Assessing Tidal Marsh Vulnerability to Sea-Level Rise in the Skagit Delta

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Abstract

Historical aerial photographs, from 1937 to the present, show Skagit Delta tidal marshes prograding into Skagit Bay for most of the record, but the progradation rates have been steadily declining and the marshes have begun to erode in recent decades despite the large suspended sediment load provided by the Skagit River. In an area of the delta isolated from direct riverine sediment supply by anthropogenic blockage of historical distributaries, 0.5-m tall marsh cliffs along with concave marsh profiles indicate wave erosion is contributing to marsh retreat. This is further supported by a "natural experiment" provided by rocky outcrops that shelter high marsh in their lee, while being bounded by 0.5-m lower eroded marsh to windward and on either side. Coastal wetlands with high sediment supply are thought to be resilient to sea level rise, but the case of the Skagit Delta shows this is not necessarily true. A combination of sea level rise and wave-generated erosion may overwhelm sediment supply. Additionally, anthropogenic obstruction of historical distributaries and levee construction along the remaining distributaries likely increase the jet momentum of river discharge, forcing much suspended sediment to bypass the tidal marshes and be exported from Skagit Bay. Adaptive response to the threat of climate change related sea level rise and increased wave frequency or intensity should consider the efficacy of restoring historical distributaries and managed retreat of constrictive river levees to maximize sediment delivery to delta marshes.

Keywords: Marsh Erosion, Estuarine Sediment Routing

Introduction

Global climate warming is predicted to cause eustatic sea level rise (SLR) of 10 to 143 cm (median estimate = 62 cm) in the Seattle area during the next century, depending on complex feedback loops in natural systems as well as socio-economic systems (National Research Council 2012). This has caused concern for the fate of tidal marshes (i.e., herbaceous and shrub-dominated tidal wetlands), which lie in a narrow elevation band between terrestrial and marine ecosystems and that are often confined by development. Tidal marshes provide important services to society, such as fishery resources and shoreline protection from storms and tsunamis (Boesch and Turner 1984, Gedan et al. 2011). In the Pacific Northwest, the question of marsh survival is socially significant because tidal marshes provide rearing habitat for juvenile salmon, especially Chinook (*Oncorhynchus tshawytscha*), a threatened species in Puget Sound and an important cultural icon. Juvenile Chinook may rear several months in the marshes of their natal river deltas before migrating to deeper coastal waters (Healey 1982, Levy and Northcote 1982). Many other fish and wildlife, ranging from commercially important invertebrates to marine mammals also depend on Pacific Northwest tidal marshes (Simenstad 1983). In response to historical anthropogenic tidal marsh losses, amounting to 99% of oligohaline and 46% of estuarine tidal wetlands in Puget Sound (Simenstad et al. 2011), there is a significant regional effort to restore this critical rearing habitat to recover Chinook salmon. Will restoration need to be greater than planned to compensate for potential SLR-related marsh losses? The Skagit Chinook recovery plan recommends a target acreage of tidal marsh restoration to recover harvestable populations of Chinook, but this target does not account for potential marsh

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losses as a result of climate change impacts (SRSC and WDFW 2005).

Tidal marsh fate depends on competition between the rate of SLR and the rate of marsh aggradation (Allen 1990). Aggradation is dominated by deposition of mineral suspended sediment in macro- and mesotidal marshes, and by organic matter accumulation in microtidal marshes (e.g., Rybczyk and Cahoon 2002, Temmerman et al. 2004). Typically, when sediment supply exceeds the rate of SLR, marshes prograde; when the reverse is true, marshes erode. When sediment supply equals SLR, marshes merely aggrade and persist without horizontal growth or retreat. Many studies have found sediment-limited marshes drowning in response to SLR (e.g., Donnelly and Bertness 2001, Hartig et al. 2002), but when sediment delivery to the marshes is sufficiently high, marshes can survive very high rates of SLR (e.g., Temmerman et al 2004, Kirwan et al. 2010). Yet, there are several examples of marsh loss despite measured accretion equaling or exceeding relative SLR (e.g., Hartig et al. 2002, Van der Wal and Pye 2004). Hypothesized alternative causes of their vulnerability include dredging for navigation, boat traffic, and cultural eutrophication. Deep navigation channels may stress marsh systems by serving as sediment sinks that compete with the marshes for sediment, and by increasing tidal currents which increase marsh erosion. Increased boat traffic produces boat wakes which can also erode marshes. Eutrophication may be increasing the production of macro-algae which smother and kill tidal marsh vegetation leading to increased marsh erosion. Recently, the role of waves in marsh retreat has received greater attention, with several studies indicating waves can cause marsh retreat even without SLR (Mariotti and Fagherazzi 2013, Mariotti and Carr 2014). However, these studies also indicate that tidal marshes can withstand high wave energy if sediment supply is sufficiently high.

This paper provides evidence for risk of SLR impacts to Skagit Delta tidal marshes despite high sediment supply from the Skagit River. We suggest net sediment delivery to tidal marshes may be distinct from gross sediment delivery to an estuarine basin because of anthropogenically influenced sediment routing away from tidal marshes. We also provide evidence of significant wave erosion of Skagit marshes despite relatively fetch-limited conditions.

Methods

Site Description

The Skagit is the largest river flowing into Puget Sound, providing 35% of the Sound's freshwater input and 40% of its sediment load (Czuba et al. 2011). The sediment yield is driven by steep terrain, recent glaciation and two active volcanoes (Beechie et al. 2013). The river drains 8544 km^2 of the Cascade Mountains and ranges from sea level to 3285 m. Most of the basin is temperate coniferous forest in National Park, Federal Wilderness, National Forest, and State and private managed forest. Mean annual precipitation ranges from 80 cm in the lowlands to > 460 cm in the mountains. Much of the valley floor and more than 90% of the 308-km^2 Skagit Delta have been isolated from riverine and tidal influence by levees below Mount Vernon and surrounding Fir Island to accommodate agriculture and other uses (Collins et al. 2003). Most of the remaining tidal wetlands are located at the outlets of the North and South Fork distributaries of the Skagit River, with a narrow fringe of marsh seaward of the bay dikes between the two distributary outlets, hereafter distinguished as the bay-fringe marsh. Marsh sediments consist of organic-rich silt, silty clay and fine sand, while the unvegetated tide flats are fine to medium sand (Grossman et al. 2011). Fine sands are delivered to the marshes primarily during floods and are highest in abundance along distributary margins, where they naturally form low levees (Hood 2007a, 2010). Due to high river discharge, the marsh is mostly oligohaline and vegetation (from low to high elevation) is dominated by threesquare bulrush (*Schoenoplectus pungens* syn. *Scirpus americanus*), Lyngby's sedge (*Carex lyngbyei*), soft-stem bulrush (*S. tabernaemontani* syn. *Scirpus validus*), narrow-leaf cattail (*Typha angustifolia*), sweetgale (*Myrica gale*), willow (*Salix* spp.), and Sitka spruce (*Picea sitchensis*). Semi-diurnal tides range nearly 4 m; during higher high spring tides the marsh surface is inundated by up to 1.5 meters. Skagit Bay has a southerly fetch of 11 km, and with southerly winter storm winds typically reaching 20 m s^{-1}, sometimes higher, waves of at least 1-m height can occur (Raubenheimer et al. 2013).

SLR in the vicinity of Skagit Bay has been documented by tide gages at Port Townsend (since 1972) and Seattle (since 1898), with a mean relative sea level trend of 1.98 ± 1.15 mm yr^{-1} at Port Townsend and 2.06 ± 0.17 mm yr^{-1} at Seattle (http://tidesandcurrents.noaa.gov/sltrends/index.shtml). Land movement has been measured with real-time continuous global positioning surveying (GPS) at these locations since 2004 for Chimacum (near Port Townsend) and since 1996 for Seattle, by the Pacific Northwest Geodetic Array at Central Washington University. The same measurements have been made since 2007 at Sedro Woolley, near the apex of the Skagit Delta, and at Mount Vernon, half-way between Sedro Woolley and the delta shoreline. During this time, Seattle has been subsiding at a rate of 2.3 mm yr^{-1}, Chimacum at 3.2 mm yr^{-1}, and the two Skagit sites at 1.4 and 1.5 mm yr^{-1} for Mount Vernon and Sedro Woolley, respectively (± 0.1 mm yr^{-1} for all sites).

Progradation Rates

Marsh progradation and erosion were evaluated by GIS analysis of historical aerial photos. True-color photos were available for 2000 and 2011, while infrared photos were available for 2004. These photos were rectified and geo-referenced by the contractors who flew the photos. Photos from 1937, 1956, 1972, and 1991 were gray-scale and rectified in a GIS relative to the 2000 photos. All photos showed the delta at low tide, with the tidal flats clearly exposed. The 2011 photos were flown in the spring and had a pixel resolution of 30 cm; details for the other photos, including sources, resolution, and rectification and digitization error, have been previously described (Hood 2004, 2006). Marsh shorelines were digitized from the photos; the mean absolute shoreline error was < 3 m for all photos (Hood 2006 for details). Shorelines were defined by abrupt transition from vegetated marsh to unvegetated tidal flat. Unvegetated tidal flats have characteristic photo-signatures that are generally distinct from vegetated marsh. An exception was the bay-fringe marsh. Tidal flat and vegetated marsh could be clearly distinguished by their contrast in the gray-scale historical photos, but this was problematic in the modern true color and infra-red photos, likely because at the lowest marsh elevations the vegetation consisted entirely of low-density three-square. Thus, the bay-fringe shoreline was delineated in the field by survey-grade real-time kinetic (RTK) GPS; 3-cm horizontal and vertical accuracy) in 2012.

Linear regression was used to evaluate trends in marsh progradation/erosion rates. The independent variable was the midpoint of the time interval between consecutive historical aerial photos; the dependent variable was the change in marsh area divided by the number of years in the interval, i.e., the mean annual rate of progradation (positive change) or erosion (negative change). Statistical significance was defined as $P < 0.05$.

Sediment Delivery

Fluvial sediment load to the delta since 1937 was determined for the midpoints of the above-mentioned air-photo time intervals using a sediment loading flow-duration curve for USGS Stream Gauge 12200500 located just above the head of tide at Mount Vernon, Washington at river kilometer 25 (Curran et al., In Review). Briefly, sediment concentrations for a range of flow conditions between 2006 and 2011 were integrated with sediment load data collected in the 1970s to develop a refined sediment rating curve for the Skagit River. The rating curve provides a model of the Skagit River sediment load and error (uncertainty) for representative stream discharge, and seasonality of sediment delivery. Seasonal differences result from different sediment transport-flow relationships and varying sediment sources between winter rainfall-driven runoff and late spring/summer snowpack- and glacier-melt runoff. Sediment loads since 1937 were determined by relating the seasonal sediment rating models of Curran et al. (In Review) to the historical flow measured at the Mount Vernon Gauge. Mean sediment loads and rates of delivery were generated for each corresponding time period of the historical marsh accretion rate analysis. We assume the load calculated at Mount Vernon is representative of the load reaching Skagit Bay because extensive river levees confine almost all flows to the river channel and its outlets; only 25-year flood events and greater overtop the levees.

Another driver of sediment delivery are episodic landslides, which occur in response to major rainstorms. In recent decades landslides provide ~ 75% of sediment inputs to the Skagit River and have been exacerbated by forestry activities (Paulson 1997). For this study, landslide rates were calculated from landslide scars evident in aerial photos (Reid and Dunne 1996) taken since the 1960s at roughly decadal intervals. The landslide inventory spanned the 627 km^2 (8% of basin area) under commercial timber management and utilized data from previous inventories.

Topographic Analysis

Topographic data for the marsh and tide flats were available from lidar flown in April 2002 during a spring low tide (altitude of 2300 m; average sample spacing of 3 m, horizontal accuracy of 24 cm, and vertical accuracy of 15 cm). The data were processed to produce a bare-earth DEM (digital elevation model) by the contractor. DEM error was determined by RTK-GPS of 696 points in the tidal marsh. In early April, most low-elevation marsh vegetation is only a few centimeters high (e.g., sedge) so the ground is essentially bare and DEM versus GPS differences were small (mean = 5 cm). Topographic features at finer resolutions were surveyed with RTK-GPS. This included random transects perpendicular to the bay-fringe shoreline to distinguish marsh cliffs and pedestals from lower elevation tide flat surfaces, as well as pioneer marsh islands and their leeward depositional tails (see below).

The relative elevations of the 1972 bay-fringe marsh edge (the peak seaward extent of the bay-fringe marsh) were delineated in a GIS and compared to bay-fringe marsh edge surveyed with GPS in 2012. The delineated seaward boundaries were projected on the 2002 DEM and 53 random perpendicular transects were extended to intersect and sample paired sets of points on the two boundaries. Elevations at each intersection were determined from the underlying DEM, and compared between years using a one-tailed paired sample t-test. Comparison of the relative elevations of the 1972 and 2012 marsh edges was exploratory in nature and assumed the relative elevation difference of the two projected marsh edges, i.e., the tide flat slope, had not changed over the intervening years. The validity of this assumption will be examined in the results.

Landform Analysis

To infer wave erosion on the bay-fringe marsh, the morphology of a known erosional landform (reference system) was compared to that of a suspected erosional landform (test system) through allometric analysis (Bull 1975, Hood 2007b). A system is allometric when the relative rate of change of one part of a system (y) is proportional to the relative rate of change of another part of the system (x), or of the whole system. Allometric models are described by power functions, $y = ax^b$, which can be linearized through log transformation. Similar allometric scaling in different systems suggest similar processes are occurring that give rise to similar forms. The reference system was provided by small pioneering marsh islands on the North Fork tidal flats that shelter a tail of sediments deposited by river currents in their lee; u-shaped scour pools are formed on the upstream side of the islands. Analogous landforms have been described in braided rivers where mid-channel islands with similar sediment tails and scour pools are initiated by large downed trees (Gurnell et al. 2005). The test system was a set of rocky outcrops in the northern end of the bay-fringe marsh that appeared to shelter high-elevation marsh in their lee (relative to prevailing storm winds and waves), while being surrounded by lower elevation marsh windward and laterally. The independent variable for allometric analysis was island area, i.e., the area of the vegetated marsh island for the reference system and the area of the rocky outcrop for the test system. The dependent variable was the area of the depositional tail for the reference system and the area of the leeward high marsh for the test system. The depositional tail of the reference system was distinguished by its higher elevation and smooth texture relative to the surrounding rippled tidal flat. The sheltered leeward marsh of the test system was distinguished in a GIS by false-color infra-red photo-signature differences between high and low marsh, and elevation differences mapped by the DEM. Where the leeward marsh formed a peninsula rather than an island, the peninsula junction with the mainland was defined as the limit of the leeward area. Linear regression of the log-transformed variables was used to compare slopes (= scaling exponent) and elevations of the reference and test system scaling relationships (Zar 1984).

Results

The Skagit North Fork marshes have shown net progradation from 1937 to the present; a few areas of local erosion were more than offset by progradation elsewhere (Figure 1). The South Fork marshes have also prograded significantly since 1937, but in recent years there have also been areas of significant erosion (Figure 2). Recent progradation includes new marsh at the mouth

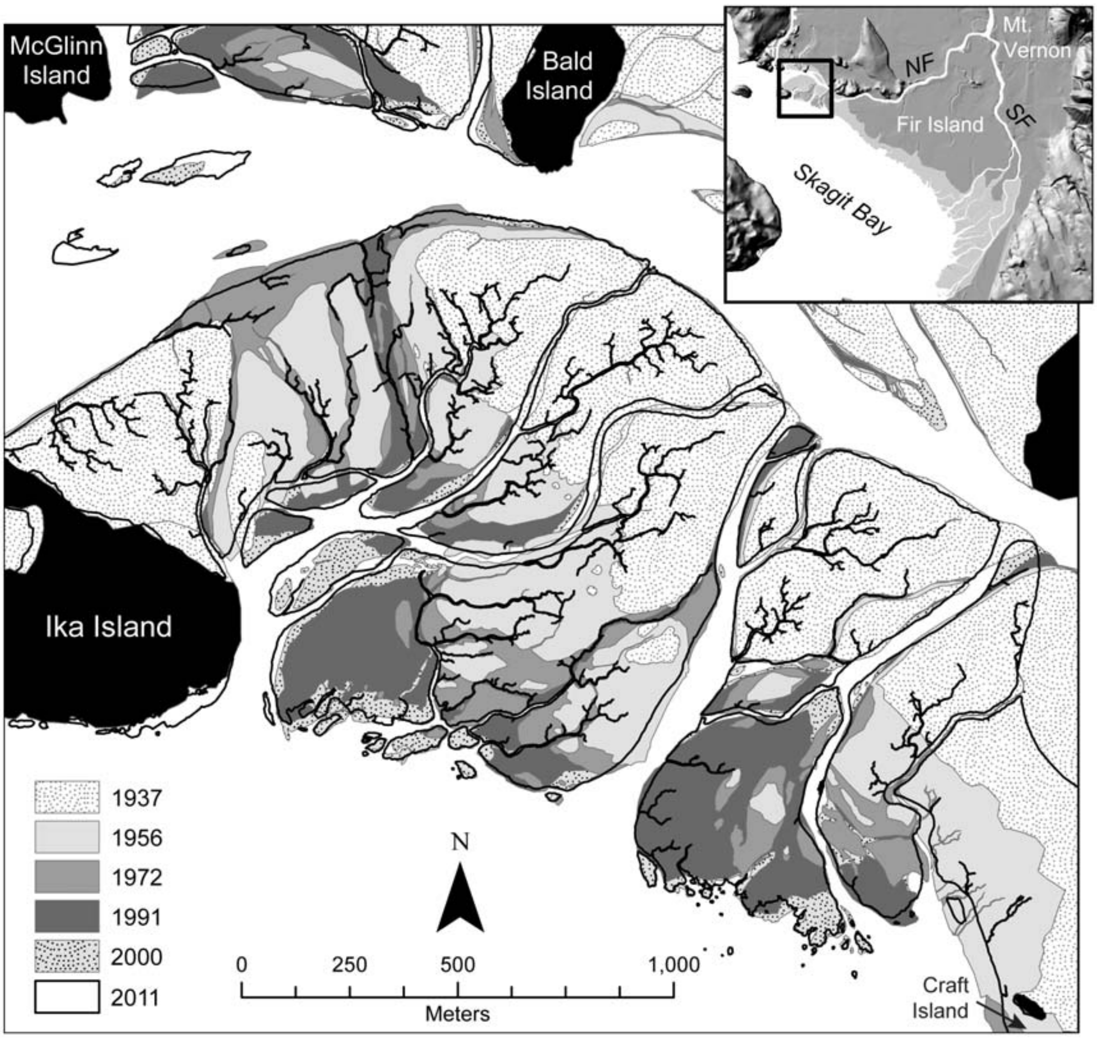

Figure 1. Marsh progradation history in the North Fork Skagit River sub-delta from 1937 to 2011. For graphic clarity only a sub-set of all available time periods are shown. The 2011 shorelines are overlain on those of previous time periods to show a few areas of local erosion or channel movement.

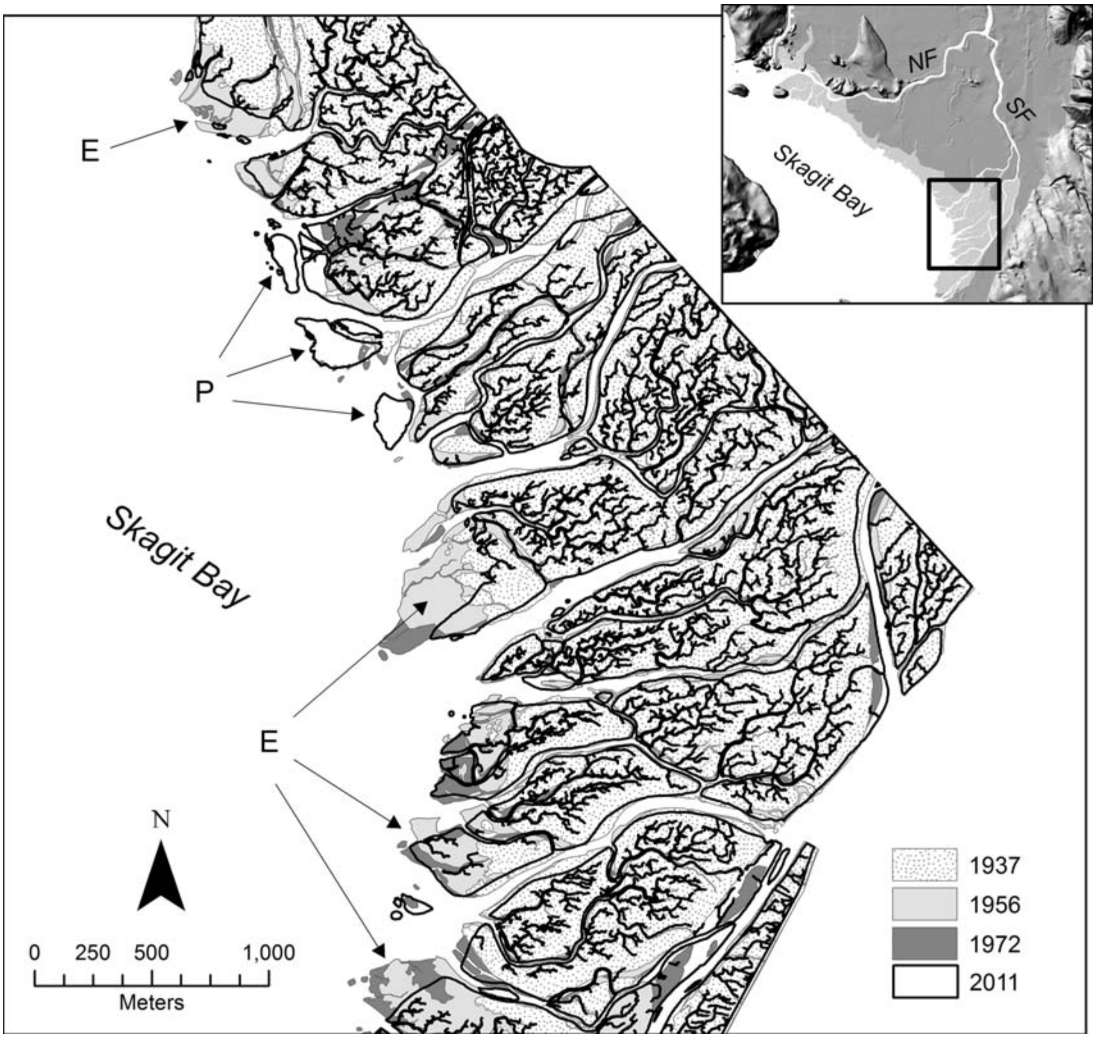

Figure 2. Marsh progradation history in the South Fork Skagit River sub-delta from 1937 to 2011. For graphic clarity only a subset of all available time periods are shown, over a portion of the South Fork area. Relatively recent progradation (areas labeled "P") has occurred at the mouth of Freshwater Slough, the principal South Fork distributary. Areas of erosion (labeled "E") are located throughout the bayward edge of the marshes.

of Freshwater Slough, the principal distributary of the South Fork system, as well as channel shoaling and narrowing in Tom Moore Slough at the southeastern edge of the delta. Erosion includes Freshwater Slough widening since 1937 and recent retreat of the seaward edge of the South Fork delta almost everywhere except the mouth of Freshwater Slough. The bay-fringe marsh prograded from 1937 to 1972; from 1972 to 2012 the marsh retreated almost everywhere along its length (Figure 3). Retreat was greatest in the north half of the marsh, averaging 120 m compared to an average of 45 m in the south half (n = 30 random spot measurements for each half). Relative to the 2002 lidar, the bay-fringe marsh shoreline was 17 ± 1 cm (mean ± standard error) lower in 1972 than in 2012 ($P << 0.0001$), assuming no significant change in tide flat slope during this time. In comparison, local SLR at a rate of 2 mm per year amounted to 8 cm during the last 40 years, while accounting for slower subsidence in the Skagit Delta relative to Seattle would suggest

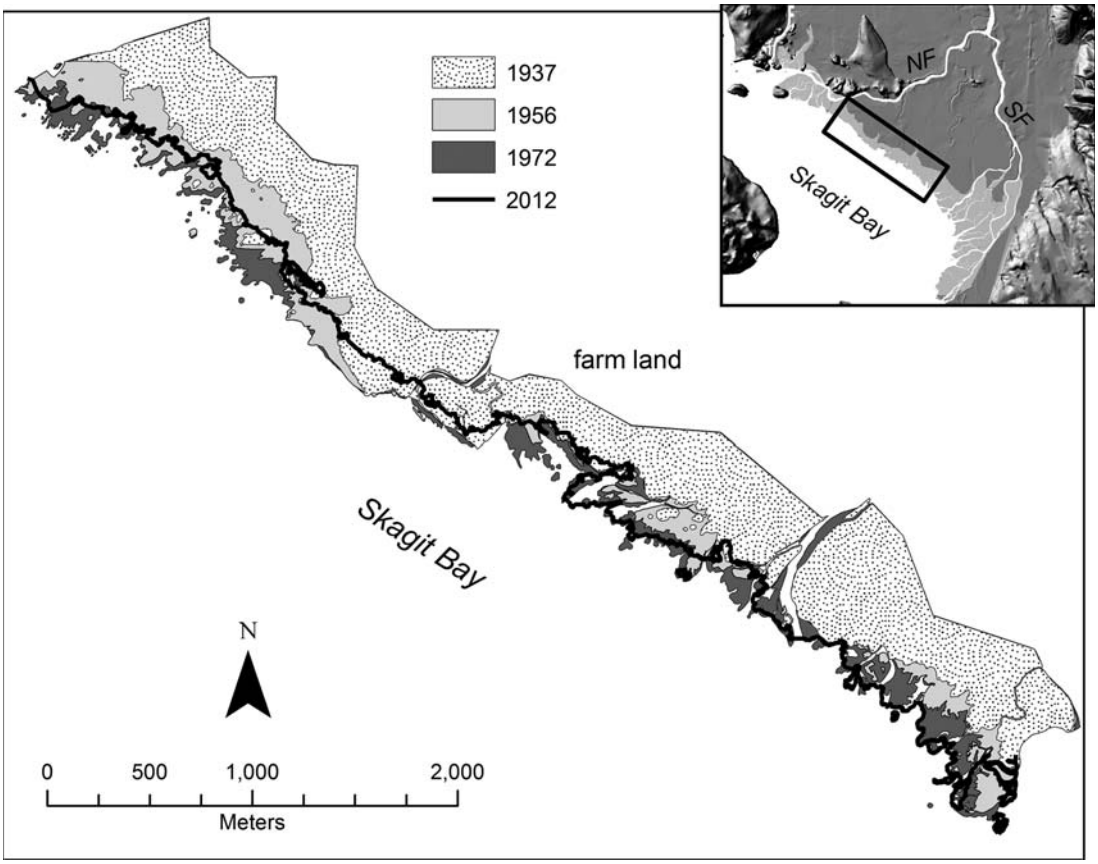

Figure 3. Marsh progradation history in the bay-fringe marshes from 1937 to 2012. For graphic clarity, only a subset of all available time periods are shown. The greatest seaward extent of the marshes occurred in 1972, with erosion along most of the marsh edge since then, but especially along the northern 70% of the shoreline.

only 5 cm of relative SLR in Skagit Bay. While progradation predominated during much of the photo-record, especially in the North and South Fork deltas, the rate of progradation declined steadily throughout the Skagit Delta (Figure 4). Net progradation rates have been negative since 1972 in the bay-fringe marsh, since 1991 in the South Fork marsh, and are close to zero currently in the North Fork marsh. In contrast to steadily declining progradation rates, sediment loads reaching Skagit Bay increased 3% from the 1940s to the early 1990s followed by an abrupt 11% decline from their maxima to the present. Sediment delivery trends are consistent with tandem Western Washington timber harvest and Skagit Basin landslide history. All three show increases from the 1960s to the late 1970s/early 1980s and a sudden decline from the 1990s to the present, with landslides lagging timber harvest and paralleling sediment delivery; sediment delivery and landslides are correlated because both are driven by precipitation/snowmelt events.

The bay-fringe marsh has a continuous marsh cliff along its length that distinguishes a comparatively high-elevation marsh dominated by sedge from low-elevation marsh dominated by three-square that grades smoothly into the sandy tide flat (Figure 5). Marsh pedestals are common seaward of the cliff and are likewise dominated by sedge. The pedestals and cliff are both ~ 0.5 m higher than the adjacent low-elevation marsh. Marsh cliffs are known to be formed by marsh erosion (Van de Koppel et al. 2005, Mariotti and Fagherrazzi 2010), so the pedestals appear to be

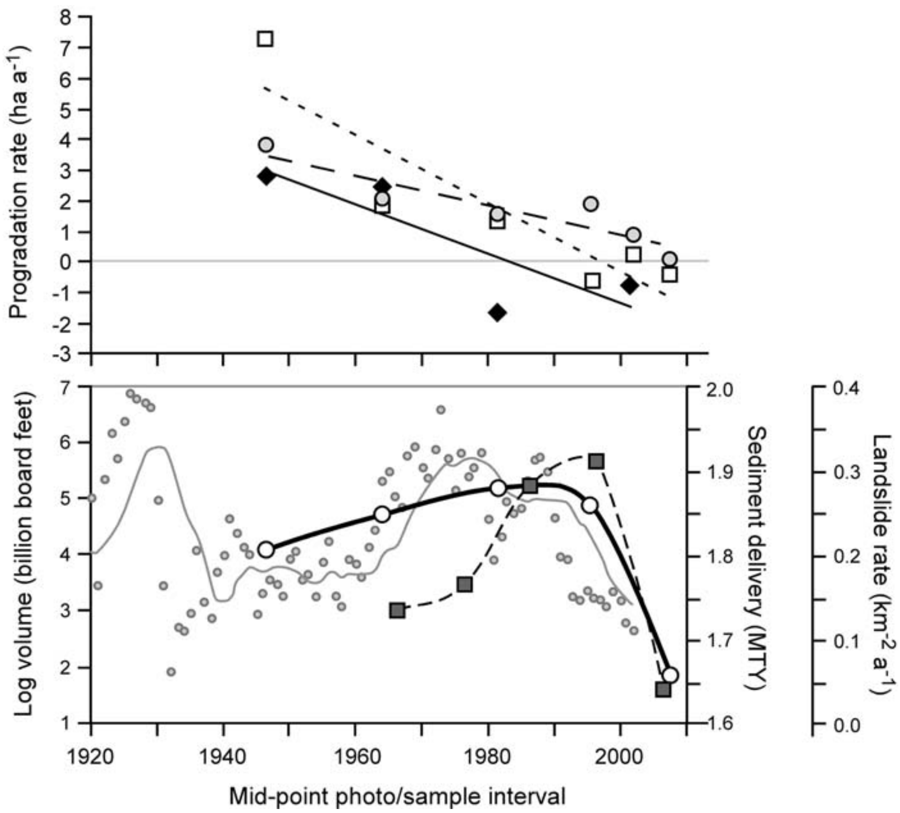

Figure 4. [Top frame] Progradation rates calculated from historical aerial photos, for the North Fork sub-delta (gray circles and dashed line; y = -0.0476x + 96.1; R^2 = 0.82); the South Fork sub-delta data (open squares and dotted line; y = -0.1118x + 223.3; R^2 = 0.81); and the bay-fringe marsh (black diamonds and solid line; y = -0.0804x + 159.5; R^2 = 0.70). Negative values represent net erosion. [Bottom frame] Skagit Basin landslide rates (dark squares) and sediment delivery to Skagit Bay (white circles) plotted for similar photo intervals as for observed progradation rates, and compared to Western Washington timber harvest (small gray circles; gray fitted line is the 10-yr moving average). Progradation declined even during a period of increasing timber harvest, subsequent landslides, and sediment delivery.

Figure 5. View of marsh cliff (near background) and a patch of marsh pedestals (foreground), field indicators of marsh erosion. Photo taken March 2010 prior to spring regrowth of vegetation. Tide flats in the foreground appear unvegetated, but are covered by threesquare by late spring or early summer. Sedge predominates on the pedestal tops and higher marsh plain.

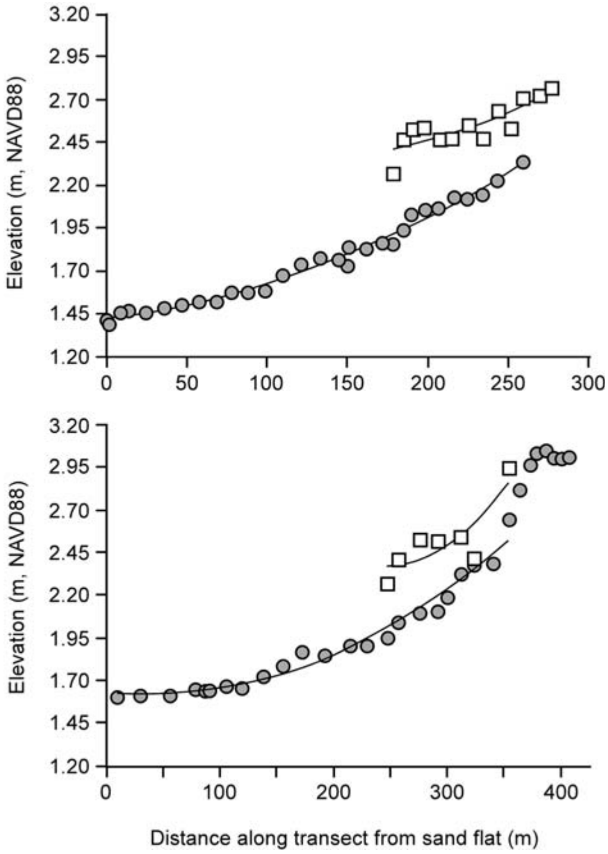

Figure 6. Representative profiles across the bay fringe marsh (grey circles), passing through areas of marsh pedestals (white squares), which were surveyed on the pedestal tops and near their base. At lower elevations vegetation is almost exclusively threesquare; sedge predominates on pedestal tops and the landward marsh plain. Fitted curves are second-order polynomials.

remnants of a retreating marsh cliff. Profiles of the bay-fringe marsh indicate the marsh pedestal and matrix marsh surfaces have concave topographies (Figure 6), which indicate long-term wave erosion (Friedrichs and Aubrey 1996, Le Hir et al. 2000).

Rocky outcrops at the north end of the bay-fringe marsh provided a natural experiment to test the role of waves on marsh erosion (Figure 7). The three smallest outcrops were 1.5 m higher than the marsh in their lee. Craft Island and an associated adjacent island were 24 and 4 m higher, respectively, than their leeward marsh. Marsh windward of these outcrops consisted exclusively of low-elevation three-square; leeward marsh was dominated by high-elevation Lyngby's sedge and tufted hairgrass (*Deschampsia caespitosa*) for the three small outcrops, and by Baltic rush (*Juncus balticus*), saltgrass (*Distichlis spicata*), and Lyngby's sedge for the Craft Island complex. Topographic signatures inferred from false color infra-red aerial photos and from lidar were confirmed in the field. Scaling of leeward marsh area with outcrop area was similar to that of leeward sediment tail area with the area of pioneering marsh islands colonizing the tidal flat. Although the elevation of the regression lines differed by a factor of 10, scaling exponents were identical, suggesting similar erosive processes were occurring for both systems (Figure 8). The 10-fold greater leeward area for the rocky outcrops is presumably due their greater height above the ground surface—the pioneering marsh islands were < 30 cm higher than their sediment tails.

Discussion

Numerical models, experimental scale deltas, and empirical observations show that with stable sea level and stable sediment supply, river delta land area (i.e., tidal marsh and floodplain) grows at a constant rate (Wolinsky et al. 2010a). Decelerating delta growth occurs when SLR leads to sediment diversion from areal expansion to vertical aggradation (Wolinsky et al. 2010b). Decelerating delta growth could result from decelerating sediment supply, but within Skagit Bay estimated sediment delivery accelerated from the 1930s to the 1980s. Sediment delivery can be increased by high rates of timber harvest, and timber harvest records for Western Washington, reflecting logging activity in the Skagit watershed, similarly showed bimodal peaks from 1920–1930 and again from 1964–1990. The latter peak was followed by a related peak in landslide frequency. Peaks in logging, landslides, and sediment delivery had no evident effect on the steadily declining marsh progradation rates. While dams can intercept river sediment, Skagit Basin dams were constructed

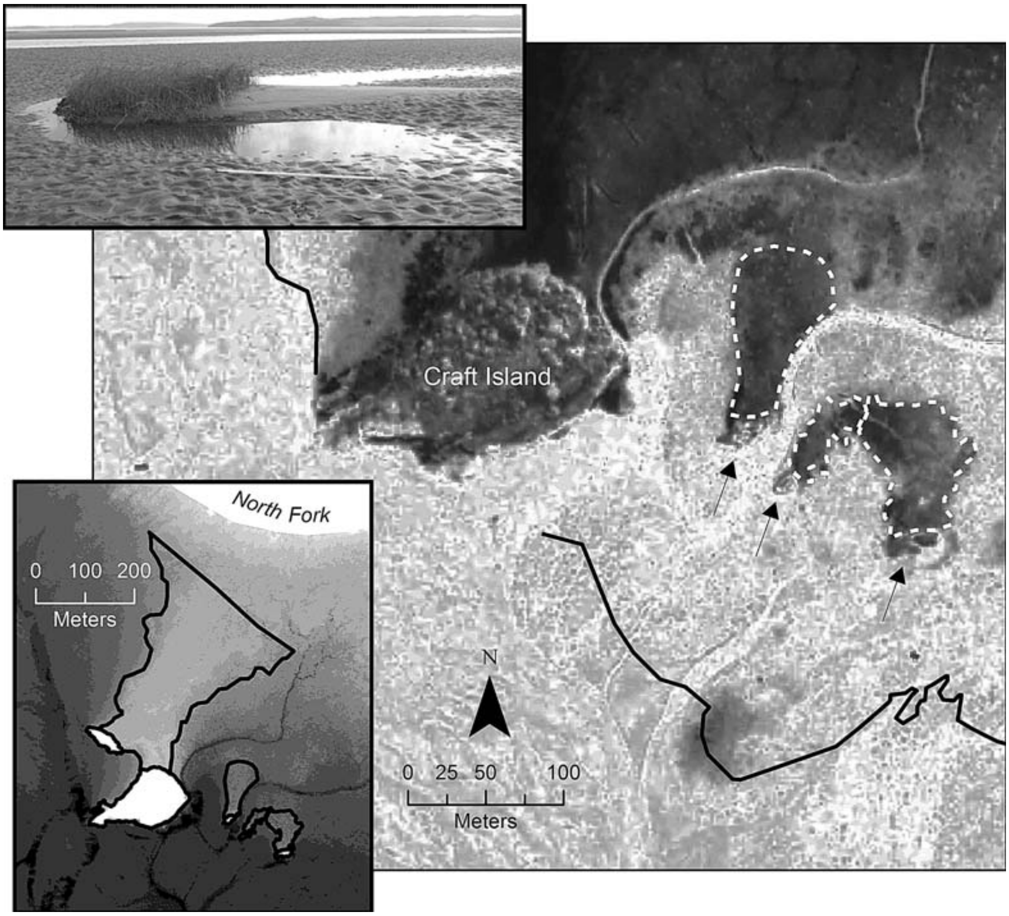

Figure 7. [Main figure] Craft Island and smaller rocky outcrops (at arrow tips), showing lee-ward protection of the tidal marsh (dashed outlines) from wave-driven erosion. The seaward marsh edge (black line) was mapped with GPS. In this photo, low elevation marsh is exclusively threesquare and difficult to distinguish from unvegetated tide flat; high elevation marsh (dark areas) is dominated by sedge. [Lower inset] A larger-scale lidar image (bare earth DEM) of the rocky outcrops and their spatial relationship to distinct leeward topography. Lighter shades (except the river) denote higher elevation. Outcrops and associated leeward areas are outlined in black. The North Fork distributary at the top of figure forms a natural levee along its bank. [Upper inset] Analogous topography of a small vegetation patch colonizing the tide flat. A u-shaped scour pool develops on the upstream and lateral island margins, while a sediment tail accumulates in the lee. A 1.5-m survey rod is in the foreground for scale.

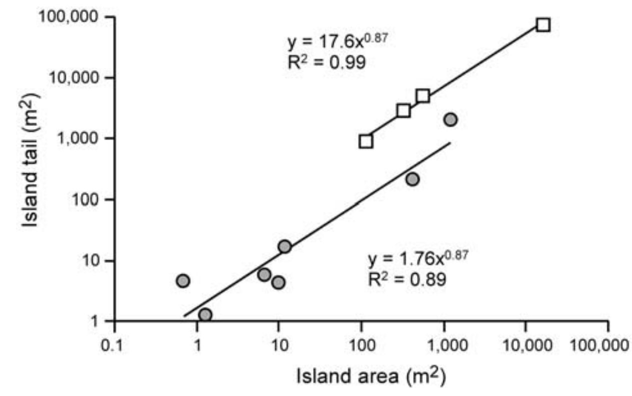

Figure 8. Scaling of island area with leeward accumulations of sediment tails for vegetation patches colonizing bare tide flats (gray circles), compared to rocky outcrop (open squares) scaling of island areas with protected leeward marsh (tails). Identical scaling exponents suggest similar or analogous processes of erosion and leeward protection.

prior to 1930, so they have likely had a constant effect on suspended sediment trapping since 1937.

From discrete suspended sediment data collected over the last 24 years just above the head of tide, an estimate of the mean suspended sediment concentration (SSC) has been derived that amounts to 162 mg L^{-1}, although when river flows above the 2-yr return frequency are excluded the mean drops to 138 mg L^{-1} (Khangaonkar et al. 2014). With this SSC history as input, a 3-D numerical model of the Skagit River plume indicated that SSC in the top 1/3 of the water column ranges from 10–130 mg L^{-1} during flood tides in the South Fork delta, 10–90 mg L^{-1} in the North Fork delta, and < 20 mg L^{-1} over the bay fringe during average flow conditions (which occurred 92% of the time over the last 24 years) (Khangaonkar et al. 2014). These results agree with measurements over the South Fork tide flats, which found SSC up to 100 mg L^{-1} during flood tides (Webster et al. 2013). High SSC over the active North and South Fork deltas contrasts with low SSC over the bay fringe. This is the result of blockage of historical distributaries that once emptied into the bay fringe area. Kirwan et al. (2010) used an ensemble of simulation models to determine how critical SLR rate thresholds for marsh persistence or erosion depend on sediment supply and tidal range. Their results suggest SLR rates of up to 10 mm yr^{-1} are survivable with SSC of 10 mg L^{-1} in systems with a 3-m tidal range. Thus, SSC < 20 mg L^{-1} over the bay fringe marsh may indicate potential vulnerability to erosion, in agreement with observed marsh erosion in this area, especially when wave erosion is included in consideration. However, the declining progradation rates in the North and South Fork deltas, with net erosion in recent decades in the South Fork delta, are inconsistent with the model predictions of Kirwan et al. (2010) given high SSC estimates in those areas.

Despite high sediment delivery, the Skagit marshes are beginning to erode. Why? First, the numerical models of Kirwan et al. (2010) assumed time- and spatially-averaged values of SSC, but Skagit River sediment delivery has a bimodal seasonality that is not always synchronous with marsh vegetation growth. Tidal marsh vegetation greatly augments sediment settling relative to bare tidal flats; the denser and taller the vegetation the greater the sedimentation (Leonard and Reed 2002, Temmerman et al. 2005). In the Skagit Delta, at least half the annual sediment load is delivered during winter storms (Lee et al., this volume), when the above-ground biomass of marsh vegetation is minimal because of seasonal senescence. For the lowest vegetation zones, dominated by three-square and Lyngby's sedge, above-ground vegetation is essentially non-existent during the winter (Kistritz et al. 1983).

Future climate warming will cause winter precipitation in the Skagit basin to increasingly take the form of rain rather than snow. This is projected to increase winter river discharge at the expense of snowpack and summer river discharge. The result will be a large increase in winter peak flows and sediment transport and a decrease in summer sediment transport (Lee et al., this volume). This will further increase the asynchrony between sediment delivery and marsh vegetation growth, and thus decrease sediment retention efficiency in the delta marshes. Second, while abundant sediments are being delivered to Skagit Bay, only a fraction is likely being delivered to the Skagit marshes. The jet momentum of Skagit River discharge into Skagit Bay has been increased by blockage in the late 1950s of several large river distributaries that once emptied to the bay fringe, and by construction of confining river levees in the late 19th Century that eliminated river access to the floodplain. These actions are analogous to pinching a garden hose to change a dribble of water into a jet. Greater jet momentum causes river-borne sediments to be transported further into Skagit Bay, thereby bypassing the tidal marshes (e.g., Syvitski et al. 2005). Additionally, fine sediments delivered to the sandy Skagit tidal flats are efficiently transported to more distal parts of the dispersal system, diminishing their availability to the marshes (Webster et al. 2013). Consequently, since the levees were constructed there has been a change from a mud-rich tidal flat to a sandy one (Grossman et al. 2011).

However, sediment delivery, retention, and deposition are only part of the story. Several lines of evidence suggest wave-mediated erosion, particularly along the bay-fringe marshes, is also significant: (1) historical aerial photos show marsh retreat in the bay-fringe and South Fork marshes from at least 1972 to the present; (2) a natural experiment contrasts rocky outcrops sheltering high-elevation marsh vegetation in their lee to marsh at similar distances from the shore consisting entirely of low-elevation marsh vegetation; (3) shoreline profiles along the bay-fringe marsh are concave, indicating erosion; (4) marsh cliffs and remnant marsh pedestals are present throughout the bay-fringe marsh, also indicating erosion. Thus, even in fetch-limited environments, such as Skagit Bay, wave erosion can impair tidal marsh persistence. Mariotti and Fagherazzi (2013) modeled wave-induced erosion on marsh boundaries in fetch-limited environments and found that when sediment supply is constrained waves can cause irreversible marsh erosion even in the absence of SLR, with effects at least comparable to those of global warming-accelerated SLR. Observations in the sediment-starved bay fringe marshes of the Skagit Delta are consistent with their conclusion. The bay-fringe marsh shoreline was 17 cm lower at its 1972 apogee compared to 2012, while SLR during that time can only account for 5 cm of that change (accounting for subsidence rate differences with Seattle). The remaining 11 cm, in agreement with Mariotti and Fagherazzi (2013), appears best explained by wave-induced erosion. However, these calculations are approximate given uncertainty in the potential spatial variation of subsidence in the Skagit Delta and the short time scale of the real-time continuous RTK observations of subsidence.

Several system stressors may be facilitating wave-induced marsh erosion. Numerical modeling suggests marsh disturbance, e.g., goose grazing, can potentially reduce vegetation biomass, thereby reducing marsh accretion rates below the rate of SLR and causing marsh erosion (Kirwan et al 2008). Field experiments in the nearby Fraser Delta supported the model results. Lesser snow geese (*Chen caerulescens caerulescens*) extensively graze three-square in the Fraser Delta. Marsh protected by goose exclosures had higher plant biomass and accretion rates, while grazed marsh showed net erosion (Kirwan et al 2008). Snow geese are also abundant in the Skagit Delta where they reach seasonal populations of up to 55,000 and likewise grub three-square rhizomes and feed on sedge shoots. The extent of their rhizome feeding has not been documented in the Skagit Delta, but they have been observed (WGH) to mow nearly all the early spring sedge growth in the marsh.

Another potential disturbance that may facilitate marsh erosion is burial of marsh vegetation by macro-algal wrack. While surveying the 2012 bay-fringe marsh shoreline, large patches of algal wrack were ubiquitous within the first 20 m of the marsh boundary; occasionally, patches were found up to 100 m into the marsh. The algal wrack consisted of gutweed (*Ulva intestinalis*) with accumulations up to 30 cm deep in patches tens of square meters in size. When the patches were removed, the lower layers were black and had a strong smell of hydrogen sulfide, indicating strongly reducing conditions. Marsh wrack is known to kill marsh vegetation by direct physical impact (crushing and obstructing sunlight for photosynthesis) and by indirect chemical impact (decomposition leading to sulfide generation and poisoning) (van Hulzen et al. 2006, Newton and Thornber 2013). Nutrient pollution causes large macro-algal blooms with ecosystem-scale consequences (Valiela et al. 1997). Given the agricultural character of the Skagit Delta, nitrogen pollution from agricultural sources may be contributing to macro-algal blooms and thus indirectly contributing to marsh erosion. Additionally, tidal marsh plants have been shown to reduce root productivity in response to N-enrichment, with the resulting decreased root strength leading to increased marsh erosion (Turner 2011, Deegan et al. 2012).

Management Implications

Historical aerial photographs clearly show that Skagit Delta marsh progradation rates have been declining and are becoming negative, with marsh loss already occurring in the bay fringe marsh and to a lesser degree in the South Fork marsh. It is also clear that storm waves contribute to marsh erosion, especially in the bay fringe marsh. SLR will exacerbate wave erosion and marsh loss. Thus, the Skagit Delta marshes show clear evidence of vulnerability to SLR. However, the fate of sediments delivered to the delta, what fractions bypass the delta or are retained in the vegetated marshes, is unclear. Better quantification of sediment fate is required to determine to what degree anthropogenic occlusion of historical distributaries and construction of constrictive levees are responsible for net sediment export from the system, and whether remedial actions such as distributary restoration or levee set-back can significantly reduce the jet momentum of the river to reduce sediment export and thereby improve marsh resilience. Also unclear is the importance of some potential biotic system stressors. While snow goose grazing is significant in the nearby Fraser Delta, their impact on Skagit Delta marshes has not been assessed. If goose grazing were shown to similarly impact the Skagit marshes, changes in hunting management might direct hunters to the most affected areas to discourage grazing. Alternatively, grazing might be managed with goose exclosures. Similarly, if algal wrack were shown to be a significant impact, this would argue for reductions in N-pollution from Skagit watershed sources to reduce algal blooms.

The Skagit tidal marshes are vulnerable to erosion over the next century due to global warming-induced SLR, changes in river hydrology, and more seasonal sediment delivery. Changes in marsh vegetation composition are also possible. For example, numerical modeling indicates SLR of 46 cm coupled with diminished snowpack and decreased summer flows will lead to a salinity increase of 1 psu in the Skagit estuary (Khangaonkar et al. 2016, this volume); higher SLR will cause a greater salinity increase. This salinity increase will likely impact vegetation species composition and distribution (Crain et al. 2004), especially for salt-sensitive woody shrubs in the currently tidal freshwater marsh. Loss of tidal shrub habitat will impact tidal beaver and the juvenile salmon that rear in low-tide beaver ponds (Hood 2012). The current Skagit Chinook recovery plan (SRSC and WDFW 2005) does not account for potential future marsh loss from climate warming and SLR, nor for vegetation change. Thus, the current plan's goal for tidal marsh habitat restoration is likely an underestimate of the amount necessary for salmon recovery. Future restoration planning should include not only greater direct restoration of historical marsh acreage, but also restoration of historical distributaries to improve delivery and distribution of freshwater, sediments, and migrating fish to the Skagit Delta marshes. Reducing river jet momentum, through distributary restoration and retreat of confining levees along existing distributaries, would likely increase retention of suspended sediments in the Skagit Delta marshes, thereby increasing their resilience to future SLR.

Our observations suggest high suspended sediment delivery is not always sufficient for marsh persistence in the face of accelerated SLR. Estuarine sediment routing, wave erosion, and biological disturbance are also critical processes affecting marsh persistence. Improving our understanding of these processes is essential to predict marsh resilience to SLR, and to take appropriate management actions to mitigate any predicted SLR impacts.

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