Spatiotemporal variation in Oregon salt marsh expansion and contraction

Erin K. Peck[1,2] & Robert. A. Wheatcroft[1]

[1]Oregon State University, College of Earth, Ocean, & Atmospheric Sciences, Corvallis, OR 97331, USA (EKP: peckerin@oregonstate.edu; RAW: rob.wheatcroft@oregonstate.edu)

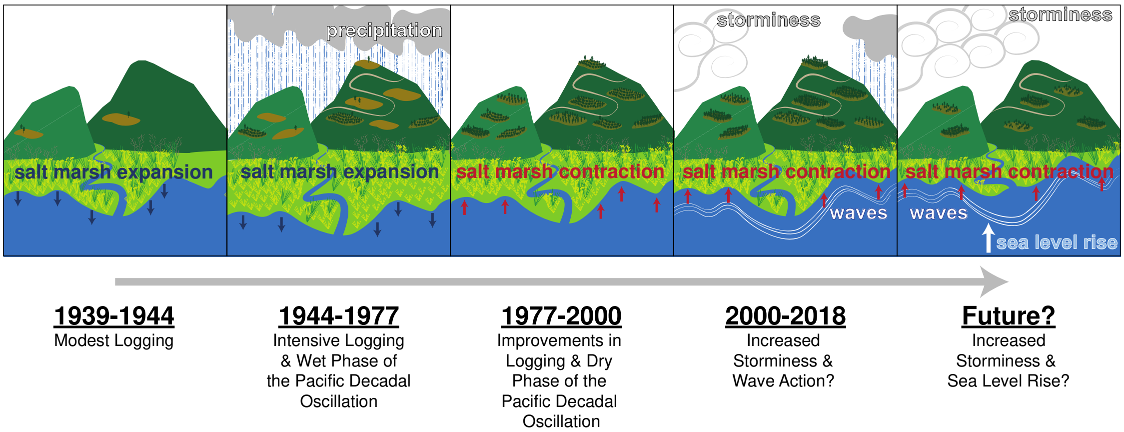
[2]University of Delaware, Plant and Soil Sciences, Newark, DE 19716, USA (Present Address)

Corresponding author: Erin Peck (peckerin@oregonstate.edu)

Key Words: salt marshes; geographic information systems; land use; sediment dynamics; morphodynamics; lateral change

Regional Key Words: USA, Oregon coast

Graphical Abstract



Abstract

Spatiotemporal patterns of salt marsh lateral change vary along the Oregon coast, reflecting complex drivers of marsh morphodynamics. To identify potential factors influencing salt marsh expansion/contraction, time-series (~10 y resolution over ~80 y) of marsh edge position and area were measured from aerial imagery in five Oregon estuaries with variable morphologies, fluvial sediment supplies, relative sea level change, and vertical accretion rates. In estuaries where there exists room for marsh growth onto unvegetated tidal flats, net lateral expansion occurs when vertical accommodation space is filled and under relatively high sediment supplies. Moreover, results suggest that conditions promoting elevated sediment supply in the mid-20th century – intensive timber harvest coincident with increased precipitation during the wet phase of the Pacific Decadal Oscillation (PDO) – caused marsh expansion. In the late 20th century, rates of expansion have slowed, sometimes giving way to net contraction; conditions favoring slowed sediment supply – reduced timber harvest and improved logging methods combined with reduced precipitation/discharge during the dry phase of the PDO – are likely culprits. More recently, edges continued to contract possibly forecasting vulnerability under future accelerated sea level rise. In addition to providing rates of salt marsh expansion/contraction for an understudied portion of the US coastline, these results highlight the importance of considering current salt marsh trajectories in the context of past land use and time-varying hydroclimate.

1 Introduction

Salt marshes provide numerous ecosystem services, including flood protection, habitat, and carbon burial (Barbier et al., 2011), yet are increasingly threatened by climate and land-use changes (Gedan et al., 2009; Weston, 2014). As such, determining rates and mechanisms of salt marsh vertical accretion and lateral expansion/contraction is of great importance, especially for the parameterization of models that can predict the futures of coastal ecosystems and their services (Fagherazzi et al., 2020; Wiberg et al., 2020). Salt marsh vertical accretion – a product of accommodation space created by relative sea level rise, sediment supplied to the marsh platform, and autochthonous organic matter accumulation – has long been assessed as a measure of salt marsh vulnerability to drowning (Redfield, 1972). However, focus on vertical rates of change may neglect that lateral expansion/contraction contributes to the overall size of the salt marsh platform, and marshes may be particularly vulnerable to edge contraction more so than elevation loss (Kirwan, Temmerman, et al., 2016). More measurements of lateral rates and drivers of change are required to improve understanding of whole-platform morphodynamics, especially as empirical studies of lateral dynamics have lagged behind mechanistic investigations (Ladd et al., 2019). Lateral contraction at the marsh-tidal flat boundary is primarily a product of edge erosion, which occurs through wave attack exacerbated by increased water levels (a product of relative sea level rise, increased storminess, and fluvial discharge; Mariotti & Carr, 2014; Mariotti & Fagherazzi, 2010). Edge erosion may deliver sediment to starved platforms and simultaneous migration into adjacent upland forests may maintain overall salt marsh extent (e.g., Mariotti & Carr, 2014; Kirwan, Walters, et al., 2016; Carr et al., 2020; Ganju et al., 2020). Conversely, progradation has been observed to occur under high sediment supplies (Ladd et al., 2019), though examples of lateral expansion are less common, especially in estuarine systems of

US East and European Coasts (Fagherazzi et al., 2020). However, these assessments have generally focused on sediment-limited systems located on passive margins with wide coastal plains (e.g., the US East Coast; Langston et al., 2020; Molino et al., 2021).

Oregon salt marshes, which are under-represented in the global morphodynamic literature (e.g., Kirwan, Temmerman, et al., 2016), may represent valuable end-member examples that provide insight into potentially under-studied drivers of lateral change. This is because Oregon rivers have naturally high sediment loads (Wise, 2018; i.e., creating mineralogenic salt marshes); hydroclimatic variations that result in decadal changes in precipitation and discharge (Wheatcroft et al., 2013); different along-margin rates of sea level change (-1.5 to +2.5 mm y^{-1}; Komar et al., 2011); and variable bay morphologies impacting wave energy, though short fetches likely limit wave attack. Additionally, an ~30 y long period (1944 to 1977) of intensive timber harvest in the Oregon Coast Range coincident with the wet phase of the Pacific Decadal Oscillation (PDO; Andrews & Kutura, 2005; Wheatcroft et al., 2013) offers an excellent opportunity to assess the impacts of increased sediment supply on patterns of salt marsh lateral expansion. How these patterns changed in response to a subsequent ~40 years (1977 to 2018) of reduced logging (Richardson et al., 2018; Wetherell et al., 2021) and shifting hydroclimate (i.e., the PDO predominately in the dry phase) reveals the lasting impact of perturbations on salt marsh sediment accumulation and sediment routing systems, globally relevant to regions that experienced a similar history (e.g., deforestation and damming). Furthermore, assessment of rates and drivers of lateral change along the Oregon coast are important to local stakeholders because these salt marshes may be particularly vulnerable to loss (Thorne et al., 2018). Indeed, independent information indicates that ~85% of U.S. West Coast vegetated tidal wetlands have been lost due to diking and tide gate construction since Euro-American incursion (Brophy et al., 2019). Looking to the future, under accelerated sea level rise, more marsh area might be vulnerable to loss, especially since steep topography associated with the Oregon Coast Range prevents significant landward migration of existing salt marshes, deemed critical to marsh survival (Mariotti & Carr, 2014; Kirwan, Walters, et al., 2016; Carr et al., 2020; Ganju et al., 2020).

To assess potential long-term drivers of salt marsh expansion/contraction, we measured lateral growth rates over the last ~80 y in five Oregon estuaries: Nehalem, Netarts, Salmon, Alsea, and Coquille. These systems vary in terms of bay morphology, mean annual fluvial sediment supply, and relative sea level changes, and are relatively unimpacted by early 20th century dikes. The importance of these natural forcings in driving marsh expansion and contraction were assessed by comparing long-term rates of edge change across estuaries. Further, to assess the importance of changing land use and hydroclimate on coastal morphodynamics, roughly decadal rates of salt marsh expansion/contraction were calculated for each estuary. These rates were binned into four distinct periods to assess the relative importance of the PDO and history of timber harvest on salt marsh expansion/contraction. The results elucidate both spatiotemporal patterns of salt marsh lateral morphodynamics and potentially provide insight into future trajectories under changing climate and land-use scenarios.

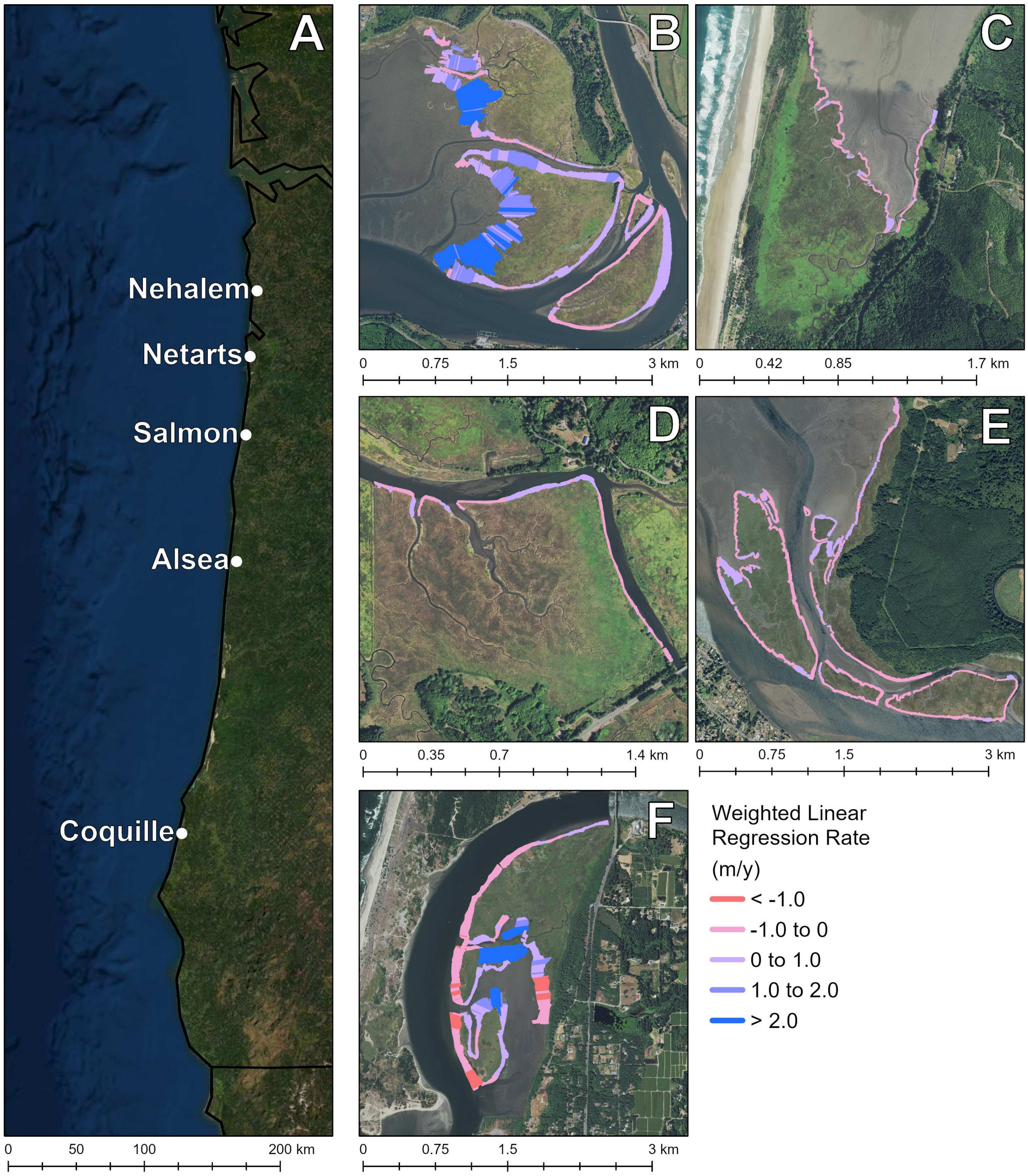


Figure 1. Oregon Coast **(a)** and aerial images from the 2018 Oregon Statewide Imagery Program of salt marshes from each estuary **(b-e)** Nehalem, Netarts, Salmon, Alsea, and Coquille, respectively). Colored transects display the rate of lateral salt marsh change from ~1940 to the present, calculated as the weighted linear regression of ≥ 6 digitized marsh edges with dates approximately every decade. Red indicates contraction, purple indicates no change, and blue indicates progradation. Transects are spaced 5 m apart.

Table 1. Estuary Characteristics

	Nehalem	Netarts	Salmon	Alsea	Coquille
Watershed Area (km^2)	2209	42	193	1221	2736
Relative Sea Level Change (mm y^{-1})	0.9 ± 1.0	1.5 ± 1.0	2.2 ± 0.9	2.8 ± 0.8	-1.4 ± 0.9
Sediment Load (x 10^3 t y^{-1})	224	2.5	20.1	110	178
Area Normalized Sediment Load (x 10^3 t km^{-2} y^{-1})[a]	56	2.6	30	52	105
High Marsh Vertical Accretion Rate (mm y^{-1})[b]	2.9 ± 1.0	1.9 ± 0.6	1.6 ± 0.3	1.7 ± 0.4	1.3 ± 0.3

[a] Sediment load is normalized to the 2018 marsh areas presented in Table S1; [b] from Peck et al., 2020

2 Methods

2.1 Sites & environmental data

The study estuaries (Figure 1) – Nehalem, Netarts, Salmon, Alsea, and Coquille – were chosen based on access to aerial photographs and variability in potential environmental drivers (Table 1). Rates of 20th century relative sea level change were previously calculated (Peck et al., 2020) as the difference in eustatic sea level rise (Mazzotti et al., 2008) and interseismic land uplift (Burgette et al., 2009). Vertical accretion rates were also previously measured by Peck et al. (2020) and provide insight into which systems are accumulating sediment faster or slower (i.e., drowning) than relative sea level rise.

Annual mean sediment loads were estimated using the U.S. Geological Survey's SPAtially Referenced Regressions On Watershed attributes (SPARROW) model (Wise, 2018), and were normalized to marsh area. Because time-varying rates of suspended sediment concentrations are unavailable for these systems, histories of timber harvest and fluvial discharge were determined as proxies for sediment yield. Volume (i.e., board feet) of timber harvested was estimated for and normalized to each watershed using county-specific timber harvest data (Andrews & Kutara, 2005) and the fraction of basin area within each county. Peak annual discharge and cumulative residual discharge (*sensu* Wheatcroft et al., 2013) were calculated from long-term (≤ 1939) daily discharge recorded on the Nehalem River near Foss, OR (USGS gauge:

14301000), Alsea River near Tidewater, OR (USGS gauge: 14306500), and South Fork of the Coquille River at Powers, OR (USGS gauge: 14325000). Salmon River is not gauged, and Netarts Bay has no major river. Monthly precipitation was determined at each of the stream gauge locations using the Parameter-elevation Regression on Independent Slopes Model (PRISM; Daly et al., 1994).

Wave heights and directions are not available for our estuaries of interest, but medium-term (≥ 15 y) hourly wind speed and direction data, which can identify expected hotspots of wave attack, were available for four stations spanning the Oregon coast (Astoria, Tillamook, Newport, and Coos) from NOAA's National Centers for Environmental Information. The wind database was queried for speeds > 10 m s^{-1}.

2.2 Lateral change

Salt marsh lateral change was quantified through comparison of roughly decadal aerial photographs from 1939 to the 1990s (scanned at the University of Oregon's Map & Aerial Photography Library) and 21st century aerial imagery downloaded from the Oregon Statewide Imagery Program (https://www.oregon.gov/geo/Pages/imagery_data.aspx; Table S1 and Figure S1). All images were georeferenced in ArcGIS Pro 2.2 using at least 10 control points and fitted using second-order polynomial transformations (e.g., Schieder et al., 2018). The seaward boundaries of salt marshes were hand digitized from georeferenced aerial photographs, and shoreline position uncertainties were estimated following Ruggiero et al. (2013). We excluded areas of marshes in which dikes or tide gates prevented inundation. To minimize the impact of unknown tidal height during image collection, low-resolution images and those that clearly displayed extensive flooding were excluded, and we focused interpretations on multi-decadal rates of shoreline and area change. Landward edges on fringing marshes were not analyzed as relatively limited rates of 20th century sea level rise have prevented much conversion of coastal forested wetlands to marsh (Brophy & Ewald, 2017). Further, in many areas the steep slopes of the hills that fringe Oregon marshes prevent landward migration.

Spatially variable rates of lateral change were calculated using the USGS Digital Shoreline Analysis System (DSAS; Himmelstoss et al., 2018) in ArcMap 10.7.1 over roughly decadal periods from 1939 to 2018 and integrated over the period of record. DSAS automatically placed transects at 5-m intervals perpendicular to digitized marsh edges. When calculating the rate of edge change integrated over all digitized edges, a weighted linear regression was fitted for any transect that passed through $\geq$ 6 edges (Figure S1). Error estimates associated with the weighted linear regression were calculated with 95% confidence intervals. When calculating the rate of change between each period in DSAS (Table S2; Figure S2), uncertainty was conservatively calculated as the sum of edge position uncertainties (Table S1) divided by the time elapsed between photographs; rate changes less than the uncertainty were considered not significant (i.e., neutral edge change; Figures 1 and S1). To compare the influence of wind waves on edge contraction, weighted linear regression rates of net change were queried for marsh edges lying perpendicular to oncoming winter and summer wind directions (wind directions relative to marsh edges were determined using the 2018 digitizations). Edges perpendicular to oncoming winds > 10 m s^{-1} are deemed exposed, and other edges are deemed protected. The mean rates of change were normalized to the percent edge length (rate x (edge exposed/total edge length)). These calculations were made for Nehalem and Alsea as these systems are comparable (similar depths and tidal ranges) and are likely more impacted by wind waves than bays that lack substantial fetch (Salmon and Coquille) or have salt marshes oriented away from the dominant oncoming wind directions (Netarts).

To calculate changes in area over time (Table S2), a current estuary extent map (Brophy et al., 2019) was used to create a fixed upslope edge position for the fringing marshes. Area uncertainties were calculated as the square of the position uncertainty. To determine the impact of time-varying hydroclimate and land-use change on marsh morphology, rates of area change were linearly interpolated to annual rates and then binned into four time periods of interest.

Spatial resolutions of aerial photographs (0.2 to 1.6 m) and root mean squared errors associated with georeferenced photographs (0.09 to 3.6 m) were consistently low; these values were generally best prior to 1980 and after 2000 (Table S1). As a result, shoreline position uncertainties (1.0 to 3.8 m) and area uncertainties (1.0 to 14 m^2, equating $\leq$ 0.1% of total area) were negligible (based conservatively on two significant figures).

3 Results

3.1 Temporally Integrated Rates of Lateral Change

Edge change rates integrated over all marsh edges from 1939 to 2018 using weighted linear regression were spatially variable (Figure 1). Coquille salt marshes experienced the fastest rates of net edge contraction and expansion (range = -1.8 to 6.1 m y^{-1}), while Salmon displayed the least amounts of edge change, ranging from -0.27 to 0.24 m y^{-1}. Net rates of edge change ranged from -0.90 to 5.1 m y^{-1} in Nehalem, from -0.31 to 0.60 m y^{-1} in Netarts, and from -0.72 to 0.92 m y^{-1} in Alsea.

Long-term area change rates, calculated as the difference in areas from the most recent and oldest photograph, revealed spatially integrated lateral fluctuations. Since 1939, Nehalem and Coquille net expanded in area by 22 and 4.6% (73 and 7.5 ha), equivalent to adding 0.92 and 0.095 ha y^{-1}, respectively (Figure 2). Netarts and Salmon have shown little net area change in the last ~80 y, having changed by 2.5 and -0.10%, respectively (2.4 and -0.067 ha or 0.030 and -9.2 x 10^{-4} ha y^{-1}). Conversely, Alsea net contracted by 3.6% (-8.0 ha), equivalent to -0.10 ha y^{-1}.

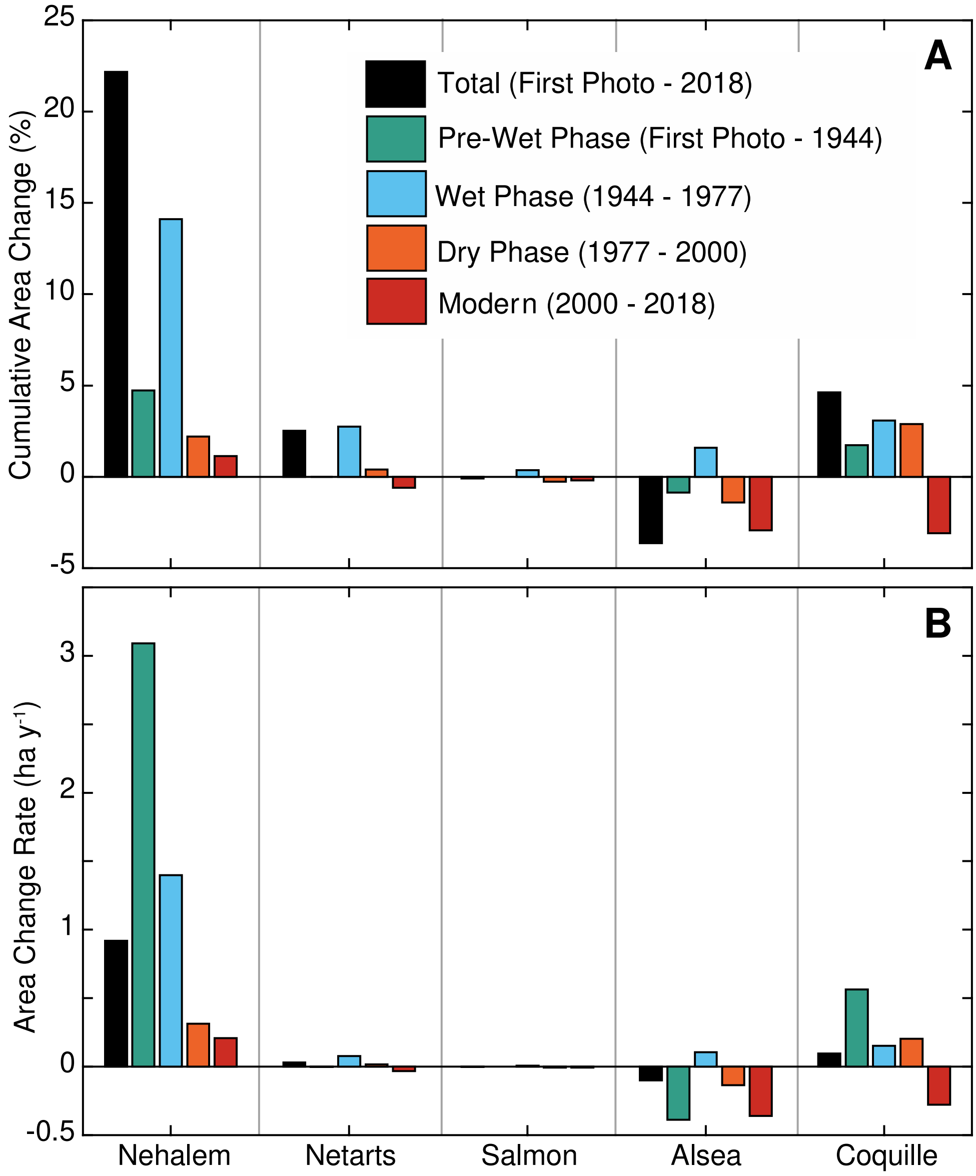


Figure 2. Bar plots of **(a)** cumulative area change and **(b)** area change rate for the five salt marshes for the total period of record and binned into five time periods. The first aerial photograph in all estuaries is 1939 except in Salmon, which is 1945. Salmon is therefore

excluded from the pre-wet phase period and the wet phase calculation is 1945 to 1977. Error bars are too small to be visible.

3.2 Temporally Variable Rates of Lateral Change

Each estuary displayed periods of salt marsh area expansion and contraction (Table S1). The fastest period of expansion occurred in Nehalem between 1939 to 1945, with the salt marsh gaining 3 ha y^{-1} (+19 ha total). Maximal contraction occurred in Coquille from 1942 to 1954, with the salt marsh losing 1.1 ha y^{-1} (-13 ha total).

When divided into four timeframes of interest, consistent patterns emerge along the Oregon coast (Figure 2). From 1939 to 1944, Nehalem and Coquille both added area (4.7 and 1.7%, respectively), while Alsea experienced its greatest loss of area (-0.88%), and Netarts did not change (-0.0053%; Salmon salt marsh did not have aerial photographs prior to 1945). From 1944 to 1977, all salt marshes gained area (Nehalem:14%, Netarts: 2.7%, Salmon: 0.37%, Alsea: 1.6%, Coquille: 3.0%). From 1977 to 2000, cumulative area gain slowed in all systems (2.2, 0.39, and 2.9% in Nehalem, Netarts, and Coquille, respectively), with Salmon and Alsea experiencing loss (-0.28 and -1.4%, respectively). From 2000 to 2018, all salt marshes either contracted (-0.60, -0.19, -2.9, and -3.1% in Netarts, Salmon, Alsea, and Coquille, respectively) or experienced the smallest addition of area, as was the case in Nehalem (1.1%).

4 Discussion

Net lateral changes since 1939 are variable amongst the five estuaries highlighting the complexity of salt marsh morphodynamics along the Oregon coast. These net lateral changes agree with earlier literature observations of general patterns of expansion/contraction, which exist for Nehalem (Johannessen, 1964), Coquille (Benner, 1992), and Alsea (Brophy, 1999). In addition to displaying variable net lateral rates of change over the last ~80 y between estuaries, rates of lateral change differed spatially along edges of each salt marsh complex and temporally on decadal timescales. To place these changes in a wider context, we investigate potential spatial and temporal factors influencing expansion/contraction.

4.1 Spatial controls on lateral expansion & contraction

Intra-estuary trends in salt marsh expansion/contraction are spatially variable (Figure 1) suggesting internal influencing factors that affect erosion are relevant. In general, edges along river channels are affected by high velocity flows and exhibit the highest rates of contraction. All salt marshes except Netarts, which is not associated with a major channel, are strongly fluvially influenced, and as such are located in the inner side of the river bends where velocities are slowest. Despite being positioned in "point bar" locations, these salt marsh edges all display areas of net contraction potentially as a combined result of high river discharge, tidal action, and wave attack from wind and wakes. For example, Coquille salt marsh displays the highest rates of net contraction (Figure 1F) on its channel edge. Conversely, edges that are protected from high-velocity channel flows appear to exhibit the fastest rates of lateral expansion as is most apparent in Nehalem and Coquille. These rapid rates of expansion are driven in part by relatively high area-normalized annual sediment loads (56 and 105 x 10^3 t km^{-2} y^{-1}, respectively; Table 1), as others have observed to be important elsewhere (e.g., Ladd et al., 2019). Rapid rates of spatially variable lateral expansion are, however, absent from the other systems. Low fluvial sediment inputs to Netarts limits edge expansion, while the lack of space (e.g., tidal flat or subtidal areas) in Salmon restricts growth.

The reasons for Alsea's lack of lateral expansion and net contraction are perhaps less clear. Alsea salt marshes have room for expansion onto tidal flats and subtidal regions of the bay and much of its edges are in protected areas. Indeed, the morphology of Alsea Bay is similar to that of Nehalem and both systems receive similarly high net fluvial sediment inputs relative to estuary areas. A major difference in these systems is the rate of relative sea level rise, which is low in Nehalem but relatively high in Alsea (0.9 ± 1.0 mm y^{-1} vs 2.8 ± 0.8 mm y^{-1}; Table 1), and relatedly, Nehalem salt marsh has been vertically accreting at a pace (2.9 ± 1.0 mm y^{-1}) exceeding the rate of relative sea level rise while Alsea has not been keeping up with sea level rise, i.e., it is drowning (1.7 ± 0.4 mm y^{-1}; Peck et al., 2020). Thus, a filled vertical accommodation space appears necessary for lateral expansion. In this way, the salt marsh edge geometry (whether the edge is a ramp or a step) may influence lateral expansion as a ramped edge is both indicative of and more conducive to expansion and a stepped edge of contraction (Goodwin & Mudd, 2020). While distinguishing ramped and stepped edges in aerial photography is difficult, others have noted these edge types as dominant features of Nehalem and Alsea, respectively. For instance, Nehalem added much of its area over the past ~80 y though growth of small (< 2 m diameter), circular, vegetated islands (termed "fairy circles"; Zhao et al., 2021) that eventually became incorporated into the prograding, ramped edge (Johannessen, 1964). Conversely, salt marsh edges in Alsea have been described as very steep and actively eroding (Dicken, 1961; Brophy, 1999). Others have observed linkages between lateral and vertical marsh morphology, though relatively less is understood about mechanisms and feedbacks driving three-dimensional growth/loss in sediment-rich systems (Ganju et al., 2020), characteristic of the Oregon coast.

A potential additional driver of intra-estuary edge contraction is wind wave attack (e.g., Fagherazzi et al., 2006; Marani et al., 2011). Most estuaries in Oregon have relatively short fetches (e.g., Salmon and Coquille) or salt marsh edges that are predominately oriented away from dominant oncoming winds (Figure 3A) from the SSW in Winter, NNW in Summer (e.g., Netarts), and are therefore likely less subject to wind-wave attack. However, when fetch is relatively long (up to 4 km), edges perpendicular to oncoming winter winds experience less expansion (Nehalem; Figure 3B) and more contraction (Alsea; Figure 3C) on average than other salt marsh edges, though neither of these rates are significantly different when compared to protected edges. Interestingly, in these same estuaries, edges perpendicular to oncoming northwesterly summer winds experience more expansion than other edges. Future field monitoring should investigate this; however, it is possible that summer wind waves redistribute estuarine sediment towards these edges resulting in growth. Regardless, both salt marshes have a smaller fraction of their edges perpendicular to oncoming summer winds than winter winds. Thus, winter wind is a greater erosive force than summer wind despite displaying similar speeds (Figure 3A), possibly because of increased water levels from fluvial discharge, onshore Ekman transport (Komar et al., 2011), and storm surge due to atmospheric rivers (Khouakhi & Villarini, 2016). Overall, however, wave attack due to strong winds does not appear to be a first order control on salt marsh edge change in Oregon estuaries given that few estuaries have long fetches and exposed areas do not generally experience more erosion than protected areas. The majority of edge contraction may be a product of fluvial discharge creating high velocity flows and weaker and more consistent wave attack, as has been observed elsewhere (Leonardi, Defne, et al., 2016; Leonardi, Ganju, et al., 2016).

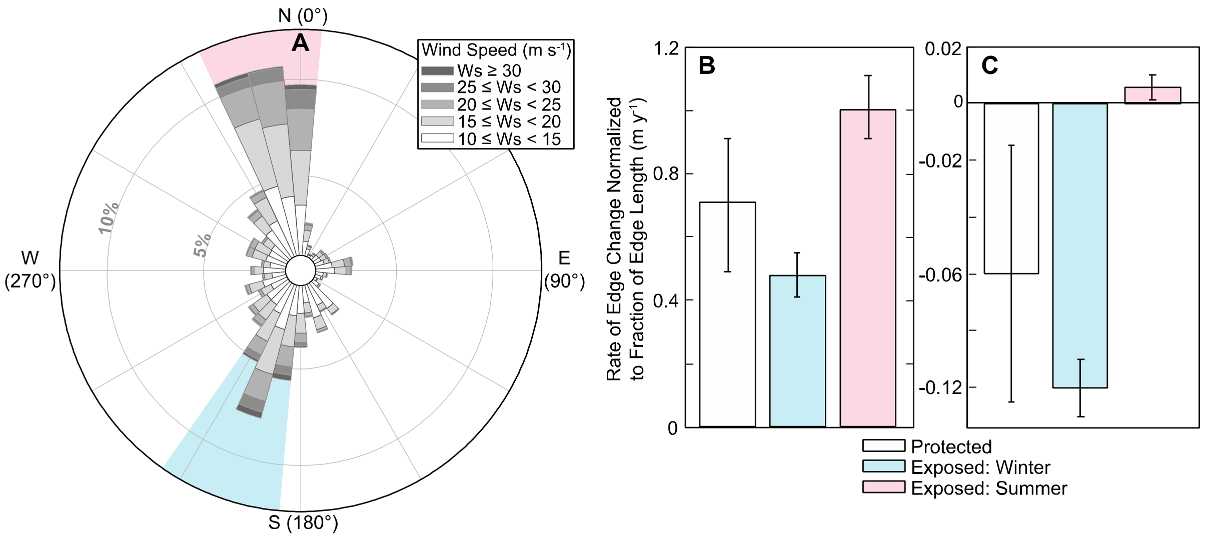


Figure 3. **(a)** Wind rose displaying the frequency (displayed as percent values that increase with each concentric gray circle) of wind speeds (displayed as colors from 10 m s^{-1} as white to greater than 30 m s^{-1} as dark gray) from differing directions (displayed as degrees on the circle) for long-term (≥ 15 y) stations along the Oregon coast. Red and blue shaded directions are predominately summer (April to October) and winter (November to March) months, respectively. **(b-c)** Nehalem and Alsea mean rates of edge change for edges protected from wind and exposed to winter and summer winds (note difference in y axis). Rates are normalized to the fraction of edge lengths of interest divided by the total edge length. Bars indicate standard deviations.

4.2 Temporal controls on lateral expansion & contraction

Rates of salt marsh lateral expansion and contraction varied significantly over the last ~80 y and were divided into four general periods (1939 to 1944, 1944 to 1977, 1977 to 2000, and 2000 to 2018; Figure 2) based on available aerial photographs and dominant forcings to assess the influences of changing land use and hydroclimate.

4.2.1 1939 to 1944

From 1939 to 1944, timber harvest and associated activities (e.g., clearcutting and road construction) began to intensify (Andrews & Kutara, 2005; Figure 4) and as a result, sediment supply was likely elevated. Removal of forest vegetation, especially from the steep terrain of the Oregon Coast Range, destabilizes slopes and accelerates sediment erosion, though there is a lag time related to root decay (~ 5 y) and a large precipitation event is frequently required to initiate mass movement (Swanston & Swanson, 1976). Log drives often accompanied by splash damming (facilitation of downstream transport of timber accumulated behind a dam by dynamiting) in the early half of the 20th century were common in Nehalem and Coquille; splash damming increased both the magnitude and frequency of discharge events, elevating sediment transport (Miller, 2010). Parts of the Nehalem basin were also influenced by the Tillamook Burns, a series of wildfires that burned ~1,400 km^2 of old growth forest in the Nehalem and adjacent basins from 1933 to 1951, further elevating downstream sediment delivery (Komar et al., 2004). Unfortunately, estimating the exact (per basin or per decade) impact of logging on sediment flux along the Oregon coast is nearly impossible because of the poor stream gauge data in most of the Coast Range; lack of timber harvest records beyond total volume per county (i.e., coarse spatial resolution); lag times between harvest, root decay, and slope destabilization; and indirect relationship between slope destabilization and sediment transport. Regardless, the general relationship between increased sediment flux and logging has been established both in a small Oregon coastal basin as part of the Alsea Watershed Study (Beschta & Jackson, 2008) and in similar geographic areas, such as Northern California, which have better stream gauge records (Sommerfield & Wheatcroft, 2007; Warrick et al., 2013).

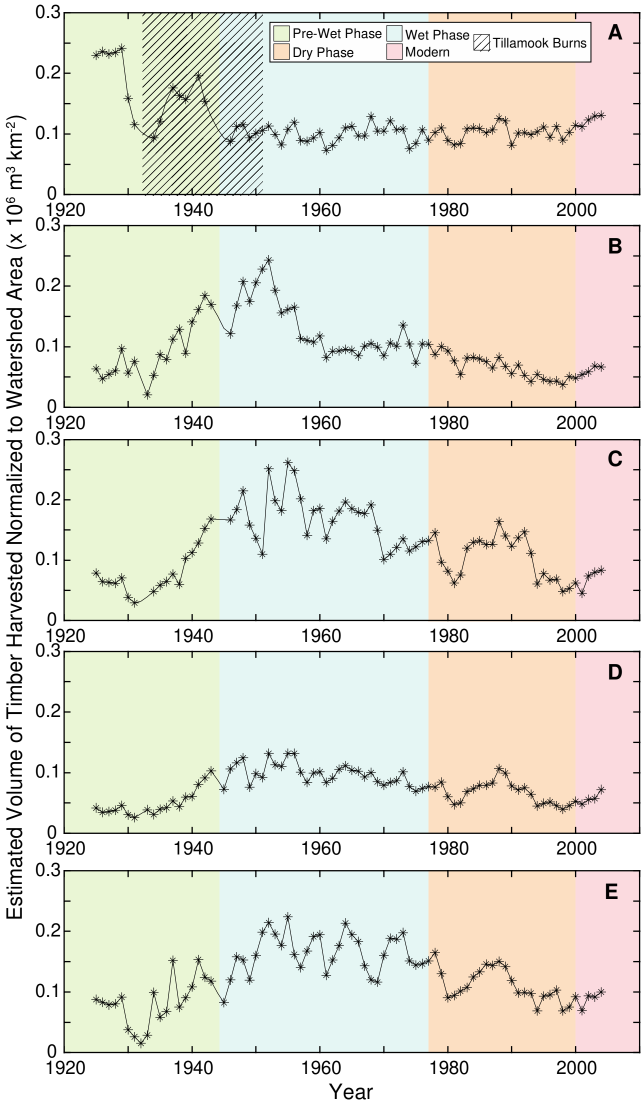


Figure 4. Volume (i.e., board feet) of timber harvested estimated for and normalized to each watershed (**a-e:** Nehalem, Netarts, Salmon, Alsea, & Coquille) based on county-specific timber harvest data (Andrews & Kutara, 2005) and the fraction of basin area within each county. The blue box indicates the wet phase of the Pacific Decadal Oscillation, which coincides with peak harvest in most basins, except Nehalem which was recovering from the Tillamook Burns (1933 to 1951).

Likely as a result of their histories of logging, Nehalem and Coquille salt marshes displayed their fastest expansion rates from 1939 to 1944 (Figure 2b). Despite the short period over which rates could be calculated (5 y), the overall addition to salt marsh area was still sizeable in both systems (Figure 2a). Additionally, given that intensive logging was widespread during this period but Netarts and Alsea both did not display growth, and indeed Alsea experienced area loss, the rapid expansion of Nehalem and Coquille could be a result of the particularly destructive splash damming that occurred in those watersheds prior to the study period (last known dates were 1928 and 1925 in Nehalem and Coquille, respectively; Miller, 2010). Moreover, Nehalem's rate of area gain may have been particularly high due to excess sediment supplied by the Tillamook Burns.

4.2.2 1944 to 1977

The next period, 1944 to 1977, was characterized by conditions that favored high fluvial suspended sediment loads during the wet phase of the PDO combined with increased sediment erosion due to maximal timber harvests in the 1950s (Andrews & Kutara, 2005; Figure 4) that continued to utilize destructive logging methods (Hatten et al., 2018; Richardson et al., 2018). The wet phase of the PDO coincides with more precipitation and numerous large storm events (evident in elevated cumulative residual discharge; Figure 5), including the December 1964 flood (Wheatcroft et al., 2013), the largest flood on record for numerous Oregon coastal rivers (St. George & Mudelsee, 2019).

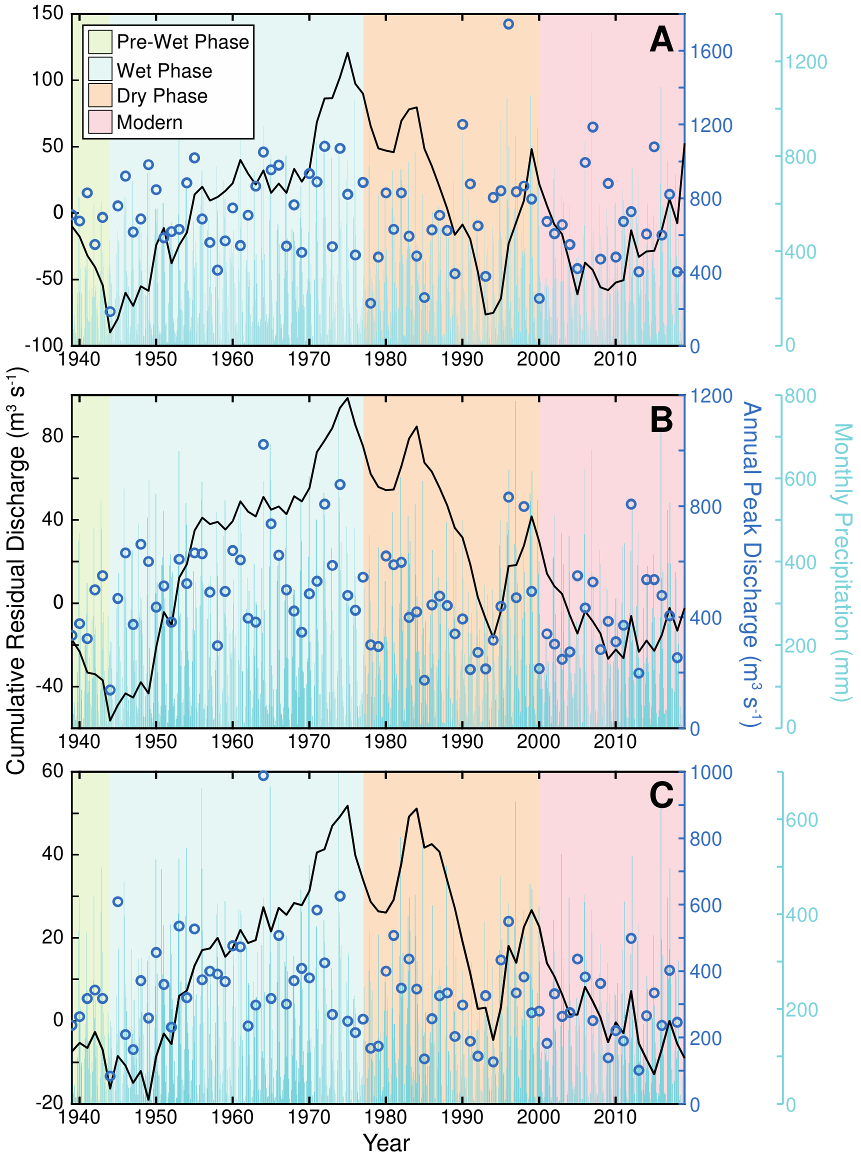


Figure 5. Cumulative residual discharge (left, black y-axis, solid line; note different y-axes scales), peak discharge (first right, dark blue y-axis, open circles; note different y-axes scales), and monthly precipitation (second right, light blue y-axis, bars; note different y-axes scales) from 1939 to the present for the **(a-c):** Nehalem, Alsea, and Coquille Rivers. Note: the Coquille gauge is located in the river headwaters (drainage area = 440 km^2).

During this period, all salt marshes displayed growth, even the systems with net neutral or negative lateral change rates calculated over the ~80 y record of aerial photographs (Figure 2). Netarts, with its limited natural suspended sediment supply (2.6 x 10^3 t km^{-2} y^{-1}), added 2.5 ha. Furthermore, Salmon salt marshes also displayed growth, though slight, despite its limited space for expansion. Perhaps most surprising, Alsea grew 3.5 ha though displaying contraction during all other time periods. The fastest growth rate was observed in Nehalem, resulting in the largest area gain (46 ha) over the last ~80 y. Although Coquille also experienced expansion, the rate was lower than the previous period. While the reason for this result is unclear, it could be related to increased channel edge erosion (Figure S1) resulted from increased discharge during the wet phase (Figure 5C). This may be especially important in Coquille, which has the largest watershed of our study sites (Table 1) and thus the greatest mean annual discharge. Additionally, cessation of splash damming two decades prior, which had been particularly prevalent in the Coquille basin (Miller, 2010), may have resulted in relatively less sediment transport from 1944 to 1977 despite increased logging.

Similar patterns of mid-century elevated sediment accumulation have been observed in Oregon Coast Range lake sediments (Richardson et al., 2018; Wetherell et al., 2021) and in continental shelf records (Wheatcroft et al., 2013), indicating preservation of the logging/wet phase signal along the sediment routing system. Unfortunately, however, disentangling the relative influences of logging and related activities (e.g., wildfire, road construction) from natural precipitation/discharge events on sediment flux and storage along the Oregon margin remains elusive given their coincidence and the coarseness of timber harvest data relative to precipitation and runoff metrics.

4.2.3 1977 to 2000

From 1977 to 2000 sediment supplies waned (Hatten et al., 2018; Richardson et al., 2018; Wetherell et al., 2021), a combined result of decreased cumulative residual discharges during the dry phase of the PDO (Figure 5) and both declining timber harvests (Andrews & Kutara, 2005; Figure 4) and improvement in timber practices. Various forest management acts (such as The Oregon Forest Practices Act and Rules first passed in 1971; ODF, 1994) were aimed at reducing erosion via numerous methods including the creation of riparian buffers; enforcement of reforestation; improvement in extraction methods and road positioning; and reduction in clear-cutting.

Likely related to these conditions favoring reduced sediment supply, lateral expansion rates slowed (Nehalem and Netarts) or reversed to net contraction (Salmon and Alsea) during this period in all estuaries except Coquille (Figure 2). Coquille experienced modest salt marsh growth during the dry phase, highlighting the complexity of morphodynamic responses. As most of the edge contraction in Coquille is along the channel edge and therefore likely a result of high velocity discharge, spatially integrated area expansion during the dry phase could be a result of reduced discharge. As additional evidence, Coquille displayed the opposite pattern – somewhat diminished rates of expansion under higher discharge conditions – during the wet phase.

4.2.4 2000 to 2018

From 2000 to 2018, the PDO switched between wet and dry phases on short time periods, cumulative residual discharges have remained relatively constant indicating neither elevated nor low discharges (Figure 5), and contemporary timber harvest methods have had little impact on suspended sediment yields (Hatten et al., 2018). During this modern period all salt marshes have displayed lateral contraction except for Nehalem, in which rates slowed but were not negative

(Figure 2). The reason for these trends is unclear though it may be part of the continued contraction of the salt marsh platforms from sizes made unsustainably large during the previous decades of higher sediment flux. Others have observed similar trends of rapid vegetated intertidal expansion followed by periods of contraction on multi-decadal/centennial timescales due to changes in land-use practices (deforestation, reforestation, and damming) that influence fluvial sediment delivery along the US East Coast (e.g., Ward et al., 1998), coast of New Zealand (e.g., Nichol et al., 2000; Pasternack et al., 2001; Kirwan et al., 2011), and coast of China (e.g., Yang et al., 2002). Rapid growth during the early and mid-halves of the 20th century may have actually promoted recent edge contraction, as steepening of the marsh boundary during progradation can result in vegetation collapse and marsh edge retreat (van de Koppel et al., 2005), and significant elevation differences between an accreting vegetated platform and adjacent tidal flat may enhance instability and thus erosion (Bouma et al., 2016; Schuerch et al., 2019).

Other explanations for contraction of Oregon salt marshes include increased storminess and/or accelerated sea level rise. While there is little evidence in the tide gauge record for increased sea level rise off the coast of Oregon over recent decades (Boon & Mitchell, 2015), offshore wind speeds have increased in the Northeast Pacific (Gower, 2002) and average winter significant wave heights offshore have increased since the mid-1970s (Allan & Komar, 2006; Ruggiero et al., 2010), perhaps having resulted in increased water levels and wave-driven edge contraction inside the bays.

4.2.4 Future & insights

If current trajectories of edge change persist, Oregon salt marshes will continue to contract. It is possible that gains in salt marsh area during the mid-20st century may be lost assuming no significant increase in fluvial suspended sediment due to intensive land-use and/or wetter climatic conditions. Further, total water levels within Oregon estuaries are generally expected to increase into the future because of climate impacts on sea level, wind waves, and discharge (Cheng et al., 2015). Given the potential for accelerations in climate change, especially relative sea level rise, the rate of area loss may dramatically increase.

On short time periods (decadal to multidecadal), these results highlight the importance of sediment supply on salt marsh lateral growth. Increases in sediment delivery to the marsh platform through changes in hydroclimate and/or land use can spur periods of growth even in systems that already have high sediment loads (as in the cases of Nehalem and Coquille) and/or conditions that might not favor growth (as in the cases of Salmon and Alsea). However, on longer time periods (~80 y) high sediment supplies, whether natural or anthropogenic, do not always result in net progradation in estuaries without substantial tidal flat or subtidal area for expansion (e.g., Salmon) and in estuaries without a filled vertical accommodation space due to relatively high rates of sea level rise (e.g., Alsea). Others have noted the importance of sediment supply on salt marsh expansion (e.g., Ladd et al., 2019), but the spatially diverse and temporally dynamic nature of the Oregon coast highlights the complexities of salt marsh morphodynamics and need for more observations from understudied regions (Wiberg et al., 2020). Ultimately, both short-term (decadal to multi-decadal) and long-term (multi-decadal to centennial) observations of lateral change are valuable to understanding the individual and cumulative impacts of the various drivers on salt marsh morphology, critical for predicting future resilience under accelerating climate change and shifting land use.

5 Conclusions

These results provide insight into net lateral rates of salt marsh expansion/contraction for an understudied but significant portion of the US coastline. Moreover, in addition to highlighting the complexity of Oregon intertidal morphodynamics, these results are applicable to other salt marshes globally, indicating that:

(1) Regardless of spatially integrated rates of salt marsh lateral change, long-term expansion occurs along protected marsh edges where water velocities slacken, whereas contraction occurs along exposed marsh edges where channel velocities are highest. In some systems, as is the case in Oregon estuaries, wave attack due to strong winds may not always be a first order control on salt marsh contraction; rather, fluvial discharge creating high velocity flows and weaker and more consistent wave attack may be more important controlling factors.

(2) Marshes will exhibit net lateral expansion when there exists room for growth onto unvegetated tidal flats, vertical accommodation space has been filled, and relatively high sediment supply.

(3) Salt marsh expansion/contraction can be relatively rapid, switching from expansion to contraction on ~20 y time scales. This result highlights the need for long-term monitoring to assess lateral trends as salt marshes that display short-term expansion may reverse to contraction in a proceeding decade, and vice versa. Moreover, empirical studies of marsh lateral expansion/contraction can help inform process-based models, critical for predicting future trajectories (Fagherazzi et al., 2020).

(4) Temporally variable salt marsh expansion/contraction is strongly influenced by changes in suspended sediment supply, which is controlled by alterations in anthropogenic land use and climatic variations. As evidence, during the wet phase of the PDO, coincident with intensive timber harvest, all Oregon salt marshes expanded despite numerous site-to-site differences in long-term lateral change rates. Conversely, during the warm phase of the PDO, concurrent with both a decrease in timber harvest magnitude and improvement of logging

practices, rates of expansion stabilized or reversed. It is quite possible that other systems with a similar land-use history (e.g., US East Coast, New Zealand) of widespread forest clearance may have had a similar salt marsh lateral trajectory of expansion followed by contraction, as other have observed (e.g., Pasternack et al., 2001; Kirwan et al., 2011).

(5) Current trends of salt marsh contraction will likely persist into the future and may be worsened by rising sea level, increased storminess, and further land management strategies that reduce suspended sediment yields.

Acknowledgments

Research took place at Oregon State University (Corvallis, OR) in the traditional homelands of the Mary's River or Ampinefu Band of Kalapuya. Following the Willamette Valley Treaty of 1855, the Kalapuya people were forcibly removed to reservations in Western Oregon. Today, living descendants of these people are a part of the Confederated Tribes of Grand Ronde Community of Oregon and Confederated Tribes of the Siletz Indians.

We are grateful to the valuable suggestions provided by the peer reviewers and editors. We thank Laura Brophy, Miguel Goñi, Jasmine King, Emerson Webb, and Rosemary Pazdral for their feedback on earlier drafts. We thank Julia Jones for sharing her GIS expertise.

Funding: Research was funded by Oregon Sea Grant [project # NA14OAR4170064; R/HBT-21-Wheatcroft]; and an NSF Research Traineeship fellowship [project # 1545188].

Data Statement: GIS data: https://doi.org/10.4211/hs.22c662d201354961ba74e61aeca43a85.

Declaration of Competing Interest: The authors declare no conflicts of interest.

References

Allan, J. C., & Komar, P. D. (2006). Climate controls on US West Coast erosion processes. *Journal of Coastal Research, 22*(3), 511-529. https://doi.org/10.2112/03-0108.1

Andrews, A., & Kutara, K. (2005). Oregon's timber harvests: 1849-2004. Salem, OR: Oregon Department of Forestry. https://www.oregon.gov/ODF/Documents/WorkingForests/oregonstimberharvests.pdf

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs, 81*(2), 169-193. https://doi.org/10.1890/10-1510.1

Beschta, R. L., & Jackson, W. L. (2008). Forest practices and sediment production in the Alsea Watershed Study. In J.D. Stednick (Ed), Hydrological and biological responses to forest practices. Springer, New York, NY, pp. 55-66.

Benner, P. A. (1992). Historical reconstruction of the Coquille River and surrounding landscape. In *Near Coastal Waters National Pilot Project: The Coquille River, Oregon*. (Action Plan for Oregon Coastal Watersheds, Estuaries and Ocean Waters, 1988-91). Environmental Protection Agency.

Boon, J. D., & Mitchell, M. (2015). Nonlinear change in sea level observed at North American tide stations. *Journal of Coastal Research, 31*(6), 1295-1305. https://doi.org/10.2112/JCOASTRES-D-15-00041.1

Bouma, T. J., Van Belzen, J., Balke, T., Van Dalen, J., Klaassen, P., Hartog, A. M., ... & Herman, P. M. J. (2016). Short-term mudflat dynamics drive long-term cyclic salt marsh dynamics. *Limnology and Oceanography, 61*(6), 2261-2275. https://doi.org/10.1002/lno.10374

Brophy, L. S., & Ewald, M. J. (2017). Modeling sea level rise impacts to Oregon's tidal wetlands: Maps and prioritization tools to help plan for habitat conservation into the future. (Report prepared for MidCoast Watersheds Council Newport, Oregon). Corvallis, OR: Institute for Applied Ecology.

Brophy, L. S., Greene, C. M., Hare, V. C., Holycross, B., Lanier, A., Heady, W. N., ... & Dana, R. (2019). Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. *PloS One, 14*(8), e0218558. https://doi.org/10.1371/journal.pone.0218558

Brophy, L.S. (1999). Final report—Yaquina and Alsea River Basins estuarine wetland site prioritization project. (Report prepared for the MidCoast Watersheds Council, Newport, Oregon). Corvallis, OR: Green Point Consulting.

Burgette, R. J., Weldon, R. J., & Schmidt, D. A. (2009). Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone. *Journal of Geophysical Research: Solid Earth, 114*, B01408. https://doi.org/10.1029/2008JB005679

Carr, S. J., Diggens, L. M., & Spencer, K. L. (2020). There is no such thing as 'undisturbed' soil and sediment sampling: sampler-induced deformation of salt marsh sediments revealed by 3D X-ray computed tomography. *Journal of Soils and Sediments, 20*, 2960-2976. https://doi.org/10.1007/s11368-020-02655-7

Cheng, T. K., Hill, D. F., Beamer, J., & García-Medina, G. (2015). Climate change impacts on wave and surge processes in a Pacific Northwest (USA) estuary. *Journal of Geophysical Research: Oceans*, *120*(1), 182-200. https://doi.org/10.1002/2014JC010268

Daly, C., Neilson, R. P., & Phillips, D. L. (1994). A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* *and Climatology*, *33*(2), 140-158. https://doi.org/ 10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2

Dicken, S. N. (1961). Some recent physical changes of the Oregon coast. (Report for the Office of Naval Research, U.S. Department of the Navy, Contract NONR-2771(04)). Eugene, OR: Department of Geography, University of Oregon.

Fagherazzi, S., Carniello, L., D'Alpaos, L., & Defina, A. (2006). Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes. *Proceedings of the National Academy of Sciences*, *103*(22), 8337-8341. https://doi.org/10.1073/pnas.0508379103

Fagherazzi, S., Mariotti, G., Leonardi, N., Canestrelli, A., Nardin, W., & Kearney, W. S. (2020). Salt marsh dynamics in a period of accelerated sea level rise. *Journal of Geophysical Research: Earth Surface, 125*(8), e2019JF005200. https://doi.org/10.1029/2019JF005200

Ganju, N. K., Defne, Z., & Fagherazzi, S. (2020). Are elevation and open-water conversion of salt marshes connected? *Geophysical Research Letters, 47*(3), e2019GL086703. https://doi.org/10.1029/2019GL086703

Gedan, K. B., Silliman, B. R., & Bertness, M. D. (2009). Centuries of human-driven change in salt marsh ecosystems. *Annual Review of Marine Science*, *1*, 117-141. https://doi.org/10.1146/annurev.marine.010908.163930

Goodwin, G. C., & Mudd, S. M. (2020). Detecting the Morphology of Prograding and Retreating Marsh Margins—Example of a Mega-Tidal Bay. *Remote Sensing, 12*(1), 13. https://doi.org/10.3390/rs12010013

Gower, J. F. R. (2002). Temperature, wind and wave climatologies, and trends from marine meteorological buoys in the northeast Pacific. *Journal of Climate, 15*(24), 3709-3718. https://doi.org/10.1175/1520-0442(2002)015<3709:TWAWCA>2.0.CO;2

Hatten, J. A., Segura, C., Bladon, K. D., Hale, V. C., Ice, G. G., & Stednick, J. D. (2018). Effects of contemporary forest harvesting on suspended sediment in the Oregon Coast Range: Alsea Watershed Study Revisited. *Forest Ecology and Management*, *408*, 238-248. https://doi.org/10.1016/j.foreco.2017.10.049

Himmelstoss, E. A., Henderson, R. E., Kratzmann, M. G., & Farris, A. S. (2018). Digital shoreline analysis system (DSAS) version 5.0 user guide. (Open-File Report 2018-1179). Reston, VA: US Geological Survey.

Johannessen, C. L. (1964). Marshes prograding in Oregon: aerial photographs. *Science, 146*(3651). 1575-1578.https://doi.org/10.1126/science.146.3651.1575

Khouakhi, A., & Villarini, G. (2016). On the relationship between atmospheric rivers and high sea water levels along the US West Coast. *Geophysical Research Letters*, *43*(16), 8815-8822. https://doi.org/10.1002/2016GL070086

Kirwan, M. L., Murray, A. B., Donnelly, J. P., & Corbett, D. R. (2011). Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. *Geology*, *39*(5), 507-510. https://doi.org/10.1130/G31789.1

Kirwan, M. L., Temmerman, S., Skeehan, E. E., Guntenspergen, G. R., & Fagherazzi, S. (2016). Overestimation of marsh vulnerability to sea level rise. *Nature Climate Change*, *6*(3), 253-260. https://doi.org/10.1038/nclimate2909

Kirwan, M. L., Walters, D. C., Reay, W. G., & Carr, J. A. (2016). Sea level driven marsh expansion in a coupled model of marsh erosion and migration. *Geophysical Research Letters, 43*(9), 4366-4373. https://doi.org/10.1002/2016GL068507

Komar, P. D., Allan, J. C., & Ruggiero, P. (2011). Sea level variations along the US Pacific Northwest coast: Tectonic and climate controls. *Journal of Coastal Research*, *27*(5), 808-823. https://doi.org/10.2112/JCOASTRES-D-10-00116.1

Komar, P. D., McManus, J., & Styllas, M. (2004). Sediment accumulation in Tillamook Bay, Oregon: natural processes versus human impacts. *Journal of Geology*, *112*(4), 455-469. https://doi.org/10.1086/421074

Ladd, C. J., Duggan-Edwards, M. F., Bouma, T. J., Pagès, J. F., & Skov, M. W. (2019). Sediment supply explains long-term and large-scale patterns in salt marsh lateral expansion and erosion. *Geophysical Research Letters, 46*(20), 11178-11187. https://doi.org/10.1029/2019GL083315

Langston, A. K., Durán Vinent, O., Herbert, E. R., & Kirwan, M. L. (2020). Modeling long-term salt marsh response to sea level rise in the sediment-deficient Plum Island Estuary, MA. *Limnology and Oceanography*, *65*(9), 2142-2157. https://doi.org/10.1002/lno.11444

Leonardi, N., Defne, Z., Ganju, N. K., & Fagherazzi, S. (2016). Salt marsh erosion rates and boundary features in a shallow Bay. *Journal of Geophysical Research: Earth Surface, 121*(10), 1861-1875. https://doi.org/10.1002/2016JF003975

Leonardi, N., Ganju, N. K., & Fagherazzi, S. (2016). A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. *Proceedings of the National Academy of Sciences, 113*(1), 64-68. https://doi.org/10.1073/pnas.1510095112

Marani, M., D'Alpaos, A., Lanzoni, S., & Santalucia, M. (2011). Understanding and predicting wave erosion of marsh edges. *Geophysical Research Letters*, *38*(21). https://doi.org/10.1029/2011GL048995

Mariotti, G., & Carr, J. (2014). Dual role of salt marsh retreat: Long-term loss and short-term resilience. *Water Resources Research, 50*(4), 2963-2974. https://doi.org/10.1002/2013WR014676

Mariotti, G., & Fagherazzi, S. (2010). A numerical model for the coupled long-term evolution of salt marshes and tidal flats. *Journal of Geophysical Research: Earth Surface, 115*(F1). https://doi.org/10.1029/2009JF001326

Mazzotti, S., Jones, C., & Thomson, R. E. (2008). Relative and absolute sea level rise in western Canada and northwestern United States from a combined tide gauge-GPS analysis. *Journal of Geophysical Research: Oceans, 113*, C11019. https://doi.org/10.1029/2008JC004835

Miller, R. R. (2010). Is the Past Present? Historical Splash-dam Mapping and Stream Disturbance Detection in the Oregon Coastal Province, (Masters Thesis). Retrieved from Oregon State University Library (https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/4m90f001t). Oregon State University. Corvallis, OR: Oregon State University.

Molino, G. D., Defne, Z., Aretxabaleta, A. L., Ganju, N. K., & Carr, J. A. (2021). Quantifying Slopes as a Driver of Forest to Marsh Conversion Using Geospatial Techniques: Application to Chesapeake Bay Coastal-Plain, United States. *Frontiers in Environmental Science, 9*, 149. https://doi.org/10.3389/fenvs.2021.616319

Nichol, S. L., Augustinus, P. C., Gregory, M. R., Creese, R., & Horrocks, M. (2000). Geomorphic and sedimentary evidence of human impact on the New Zealand coastal landscape. *Physical Geography, 21*(2), 109-132. https://doi.org/10.1080/02723646.2000.10642702

Oregon Department of Forestry (ODF). (1994). The Oregon Forest Practices Act Water Protection Rules: Scientific and Policy Considerations. ODF, Salem, OR, p. 66.

Pasternack, G. B., Brush, G. S., & Hilgartner, W. B. (2001). Impact of historic land-use change on sediment delivery to a Chesapeake Bay subestuarine delta. *Earth Surface Processes and Landforms*, *26*(4), 409-427.

Peck, E. K., Wheatcroft, R. A., & Brophy, L. S. (2020). Controls on sediment accretion and blue carbon burial in tidal saline wetlands: Insights from the Oregon coast, USA. *Journal of Geophysical Research: Biogeosciences, 125*(2), e2019JG005464. https://doi.org/10.1029/2019JG005464

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data created 4 Feb 2014 (accessed 11 Feb 2022).

Redfield, A. C. (1972). Development of a New England salt marsh. *Ecological monographs, 42*(2), 201-237. https://doi.org/10.2307/1942263

Richardson, K. N. D., Hatten, J. A., & Wheatcroft, R. A. (2018). 1500 years of lake sedimentation due to fire, earthquakes, floods and land clearance in the Oregon Coast Range: Geomorphic sensitivity to floods during timber harvest period. *Earth Surface Processes and Landforms, 43*(7), 1496-1517. https://doi.org/10.1002/esp.4335

Ruggiero, P., Komar, P. D., & Allan, J. C. (2010). Increasing wave heights and extreme value projections: The wave climate of the US Pacific Northwest. *Coastal Engineering, 57*(5), 539-552. https://doi.org/10.1016/j.coastaleng.2009.12.005

Ruggiero, P., Kratzmann, M. G., Himmelstoss, E. A., Reid, D., Allan, J., & Kaminsky, G. (2013). National assessment of shoreline change: historical shoreline change along the

Pacific Northwest coast. (Open-File Report 2012-1007). Reston, VA: US Geological Survey.

Schieder, N. W., Walters, D. C., & Kirwan, M. L. (2018). Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA. *Estuaries and Coasts, 41*(4), 940-951. https://doi.org/10.1007/s12237-017-0336-9

Schuerch, M., Spencer, T., & Evans, B. (2019). Coupling between tidal mudflats and salt marshes affects marsh morphology. *Marine Geology, 412*, 95-106. https://doi.org/10.1016/j.margeo.2019.03.008

Sommerfield, C. K., & Wheatcroft, R. A. (2007). Late Holocene sediment accumulation on the northern California shelf: Oceanic, fluvial, and anthropogenic influences. *Geological Society of America Bulletin*, *119*(9-10), 1120-1134. https://doi.org/10.1130/B26019.1

St. George, S., & Mudelsee, M. (2019). The weight of the flood-of-record in flood frequency analysis. *Journal of Flood Risk Management, 12*, e12512. https://doi.org/10.1111/jfr3.12512

Swanston, D.N., & Swanson, E.J. (1976). Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. In: Coates D.R. (Ed), Geomorphology and engineering. Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa., pp. 199–221.

Thorne, K., MacDonald, G., Guntenspergen, G., Ambrose, R., Buffington, K., Dugger, B., ... & Takekawa, J. (2018). US Pacific coastal wetland resilience and vulnerability to sea-level rise. *Science Advances, 4*(2), eaao3270. https://doi.org/10.1126/sciadv.aao3270

van de Koppel, J., Wal, D. V. D., Bakker, J. P., & Herman, P. M. (2005). Self-organization and vegetation collapse in salt marsh ecosystems. *The American Naturalist, 165*(1), E1-E12. https://doi.org/10.1086/426602

Ward, L. G., Kearney, M. S., & Stevenson, J. C. (1998). Variations in sedimentary environments and accretionary patterns in estuarine marshes undergoing rapid submergence, Chesapeake Bay. *Marine Geology, 151*(1-4), 111-134. https://doi.org/10.1016/S0025-3227(98)00056-5

Warrick, J. A., Madej, M. A., Goñi, M. A., & Wheatcroft, R. A. (2013). Trends in the suspended-sediment yields of coastal rivers of northern California, 1955–2010. *Journal of Hydrology*, *489*, 108-123. https://doi.org/10.1016/j.jhydrol.2013.02.041

Weston, N. B. (2014). Declining sediments and rising seas: an unfortunate convergence for tidal wetlands. *Estuaries and Coasts, 37*(1), 1-23. https://doi.org/10.1007/s12237-013-9654-8

Wetherell, L. R., Ely, L. L., Roering, J. J., Walsh, M. K., Burchfield, M. J., Nace, K. E., ... & Struble, W. T. (2021). Quantifying sedimentation patterns of small landslide-dammed lakes in the central Oregon coast range. *Earth Surface Processes and Landforms (46)*7, 1-18. https://doi.org/10.1002/esp.5106

Wheatcroft, R. A., Goñi, M. A., Richardson, K. N., & Borgeld, J. C. (2013). Natural and human impacts on centennial sediment accumulation patterns on the Umpqua River margin, Oregon. *Marine Geology*, *339*(1), 44-56. https://doi.org/10.1016/j.margeo.2013.04.015

Wiberg, P. L., Fagherazzi, S., & Kirwan, M. L. (2020). Improving predictions of salt marsh evolution through better integration of data and models. *Annual review of marine science*, *12*, 389-413. https://doi.org/10.1146/annurev-marine-010419-010610

Wise, D. R. (2018). Updates to the suspended sediment SPARROW model developed for western Oregon and northwestern California. (Scientific Investigations Report 2018-5156). Reston, VA: US Geological Survey.

Yang, S. L., Zhao, Q. Y., & Belkin, I. M. (2002). Temporal variation in the sediment load of the Yangtze River and the influences of human activities. *Journal of Hydrology, 263*(1-4), 56-71. https://doi.org/10.1016/S0022-1694(02)00028-8

Zhao, L. X., Zhang, K., Siteur, K., Li, X. Z., Liu, Q. X., & van de Koppel, J. (2021). Fairy circles reveal the resilience of self-organized salt marshes. *Science Advances*, *7*(6), eabe1100. https://doi.org/10.1126/sciadv.abe1100