (-5)	-2 (-100)	2 (100)	-3 (-18)	-11 (-69)	-1 (0)	12 (4)
Skokomish	-2 (0)	42 (9)	-13 (-5)	-57 (-21)	0 (0)	14 (1,400)	0 (0)	23 (39)	-15 (-2)	22 (3)
Juan de Fuca	**-222 (-7)**	**-677 (-22)**	**11 (3)**	**207 (64)**	**-996 (-93)**	**-1,012 (-94)**	**-10 (-14)**	**-36 (-51)**	**-1,217 (-26)**	**-1,518 (-33)**
Dungeness	-10 (-2)	-161 (-28)	0 (0)	50 (68)	3 (-)	21 (-)	0 (0)	-8 (-67)	-7 (-1)	-98 (-15)
Elwha	-2	-7	4	47	6	8	-9	-22	-1	26

	(-6)	(-19)	(36)	(427)	(-)	(-)	(-23)	(-56)	(-1)	(30)
North Central	**-215 (-11)**	**-558 (-28)**	**44 (10)**	**276 (61)**	**23 (59)**	**46 (118)**	**0 (0)**	**-1 (-6)**	**-148 (-6)**	**-237 (-9)**
San Juan	**-368 (-3)**	**-1,922 (-17)**	**26 (3)**	**508 (52)**	**-114 (-66)**	**157 (91)**	**0 (0)**	**-72 (-66)**	**-456 (-4)**	**-1,319 (-10)**
Nooksack	-13 (-1)	-120 (-8)	0 (0)	187 (39)	10 (111)	57 (633)	0 (0)	-73 (-87)	-3 (0)	51 (2)
Samish	-11 (-1)	-79 (-5)	0 (0)	62 (163)	0 (0)	40 (1,000)	0 (0)	2 (18)	-11 (-1)	25 (2)
South	**-410 (-7)**	**-439 (-8)**	**13 (2)**	**25 (3)**	**-45 (-82)**	**-23 (-42)**	**0 (0)**	**7 (14)**	**-442 (-7)**	**-430 (-7)**
Deschutes	28 (32)	34 (39)	-25 (-23)	-32 (-30)	-2 (-100)	0 (0)	0 (-)	0 (-)	1 (1)	2 (1)
Nisqually	-9 (-1)	-9 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	7 (30)	-9 (-1)	-2 (0)
South Central	**-412 (-11)**	**-812 (-21)**	**105 (41)**	**-12 (-5)**	**-46 (-45)**	**254 (249)**	**-13 (-57)**	**15 (65)**	**-366 (-9)**	**-555 (-13)**
Duwamish	0 (0)	-2 (-14)	12 (600)	0 (0)	4 (67)	40 (800)	-2 (-33)	8 (160)	14 (48)	46 (177)
Puyallup	-1 (-3)	-2 (-7)	2 (27)	0 (0)	0 (-)	1 (-)	-7 (-54)	7 (50)	-6 (-13)	6 (13)
Whidbey	**-510 (-5)**	**-3,505 (-31)**	**189 (6)**	**1,511 (50)**	**23 (23)**	**384 (384)**	**-96 (-11)**	**-460 (-53)**	**-394 (-3)**	**-2,070 (-14)**
Skagit	-63 (-1)	-1,413 (-33)	26 (2)	238 (14)	13 (28)	24 (52)	-26 (-8)	-210 (-67)	-50 (-1)	-1,361 (-22)
Snohomish	-93 (-10)	-724 (-78)	139 (36)	1,111 (285)	1 (5)	297 (1,485)	-65 (-14)	-244 (-53)	-18 (-1)	440 (24)
Stillaguamish	-32 (-1)	-255 (-10)	2 (0)	15 (2)	0 (0)	0 (0)	0 (0)	0 (0)	-30 (-1)	-240 (-7)
Salish Sea	**-2,158 (-5)**	**-7,413 (-19)**	**426 (6)**	**2,441 (37)**	**-1,227 (-75)**	**-258 (-16)**	**-144 (-9)**	**-529 (-43)**	**-3,073 (-6)**	**-5,759 (-12)**

Table 11: The projected amount of local persistence between initial conditions and (a) 2025, (b) 2050, (c) 2075, and (d) 2100 under the low and high SLR scenarios for each sub-basin, large river delta, and the Salish Sea study area. Percent of initial wetland area that is projected to persist is included in parentheses.

(a) 2025

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**3,330 (99)**	**3,319 (99)**	**1,113 (100)**	**1,100 (99)**	**29 (26)**	**28 (25)**	**104 (100)**	**103 (99)**	**4,576 (97)**	**4,550 (97)**
Dosewallips	140 (100)	140 (100)	47 (100)	48 (100)	3 (100)	3 (100)	4 (100)	4 (100)	195 (100)	194 (99)
Duckabush	118 (100)	118 (100)	31 (100)	31 (100)	1 (100)	1 (100)	7 (100)	7 (100)	157 (100)	157 (100)
Hamma Hamma	126 (100)	125 (99)	23 (100)	22 (100)	1 (100)	1 (100)	9 (100)	9 (100)	159 (100)	147 (99)
Quilcene	66 (100)	66 (100)	226 (100)	224 (99)	1 (50)	1 (50)	16 (100)	15 (94)	309 (99)	306 (98)
Skokomish	448 (98)	448 (98)	267 (100)	260 (97)	1 (1)	1 (100)	59 (100)	59 (100)	775 (99)	768 (98)
Juan de Fuca	**3,116 (99)**	**3,118 (99)**	**324 (100)**	**323 (100)**	**28 (3)**	**1,073 (100)**	**70 (100)**	**57 (81)**	**3,538 (77)**	**4,571 (99)**
Dungeness	582 (100)	581 (99)	74 (100)	74 (100)	0 (-0)	1 (100)	11 (100)	11 (100)	667 (100)	667 (100)
Elwha	36 (100)	36 (100)	11 (100)	11 (100)	0 (-)	0 (-)	40 (100)	28 (70)	87 (100)	75 (86)
North Central	**1,967 (99)**	**1,951 (98)**	**455 (100)**	**455 (100)**	**10 (26)**	**8 (20)**	**17 (100)**	**17 (100)**	**2,439 (97)**	**2,431 (97)**
San Juan	**11,597 (100)**	**11,544 (99)**	**984 (100)**	**984 (100)**	**21 (12)**	**20 (12)**	**109 (100)**	**109 (100)**	**12,711 (99)**	**12,657 (98)**
Nooksack	1,466 (100)	1,465 (100)	485 (100)	485 (100)	9 (100)	9 (100)	84 (100)	84 (100)	2,044 (100)	2,043 (100)
Samish	1,525 (100)	1,524 (100)	38 (100)	38 (100)	4 (100)	4 (100)	11 (100)	11 (100)	1,578 (100)	1,577 (100)
South	**5,671 (100)**	**5,673 (100)**	**774 (100)**	**748 (96)**	**9 (17)**	**53 (96)**	**51 (100)**	**51 (100)**	**6,505 (99)**	**6,525 (99)**
Deschutes	87 (100)	87 (100)	108 (100)	82 (75)	0 (0)	2 (100)	0 (-)	0 (-)	195 (99)	171 (86)

Nisqually	659 (100)	659 (100)	225 (100)	224 (100)	1 (100)	1 (100)	23 (100)	23 (100)	908 (100)	907 (100)
South Central	**3,762 (99)**	**3,733 (98)**	**256 (100)**	**254 (99)**	**9 (9)**	**6 (6)**	**7 (30)**	**7 (3)**	**4,034 (96)**	**4,000 (95)**
Duwamish	14 (100)	14 (100)	2 (100)	2 (100)	0 (0)	0 (0)	1 (20)	1 (20)	17 (65)	17 (65)
Puyallup	28 (100)	28 (100)	3 (100)	3 (100)	0 (-)	0 (-)	6 (43)	6 (43)	37 (82)	37 (82)
Whidbey	**11,140 (100)**	**11,074 (99)**	**3,008 (100)**	**3,005 (100)**	**68 (67)**	**60 (60)**	**865 (99)**	**811 (93)**	**15,081 (100)**	**14,950 (99)**
Skagit	4,228 (100)	4,216 (100)	1,677 (100)	1,677 (100)	46 (98)	45 (98)	311 (99)	300 (96)	6,262 (100)	6,238 (100)
Snohomish	923 (100)	894 (96)	390 (100)	388 (100)	11 (55)	5 (24)	454 (98)	411 (89)	1,778 (99)	1,698 (94)
Stillaguamish	2,677 (100)	2,677 (100)	823 (100)	823 (100)	10 (100)	10 (91)	84 (100)	84 (100)	3,594 (100)	3,591 (100)
Salish Sea	**39,103 (100)**	**38,948 (99)**	**6,678 (100)**	**6,634 (99)**	**171 (11)**	**1,247 (76)**	**1,216 (99)**	**1,148 (93)**	**47,169 (97)**	**47,977 (98)**

(b) 2050

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**3,229 (96)**	**3,199 (95)**	**1,106 (99)**	**1,068 (96)**	**28 (25)**	**27 (24)**	**103 (99)**	**101 (96)**	**4,466 (95)**	**4,395 (94)**
Dosewallips	138 (99)	138 (99)	47 (100)	47 (100)	3 (3)	3 (100)	4 (4)	4 (100)	192 (99)	192 (99)
Duckabush	117 (99)	117 (99)	31 (100)	31 (100)	1 (100)	1 (100)	7 (100)	7 (100)	156 (99)	156 (99)
Hamma Hamma	124 (98)	124 (98)	23 (100)	23 (100)	1 (100)	1 (100)	9 (100)	9 (100)	157 (99)	157 (99)
Quilcene	65 (98)	65 (98)	225 (99)	217 (96)	1 (50)	0 (0)	16 (94)	13 (76)	307 (98)	295 (95)
Skokomish	445 (98)	444 (97)	263 (99)	245 (91)	1 (100)	1 (100)	59 (100)	59 (100)	768 (98)	749 (95)
Juan de Fuca	**2,992 (95)**	**2,921 (93)**	**324 (100)**	**324 (100)**	**28 (3)**	**17 (2)**	**70 (100)**	**49 (70)**	**3,414 (74)**	**3,311 (72)**

Dungeness	576 (99)	566 (97)	74 (100)	73 (100)	0 (-)	0 (-)	11 (100)	10 (91)	661 (99)	649 (97)
Elwha	34 (94)	33 (92)	11 (100)	10 (100)	0 (-)	0 (-)	40 (100)	23 (86)	85 (98)	66 (77)
North Central	**1,874 (94)**	**1,822 (91)**	**455 (100)**	**455 (100)**	**9 (23)**	**5 (13)**	**17 (100)**	**16 (100)**	**2,355 (94)**	**2,298 (92)**
San Juan	**11,423 (98)**	**11,199 (96)**	**984 (100)**	**984 (100)**	**21 (12)**	**20 (12)**	**109 (100)**	**55 (50)**	**12,537 (97)**	**12,258 (95)**
Nooksack	1,459 (100)	1,458 (100)	485 (100)	485 (100)	9 (100)	9 (100)	84 (100)	30 (36)	2,037 (100)	1,982 (97)
Samish	1,516 (99)	1,511 (99)	38 (100)	38 (100)	4 (100)	4 (100)	11 (100)	11 (100)	1,569 (99)	1,564 (99)
South	**5,398 (95)**	**5,377 (95)**	**743 (96)**	**739 (95)**	**9 (16)**	**9 (16)**	**51 (100)**	**51 (100)**	**6,205 (94)**	**6,176 (94)**
Deschutes	86 (99)	86 (99)	82 (75)	78 (73)	0 (0)	0 (0)	0 (-)	0 (-)	168 (85)	164 (84)
Nisqually	650 (99)	650 (99)	225 (100)	224 (100)	1 (100)	1 (100)	23 (100)	23 (100)	899 (99)	898 (99)
South Central	**3,568 (94)**	**3,479 (91)**	**255 (100)**	**251 (98)**	**7 (7)**	**6 (6)**	**7 (30)**	**7 (32)**	**3,837 (92)**	**3,743 (89)**
Duwamish	13 (87)	13 (87)	2 (100)	2 (100)	0 (0)	0 (0)	1 (20)	1 (20)	16 (59)	16 (57)
Puyallup	27 (96)	27 (93)	3 (100)	3 (100)	0 (-)	0 (-)	6 (43)	6 (43)	36 (80)	36 (78)
Whidbey	**10,925 (98)**	**10,634 (95)**	**3,005 (100)**	**2,997 (100)**	**64 (63)**	**52 (51)**	**858 (98)**	**734 (84)**	**14,852 (98)**	**14,417 (95)**
Skagit	4,206 (99)	4,148 (98)	1,678 (100)	1,674 (100)	45 (98)	43 (93)	310 (99)	262 (84)	6,239 (100)	6,127 (98)
Snohomish	904 (98)	771 (83)	390 (100)	386 (99)	8 (38)	0 (0)	448 (97)	378 (82)	1,750 (97)	1,535 (85)
Stillaguamish	2,661 (99)	2,660 (99)	823 (100)	822 (100)	10 (91)	10 (91)	84 (100)	84 (100)	3,578 (100)	3,576 (99)
Salish Sea	**38,003 (97)**	**37,319 (95)**	**6,639 (99)**	**6,582 (99)**	**165 (10)**	**135 (8)**	**1,209 (98)**	**1,007 (82)**	**46,016 (94)**	**45,043 (92)**

(c) 2075

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**3,198 (95)**	**3,140 (93)**	**1,098 (98)**	**1,025 (92)**	**28 (25)**	**27 (24)**	**103 (98)**	**95 (91)**	**4,427 (94)**	**4,287 (91)**
Dosewallips	138 (99)	138 (99)	47 (100)	47 (100)	3 (100)	2 (100)	4 (100)	4 (100)	192 (99)	191 (99)
Duckabush	117 (99)	117 (99)	31 (100)	31 (100)	1 (100)	1 (100)	7 (100)	7 (100)	156 (99)	156 (99)
Hamma Hamma	124 (98)	123 (98)	23 (100)	23 (100)	1 (100)	1 (100)	9 (100)	9 (100)	157 (99)	156 (98)
Quilcene	65 (98)	65 (98)	223 (98)	207 (91)	1 (50)	0 (0)	15 (94)	8 (47)	304 (98)	280 (90)
Skokomish	444 (97)	441 (96)	259 (97)	225 (84)	1 (1)	1 (100)	59 (100)	59 (100)	763 (97)	726 (93)
Juan de Fuca	**2,969 (94)**	**2,781 (89)**	**324 (100)**	**322 (99)**	**28 (3)**	**14 (1)**	**70 (100)**	**39 (56)**	**3,391 (74)**	**3,156 (68)**
Dungeness	575 (99)	543 (93)	74 (100)	74 (100)	0 (-)	0 (0)	11 (100)	4 (64)	660 (99)	624 (93)
Elwha	34 (94)	31 (86)	11 (36)	10 (100)	0 (-)	0 (-)	40 (100)	18 (46)	85 (98)	59 (69)
North Central	**1,843 (93)**	**1,677 (84)**	**455 (100)**	**455 (100)**	**7 (18)**	**5 (13)**	**17 (100)**	**16 (94)**	**2,322 (93)**	**2,153 (86)**
San Juan	**11,362 (98)**	**10,803 (93)**	**984 (100)**	**984 (100)**	**20 (12)**	**162 (93)**	**109 (100)**	**60 (55)**	**12,475 (97)**	**12,009 (93)**
Nooksack	1459 (100)	1,448 (99)	485 (100)	484 (100)	9 (100)	1 (11)	84 (100)	37 (44)	2,037 (100)	1,970 (96)
Samish	1,515 (99)	1,502 (98)	38 (100)	31 (79)	4 (100)	4 (100)	11 (100)	9 (82)	1,568 (99)	1,546 (98)
South	**5,378 (95)**	**5,350 (94)**	**744 (96)**	**734 (95)**	**9 (17)**	**9 (16)**	**51 (100)**	**51 (100)**	**6,182 (94)**	**6,144 (94)**
Deschutes	86 (99)	86 (99)	80 (75)	76 (70)	0 (0)	0 (0)	0 (-)	0 (-)	166 (85)	162 (82)
Nisqually	650 (99)	650 (99)	225 (100)	225 (100)	1 (100)	1 (100)	23 (100)	23 (100)	899 (99)	899 (99)
South Central	**3,502**	**3,267**	**254**	**248**	**6**	**6**	**7**	**7**	**3,769**	**3,528**

	(92)	**(86)**	**(99)**	**(97)**	**(6)**	**(6)**	**(32)**	**(32)**	**(90)**	**(84)**
Duwamish	13 (87)	13 (87)	2 (100)	2 (100)	1 (20)	1 (20)	0 (20)	1 (17)	16 (59)	16 (57)
Puyallup	27 (96)	26 (93)	3 (100)	3 (100)	0 (-)	0 (-)	6 (43)	6 (43)	36 (80)	35 (78)
Whidbey	**10,842 (97)**	**9,711 (87)**	**3,004 (100)**	**2,988 (99)**	**57 (56)**	**46 (46)**	**798 (91)**	**516 (53)**	**14,701 (97)**	**13,261 (87)**
Skagit	4,194 (99)	3,884 (92)	1,677 (100)	1,670 (99)	45 (98)	39 (87)	295 (94)	132 (42)	6,211 (99)	5,725 (91)
Snohomish	873 (94)	506 (55)	388 (99)	381 (98)	2 (10)	0 (0)	407 (88)	290 (63)	1,670 (93)	1,177 (66)
Stillaguamish	2,661 (99)	2,633 (98)	823 (100)	823 (100)	10 (91)	8 (73)	84 (100)	84 (100)	3,578 (100)	3,548 (99)
Salish Sea	**37,713 (96)**	**35,667 (91)**	**6,625 (99)**	**6,519 (98)**	**154 (9)**	**266 (16)**	**1,147 (93)**	**778 (63)**	**45,639 (93)**	**43,230 (88)**

(d) 2100

	Tidal flat		**Regularly flooded emergent**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**3,116 (93)**	**3,023 (90)**	**1,088 (98)**	**973 (87)**	**28 (25)**	**26 (23)**	**102 (97)**	**86 (82)**	**4,334 (92)**	**4,108 (88)**
Dosewallips	136 (97)	136 (97)	47 (100)	47 (100)	3 (100)	2 (100)	4 (100)	3 (75)	190 (98)	188 (97)
Duckabush	116 (98)	116 (98)	30 (97)	30 (100)	1 (100)	1 (100)	7 (100)	7 (100)	154 (98)	154 (99)
Hamma Hamma	122 (97)	121 (96)	23 (100)	23 (100)	1 (100)	1 (100)	9 (100)	9 (100)	155 (97)	154 (97)
Quilcene	65 (98)	65 (98)	222 (98)	194 (85)	0 (0)	0 (0)	14 (82)	5 (31)	301 (96)	264 (85)
Skokomish	442 (97)	436 (95)	225 (95)	205 (76)	1 (100)	1 (100)	59 (100)	59 (100)	757 (96)	695 (89)
Juan de Fuca	**2,920 (93)**	**2,458 (78)**	**323 (100)**	**321 (99)**	**28 (3)**	**14 (1)**	**60 (86)**	**35 (50)**	**3,331 (72)**	**2,828 (61)**
Dungeness	573 (98)	422 (72)	74 (100)	73 (100)	0 (-)	0 (-)	11 (100)	4 (33)	658 (99)	499 (75)
Elwha	34	29	11	11	0	0	31	17	76	57

	(36)	(81)	(100)	(100)	(-)	(-0)	(78)	(44)	(87)	(66)
North Central	**1,773 (89)**	**1,421 (71)**	**455 (100)**	**455 (100)**	**5 (13)**	**4 (10)**	**17 (100)**	**15 (94)**	**2,250 (90)**	**1,895 (76)**
San Juan	**11,254 (97)**	**9,685 (83)**	**984 (100)**	**983 (100)**	**20 (12)**	**10 (6)**	**109 (100)**	**26 (24)**	**12,367 (96)**	**10,704 (83)**
Nooksack	1,453 (99)	1,346 (92)	485 (100)	485 (100)	9 (100)	0 (0)	54 (64)	7 (8)	2,001 (98)	1,838 (90)
Samish	1,513 (99)	1,446 (95)	38 (100)	38 (100)	4 (100)	4 (100)	11 (100)	6 (55)	1,566 (99)	1,494 (95)
South	**5,233 (92)**	**5,176 (91)**	**743 (96)**	**729 (94)**	**9 (16)**	**8 (15)**	**51 (100)**	**51 (100)**	**6,036 (92)**	**5,964 (91)**
Deschutes	86 (99)	85 (98)	80 (74)	72 (67)	0 (0)	0 (0)	0 (-)	0 (-)	166 (84)	157 (81)
Nisqually	649 (99)	649 (99)	224 (100)	224 (100)	1 (100)	1 (100)	23 (100)	23 (100)	897 (99)	897 (99)
South Central	**3,377 (89)**	**2,983 (78)**	**252 (99)**	**244 (95)**	**6 (6)**	**100 (98)**	**7 (30)**	**21 (91)**	**3,642 (87)**	**3,348 (80)**
Duwamish	13 (87)	12 (86)	2 (100)	2 (100)	0 (0)	5 (5)	1 (17)	5 (5)	16 (55)	24 (92)
Puyallup	27 (93)	25 (89)	3 (100)	3 (100)	0 (-)	0 (-)	6 (46)	13 (14)	36 (80)	41 (91)
Whidbey	**10,646 (95)**	**7,616 (68)**	**3,003 (100)**	**2,972 (99)**	**54 (54)**	**35 (35)**	**777 (89)**	**409 (47)**	**14,480 (96)**	**11,032 (73)**
Skagit	4,163 (98)	2,798 (66)	1,675 (100)	1,661 (99)	45 (98)	31 (67)	287 (92)	101 (32)	6,170 (98)	4,591 (73)
Snohomish	825 (89)	181 (20)	389 (99)	374 (96)	0 (0)	0 (0)	394 (86)	216 (47)	1,608 (89)	771 (43)
Stillaguamish	2,645 (99)	2,422 (90)	823 (100)	822 (100)	10 (91)	6 (55)	84 (100)	83 (99)	3,562 (99)	3,333 (93)
Salish Sea	**37,001 (94)**	**31,534 (80)**	**6,612 (99)**	**6,437 (96)**	**148 (9)**	**194 (12)**	**1,115 (90)**	**636 (51)**	**44,876 (92)**	**38,801 (79)**

Table 12: Projected amount of transgressive migration (hectares) into undeveloped dry land between initial conditions and (a) 2025, (b) 2050, (c) 2075, and (d) 2100 under the low and high SLR scenarios for each sub-basin, large river delta, and the Salish Sea study area.

(a) 2025

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**0**	**0**	**1**	**3**	**1**	**5**	**0**	**0**	**2**	**8**
Dosewallips	0	0	0	0	0	0	0	0	0	0
Duckabush	0	0	0	0	0	0	0	0	0	0
Hamma Hamma	0	0	0	0	0	0	0	0	0	0
Quilcene	0	0	0	0	0	0	0	0	0	0
Skokomish	0	0	0	0	0	0	0	0	0	0
Juan de Fuca	**0**	**0**	**0**	**0**	**0**	**37**	**0**	**0**	**0**	**37**
Dungeness	0	0	0	0	0	1	0	0	0	1
Elwha	0	0	0	0	0	4	0	0	0	4
North Central	**0**	**0**	**0**	**18**	**4**	**0**	**0**	**0**	**4**	**18**
San Juan	**0**	**0**	**0**	**2**	**0**	**2**	**0**	**0**	**0**	**4**
Nooksack	0	0	0	0	0	0	0	0	0	0
Samish	0	0	0	0	0	0	0	0	0	0
South	**0**	**0**	**1**	**0**	**0**	**7**	**0**	**0**	**1**	**7**
Deschutes	0	0	0	0	0	1	0	0	0	1
Nisqually	0	0	0	0	0	0	0	0	0	0
South Central	**0**	**0**	**0**	**4**	**3**	**10**	**0**	**1**	**3**	**15**
Duwamish	0	0	0	0	1	2	0	1	1	3
Puyallup	0	0	0	0	0	0	0	0	0	0
Whidbey	**0**	**0**	**0**	**0**	**5**	**66**	**0**	**0**	**5**	**66**
Skagit	0	0	0	0	0	4	0	0	0	4
Snohomish	0	0	0	0	3	55	0	0	3	55
Stillaguamish	0	0	0	0	0	1	0	0	0	1
Salish Sea	**0**	**1**	**2**	**9**	**13**	**141**	**0**	**1**	**15**	**152**

(b) 2050

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	High	Low	High	Low	High	Low	High	Low	High
Hood Canal	**0**	**0**	**6**	**17**	**3**	**21**	**0**	**0**	**9**	**38**
Dosewallips	0	0	0	0	0	0	0	0	0	0
Duckabush	0	0	0	0	0	0	0	0	0	0
Hamma Hamma	0	0	0	0	0	0	0	0	0	0
Quilcene	0	0	0	0	0	0	0	0	0	0
Skokomish	0	0	0	0	0	0	0	0	0	0
Juan de Fuca	**0**	**0**	**0**	**0**	**6**	**87**	**0**	**0**	**6**	**87**
Dungeness	0	0	0	0	0	19	0	0	0	19
Elwha	0	0	0	0	3	14	0	0	3	14
North Central	**0**	**1**	**0**	**23**	**18**	**57**	**0**	**0**	**18**	**81**
San Juan	**0**	**1**	**0**	**7**	**2**	**61**	**0**	**2**	**2**	**71**
Nooksack	0	0	0	0	0	13	0	2	0	15
Samish	0	0	0	0	0	0	0	0	0	0
South	**0**	**0**	**4**	**11**	**1**	**4**	**0**	**0**	**5**	**15**
Deschutes	0	0	0	1	1	0	0	0	1	1
Nisqually	0	0	0	0	0	0	0	0	0	0
South Central	**0**	**0**	**4**	**23**	**12**	**74**	**1**	**4**	**17**	**101**
Duwamish	0	0	1	3	2	14	1	3	4	20
Puyallup	0	0	0	0	0	0	0	1	0	1
Whidbey	**0**	**0**	**0**	**70**	**66**	**98**	**0**	**4**	**66**	**172**
Skagit	0	0	0	5	5	17	0	0	5	22
Snohomish	0	0	0	55	53	46	0	3	53	104
Stillaguamish	0	0	0	1	1	1	0	0	1	2
Salish Sea	**0**	**2**	**15**	**148**	**106**	**382**	**1**	**7**	**122**	**539**

(c) 2075

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Low	High	Low	High	Low	High	Low	High	Low	High
Hood Canal	**0**	**0**	**17**	**51**	**6**	**30**	**0**	**0**	**23**	**81**
Dosewallips	0	0	0	0	0	0	0	0	0	0

Duckabush	0	0	0	0	0	0	0	0	0	0
Hamma Hamma	0	0	0	0	0	0	0	0	0	0
Quilcene	0	0	0	1	0	3	0	0	0	4
Skokomish	0	0	0	0	0	0	0	0	0	0
Juan de Fuca	**0**	**0**	**0**	**87**	**40**	**55**	**0**	**0**	**40**	**142**
Dungeness	0	0	0	18	1	23	0	0	1	41
Elwha	0	0	0	14	5	7	0	0	5	24
North Central	**0**	**1**	**1**	**85**	**41**	**104**	**0**	**0**	**42**	**190**
San Juan	**0**	**3**	**3**	**0**	**5**	**342**	**0**	**8**	**8**	**353**
Nooksack	0	0	0	0	1	29	0	2	1	31
Samish	0	0	0	0	0	57	0	6	0	63
South	**0**	**0**	**10**	**11**	**0**	**31**	**0**	**0**	**10**	**32**
Deschutes	0	0	1	1	0	1	0	0	1	2
Nisqually	0	0	0	0	0	0	0	0	0	0
South Central	**0**	**1**	**18**	**108**	**20**	**69**	**0**	**7**	**38**	**185**
Duwamish	0	0	2	17	4	19	0	4	6	40
Puyallup	0	0	0	1	0	1	0	3	0	5
Whidbey	**0**	**1**	**4**	**176**	**95**	**301**	**1**	**29**	**100**	**507**
Skagit	0	0	0	22	13	12	0	0	13	24
Snohomish	0	0	3	105	65	215	0	27	68	347
Stillaguamish	0	0	0	2	1	7	0	1	1	10
Salish Sea	**1**	**6**	**52**	**504**	**203**	**877**	**1**	**17**	**257**	**1,404**

(d) 2100

	Tidal flat		**Emergent marsh**		**Transitional scrub-shrub**		**Tidal swamp**		**Total**	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Hood Canal	**0**	**0**	**31**	**98**	**8**	**44**	**0**	**29**	**39**	**171**
Dosewallips	0	0	0	0	0	1	0	0	0	1
Duckabush	0	0	0	0	0	0	0	0	0	0
Hamma Hamma	0	0	0	0	0	0	0	0	0	0
Quilcene	0	0	0	4	0	2	0	0	0	6
Skokomish	0	0	0	0	0	14	0	29	0	43
Juan de Fuca	**0**	**1**	**0**	**144**	**50**	**38**	**0**	**0**	**50**	**183**
Dungeness	0	0	0	40	3	13	0	0	3	53

Elwha	0	0	0	22	6	6	0	0	6	28
North Central	**1**	**1**	**18**	**196**	**57**	**59**	**0**		**76**	**256**
San Juan	**0**	**6**	**8**	**344**	**39**	**258**	**0**	**10**	**47**	**618**
Nooksack	0	0	0	31	10	33	0	3	10	67
Samish	0	0	0	57	0	34	0	7	0	98
South	**0**	**0**	**16**	**56**	**1**	**22**	**0**	**0**	**17**	**78**
Deschutes	0	0	1	2	0	1	0	0	1	3
Nisqually	0	0	0	0	0	0	0	0	0	0
South Central	**1**	**1**	**47**	**0**	**50**	**252**	**3**	**17**	**101**	**270**
Duwamish	0	0	7	0	10	40	3	8	20	48
Puyallup	0	0	1	0	0	1	0	8	1	9
Whidbey	**0**	**1**	**77**	**491**	**67**	**269**	**1**	**3**	**145**	**764**
Skagit	0	0	8	35	14	36	0	1	22	72
Snohomish	0	0	62	327	20	151	1	1	83	479
Stillaguamish	0	0	1	9	1	5	0	1	2	15
Salish Sea	**2**	**9**	**193**	**1,257**	**259**	**908**	**4**	**60**	**458**	**2,234**

Table 13: Transition matrices for the Salish Sea study area under the low (a-d) and high (e-h) scenarios comparing initial conditions (rows) to 2100 conditions (columns). The diagonal from the top-left to the bottom-right (highlighted in gray) represents areas that are the same in 2004 and each time-step. Green boxes with a plus sign (+) underneath represent wetland or land classes that are projected to increase between initial conditions and each time-step. Red boxes with a negative sign (-) underneath represent land or wetland classes that are projected to decline between initial conditions and each time-step. Differences in initial and total values are due to rounding.

(a) 2025 low

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	196	39,103						39,299
Emergent marsh		4	6,678					6,682
Transitional scrub-shrub		14	1,446	172		4		1,636
Tidal swamp			1		1,216		17	1,234
Undeveloped dry land			2	13		1,204,821	361	1,205,197
Other	1,542	1	3			2	82,114	83,662
Total	664,122	39,122	8,130	185	1,216	1,204,827	82,492	2,000,094
	+	-	+	-	-	-	-	

(b) 2050 low

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	1,296	38,003						39,299
Emergent marsh		42	6,639					6,681
Transitional scrub-shrub	9	1,258	201	165		2		1,635
Tidal swamp		13	11		1,209		1	1,234
Undeveloped dry land	1		15	106	1	1,204,619	454	1,205,196
Other	1,579	1	3	2			82,075	83,660
Total	665,269	39,317	6,869	273	1,210	1,204,621	82,530	2,000,089
	+	+	+	-	-	-	-	

(c) 2075 low

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	1,585	37,713						39,298
Emergent marsh		56	6,625					6,681
Transitional scrub-shrub	1,209	66	206	154		1		1,636
Tidal swamp	10	4	59		1,147		14	1,234
Undeveloped dry land	5	1	52	203	1	1,204,346	590	1,205,198
Other	1,641	1	4	3			82,014	83,663
Total	666,834	37,841	6,946	360	1,148	1,204,347	82,618	2,000,094
	+	-	+	-	-	-	-	

(d) 2100 low

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	2,298	37,001						39,299
Emergent marsh		69	6,612					6,681
Transitional scrub-shrub	1,217	66	204	148		1		1,636
Tidal swamp	10	3	92		1,115		13	1,233
Undeveloped dry land	11	2	193	259	4	1,204,011	717	1,205,197
Other	1,691		6	2			81,963	83,662
Total	667,611	37,141	7,107	409	1,119	1,204,012	82,693	2,000,092
	+	-	+	-	-	-	-	

(e) 2025 high

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	351	38,948						39,299
Emergent marsh		49	6,634					6,683
Transitional scrub-shrub		14	375	1,247				1,636
Tidal swamp			52		1,148		34	1,234
Undeveloped dry land		1	9	141	1	1,204,610	434	1,205,196
Other	128	1	4	11		1	83,515	83,660
Total	662,863	39,013	7,074	1,399	1,149	1,204,611	83,983	2,000,091
	+	-	+	-	-	-	+	

(f) 2050 high

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	1,980	37,319						39,299
Emergent marsh		100	6,582					6,682
Transitional scrub-shrub	9	1,281	209	135		1		1,635
Tidal swamp		14	136		1,007		77	1,234
Undeveloped dry land	8	2	148	382	7	1,203,996	652	1,205,195
Other	1,671	1	10	51	10		81,919	83,662
Total	666,052	38,717	7,085	568	1,024	1,203,997	82,648	2,000,091
	+	-	+	-	-	-	-	

(g) 2075 high

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	3,632	35,667						39,299
Emergent marsh		161	6,519					6,680
Transitional scrub-shrub	1,090	77	203	266				1,636
Tidal swamp	10	4	358		778		85	1,235
Undeveloped dry land	22	6	504	877	17	1,202,895	876	1,205,197
Other	1,783	1	55	656	14		81,154	83,663
Total	668,921	35,916	7,639	1,799	809	1,202,895	82,115	2,000,094
	+	-	+	+	-	-	-	

(h) 2100 high

Hectares	Open water	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Undeveloped dry land	Other	Total
Open water	662,384							662,384
Tidal flat	7,765	31,534						39,299
Emergent marsh	1	243	6,437					6,681
Transitional scrub-shrub	1,211	96	135	194				1,636
Tidal swamp		3	573		636		23	1,235
Undeveloped dry land	38	9	1,257	908	60	1,201,900	1,026	1,205,198
Other	1,967	1	720	276	10		80,686	83,660
Total	673,366	31,886	9,122	1,378	706	1,201,900	81,735	2,000,093
	+	-	+	-	-	-	-	

Table 14: Sensitivity analysis for the Hood Canal sub-basin in 2100 under the high SLR scenario.

	Tidal flat	Emergent marsh	Transitional scrub-shrub	Tidal swamp	Total
Historical SL trend +	0	0	3	0	0
Historical SL trend -	0	0	-3	0	0
Great Diurnal Tide Range +	2	0	-1	0	1
Great Diurnal Tide Range -	-2	0	9	0	-1
Salt Elev. +	0	1	18	-2	1
Salt Elev. -	0	-2	-11	2	-1
Marsh Erosion +	0	0	0	0	0
Marsh Erosion -	0	0	0	0	0
T.Flat Erosion +	-1	0	0	0	0
T.Flat Erosion -	1	0	0	0	0
Irreg. Flood Marsh Accr +	0	0	0	0	0
Irreg. Flood Marsh Accr -	0	0	0	0	0
Tidal Swamp Accr +	0	0	0	0	0
Tidal Swamp Accr -	0	0	0	0	0
Reg Flood Max. Accr. +	0	0	0	0	0
Reg Flood Max. Accr. -	0	0	0	0	0
Reg Flood Min. Accr. +	0	0	0	0	0
Reg Flood Min. Accr. -	0	0	0	0	0
Reg Flood Elev a coeff. +	0	0	0	0	0
Reg Flood Elev a coeff. -	0	1	0	0	0
Reg Flood Elev b coeff. +	0	1	0	0	0
Reg Flood Elev b coeff. -	0	0	0	0	0
Beach Sed. Rate +	0	0	0	0	0
Beach Sed. Rate -	0	0	0	0	0

Figures

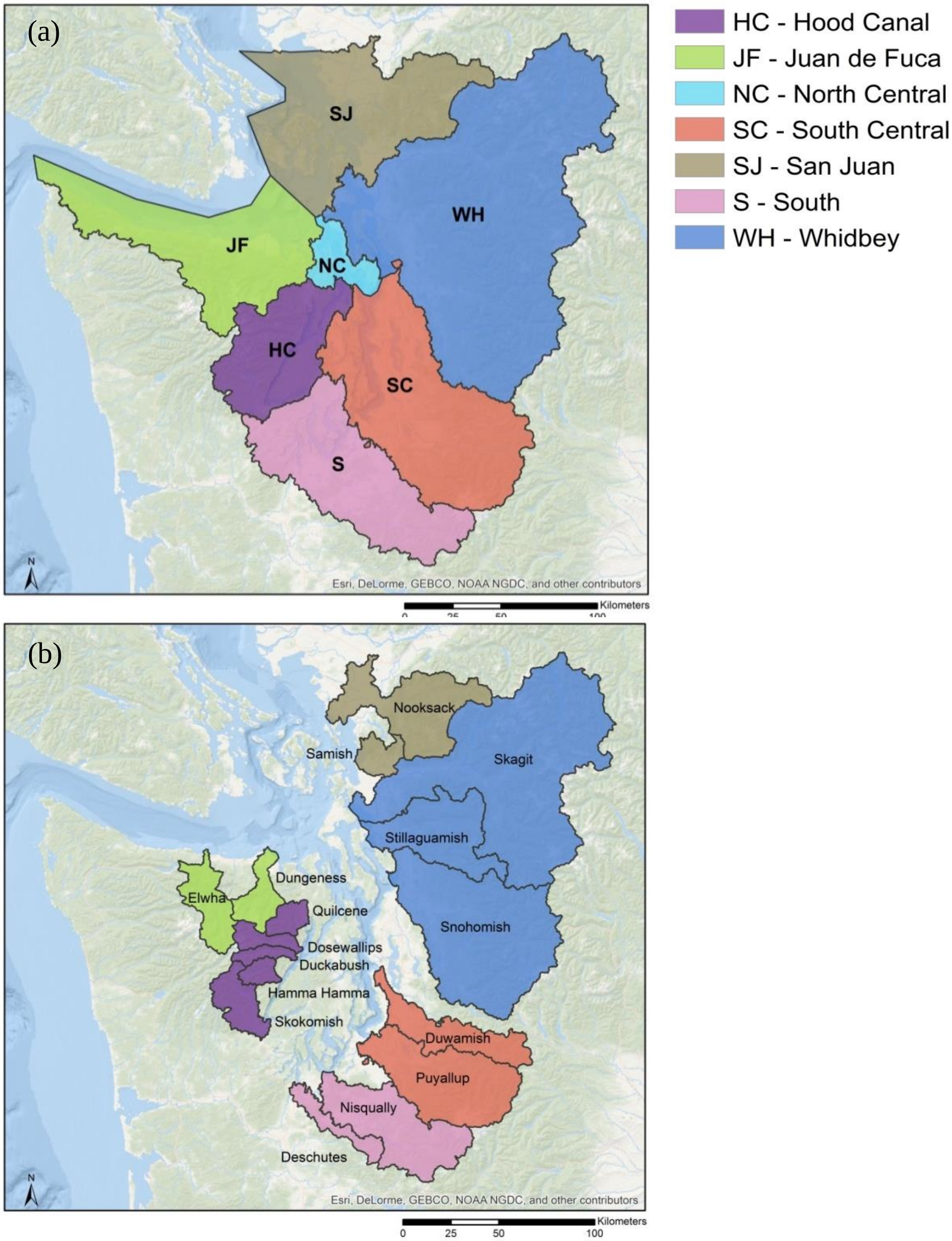


Figure 1: (a) Study area encompassing the U.S. portion of the Salish Sea, divided into 7 sub-basins: Hood Canal, San Juan Islands – Georgia Strait, Strait of Juan de Fuca, North Central Puget Sound, South Puget Sound, South Central Puget Sound, and Whidbey. (b) The 16 largest river deltas in the U.S. portion of the Salish Sea color coded to each sub-basin.

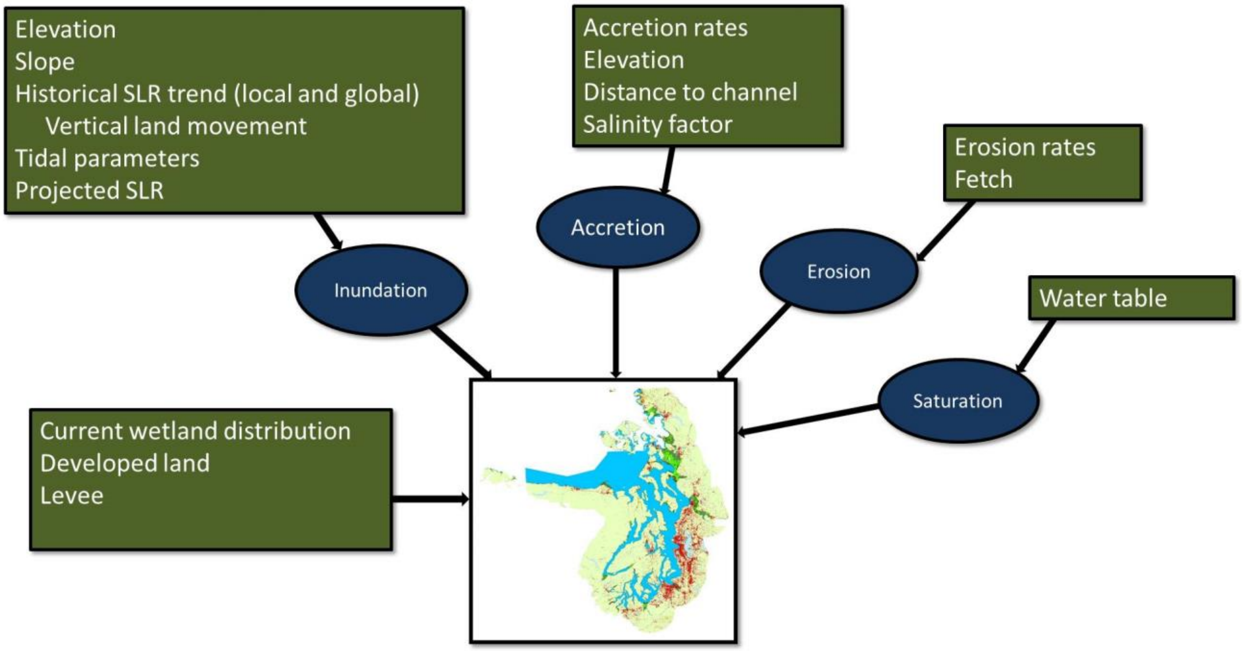


Figure 2: Schematic of baseline model inputs and parameter inputs for each process for the Sea Level Affecting Marshes Model (SLAMM).

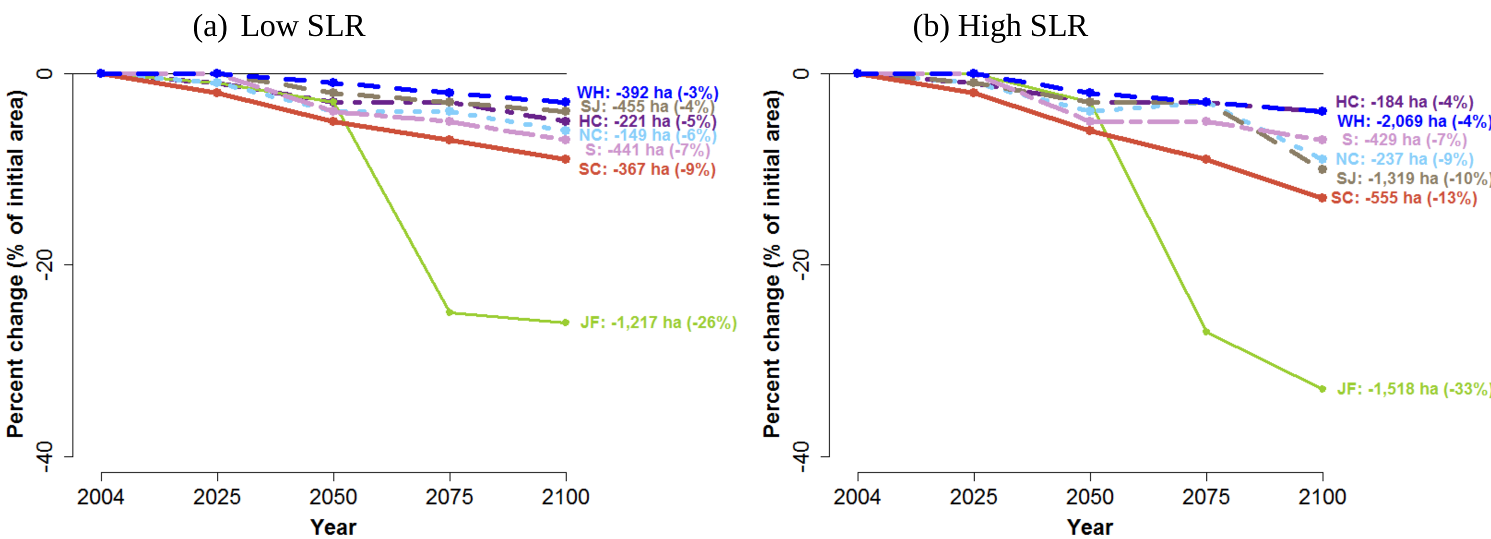
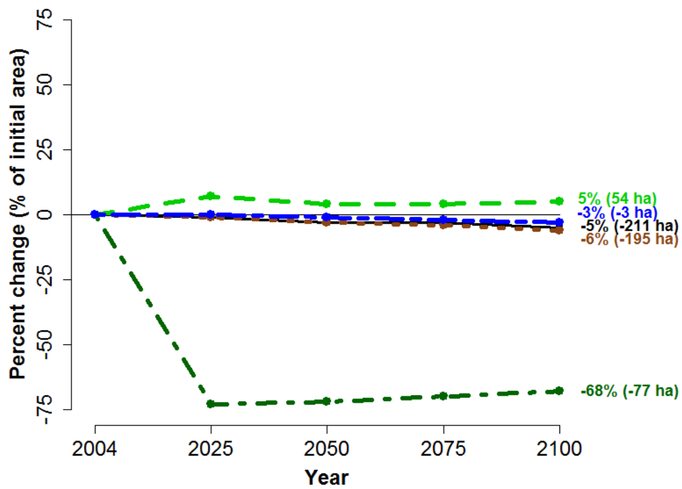
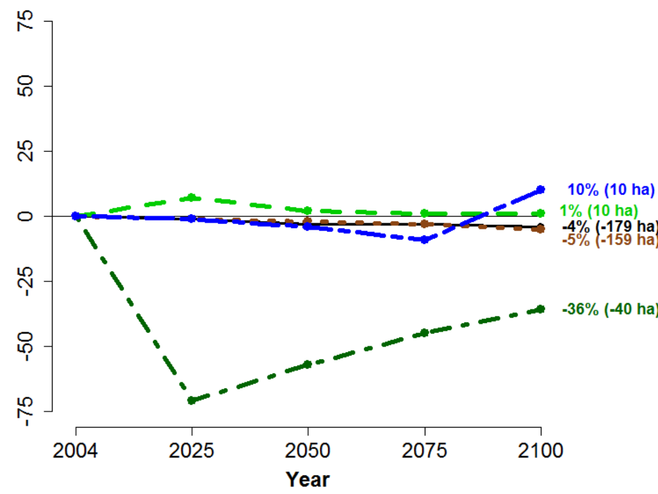


Figure 3: Projected percent change of total wetland change projected for each sub-basin under the (a) low and (b) high SLR scenarios. The projected absolute change in wetland area between initial conditions and 2100 is indicated to the right of each line with the percent change in parentheses.

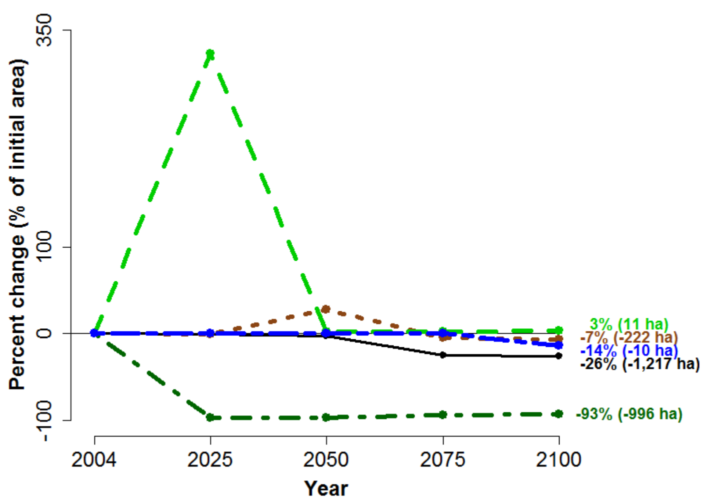
HC low



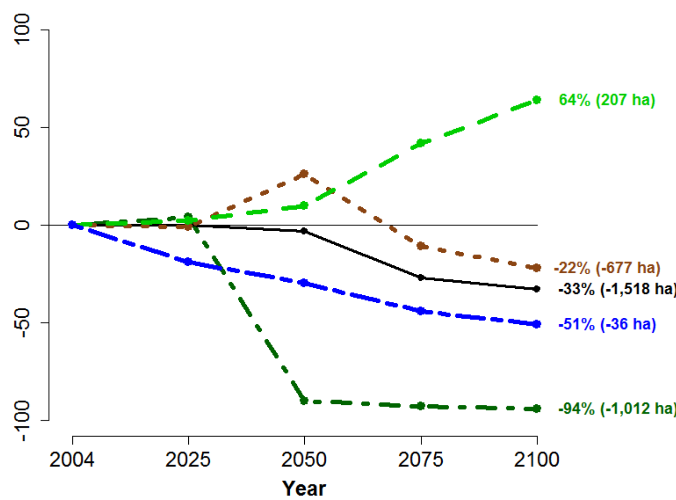
HC high



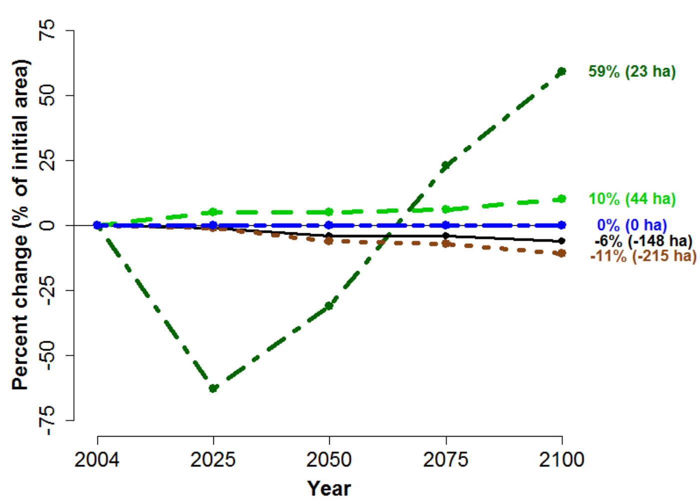
JF low



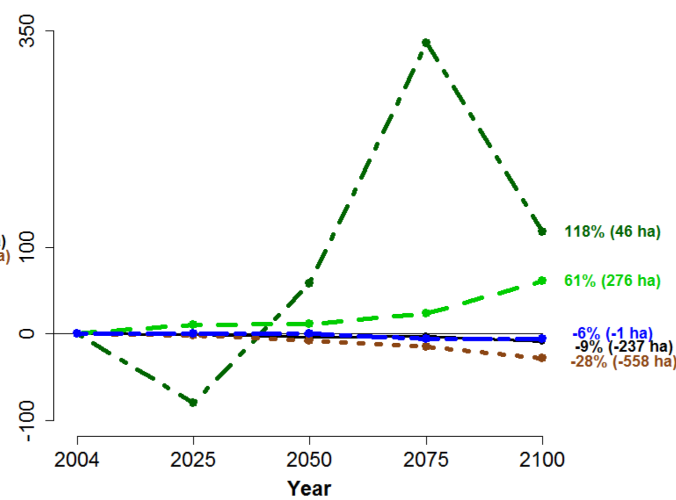
JF low

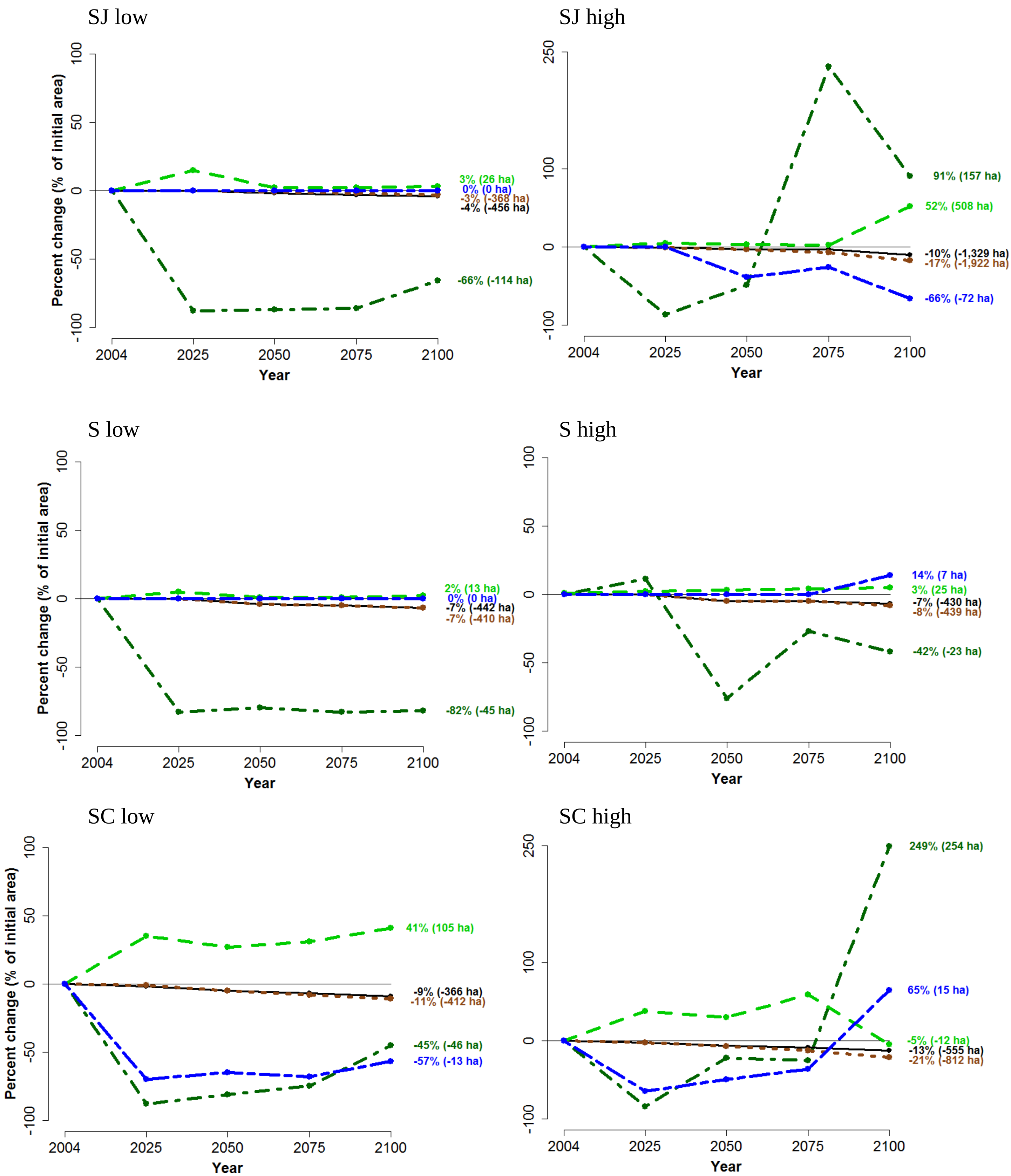


NC low



NC high




SJ low
Percent change (% of initial area)
Year
3% (26 ha)
0% (0 ha)
-3% (-368 ha)
-4% (-456 ha)
-66% (-114 ha)
SJ high
Year
91% (157 ha)
52% (508 ha)
-10% (-1,329 ha)
-17% (-1,922 ha)
-66% (-72 ha)
S low
Percent change (% of initial area)
Year
2% (13 ha)
0% (0 ha)
-7% (-442 ha)
-7% (-410 ha)
-82% (-45 ha)
S high
Year
14% (7 ha)
3% (25 ha)
-7% (-430 ha)
-8% (-439 ha)
-42% (-23 ha)
SC low
Percent change (% of initial area)
Year
41% (105 ha)
-9% (-366 ha)
-11% (-412 ha)
-45% (-46 ha)
-57% (-13 ha)
SC high
Year
249% (254 ha)
65% (15 ha)
-5% (-12 ha)
-13% (-555 ha)
-21% (-812 ha)

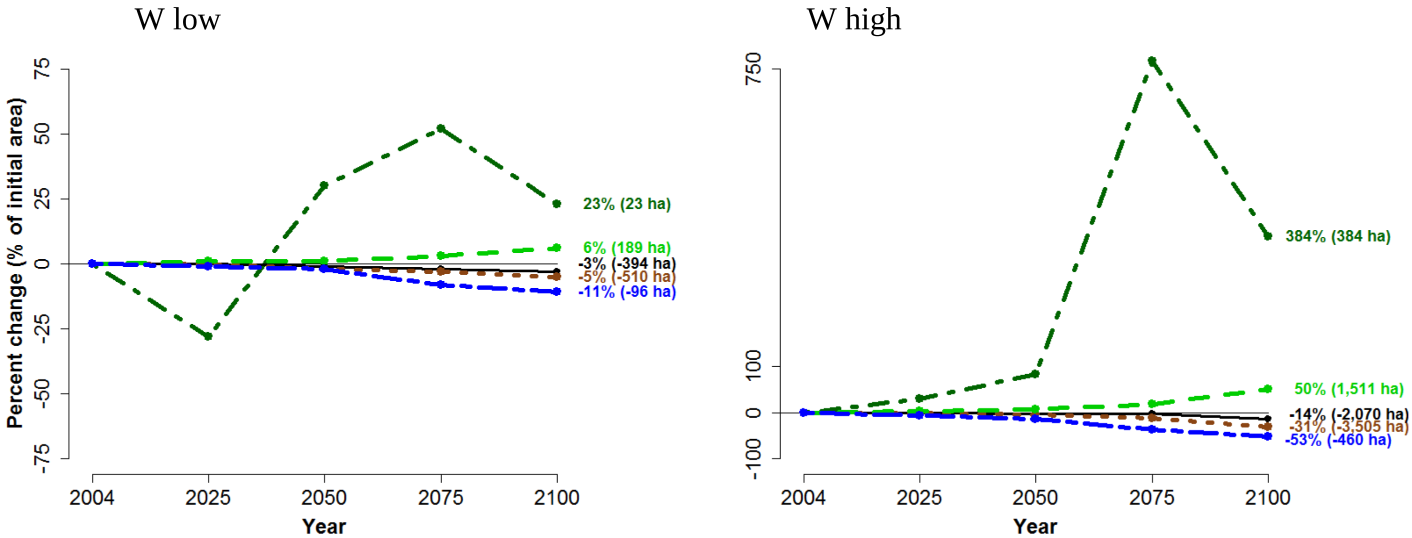


Figure 4: Percent change in wetland area as a percent of initial area for tidal flat (short-dash brown), emergent marsh (dashed light green), transitional scrub-shrub (dot-dash dark green), tidal swamp (long-short dash blue), and total (solid black) in each of the sub-basins under the low and high SLR scenarios. Percent change at 2100 is displayed to the right of each line with the absolute change in hectares in parentheses.

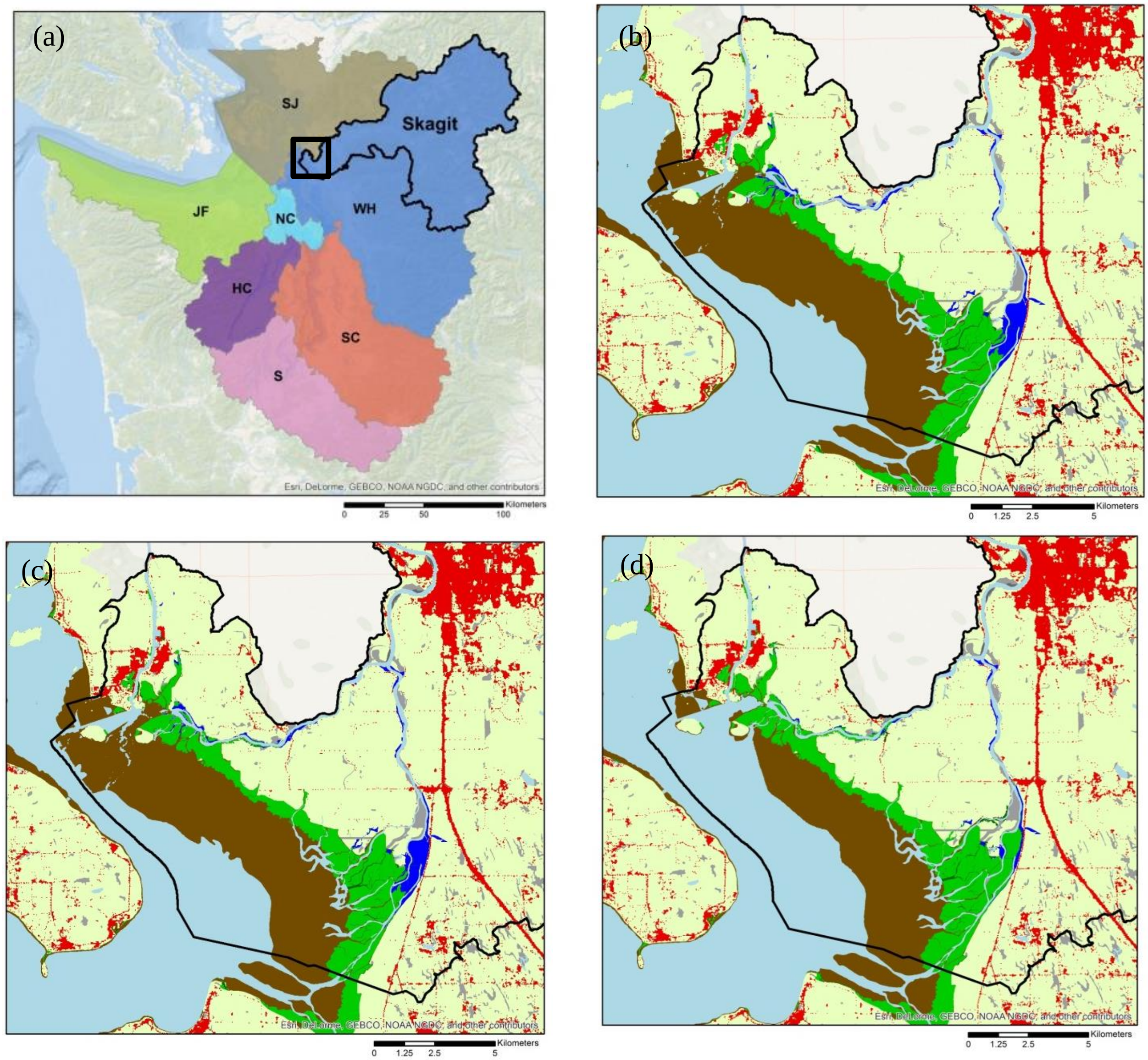


Figure 5: (a) The Skagit River watershed is outlined in black in the Whidbey sub-basin. The Skagit River delta is outlined in the black box. (b) The initial wetland area as modeled by SLAMM for the Skagit River delta. (c) Projected wetland extent in 2100 under the low SLR scenario. (d) Projected wetland extent in 2100 under the high SLR scenario. In b-d, red is developed land, cream is undeveloped dry land, dark blue is tidal swamp, dark green is transitional scrub-shrub, light green is emergent marsh, brown is tidal flat, grey is other wetland and land cover type, and light blue is open water.

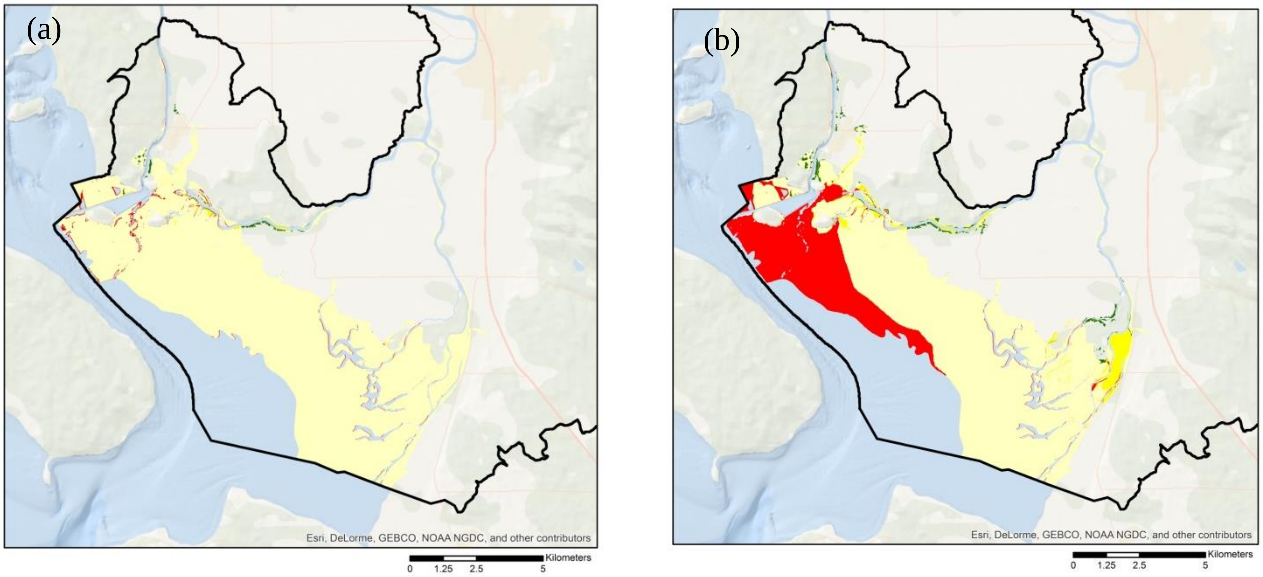


Figure 6: Projected wetland changes for 2100 under the (a) low and (b) high SLR scenarios. Red represents wetland loss, green represents wetland gain from undeveloped dry land or non-tidal wetland and land cover types, yellow represents transitions from one tidal wetland class to another, and cream represents local persistence of tidal wetlands.

Chapter 3: Incorporating climate change into strategic conservation, restoration, and management of tidal wetlands in the U.S. portion of the Salish Sea

Abstract

Strategic conservation and restoration of tidal wetlands under a climate change framework is important for the allocation of resources for long-term benefits. The Sea Level Affecting Marshes Model was utilized to simulate tidal wetland conversion in the U.S. portion of the Salish Sea under a low and high sea level rise scenario. The projected change in total wetland area between initial conditions and 2100 switched from a decline with levee protection to an expansion without levee protection in the San Juan and Whidbey sub-basins and the Skagit and Stillaguamish River deltas under both SLR scenarios. A cluster analysis was then conducted to identify priority river deltas for conservation and restoration based on historical potential and degradation level under a climate change framework. The Skagit, Stillaguamish, and Snohomish river deltas were identified as high priority for conservation and restoration, followed by the Nooksack and Samish. Gradients of conservation and restoration priorities identified in this study can also be used to select sites based on additional criteria, such as size, location preferences, land ownership, and political and economic feasibility.

Keywords tidal wetlands, sea level rise, conservation, restoration

Introduction

The primary goals of coastal and estuarine conservation and restoration projects are often to preserve existing ecosystems and revive lost and degraded structure and function (NRC 1992; Bernhardt et al. 2005). Many of these restoration efforts often fail to consider the projected impacts of future climate change. However, coastal ecosystems, such as tidal wetlands, are at risk of future climate change impacts, such as hydrologic alterations and submergence due to accelerated sea level rise (Desantis et al. 2007; Swanson et al. 2014). Climate change should be incorporated into conservation and restoration projects so that efforts can be successful and persist into the future (Callaway et al. 2007; Pressey et al. 2007; Lawler 2009).

Tidal wetlands have historically been drained and converted into dry land (Dahl 1990) for agriculture (Bortleson et al. 1980), industry (Boule et al. 1983), and housing and have been extensively altered with levees for protection against coastal threats. During the last ~150 years, 90% of tidal swamps, 98.5% of transitional scrub-shrub, 46% of emergent marsh, and 24% of tidal flats have been lost in the 16 largest river deltas throughout the U.S. portion of the Salish Sea, Washington (Simenstad et al. 2011). With this degradation, the ecosystem services that tidal wetlands provide are lost or greatly reduced, such as coastal protection from sea level rise and storm surges; water quality maintenance; carbon sequestration; and habitat provision for economically important bivalves, crustaceans, and fish (Costanza et al. 1997; Martínez et al. 2007).

Recently, there have been many tidal wetland restoration projects completed around the Salish Sea and more in the planning stages (WARCO 2010). These projects have been largely motivated by the goal of restoring habitat for threatened and endangered salmon species, such as the endangered Chinook salmon (USFWS 2015). Tidal wetlands have been identified as important ecosystems for promoting the rearing and growth of juvenile Pacific salmon, particularly Chinook and chum (Levy and Northcote 1982; Simenstad et al. 1982).

In order to promote the use of strategic management in the U.S. portion of the Salish Sea, the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) developed a strategic framework for nearshore conservation and restoration (Cereghino et al. 2012). The framework was designed to determine where conservation, restoration, or enhancement of nearshore ecosystems would meet local and regional recovery goals of river deltas, beaches, barrier embayments, and coastal inlets. Three sets of assessment metrics were developed to determine the (1) historical extent and complexity of a site, (2) level of degradation, and (3) risk of uniquely challenging sources of degradation (Cereghino et al. 2012).

Based on the level of degradation, three management approaches were identified: (1) protection, (2) restoration, and (3) enhancement. Protection was recommended for sites with relatively low degradation with the management goal of preventing loss of ecosystem processes and functions. Restoration was recommended for sites with moderate degradation and opportunity to improve ecosystem functioning and increase ecosystem services. Enhancement was recommended for sites with high levels of intense degradation in which restoring ecosystem services would be prohibitively challenging (Cereghino et al. 2012). An example of an enhancement action is improving the water quality of runoff into rivers and deltas.

Physical or societal system-scale constraints may prevent restoration in coastal systems that are highly altered and degraded (Simenstad et al. 2006). Highly urbanized and industrialized estuaries are among the most constrained systems. In these systems, restoration may not be feasible, but rehabilitation and enhancement efforts may be appropriate (Simenstad et al. 2006).

The Duwamish River entering into the Port of Seattle is an example of an industrially constrained river (Simenstad et al. 2005). Less than 3% of historical tidal wetlands remain in the Duwamish River, and the system has been heavily polluted by toxic contaminants.

Passive restoration, such as levee removal or breaching, is a common restoration practice to reintroduce tidal inundation to historical wetland areas (Cornu and Sadro 2002; Simenstad et al. 2006). There should be an explicit consideration of the impacts of accelerated sea level rise and other climate change drivers in strategic planning of restoration and conservation (Callaway et al. 2007) of tidal wetlands in the Salish Sea, particularly in the content of local and regional variability among sub-basins and deltas. Modeling wetland change, local persistence, and transgressive migration under the influence of future climate change and accelerated sea level rise can help identify priority areas for restoration and levee removal.

The first objective of this study was to conduct a spatial analysis of potential responses of tidal wetlands to future climate change without levee protection in the U.S. portion of the Salish Sea by addressing the following question:

(1) What is the difference in projected change in wetland area and amount of transgressive migration with and without levee protection?

This analysis is similar to the analysis conducted in Chapter 2 but with the removal of levee protection. By addressing this question, areas for restoration under a climate change context can be identified and prioritized.

The second objective was to add climate change metrics to the PSNERP strategic conservation and restoration framework. In this way, the PSNERP framework was used as a baseline of constraints to which to add climate change metrics that could support or alter the PSNERP strategic priorities. The following questions were addressed:

(2) Which river deltas are identified as priority for conservation and restoration based on historical potential, degradation level, and wetland responses to climate change?

(3) Do these priorities differ from priorities identified without climate change metrics?

By addressing these questions, planners can strategically prioritize areas for conservation and restoration that have high potential to revive lost ecosystem services which will also persist under future climate change and accelerated sea level rise.

Methods

Study site

The study was conducted over the U.S. portion of the Salish Sea, Washington. Since over 90% of historical wetlands were located in river deltas, the cluster analysis was only conducted for the 16 largest river deltas (Figure 1). Potential changes to tidal wetland distribution and area in the U.S. portion of the Salish Sea were simulated using SLAMM under the NRC 0.5 m and the NRC 1.4 m climate change scenario (NRC 2012) (see Chapter 2). The PSNERP spatially explicit geodatabase was utilized as the initial tidal wetland conditions (Simenstad et al. 2011).

Modeling wetland responses to climate change with no levee protection

The SLAMM analyses described in Chapter 2 was repeated without levee protection. The levee layer was a combination of the PSNERP tidal barrier locations and the protection of all agricultural land (i.e., NLCD land cover classified as Pasture/Hay or Cultivated Crops). Removal of this levee layer allows agriculture land to be inundated but does not necessarily represent complete levee removal. In some instances, current levees are detected in the elevation layer. These high elevation areas remain through the analysis.

Climate change metrics for cluster analysis

The results from Chapter 2 were used to create conservation potential, restoration potential, and degradation level metrics for each of the 16 largest river deltas in the Salish Sea. The conservation potential metrics were intended to identify areas with high potential for conservation strategies under a climate change context. Two sets of conservation potential metrics were used: one with absolute values and one with relative values. The conservation potential metrics with absolute values included the projected total wetland area and total area of each wetland type in 2100, projected amount of local persistence of each wetland type between initial conditions and 2100, and projected amount of natural transgressive migration between initial conditions and 2100 under both SLR scenarios with levee protection. The conservation potential metrics with relative values included the percent of initial wetland area that was projected to locally persist between initial conditions and 2100 for each wetland type and total wetland area, percent change of each wetland type and total wetland area projected between initial conditions and 2100, and the absolute amount of projected transgressive migration between initial conditions and 2100 under both SLR scenarios with levee protection.

The restoration potential metrics included the difference in projected wetland area between simulations with and without levee protection for 2100 under both SLR scenarios; total change in wetland area under the no levee protection simulations in 2100 under both SLR scenarios; projected amount of transgressive migration between initial conditions and 2100 under both SLR scenarios; and the 4 historical potential metrics from Cereghino et al. (2012), which included current watershed area, swamp area, wetland area, and delta length relative to historical conditions.

The degradation metrics included the difference in projected wetland area between simulations with and without levee protection for 2100 under both SLR scenarios; total change in projected wetland area under the no levee protection simulation in 2100 under both SLR scenarios; and the 5 degradation metrics from Cereghino et al. (2012), which included lost delta length and wetland loss between historical and current conditions, tidal flow degradation, nearshore impervious, and watershed impervious for current conditions

Cluster analysis

Cluster analyses were conducted on each set of climate change metrics separately. The conservation potential metrics were column standardized. The metrics from Cereghino et al. (2012) that were in absolute numbers were square root transformed. All restoration potential and degradation level metrics were standardized by using range division. The Euclidean distance matrix was calculated. A multivariate hierarchical agglomerative cluster analysis was performed using average-linkage grouping. The agglomerative coefficient and Cophenetic correlation coefficient were calculated. A scree plot was used to estimate the appropriate number of clusters. The ranks of the degradation and restoration potential clusters were added for each river delta to determine priority rankings for restoration.

Results

What is the difference in projected wetland area and transgressive migration with and without levee protection?

The amount of initial tidal wetland area varied among sub-basins and large river deltas (Table 1). The initial area of transitional scrub-shrub and tidal swamp was low compared to tidal flat and emergent marsh.

In Chapter 2, the total wetland area was projected to decline in all sub-basins between initial conditions and 2100 under both SLR scenarios with levee protection (Table 2), while projected changes in individual wetland types varied. Emergent marsh was projected to expand (except in the South Central sub-basin under the high SLR scenario), tidal flat was projected to decline, while transitional scrub-shrub and tidal swamp changes were projected to vary between initial conditions and 2100 under both SLR scenarios with levee protection.

The projected change in total wetland area switched from a decline with levee protection to an expansion without levee protection in the San Juan and Whidbey sub-basins between initial conditions and 2100 under both SLR scenarios (Table 2). The projected change in total wetland area between initial conditions and 2100 also switched from a decline with levee protection to an expansion without levee projection in the Nooksack (decline with levee protection is <1%) and Snohomish under the low SLR scenario and the Skagit and Stillaguamish under both SLR scenarios (Table 2). The projected expansion of total wetland area increased without levee protection compared to with levee protection in the Nooksack, Samish, and Snohomish River deltas between initial conditions and 2100 under the high SLR scenario.

Tidal wetland change was projected to remain the same without levee protection compared to with levee protection in the Juan de Fuca, South, and South Central between initial condition and 2100 under the low SLR scenario; in the Hood Canal sub-basin under the high SLR scenario; and in the North Central sub-basin under both SLR scenarios. By contrast, the change in total wetland area in the Hood Canal sub-basin was projected to decline even more without levee protection compared to levee protection between initial conditions and 2100 under the low SLR scenario, as well as in the South Central sub-basin under the high SLR scenario. The projected decline was reduced without levee protection compared to with levee protection in the Juan de Fuca and South sub-basins under the high SLR scenario.

Transitional scrub-shrub area was often projected to expand between initial conditions and 2100 with no levee protection (Table 2). While emergent marsh was projected to expand with levee protection under most scenarios and sites, it was projected to decline with no levee protection in many sub-basins and river deltas. Tidal flat and tidal swamp area was not projected to differ much with or without levee protection compared to emergent marsh and transitional scrub-shrub.

The projected amount of transgressive migration was much higher without levee protection compared to with levee protection in the San Juan and Whidbey sub-basins between initial conditions and 2100 under both SLR scenarios (Table 3). Moderate increase in the amount of transgressive migration without levee protection were projected for the Juan de Fuca and South sub-basins between initial conditions and 2100 under the high SLR scenario. Only small or no changes were projected for the remaining sub-basins under the low SLR scenario as well as the South Central sub-basin under the high SLR scenario. The largest amounts of transgressive migration were projected for emergent marsh and transitional scrub-shrub.

The projected amount of transgressive migration was much higher without levee protection compared to with levee protection in the Nooksack, Skagit, Snohomish, and Stillaguamish River deltas under both SLR scenarios as well as in the Dungeness and Samish River deltas under the high SLR scenario (Table 3). By contrast, very little or no transgressive migration was projected in river deltas in the Hood Canal basin.

What river deltas are identified as priority for conservation and restoration based on historical potential, degradation level, and wetland responses to climate change?

Conservation

River deltas were grouped into 7 clusters of conservation potential using absolute wetland values (Figure 3a). The agglomerative coefficient was 0.87, which indicates that river deltas quickly grouped into distinct clusters. The Cophenetic correlation coefficient was 0.92, indicating that the cluster representation of river deltas is highly correlated with the original river delta dissimilarity. High conservation potential was identified in river deltas with high wetland area, high local persistence, and large amounts of transgressive migration. The Skagit, Stillaguamish, and Snohomish were grouped individually with the highest conservation potential, respectively (Figure 3). The Nooksack and Samish were also grouped individually and had mid-high conservation potential. The Dungeness, Nisqually, and Skokomish were grouped together with mid-low conservation potential, and the remaining 8 river deltas were grouped together with the lowest conservation potential.

River deltas were grouped into 5 clusters of conservation potential using relative wetland values (Figure 4a). The agglomerative coefficient was 0.84, which indicates that river deltas quickly agglomerated into distinct clusters. The Cophenetic correlation coefficient was 0.90, indicating that the cluster representation of river deltas was highly correlated with the original river delta dissimilarity. High conservation potential was identified in river deltas with wetland expansion or low wetland decline, high local persistence, and large amounts of transgressive migration. The Skagit and Stillaguamish River deltas were grouped individually with the highest conservation potential (Figure 4). The Nooksack, Samish, and Snohomish were grouped together with mid-high conservation potential. The Dungeness and Skokomish were grouped together with mid-low conservation potential, and the remaining 9 river deltas were grouped together with the lowest conservation potential.

Restoration

River deltas were grouped into 9 clusters of restoration potential (Figure 5a). The agglomerative coefficient was 0.80 and the Cophenetic correlation coefficient was 0.96. High restoration potential was determined based on large amounts of transgressive migration without levee protection, large differences in total wetland area between levee and no levee protection, wetland expansions and low wetland declines without levee protection, high historical swamp and wetland area, long historical delta length, and large watershed area. The Skagit, Snohomish, and Stillaguamish were clustered individually with the highest restoration potential (Figure 5). The Nooksack and Samish were clustered individually with mid-high potential. The Nisqually, Duwamish, and Puyallup had mid-low restoration potential, while the remaining 8 river deltas had low restoration potential.

River deltas were grouped into 4 clusters of degradation level (Figure 6a). The agglomerative coefficient was 0.66 and the Cophenetic correlation coefficient was 0.87, suggesting that the cluster strength was not as strong for degradation as it was for protection or restoration potential. The Duwamish had the highest degradation level followed by the Deschutes and Puyallup (Figure 6). The Stillaguamish, Nooksack, Dungeness, Nisqually, Elwha, Dosewallips, Duckabush, Skokomish, Hamma Hamma, and Quilcene were clustered together with mid-low degradation. The Snohomish, Samish, and Skagit were clustered together with the lowest degradation level.

The ranks of the degradation and potential clusters were added for each river delta (Table 4). The highest ranking had low degradation and high potential, signifying high priority for restoration. The Skagit, Snohomish, Stillaguamish had the highest 3 rankings (Figure 7). The Nooksack and Samish had the 4th highest ranking, followed by the Nisqually and then the Puyallup. The Dosewallips, Duckabush, Dungeness, Duwamish, Elwha, Hamma Hamma, Quilcene, and Skokomish had the 7th highest ranking, and the Deschutes had the lowest.

Do these priorities differ from priorities identified without climate change metrics?

Without climate change metrics, high priority restoration was recommended for the two deltas with the highest historical potential (Skagit and Snohomish) (Cereghino et al. 2012). With climate change metric, the Skagit, Snohomish, and Stillaguamish are identified as the highest priority for restoration. Enhancement was recommended for the three most urban river deltas

(Duwamish, Puyallup, and Deschutes) without climate change metrics, while Deschutes was recommended for enhancement with climate change metrics. Without climate change metrics, restoration was recommended for the seven Olympic deltas (Elwha, Dungeness, Quilcene, Dosewallips, Duckabush, Hamma Hamma, and Skokomish) and four of the Cascade deltas (Nooksack, Samish, Stillaguamish, and Nisqually). With climate change metrics, restoration was recommended for eight groups of river deltas from high to low priority instead of only three groups of priorities.

Discussion

Projected responses of tidal wetlands to future climate change are highly varied, and conservation and restoration strategies of wetlands planned under a climate change context should also be varied and adaptive (Callaway et al. 2007; Lawler 2009). One umbrella strategy will not be appropriate for the entire Salish Sea region, but individual strategies must be tailored to local and regional spatial and temporal variability.

The first part of this analysis compared the projected changes of tidal wetlands with and without levee protection. Tidal wetlands historically experienced extensive loss and degradation throughout the Salish Sea (Simenstad et al. 2011). The magnitude and extent of this loss and degradation has reduced the buffering capacity of tidal wetlands against potential future losses from sea level rise and other climate change drivers (Callaway et al. 2007). Restoration of tidal inundation to lost historical wetlands is an important and increasingly common management strategy. Levee removal is a common form of passive restoration throughout the Salish Sea (Cornu and Sadro 2002; Simenstad et al. 2006). This analysis identified river deltas where levee removal would result in wetland expansions and reduced wetland declines into the future under accelerated sea level rise.

The projected change in total wetland area switched from a decline with levee protection to an expansion without levee protection in the Nooksack and Snohomish River deltas between initial conditions and 2100 under the low SLR scenario and the Skagit and Stillaguamish River deltas under both SLR scenarios. Additionally, the projected expansion of total wetland area increased without levee protection compared to with levee protection in the Nooksack, Samish, and Snohomish River deltas between initial conditions and 2100 under the high SLR scenario. Some of these gains are attributed to the initial removal of levees and other tidal barriers, while some can be attributed to natural transgressive migration post-restoration (Brinson et al. 1995; Feagin et al. 2010).

The projected amount of transgressive migration was higher with no levee protection compared to with levee protection in the Nooksack, Skagit, Snohomish, and Stillaguamish River deltas between initial conditions and 2100 under both SLR scenarios as well as the Dungeness and Samish River deltas under the high SLR scenario. By contrast, very little or no transgressive migration was projected in river deltas in the Hood Canal sub-basin.

The projected expansions of transitional scrub-shrub and tidal swamp suggest that these areas should be prioritized for early restoration. The woody vegetation in these wetland classes take time to grow and develop into healthy, robust systems (Mathews et al. 2009; Moreno-Mateos et al. 2012). Additionally, leveed land tends to subside compared to adjacent wetland due to compaction and decomposition (Knowles 2010). Once tidal inundation and sediment supply is returned to leveed land, time is required for sediment to re-build the surface elevation. Early restoration will allow more time for sediment accretion in subsided areas before it is most critical to have these wetlands as a buffer against accelerated sea level rise in later decades.

The second part of this analysis identified protection and restoration priorities based on historical potential, degradation level, and projected responses of tidal wetlands to accelerated sea level rise. The conservation of currently healthy wetlands that are projected to have the adaptive capacity to locally persist under accelerated sea level rise is important to buffer against future wetland losses. Additionally, it is critical to prevent the development of currently undeveloped dry land into which tidal wetlands are projected to migrate (Pearsall 2005; Callaway et al. 2007).

Many different criteria are often used for selecting the location and size of conservation and restoration sites. For instance, conservation priority may be given to more natural sites or restoration may focus on the size of the site. Large areas of restored tidal wetlands often recover structure and function more quickly than small areas (Moreno-Mateos et al. 2012). Additionally, large marsh areas tend to have more complex tidal channels, which provide salmon with deep channels for foraging (Coats et al. 1995; Simenstad et al. 2000).

The conservation potential analysis was conducted using the amount of wetland persistence and then using the relative amount of persistence. However, since some river deltas had such small amounts of initial wetland area, such as the Duwamish, the total amount of wetland was also incorporated into the relative values analysis. According to the protection potential cluster analysis using absolute persistence, the Skagit, Stillaguamish, and Snohomish river deltas have the highest protection potential and, therefore, would benefit from identification as high priority deltas for tidal wetland conservation. The Nooksack and Samish were classified as second-priority conservation deltas, followed by the Dungeness, Nisqually, and Skokomish River deltas.

While the protection priorities using absolute values were similar to those priorities derived using relative values of percent persistence, the priority rankings of some river deltas shifted slightly. The Snohomish was identified as secondary priority compared to high priority, and the Nisqually was identified as low priority compared to mid-low priority when derived using relative values.

Restoration priorities differed slightly when climate change metrics were included in addition to historical potential and degradation level. The range of priority rankings was also greater when climate change was incorporated compared to only using historical potential and degradation. Cereghino et al. (2012) identified 3 priority categories for restoration of river deltas: high priority restoration, restoration, and enhancement. The climate change analysis identified a gradient of 8 priority rankings.

Without climate change metrics, high priority restoration was recommended for the two deltas with the highest historical potential (Skagit and Snohomish), restoration was recommended for the seven Olympic deltas (Elwha, Dungeness, Quilcene, Dosewallips, Duckabush, Hamma Hamma, and Skokomish) and four of the Cascade deltas (Nooksack, Samish, Stillaguamish, and Nisqually), and enhancement was recommended for the three most urban river deltas (Duwamish, Puyallup, and Deschutes) (Cereghino et al. 2012).

Under a climate change framework, high priority river deltas for restoration are the Skagit, Snohomish, and Stillaguamish. The Nooksack and Samish followed by the Nisqually and then the Puyallup were identified as moderate to moderate-high priorities.

The Deschutes River delta was identified as the lowest priority, which suggests the need for enhancement instead of actual restoration. Although the climate change metrics suggest that the Duwamish and Puyallup are grouped with the second-lowest priority, the extensive degradation, industrialization, and pollution of these rivers (Simenstad et al. 2005) must be considered and acknowledged as system-scale constraints that prevent feasible restoration (Simenstad et al. 2006). Regardless of projected changes in tidal wetland area, rehabilitation and enhancement efforts may be the most appropriate strategy for these three most urbanized and industrialized river deltas (Simenstad et al. 2006; Cereghino et al. 2012).

There are many other factors that must be considered when strategically planning conservation and restoration. Restoration in certain areas is not always economically and socially feasible and trade-offs must be made. For instance, the Skagit River Valley is a large center for agriculture, and large restoration efforts that impose on this valued agricultural land may not be politically or economically feasible or socially accepted.

While this study provided insight into identifying conservation and restoration priority deltas under a climate change context in the Salish Sea, there were data and analysis limitations that must be considered and are discussed in detail in Chapter 2. These limitations include the accuracy of current wetland distributions and extents, spatial resolution of elevation data, and sensitivities to tidal parameters. Additionally, the comparison of levee protection to no levee protection had limitation due to an insufficient database of levee locations and heights throughout the Salish Sea. The PSNERP geodatabase contains a data layer of limited location and length of tidal barriers. When SLAMM simulations were run with this layer, however, extensive flooding of dry land occurred, especially in the Skagit River Valley. In order to restrict this flooding, all agriculture land in the Salish Sea was assumed to be protected from tidal inundation during all simulations with levee protection (Collins and Montgomery 2001). This combined levee data layer, however, may not be an accurate representation of actual conditions, and these inaccuracies will be inherently reflected in the results.

Despite these data limitations and uncertainties, the results of this analysis have important and useful implications for strategic conservation and restoration of tidal wetlands under a climate change context by identifying gradients of conservation and restoration priorities for the 16 largest river deltas in the Salish Sea. As scientists, managers, and planners consider the status of tidal wetlands in terms of their sustainability into the future, it is important to take climate change into consideration when identifying river deltas to invest time and money for the most long-term benefit (Callaway et al. 2007; Lawler 2009).

The gradient of priority rankings for conservation and restoration can also be used to select sites based on additional criteria. For instance, an organization may only have resources to restore or conserve a certain size of tidal wetland area. The planners can select their site from the rankings of only the river deltas or leveed locations that fit their size criteria. Additionally, local groups may want to identify the best site to restore in a given region or sub-basin if site fidelity is an important criterion. In order for conservation and restoration efforts of existing tidal wetlands to be successful and persist into the future, this study shows that climate change should be considered. Identifying priority deltas for tidal wetland conservation and restoration under a climate change framework will be beneficial for the allocation of resources in the short- and long-term by identifying areas in which tidal wetlands are projected to exist with conservation and restoration under accelerated sea level rise.

Acknowledgements Funding was provided by the Northwest Climate Science Center Fellowship and the School of Aquatic and Fishery Sciences, College of the Environment, University of Washington.

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Tables:

Table 1: Amount of initial wetland area (hectares) in each sub-basin, large river delta, and the Salish Sea study area. The input value is the wetland area from the combined PSNERP and NWI dataset. The modeled value is the initial wetland area as modeled by SLAMM.

	Tidal flat		Emergent marsh		Transitional scrub-shrub		Tidal swamp		Total	
	Input	Modeled	Input	Modeled	Input	Modeled	Input	Modeled	Input	Modeled
Hood Canal	**3,132**	**3,362**	**785**	**1,115**	**29**	**113**	**104**	**104**	**4,050**	**4,694**
Dosewallips	140	140	47	47	3	3	4	3	194	194
Duckabush	118	118	31	31	1	1	7	7	157	157
Hamma Hamma	130	126	23	23	1	1	9	9	164	159
Quilcene	46	66	246	227	1	2	17	16	310	311
Skokomish	56	456	673	268	1	1	59	59	789	784
Juan de Fuca	**3,630**	**3,142**	**321**	**324**	**14**	**1,073**	**78**	**70**	**4,042**	**4,609**
Dungeness	600	583	74	74	0	0	11	11	685	668
Elwha	42	36	11	11	0	0	40	40	92	87
North Central	**2,258**	**1,992**	**455**	**455**	**5**	**38**	**17**	**17**	**2,735**	**2,502**
San Juan	**12,736**	**11,629**	**988**	**985**	**20**	**173**	**84**	**109**	**13,828**	**12,896**
Nooksack	1,467	1,466	485	485	9	9	58	84	2,019	2,044
Samish	1,527	1,525	38	38	4	4	11	11	1,580	1,578
South	**5,775**	**5,688**	**669**	**777**	**11**	**54**	**53**	**51**	**6,508**	**6,570**
Deschutes	88	87	109	108	0	2	0	0	196	197
Nisqually	659	659	225	225	1	1	23	23	908	908
South Central	**4,522**	**3,812**	**311**	**256**	**6**	**102**	**7**	**23**	**4,846**	**4,193**
Duwamish	14	14	2	2	0	5	1	1	17	22
Puyallup	31	28	4	3	0	0	6	6	41	37
Whidbey	**11,652**	**11,171**	**2,930**	**3,009**	**56**	**101**	**970**	**873**	**15,608**	**15,154**
Skagit	4,294	4,230	1,700	1,678	47	47	309	315	6,350	6,270
Snohomish	1,018	927	296	390	0	20	560	461	1,875	1,798
Stillaguamish	2,720	2,677	817	823	10	10	84	84	6,631	3,594
Salish Sea	**42,090**	**39,299**	**7,307**	**6,682**	**140**	**1,636**	**1,306**	**1,234**	**50,843**	**48,851**

Table 2: The projected amount of wetland change (hectares) for levee protection and no levee protection between initial conditions and 2100 for the (a) low and (b) high SLR scenarios. Relative changes (percent change) included in parentheses. The percent change could not be calculated when the initial areas was 0 ha and is symbolized by (-).

(a) 2100 low

	Tidal flat			Emergent marsh			Transitional scrub-shrub			Tidal swamp			Total		
	With	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**
Hood Canal	**-195 (-6)**	**-246 (-7)**	***-51 (-1)***	**54 (5)**	**54 (5)**	***0 (0)***	**-77 (-68)**	**-77 (-68)**	***0 (0)***	**-3 (-3)**	**-3 (-3)**	***0 (0)***	**-221 (-5)**	**-272 (-6)**	***-51 (-1)***
Dosewallips	-4 (-3)	-4 (-3)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-4 (-2)	-4 (-2)	*0 (0)*
Duckabush	-2 (-2)	-1 (-1)	*1 (1)*	-1 (-3)	0 (0)	*1 (3)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-3 (-2)	-1 (-1)	*2 (1)*
Hamma Hamma	-4 (-3)	-4 (-3)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-4 (-3)	-4 (-3)	*0 (0)*
Quilcene	5 (8)	5 (8)	*0 (0)*	-1 (0)	-1 (0)	*0 (0)*	-2 (-100)	-2 (-100)	*0 (0)*	-3 (-18)	-3 (-18)	*0 (0)*	-1 (0)	-1 (0)	*0 (0)*
Skokomish	-2 (0)	-2 (0)	*0 (0)*	-13 (-5)	-13 (-5)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-15 (-2)	-15 (-2)	*0 (0)*
Juan de Fuca	**-222 (-7)**	**-221 (-7)**	***1 (0)***	**11 (3)**	**11 (3)**	***0 (0)***	**-996 (-93)**	**-993 (-93)**	***3 (0)***	**-10 (-14)**	**-10 (-14)**	***0 (0)***	**-1,217 (-26)**	**-1,213 (-26)**	***4 (0)***
Dungeness	-10 (-2)	-10 (-2)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	3 (-)	4 (-)	*1 (-)*	0 (0)	0 (0)	*0 (0)*	-7 (-1)	-6 (-1)	*1 (0)*
Elwha	-2 (-6)	-2 (-6)	*0 (0)*	4 (36)	4 (36)	*0 (0)*	6 (-)	6 (-)	*0 (0)*	-9 (-23)	-9 (-23)	*0 (0)*	-1 (-1)	-1 (-1)	*0 (0)*
North Central	**-215 (-11)**	**-215 (-11)**	***0 (0)***	**44 (10)**	**49 (11)**	***5 (1)***	**23 (59)**	**25 (64)**	***2 (5)***	**0 (0)**	**0 (0)**	***0 (0)***	**-148 (-6)**	**-141 (-6)**	***7 (0)***
San Juan	**-368 (-3)**	**-368 (-3)**	***0 (0)***	**26 (3)**	**436 (44)**	***410 (1)***	**-114 (-66)**	**110 (64)**	***224 (130)***	**0 (0)**	**1 (1)**	***1 (1)***	**-456 (-4)**	**179 (1)**	***635 (5)***
Nooksack	-13 (-1)	-13 (-1)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	10 (111)	69 (767)	*59 (656)*	0 (0)	0 (0)	*0 (0)*	-3 (0)	56 (3)	*59 (3)*
Samish	-11 (-1)	-11 (-1)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-11 (-1)	-11 (-1)	*0 (0)*
South	**-410 (-7)**	**-410 (-7)**	***0 (0)***	**13 (2)**	**13 (2)**	***0 (0)***	**-45 (-82)**	**-45 (-82)**	***0 (0)***	**0 (0)**	**0 (0)**	***0 (0)***	**-442 (-7)**	**-442 (-7)**	***0 (0)***
Deschutes	28 (32)	28 (32)	*0 (0)*	-25 (-23)	-25 (-23)	*0 (0)*	-2 (-100)	-2 (-100)	*0 (0)*	0 (-)	0 (-)	*0 (0)*	1 (1)	1 (1)	*0 (0)*

Nisqually	-9 (-1)	-9 (-1)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-9 (-1)	-9 (-1)	*0 (0)*
South Central	**-412 (-11)**	**-412 (-11)**	***0 (0)***	**105 (41)**	**106 (42)**	***1 (1)***	**-46 (-45)**	**-46 (-45)**	***0 (0)***	**-13 (-57)**	**-13 (-57)**	***0 (0)***	**-366 (-9)**	**-365 (-9)**	***1 (0)***
Duwamish	0 (0)	0 (0)	*0 (0)*	12 (600)	12 (600)	*0 (0)*	4 (67)	4 (67)	*0 (0)*	-2 (-33)	-2 (-33)	*0 (0)*	14 (48)	14 (48)	*0 (0)*
Puyallup	-1 (-3)	-1 (-3)	*0 (0)*	2 (27)	2 (27)	*0 (0)*	0 (-)	0 (-)	*0 (0)*	-7 (-54)	-7 (-54)	*0 (0)*	-6 (-13)	-6 (-13)	*0 (0)*
Whidbey	**-510 (-5)**	**-483 (-4)**	***27 (1)***	**189 (6)**	**157 (5)**	***-32 (-1)***	**23 (23)**	**1,768 (1,750)**	***1,745 (1,727)***	**-96 (-11)**	**-49 (-6)**	***47 (5)***	**-394 (-3)**	**1,393 (9)**	***1,787 (12)***
Skagit	-63 (-1)	-63 (-1)	*0 (0)*	26 (2)	44 (3)	*18 (1)*	13 (28)	1,003 (2,180)	*990 (2,152)*	-26 (-8)	11 (4)	*37 (12)*	-50 (-1)	995 (16)	*1,045 (17)*
Snohomish	-93 (-10)	1 (0)	*94 (10)*	139 (36)	84 (22)	*-55 (-14)*	1 (5)	550 (2,619)	*449 (2,614)*	-65 (-14)	-65 (-14)	*0 (0)*	-18 (-1)	570 (32)	*588 (33)*
Stillaguamish	-32 (-1)	-32 (-1)	*0 (0)*	2 (0)	1 (0)	*-1 (0)*	0 (0)	318 (2,891)	318 (2,891)	0 (0)	13 (15)	*13 (15)*	-30 (-1)	300 (8)	*330 (9)*
Salish Sea	**-2,158 (-5)**	**-2,137 (-5)**	***21 (0)***	**426 (6)**	**806 (12)**	***380 (6)***	**-1,227 (-75)**	**748 (46)**	***1,975 (121)***	**-144 (-9)**	**-70 (-6)**	***74 (3)***	**-3,073 (-6)**	**-653 (-1)**	***2,420 (5)***

(b) 2100 high

	Tidal flat			Emergent marsh			Transitional scrub-shrub			Tidal swamp			Total		
	With	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**	**With**	**Without**	**Diff.**
Hood Canal	**-159 (-5)**	**-159 (-5)**	*0 (0)*	**10 (1)**	**10 (1)**	*0 (0)*	**-40 (-36)**	**-40 (-36)**	*0 (0)*	**10 (10)**	**10 (10)**	*0 (0)*	**-179 (-4)**	**-179 (-4)**	*0 (0)*
Dosewallips	-4 (-3)	-4 (-3)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	1 (50)	1 (50)	*0 (0)*	-1 (-25)	-1 (-25)	*0 (0)*	-4 (-2)	-4 (-2)	*0 (0)*
Duckabush	-2 (-2)	-2 (-2)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-2 (-1)	-2 (-1)	*0 (0)*
Hamma Hamma	-5 (-4)	-4 (-3)	*1 (1)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	0 (0)	0 (0)	*0 (0)*	-5 (-3)	-4 (-3)	*1 (0)*
Quilcene	33 (50)	34 (52)	*1 (2)*	-12 (-5)	-37 (-16)	*-25 (-11)*	2 (100)	16 (1,600)	*14 (1,500)*	-11 (-69)	-11 (-69)	*0 (0)*	12 (4)	2 (1)	*-10 (-3)*
Skokomish	42 (9)	44 (10)	*2 (10)*	-57 (-21)	-58 (-22)	*-1 (-1)*	14 (1,400)	14 (1,400)	*0 (0)*	23 (39)	23 (39)	*0 (0)*	22 (3)	23 (3)	*1 (0)*
Juan de Fuca	**-677 (-22)**	**-653 (-21)**	***24 (1)***	**207 (64)**	**16 (15)**	***-191 (49)***	**-1,012 (-94)**	**237 (22)**	***1,249 (116)***	**-36 (-51)**	**-34 (-49)**	***2 (2)***	**-1,518 (-33)**	**-434 (-9)**	***1,084 (24)***
Dungeness	-161	-161	*0*	50	0	*-50*	21	91	*70*	-8	-6	*2*	-98	-76	*22*

	(-28)	(-28)	(0)	(68)	(0)	(-68)	(-)	(9,100)	(-)	(-67)	(-55)	(12)	(-15)	(-11)	(4)
Elwha	-7 (-19)	-7 (-19)	0 (0)	47 (427)	12 (109)	-35 (-318)	8 (-)	32 (-)	24 (-)	-22 (-56)	-21 (-54)	1 (2)	26 (30)	16 (19)	-10 (-11)
North Central	**-558 (-28)**	**-558 (-28)**	**0 (0)**	**276 (61)**	**286 (63)**	**10 (2)**	**46 (118)**	**50 (128)**	**4 (10)**	**-1 (-6)**	**-1 (-6)**	**0 (0)**	**-237 (-9)**	**-223 (-9)**	**4 (0)**
San Juan	**-1,922 (-17)**	**-1,912 (-16)**	**10 (10)**	**508 (52)**	**3,032 (308)**	**2,524 (256)**	**157 (91)**	**1,539 (890)**	**1,382 (799)**	**-72 (-66)**	**-75 (-68)**	**-3 (-2)**	**-1,319 (-10)**	**2,584 (20)**	**3,903 (3)**
Nooksack	-120 (-8)	-120 (-8)	0 (0)	187 (39)	447 (92)	260 (53)	57 (633)	271 (3,011)	214 (2,378)	-73 (-87)	-74 (-87)	-1 (0)	51 (2)	524 (26)	473 (24)
Samish	-79 (-5)	-79 (-5)	0 (0)	62 (163)	560 (1,436)	498 (1,273)	40 (1,000)	590 (14,750)	550 (13,750)	2 (18)	1 (9)	-1 (-9)	25 (2)	1,072 (68)	1,047 (66)
South	**-439 (-8)**	**-436 (-8)**	**3 (0)**	**25 (3)**	**-5 (-1)**	**-30 (-4)**	**-23 (-42)**	**46 (85)**	**69 (127)**	**7 (14)**	**7 (14)**	**0 (0)**	**-430 (-7)**	**-388 (-6)**	**42 (1)**
Deschutes	34 (39)	33 (38)	-1 (-1)	-32 (-30)	-33 (-31)	-1 (-1)	0 (0)	2 (100)	2 (100)	0 (-)	0 (-)	0 (-)	2 (1)	2 (1)	0 (0)
Nisqually	-9 (-1)	-9 (-1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	7 (30)	0 (0)	-7 (-30)	-2 (0)	-9 (-1)	-7 (-1)
South Central	**-812 (-21)**	**-863 (-23)**	**-51 (-2)**	**-12 (-5)**	**83 (32)**	**95 (37)**	**254 (249)**	**159 (154)**	**-95 (-95)**	**15 (65)**	**1 (4)**	**-14 (61)**	**-555 (-13)**	**-620 (-15)**	**-65 (-2)**
Duwamish	-2 (-14)	-2 (-14)	0 (0)	0 (0)	5 (250)	5 (250)	40 (800)	35 (700)	-5 (-100)	8 (160)	4 (80)	-4 (-80)	46 (177)	42 (162)	-4 (-15)
Puyallup	-2 (-7)	-3 (-11)	-1 (-4)	0 (0)	0 (0)	0 (0)	1 (-)	1 (-)	0 (0)	7 (50)	0 (0)	-7 (-50)	6 (13)	-2 (-4)	-8 (-17)
Whidbey	**-3,505 (-31)**	**-3,467 (-31)**	**38 (0)**	**1,511 (50)**	**366 (12)**	**-1,145 (-48)**	**384 (384)**	**6,940 (6,940)**	**6,556 (6,556)**	**-460 (-53)**	**-345 (-40)**	**115 (13)**	**-2,070 (-14)**	**3,494 (23)**	**5,564 (37)**
Skagit	-1,413 (-33)	-1,402 (-33)	11 (0)	238 (14)	129 (8)	-109 (-6)	24 (52)	3,775 (8,207)	3,754 (8,155)	-210 (-67)	-152 (-49)	58 (18)	-1,361 (-22)	2,350 (38)	3,711 (60)
Snohomish	-724 (-78)	-719 (-78)	5 (0)	1,111 (285)	226 (58)	-885 (-227)	297 (1,485)	2,456 (11,695)	2,159 (10,210)	-244 (-53)	-201 (-44)	43 (9)	440 (24)	1,762 (98)	1,322 (74)
Stillaguamish	-255 (-10)	-255 (-10)	0 (0)	15 (2)	7 (1)	-8 (-1)	0 (0)	593 (5,391)	593 (5,391)	0 (0)	23 (27)	23 (27)	-240 (-7)	368 (10)	608 (17)
Salish Sea	**-7,413 (-19)**	**-7,400 (-19)**	**13 (0)**	**2,441 (37)**	**3,690 (55)**	**1,249 (18)**	**-258 (-16)**	**8,976 (549)**	**9,234 (565)**	**-529 (-43)**	**-613 (-50)**	**-84 (-7)**	**-5,759 (-12)**	**4,653 (10)**	**10,412 (22)**

Table 3: The projected amount of transgressive migration (hectares) for levee protection and no levee protection between initial conditions and 2100 for the (a) low and (b) high SLR scenarios.

(a) 2100 low

	Tidal flat			Emergent marsh			Transitional scrub-shrub			Tidal swamp			Total		
	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.
Hood Canal	**0**	**0**	***0***	**31**	**31**	***0***	**8**	**8**	***0***	**0**	**0**	***0***	**39**	**39**	***0***
Dosewallips	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Duckabush	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Hamma Hamma	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Quilcene	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Skokomish	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Juan de Fuca	**0**	**0**	***0***	**0**	**0**	***0***	**50**	**52**	***2***	**0**	**0**	***0***	**50**	**52**	***2***
Dungeness	0	0	*0*	0	0	*0*	3	4	*1*	0	0	*0*	3	4	*1*
Elwha	0	0	*0*	0	0	*0*	6	6	*0*	0	0	*0*	6	0	*0*
North Central	**1**	**1**	***0***	**18**	**19**	***1***	**57**	**59**	***2***	**0**	**0**	***0***	**76**	**79**	***3***
San Juan	**0**	**0**	***0***	**8**	**413**	***405***	**39**	**263**	***224***	**0**	**1**	***1***	**47**	**677**	***630***
Nooksack	0	0	*0*	0	3	*3*	10	69	*59*	0	1	*1*	10	73	*63*
Samish	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
South	**0**	**0**	***0***	**16**	**16**	***0***	**1**	**1**	***0***	**0**	**0**	***0***	**17**	**17**	***0***
Deschutes	0	0	*0*	1	1	*0*	0	0	*0*	0	0	*0*	1	1	*0*
Nisqually	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
South Central	**1**	**1**	***0***	**47**	**48**	***1***	**50**	**50**	***0***	**3**	**3**	***0***	**101**	**102**	***1***
Duwamish	0	0	*0*	7	7	*0*	10	10	*0*	3	3	*0*	20	20	*0*
Puyallup	0	0	*0*	1	1	*0*	0	0	*0*	0	0	*0*	1	1	*0*
Whidbey	**0**	**1**	***1***	**77**	**39**	***-38***	**67**	**1,810**	***1,743***	**1**	**50**	***49***	**145**	**1,900**	***1,755***
Skagit	0	0	*0*	8	36	*28*	14	1,004	*990*	0	37	*37*	22	1,077	*1,055*
Snohomish	0	0	*0*	62	2	*-60*	20	566	*546*	1	3	*2*	83	571	*488*
Stillaguamish	0	0	*0*	1	0	*-1*	1	319	*318*	0	13	*13*	2	332	*330*
Salish Sea	**2**	**3**	***1***	**193**	**564**	***371***	**259**	**2,230**	***1,971***	**4**	**51**	***47***	**458**	**2,848**	***2,390***

(b) 2100 high

	Tidal flat			Emergent marsh			Transitional scrub-shrub			Tidal swamp			Total		
	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.	With	Without	Diff.
Hood Canal	**0**	**0**	***0***	**98**	**98**	***0***	**44**	**44**	***0***	**29**	**29**	***0***	**171**	**171**	***0***
Dosewallips	0	0	*0*	0	0	*0*	1	1	*0*	0	0	*0*	1	1	*0*
Duckabush	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Hamma Hamma	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
Quilcene	0	0	*0*	4	0	*-4*	2	8	*6*	0	0	*0*	6	8	*2*
Skokomish	0	0	*0*	0	0	*0*	14	14	*0*	29	29	*0*	43	43	*0*
Juan de Fuca	**1**	**0**	***-1***	**144**	**0**	***-144***	**38**	**210**	***172***	**0**	**1**	***1***	**183**	**211**	***28***
Dungeness	0	0	*0*	40	0	*0*	13	77	*64*	0	1	*1*	53	78	*25*
Elwha	0	0	*0*	22	0	*0*	6	27	*21*	0	1	*1*	28	28	*0*
North Central	**1**	**1**	***0***	**196**	**202**	***6***	**59**	**63**	***4***	**0**	**0**	***0***	**256**	**266**	***10***
San Juan	**6**	**7**	***1***	**344**	**2,841**	***2,497***	**258**	**1,624**	***1,366***	**10**	**10**	***0***	**618**	**4,482**	***3,864***
Nooksack	0	0	*0*	31	288	*257*	33	236	*203*	3	3	*0*	67	527	*460*
Samish	0	0	*0*	57	910	*853*	34	583	*549*	7	7	*0*	98	1,500	*1,402*
South	**0**	**1**	***1***	**56**	**0**	***-56***	**22**	**89**	***67***	**0**	**0**	***0***	**78**	**90**	***12***
Deschutes	0	0	*0*	2	0	*-2*	1	3	*2*	0	0	*0*	3	3	*0*
Nisqually	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*	0	0	*0*
South Central	**1**	**1**	***0***	**0**	**1**	***1***	**252**	**252**	***0***	**17**	**17**	***0***	**270**	**271**	***1***
Duwamish	0	0	*0*	0	0	*0*	40	40	*0*	8	8	*0*	48	48	*0*
Puyallup	0	0	*0*	0	0	*0*	1	1	*0*	8	8	*0*	9	9	*0*
Whidbey	**1**	**2**	***1***	**491**	**0**	***-491***	**269**	**6,121**	***5,852***	**3**	**111**	***108***	**764**	**6,234**	***5,470***
Skagit	0	0	*0*	35	0	*-35*	36	3,770	*3,734*	1	56	*55*	72	3,826	*3,754*
Snohomish	0	0	*0*	327	0	*-327*	151	1,664	*1,513*	1	39	*38*	479	1,703	*1,224*
Stillaguamish	0	0	*0*	9	0	*-9*	5	596	*591*	1	24	*23*	15	620	*605*
Salish Sea	**9**	**10**	***1***	**1,257**	**3,002**	***1,745***	**908**	**8,457**	***7,549***	**60**	**131**	***71***	**2,234**	**11,600**	***9,366***

Table 4: Ranking of degradation and restoration potential cluster analyses and the overall rank for restoration priority based on the sum of the degradation and restoration potential rankings.

River	Degradation (low-high)	Restoration (high-low)	Total	Rank
Skagit	1	1	2	1
Snohomish	1	2	3	2
Stillaguamish	2	3	5	3
Nooksack	2	4	6	4
Samish	1	5	6	4
Nisqually	2	6	8	5
Puyallup	3	7	10	6
Dosewallips	2	9	11	7
Duckabush	2	9	11	7
Dungeness	2	9	11	7
Duwamish	4	7	11	7
Elwha	2	9	11	7
Hamma Hamma	2	9	11	7
Quilcene	2	9	11	7
Skokomish	2	9	11	7
Deschutes	3	9	12	8

Figures

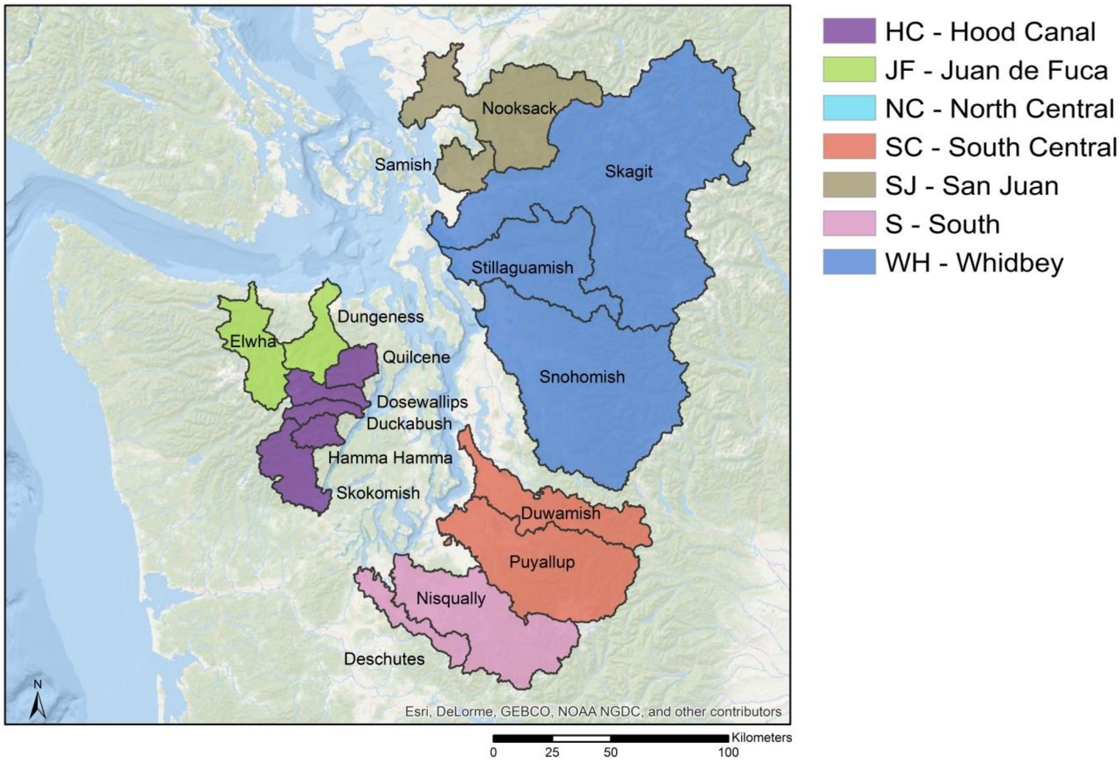

Figure 1: Study site encompassing the 16 largest river deltas in the U.S. portion of the Salish Sea color coded to sub-basin.

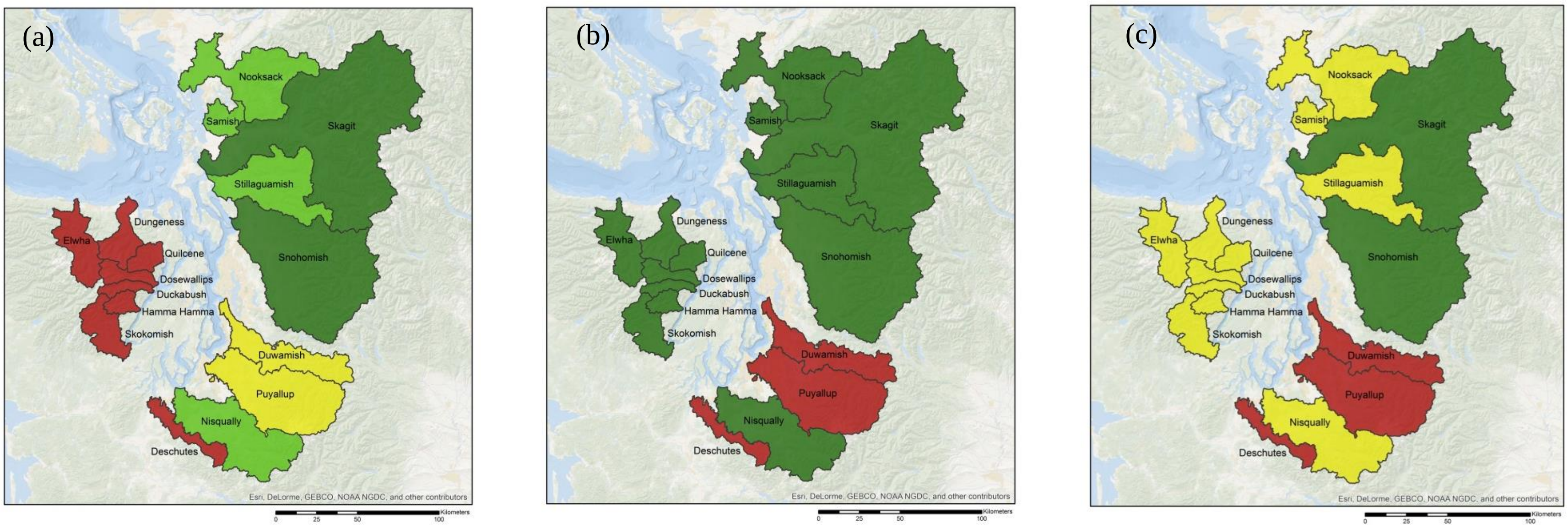

Figure 2: (a) Historical potential, (b) degradation level, (c) and recommendation from Cereghino et al. (2012). (a) Gradient of historical potential is from high potential in green to low potential in red. (b) Low degradation level is in green and high degradation level is in red. (c) The high restoration recommendation is in green, the restore recommendation is in yellow, and the enhance recommendation is in red.

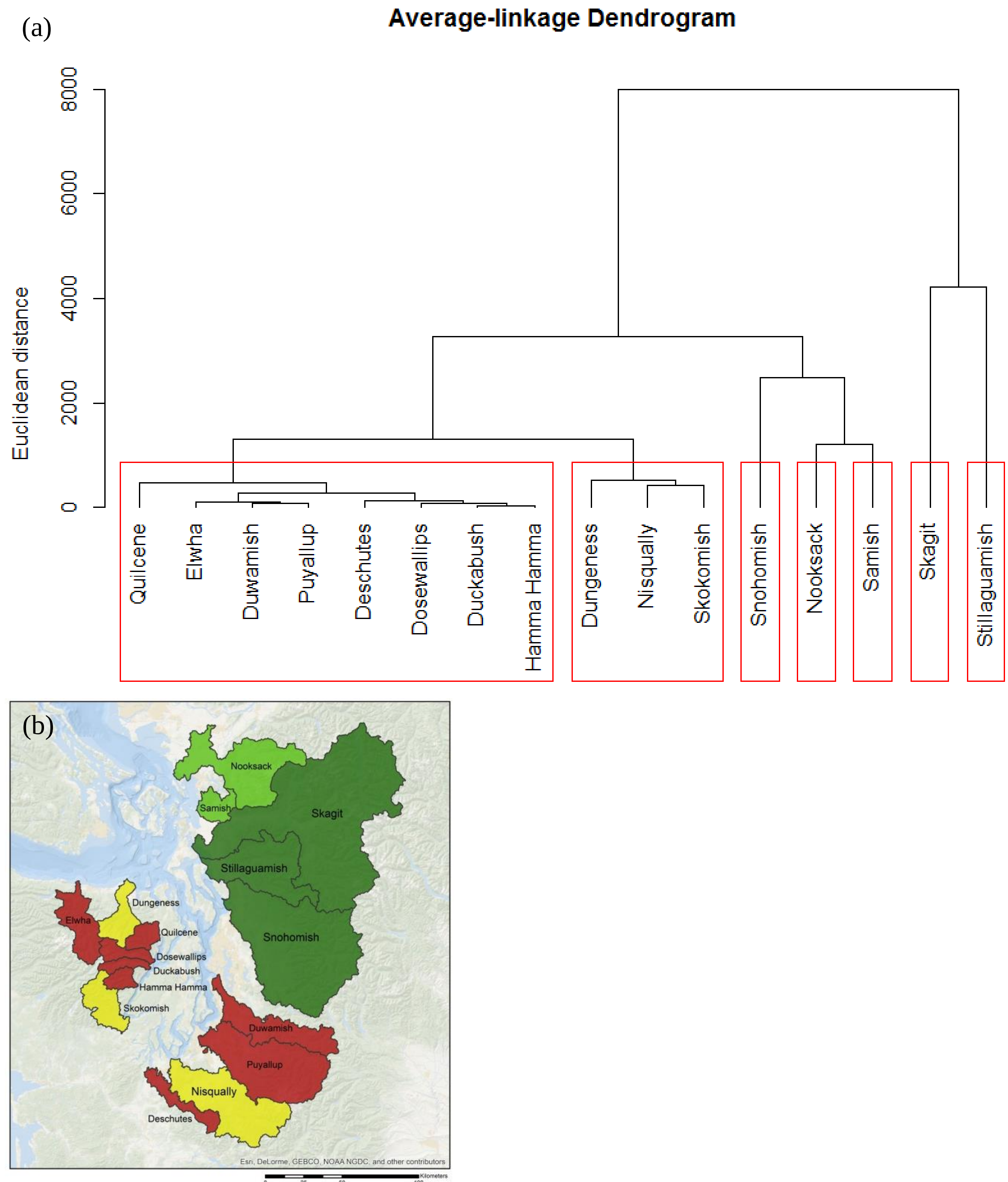

Figure 3: (a) Dendrogram from cluster analysis for conservation potential with absolute wetland values. (b) Map of conservation priority categories from high priority in dark green to low priority in red.

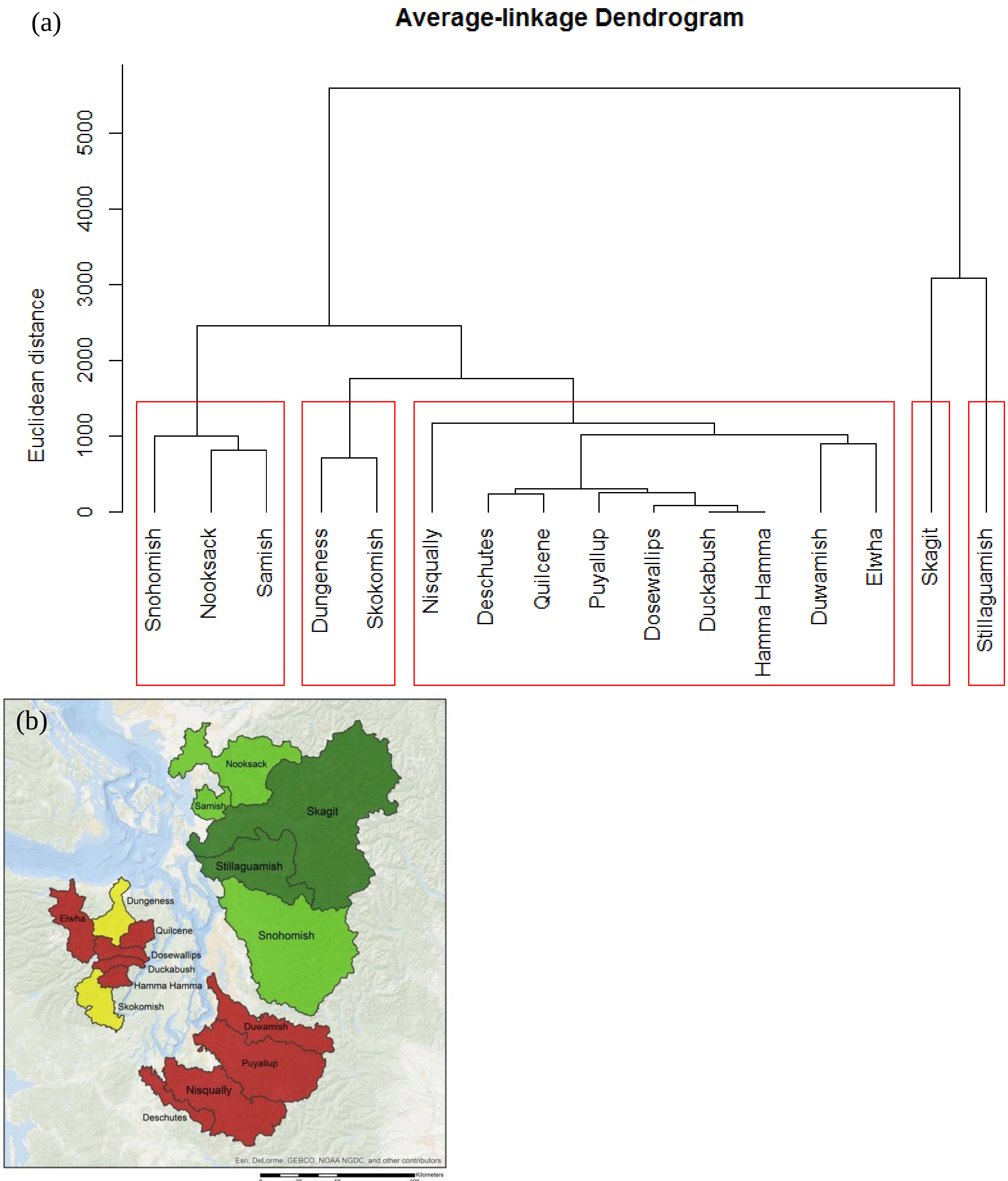

Figure 4: (a) Dendrogram from cluster analysis for conservation potential with relative wetland values. (b) Map of conservation priority categories from high priority in dark green to low priority in red.

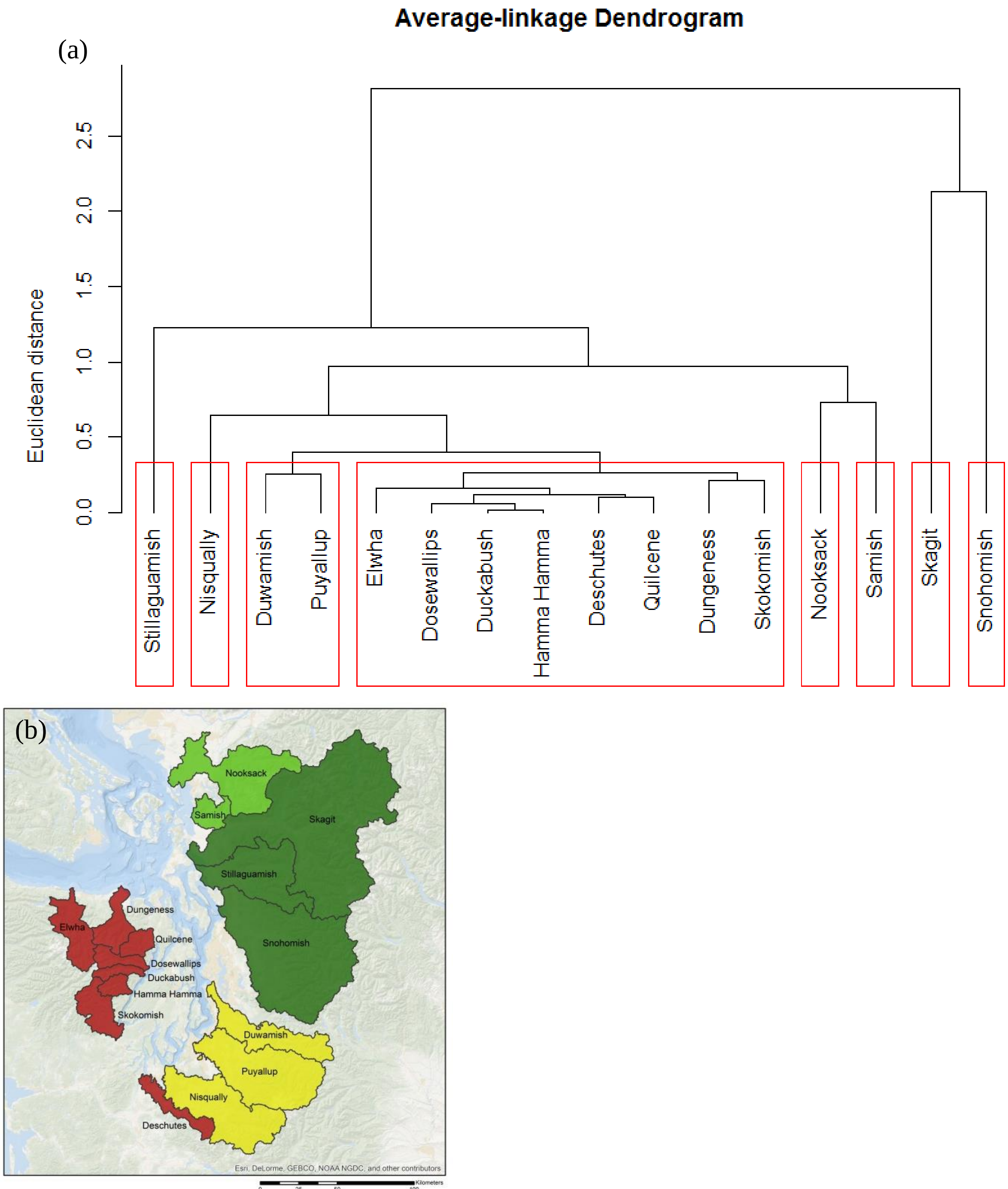

Figure 5: (a) Dendrogram from cluster analysis for restoration potential. (b) Map of restoration potential categories from high priority in dark green to low priority in red.

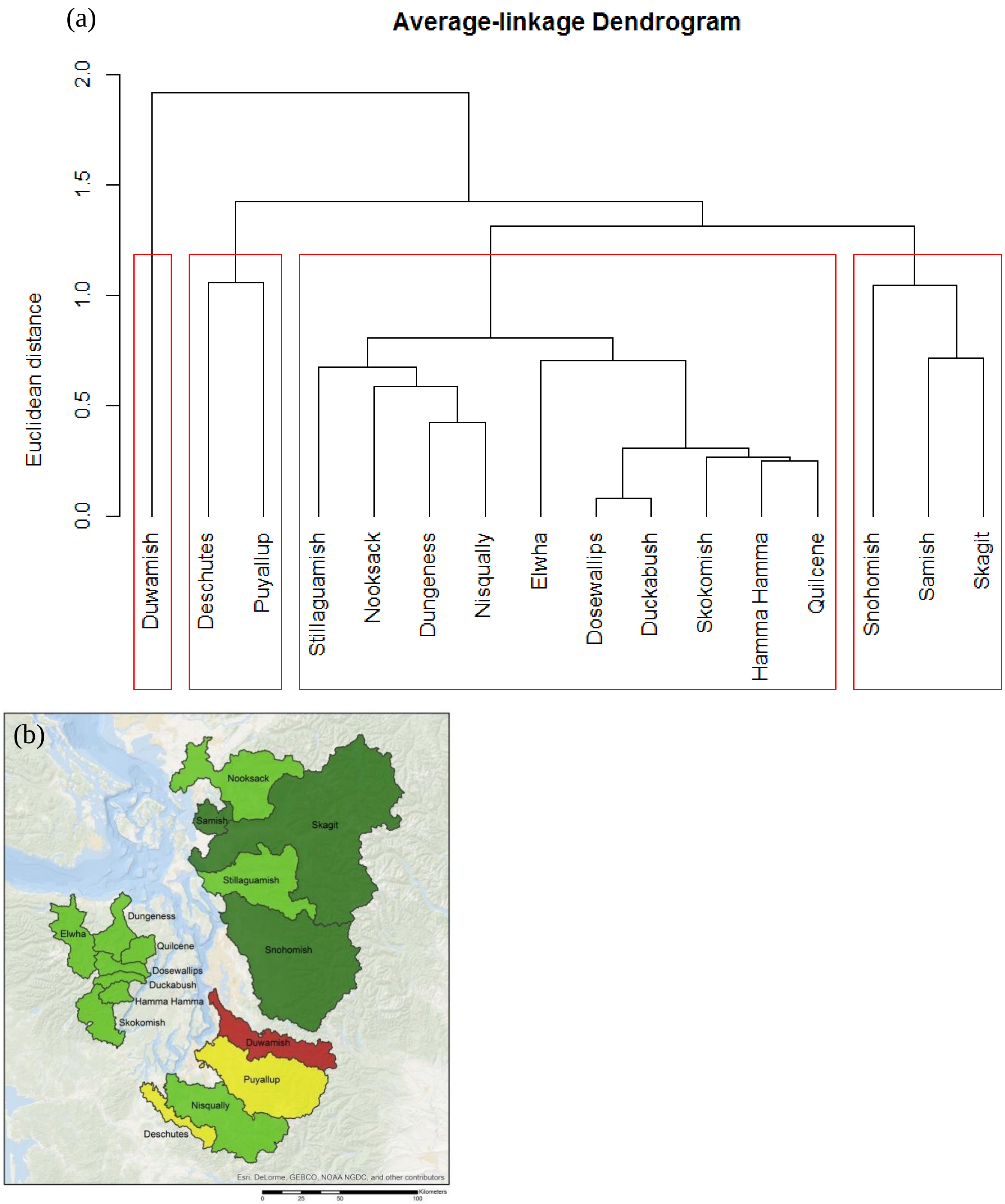

Figure 6: (a) Dendrogram from cluster analysis for degradation level. (b) Map degradation categories from high degradation in red to low degradation in dark green.

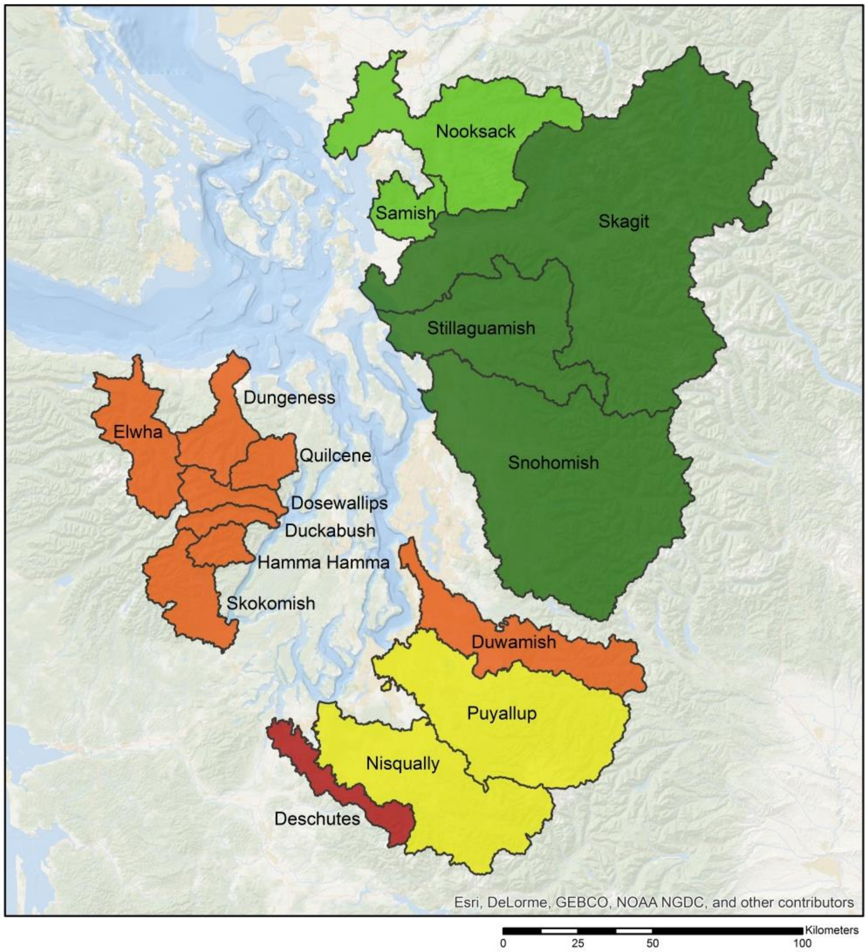

Figure 7: Map of restoration priorities based on historical potential and degradation level under a climate change context from high priority in dark green to low priority in red. See Table 4 for individual rankings of river deltas.

Conclusion

The Salish Sea is a dynamic system in which estuarine and nearshore ecosystem processes vary spatially and temporally. Many of these ecosystem processes affect the ability of tidal wetlands to respond to future climate change. Tidal wetlands throughout the world, not just in the Pacific Northwest, are at risk of future climate change impacts, such as hydrologic alterations and submergence due to accelerated sea level rise (Desantis et al. 2007; Swanson et al. 2014).

In order for conservation and restoration efforts of existing tidal wetlands to be successful and persist into the future, climate change should be considered (Callaway et al. 2007; Pressey et al. 2007; Lawler 2009). In addition, climate change may offer new opportunities for tidal wetland expansion by inundating dry land and facilitating transgressive migration into adjacent uplands (Brinson et al. 1995). Although there have been various delta-scale studies of climate change impacts on wetland systems, there has yet to be a study conducted to assess variation in the adaptive capacity and transgressive migration potential of tidal wetlands across the entire U.S. Salish Sea region.

The overall goal of this thesis was to explore the variability of potential climate change influences on tidal wetlands and discuss implications for strategic conservation and restoration of current and future wetland areas. Since sediment accretion is a vital mechanism for tidal wetland persistence under sea level rise, the overall objective of Chapter 1 was to determine the relationship between sediment accretion and surface elevation in a restored and a natural wetland in the Stillaguamish River delta. The objective of Chapter 2 was to conduct a spatial analysis of potential tidal wetland responses to future climate change in the U.S. portion of the Salish Sea in order to simulate potential changes in tidal wetland distribution and extent under the influence of climate change and accelerated sea level rise. The objectives of Chapter 3 were to model the projected changes in tidal wetland without levee protection and to apply the findings of Chapter 2 to a framework identifying priority river deltas for strategic conservation and restoration of tidal wetlands.

Chapter 1 summary

Sediment accretion is vital for the persistence of tidal wetlands under the influence of future climate change impacts, especially accelerated sea level rise. Sediment accretion rates were measured for 1 year using sediment pins along elevation gradients in a restored zone and a reference zone in the Stillaguamish River delta. There was a negative linear relationship between sediment accretion rates and surface elevation in the restored zone but a quadratic relationship in the reference zone. Vegetation, including dominant vegetation species and vegetation height, also helped explain the pattern of sediment accretion rates. These results support that sediment accretion is controlled by many interacting and compounding factors, including surface elevation and vegetation. These relationships can be used to model the potential adaptive capacity of tidal wetlands to future accelerated sea level rise.

Chapter 2 summary

Modeling potential tidal wetland responses to future climate change is important for the development of strategic conservation, restoration, and management of these degraded and lost ecosystems. The Sea Level Affecting Marshes Model (SLAMM) was utilized to simulate tidal wetland conversion in the U.S. portion of the Salish Sea under a low and high sea level rise scenario. Total tidal wetland area was projected to decline under both sea level rise scenarios, but some wetland types (e.g., emergent marsh) were projected to expand. Projected local persistence was greater for tidal flat and emergent marsh compared to transitional scrub-shrub and tidal swamp. Although the projected amount of transgressive migration was small, this process may serve as a buffer for wetland loss by providing upland for the establishment of new wetland areas under accelerated sea level rise. The spatial distribution of potential tidal wetland responses to climate change can help identify priority needs for the restoration of loss wetland area, conservation of persistent tidal wetlands, and conservation of dry land to preserve areas for future migration.

Chapter 3 summary

Strategic conservation and restoration of tidal wetlands under a climate change framework is important for the allocation of resources for long-term benefits. The Sea Level Affecting Marshes Model was utilized to simulate the change in wetland area without levee protection. The projected change in total wetland area between initial conditions and 2100 switched from a decline with levee protection to an expansion without levee protection in the San Juan and Whidbey sub-basins and the Skagit and Stillaguamish River deltas under both SLR scenarios. A cluster analysis was then conducted to identify priority river deltas for conservation and restoration based on historical potential and degradation level under a climate change framework. The Skagit, Stillaguamish, and Snohomish river deltas were identified as high priority for conservation and restoration, followed by the Nooksack and Samish. Gradients of conservation and restoration priorities identified in this study can be used to select sites based on additional criteria, such as size or location preferences, land ownership constraints, and political and economic feasibility.

Limitations and data gaps

Preparing for the impacts of climate change is challenging because of uncertainties surrounding projections into the future, such as those associated with greenhouse gas emission levels, the ability of Earth systems to sequester carbon, and the effectiveness of human mitigation strategies (Adger et al. 2003).

Additionally, there are many limitations in modeling potential ecological responses to projected accelerated sea level rise and other climate change drivers. While many different models have been developed to simulate potential responses of tidal wetlands to accelerated sea level rise, they each have their own set of benefits and limitations. The Sea Level Affecting Marshes Model (SLAMM) was chosen for this analysis and has been previously used for select locations in the Salish Sea (e.g., Park et al. 1993; Glick et al. 2007).

The conversion of wetland and land cover classes in SLAMM is based on a specified range of surface elevation for each class, salinity, and water saturation. The amount of time vegetation may need to grow, particularly for transitional scrub-shrub and tidal swamps, and actually establish a healthy wetland community is not accounted for in the modeling processes. Additionally, SLAMM uses the 2001 IPCC sea level rise scenarios. While a particular rise in sea level can be specified, the relationship between time and sea level rise is scaled up and the trend of acceleration may not represent the most current projections.

There are also many data gaps and limitations for the Salish Sea that are input parameters for SLAMM. For instance, while the PSNERP geodatabase contains the most extensive database of current wetland distributions, it has not been updated since 2006 (Simenstad et al. 2011). Since then, many natural and anthropogenic changes to the distribution and extent of tidal wetlands have occurred in the Salish Sea. For instance, many restoration projects have since been completed. Additionally, the PSNERP geodatabase only included the location and extent of tidal wetlands. The distribution and extent of freshwater wetlands had to be taken from a different source, which contains its own errors and uncertainties. There is also no sufficient database of levee locations and heights throughout the Salish Sea.

The lowest elevation resolution used in the unioned DEM was 9.1 m by 9.1 m, which dictated the spatial resolution of the analysis. Many tidal wetland structures and processes occur at spatial scales smaller than this resolution and are, therefore, excluded from this analysis. Particularly, tidal creeks often occur at small spatial scales, but have strong influences on tidal wetland sediment dynamics (Hood 2007).

Areas of future research

Since there are still many data gaps in the Salish Sea, more field studies are needed to improve modeling. More research is needed on the projected changes in river discharge and sediment load under the influence of climate change. Additionally, more research is needed on the relationship between sediment load and sediment delivery to tidal wetlands. Very few studies have been published on sediment accretion rates in the Salish Sea (except see Thom 1992). More sediment accretion measurements are needed throughout the region and in different wetland types.

Additionally, sediment accretion is only one aspect controlling surface elevation change in tidal wetlands, in addition to subsurface processes, such as compaction, decomposition, and subsidence (Reed 1995; Nyman et al. 1993). In order to measure the combined influence of these processes on surface elevation change, sediment elevation tables should be used (USGS 2010).

Another area of future research would be to explore projected changes in tidal wetland area with varied amounts and locations of levee removal. The timing of levee removal is also important to consider. Tidal swamps and transitional scrub-shrub take longer to develop healthy and robust ecosystems compared to emergent marsh and tidal flat. Additionally, leveed land tends to subside compared to adjacent wetland due to compaction and decomposition (Knowles 2010). Once tidal inundation and sediment supply is returned to leveed land, time is required for sediment to re-build the surface elevation. Early restoration will allow more time for sediment accretion in subsided areas before it is most critical to have these wetlands as a buffer against accelerated sea level rise in later decades.

Interviewing conservation and restoration planners and managers would be useful in determining localized priorities and criteria for the analysis in Chapter 3. The framework for identifying priority sites for conservation and restoration could be regenerated and made adaptable based on project-specific criteria and goals. Analyzing priorities based on different spatial scales would also be beneficial, such as identifying smaller units of priority within a river delta to determine which specified location within a delta would benefit most from conservation or restoration. Overall, identifying priority areas for tidal wetland conservation and restoration under a climate change framework by modeling potential tidal wetland responses to accelerated sea level rice is beneficial for the allocation of resources now and into the future.

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