Journal of Coastal Research	35	4	765–775	Coconut Creek, Florida	July 2019

Impacts of Submerging and Emerging Shorelines on Various Biota and Indigenous Alaskan Harvesting Patterns

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ABSTRACT

Johnson, A.C.; Noel, J.; Gregovich, D.P.; Kruger, L.E., and Buma, B., 2019. Impacts of submerging and emerging shorelines on various biota and indigenous Alaskan harvesting patterns. *Journal of Coastal Research,* 35(4), 765–775. Coconut Creek (Florida), ISSN 0749-0208.

Future alongshore benthic species shoreline lengths undergoing both sea level rise and relative sea level lowering (postglacial isostatic rebound) where SE Alaska Natives regularly conduct traditional and cultural harvests were approximated. From 30-km radii of six community centers, shorelines were examined by merging relevant portions of the NOAA ShoreZone database (utilizing alongshore bioband length segments as accounting units) with nearshore bathymetry and measures of mean global sea-level rise along with local GPS information of isostatic rebound rate. For this analysis, adjustments for the year 2108 were made by using 9868 alongshore length units (totaling 3466 km), each unit having uniform substrate and biologic type, by conducting geometric analysis of shoreline attributes. Given up to 1.8 m of sea level lowering, up to 30% decreases in estuary shoreline lengths are predicted. Trends, verified with both archeologic and land ownership records, confirm utility of simple geometric-based assessments (bathtub approach), particularly for low-energy bays with minimal stream input and bedrock/sediment–dominated shorelines and sites dominated by either isostatic rebound, sea level rise, or both. Predicted changes have implications for traditional and cultural gathering, food webs, and ocean carbon sequestration rates. For example, greater change in shoreline length segments is predicted for protected low-slope gradient bays and estuaries dominated by eelgrass (*Zostera marina*) and inferred butter clam (*Saxidomus gigantean*) habitats than for exposed, rocky, steep-gradient peninsulas with red foliose algae, including dulce (*Palmaria* sp.) and bull kelp (*Nereocystis luetkeana*).

ADDITIONAL INDEX WORDS: *Climate change, coastal resilience and vulnerability, landform, isostatic rebound, sea-level rise, adaptation.*

INTRODUCTION

Coastal geomorphic change results from sea-level rise and relative sea-level lowering associated with land rebound (postglacial isostatic rebound) subsequent to glacier retreat (Elliot *et al.*, 2010; Larsen *et al.*, 2005; Snay *et al.*, 2016), along with other processes. Although sea-level rise is a noted climatic change threatening community viability (Hauer, Evans, and Mishra, 2016; Pachauri *et al.*, 2014), effects of isostatic rebound may also be significant (Kont *et al.*, 2008; Reeder-Myers *et al.*, 2015). Where land was once covered with kilometers of ice (*e.g.*, northern Baltic, Hudson Bay, and SE Alaska), rates of land uplift subsequent to glacial retreat may surpass 30 mm annually (*e.g.*, Yakutat in northern SE Alaska; not incorporating concurrent sea-level rise rates). Yakutat is currently experiencing the greatest uplift rates currently found anywhere in the world (Larsen *et al.*, 2005). In addition to displacement of communities, changing shorelines alter both access to and use of important coastal resources and traditional lifestyles, including harvesting, food processing, consumption, sharing, marketing, and spiritual practices (Ballew *et al.*, 2006). Traditional and cultural gathering (also called subsistence, typically deemed an unsatisfactory regulatory term to indigenous peoples, *e.g.*, Newton and Moss, 2005) are integral to indigenous communities globally, but spatially relevant assessments of predicted resource alterations attributed to the effects of land rebound on coastal change are rare. General understanding of shoreline dynamics affecting communities can be gained by linking physical processes, including sea-level rise and isostatic rebound, with coastal biologic attributes.

Southeast Alaska's coast length of nearly 48,000 km (Stekoll, 2006) provides multiple benefits to communities and ecosystems. "Beach foods," including intertidal plants, shellfish, and seaweed (Newton and Moss, 2005) make up a large proportion of the total diet of Alaska Natives living in rural communities of SE Alaska (Ballew *et al.*, 2006; Sill and Koster, 2017). Traditionally and culturally gathered seaweeds include dulse (*Palmaria* sp.), black seaweed (*Porphyra* sp.), and ribbon seaweed (*Alaria* sp.) (Demetropoulos and Langdon, 2004; Garza, 1989; Mouritsen *et al.*, 2013; Turner, 2003). Other

DOI: 10.2112/JCOASTRES-D-18-00119.1 received 25 August 2018; accepted in revision 17 February 2019; corrected proofs received 27 March 2019; published pre-print online 1 May 2019.
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Table 1. *Typical characteristics of coastal Alaska biobands (adapted from Harper and Morris, 2014; tables 21 and A-12).*

Shore Location	Name (bioband)	Indicator Species	Physical Description
Supratidal	Dune grass (GRA)	*Laymus mollis*	Found in estuaries and lagoons, usually associated with fresh water
	Sedges (SED)	*Carex lynbyei*	
	Salt marsh (PUC)	*Puccinellia* sp., *Plantago maritima*, *Glaux maritima*	
Upper to mid-intertidal	Rockweed (FUC)	*Fucus distichus*	Appears on bedrock cliffs, boulders, cobbles, or gravel beaches in vicinity of barnacles and green algae (*Ulva* sp.)
	Blue mussel (BMU)	*Mytilus trossulus*	
Lower intertidal and nearshore subtidal	Soft brown kelps (SBR)	*Saccharina latissimi, Cystoseira* sp., *Sargassum muticum*	Nonfloating kelps
	Dark brown kelps (CHB)	*Laminaria* sp. *Lessoniopsis littoralis*	Intertidal stalked kelps
	Alaria (ALA)	*Alaria marginata*	On bedrock, boulders
	Red algae (RED)	*Coralina* sp., *Lithothamnion* sp., *Odonthalia* sp., *Neorhodomela* sp., *Palmaria* sp., *Neoptilota* sp., *Mazzaella* sp., *Porphyra* sp.	On most substrates except fine sediments
Lower intertidal and nearshore subtidal	Surfgrass (SUR)	*Phyllospadix* sp.	Surfgrass in tide pools, rock platforms
	Eelgrass (ZOS)	*Zostera marina*	Eelgrass in estuaries
Subtidal	Dragon kelp (ALF)	*Eularia fistulosa*	Canopy-forming kelps typically found on rock and gravels
	Giant kelp (MAC)	*Macrocystis pyrifera*	
	Bull kelp (NER)	*Nerecystis luetkeana*	

important benthic species gathered include blue mussels (*Mytilus edulis*), butter clams (*Saxidomus gigantean*), cockles (*Clinocardium nuttalli*) (Lepofsky *et al*., 2015), and Pacific herring (*Clupea pallasii*) eggs, locally called "Alaska grapes" (Schroeder and Kookesh, 1990). Herring eggs are harvested from intertidal and subtidal substrates such as bull kelp (*Nereocystis luetkeana*), rockweed (*Fucus* sp.), eelgrass (primarily *Zostera marina*), and hemlock (*Tsuga heterophylla*) boughs that have been placed along shorelines to collect the adhesive eggs (Schroeder and Kookesh, 1990; Thornton *et al*., 2010). Kelp and eelgrass, found on subtidal exposed rocky and protected muddy substrates, respectively, have been shown to reduce coastal erosion by attenuating waves and enhancing sedimentation (Christianen *et al*., 2013; Eckman, Duggins, and Sewell, 1989). Eelgrass and kelp are also important to food webs by providing rearing areas for juvenile salmon, blue mussel larvae, and red king crab larvae (Koski, 2009; Steneck *et al*., 2002). Furthermore, eelgrass provides an important ecosystem service (Waycott *et al*., 2009) by sequestering carbon at rates that may surpass adjacent terrestrial forests (Fourqurean *et al*., 2012) and reducing ocean acidification rates (Arnold *et al*., 2012). With alteration of shorelines, some food resources and ecosystem services may be more vulnerable to change than others.

Simple geometric methods (*e.g*., bathtub approach) have been used to assess accurately the response of fluctuating sea level to shifts in alongshore length of species in some, but not all, areas. Rocky coasts, constituting 80% of shorelines globally (Emery and Kuhn, 1982) are most appropriate for such simple geometric methods for predicting coastal change and species alteration (Jackson and McIlvenny, 2011). Where coastal response to sea-level fluctuations are characterized by dynamic geomorphic processes (*e.g*., deltas, exposed beaches, estuaries with input from large rivers), simple geometric methods for assessing species changes are less applicable (Kidwell *et al*., 2017; Passeri *et al*., 2015). Coastal resource assessments have benefited from mapping systems, including ShoreZone (Harper and Morris, 2014; Howes, Harper, and Owens, 1994), an inventory system that has been applied to the coasts of Oregon, Washington, British Columbia, and two-thirds of Alaska (Lindstrom, 2009). ShoreZone catalogs coastal substrate type and associated species into searchable web-accessible databases. ShoreZone's three intertidal zones—supratidal, intertidal, and subtidal—are grouped into four categories based on species presence, as related to water depth, substrate type, and exposure: (1) supratidal, (2) upper to mid-intertidal, (3) lower intertidal and nearshore subtidal, and (4) subtidal (Table 1; Harper and Morris, 2014). ShoreZone lists a variety of attributes for each alongshore length unit, each having uniform substrate, wave exposure, and species. ShoreZone alongshore length units, ranging from meters to kilometers, include information on sea grasses, benthic shellfish, and seaweeds. Shoreline substrate type categories listed in the database include rock, rock and sediment, sediment, and delineation of fans, mud (Harper and Morris, 2014, table 9), and estuary-dominated coastlines (Harper and Morris, 2014, table 13). Fans include deltaic alluvial deposits (directly associated with streams), sediment includes sand and gravel, and rock/sediment includes both rock and sediment (Table 2). Identified ShoreZone alongshore species support traditional and cultural lifestyles, food webs, and coastal stability. The ShoreZone database along with an evaluation of sea-level rise and isostatic rebound rate provides a means to identify vulnerable community resources.

The goal of this study was to assess current and future resources in the vicinity of SE Alaska Native communities. The three overarching research objectives were: (1) determine current physical attributes (slope, substrate, exposure) and associated coastal biobands (resources) associated with shoreline communities in SE Alaska, (2) predict resources most sensitive to future sea-level change, and (3) evaluate the extent to which a simple geometric approach was appropriate for assessing coastal response to fluctuating sea level in lieu of known dynamic and highly adaptive biological and geomorphic processes underlying shoreline change.

Table 2. *Typical characteristics of coastal Alaska substrates (adapted and summarized from Harper and Morris, 2014, tables 9, 11, and 12). Analyses were not conducted on anthropogenic and current-dominated substrate types.*

Substrate Type or Wave Structuring Shoreline Type	Description	ShoreZone-Related ID (also called BC class)
Rock	Rock ramp, platform, or cliffs dominate the intertidal zone, with little or no unconsolidated sediment or organics (<10% of the overall unit area)	1–5
Rock/sediment	Bedrock ramp, platform, or cliff with gravel or sand beach	6–20
Sediment	Gravel or sand beach	21, 22, 25, 27, 28, 30
Fan	Alluvial fans (sand and gravel associated with streams)	23, 24, 26
Estuary/mud	Mudflat, including estuaries dominated by fine mud or peat substrates	29, 31
Anthropogenic	Permeable and impermeable human-made structures	32, 33
Current-dominated	Elongate channels where tidal currents are the dominant structuring process	34

Study Areas

The SE Alaska communities of Yakutat, Hoonah, Angoon, Kake, Klawock, and Kasaan (from north to south) were chosen as the six study locations (Figure 1), given low human impacts. Specifically, within 30 km of community centers, <1% of shorelines were altered by development, including boat ramps, concrete bulkheads, dikes, landfills, sheet piles, rip rap, or wooden bulkhead structures. The communities, ranging in population from 67 to 860, are composed of 45%–88% Alaska Native residents (Alaska Department of Labor and Workforce Development, 2010). The communities rely on the ferry system and airplanes for outside supplies because they are not connected to the Alaska mainland road system. Communities in SE Alaska, compared with the rest of the United States, have a higher cost of living (Alaska Department of Labor and Workforce Development, 2016), have greater unemployment (mean of 10%–15%; Alaska Department of Labor and Workforce Development, 2017), and rely on gathering and harvesting both as a cultural practice and as a means to make ends meet (Dombrowski, 2007; George and Bosworth, 1988; Kruger 2005; Wolfe 2004). For example, >90% of Hoonah and Angoon households rely on subsistence activities in sites occurring mostly within a 30-km radius from community centers (Hoonah and Angoon; Sill and Koster, 2017; *e.g.*, marine invertebrate collection sites). Shorelines in the vicinity of the chosen study areas have been used by Alaska Native Tlingit and Haida people for more than 10,000 years (Carrara, Ager, and Baichtal, 2007; Moss and Erlandson, 1995). During this time period, shorelines have both emerged and submerged (Carlson and Baichtal, 2015; Moss and Erlandson, 1995), as evidenced by relic ancient fishing camps found in both underwater and inland locations. These shoreline changes are associated with isostatic rebound, tectonic shift, and rise and fall of sea level (Carlson and Baichtal, 2015). The historic ability to move communities and camps for adaption to changing resources is now difficult because of land ownership restrictions.

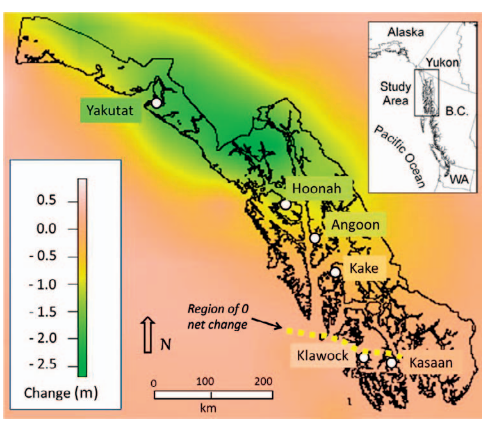

Figure 1. Location map (inset), community study locations, and elevation change relative to current mean sea level used to predict shoreline changes for 2108 in SE Alaska. Land change relative to sea level was spatially integrated from published GPS locations (Elliot *et al.*, 2010). Northern communities are Yakutat, Hoonah, and Angoon; southern communities are Kake, Klawock, and Kasaan.

The geography and geology of the community study areas vary considerably. Yakutat is dominated by glaciers, streams, and extensive (>20 km) exposed beaches along shorelines. Hoonah and Angoon are dominated by nonglaciated mountain peaks and extensive shallow estuaries. Kake, Klawock, and Kasaan have nonglaciated mountain summits and extensive rocky shorelines. High levels of precipitation in SE Alaska result from steep mountains forming an orographic barrier to weather patterns moving landward from the Pacific Ocean (Neal, Walter, and Coffeen, 2002). Mean annual precipitation ranges from 137 cm y^{-1} in Kake to 364 cm y^{-1} in Yakutat (driest and wettest communities, respectively; Western Regional Climate Center, 2019).

Nearshore benthic shoreline species include eelgrass, blue mussel, butter clam habitats inferred from ShoreZone substrate and exposure classes, bull kelp, and foliose red algae, including dulse and black seaweed (Table 1). The presence of shoreline species is related to various coastal features, including substrate, exposure, and slope.

METHODS

Creation of the database included six main steps and the use of a GIS. All maps were projected to NAD83 Alaska Zone 1 and used the Alaska DNR Alaska_coast63 as the base map for analysis (see Supplementary Appendix S1 for further technical detail). Processing was conducted with Esri ArcGIS 10.3, and statistical analysis and plotting were conducted with R 3.2.2 software (R Core Development Team, 2015).

Step 1: Obtaining Physical and Biotic Attributes of the Marine Shoreline

To gather relevant spatial data, a set of modified circular regions with radii of 30 km (a distance supported by maps of a)

b)

Figure 2. Examples of eelgrass (a) as a continuous alongshore green band at low-tide water edge (photo credit: ShoreZone) and (b) as a dense patch located under a snorkeling researcher in a small bay (photo credit: Earthwatch).

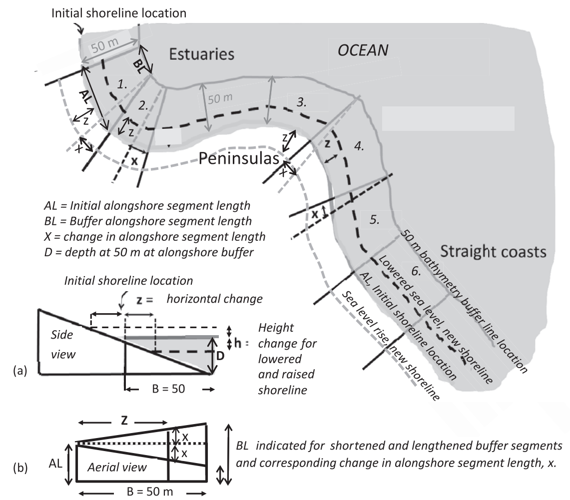

Figure 3. Illustration of shoreline, shoreline shape, and parameters used in equations to calculate alongshore segment length change. Initially (a) the horizontal change in initial shoreline location is calculated and then (b) the change in alongshore segment length can be calculated.

harvest areas, *e.g.*, Sill and Koster, 2017; Wolfe, 2004) centered on the six communities was created. Some of the circular regions were subsequently modified to exclude shorelines determined to be relatively inaccessible to communities. For example, when the radii extended across an inland including a mountainous area, the opposite side of an island (which would be >30 km by water) was excluded. Bioband alongshore length units lying within these regions were selected and exported from the ShoreZone database.

Latitude, longitude, and distance to community center were collected for each shoreline length unit. Alongshore units with human-altered shorelines or narrow, elongate channels having extreme currents and lacking substrate information were removed from the database (Table 2). The resulting initial table, consisting of data for 10,878 shoreline length units, was subsequently refined (see step 2). Eelgrass, blue mussels, mixed filamentous and foliose red algae, and canopy kelp species information, specified as either continuous, or absent, patchy, or continuous, was drawn from the ShoreZone database (Figure 2a,b). In the ShoreZone database, "patchy" indicates that the species is visible in less than half (approximately 25%–50%) of the alongshore unit length, and "continuous" indicates that the species is visible in more than half (50%–100%) of the unit's alongshore length (Harper and Morris, 2014). Queries (ShoreZone, 2014) for likely presence of butter clams were determined by selecting exposure classes that were designated as semiprotected and protected and having substrate classes 24–28 and 30, substrates generally classified as sands and gravels, as evidenced by traditional and cultural harvesting activities.

Step 2: Selection of Shoreline Segments and Bathymetry

The small portion (<1%) of the ShoreZone alongshore segments deviating >50% from the reference base map, Alaska DNR Alaska_coast63, were removed from the database because they did not accurately represent shoreline locations (also see Supplementary Appendix S1). This reduced the number of ShoreZone units in the analysis to 9868, having a segment mean length of 352 m. Once the bathymetry was obtained (National Marine Fisheries Service, in press), bathymetry lines 50 m offshore, paralleling the original ShoreZone alongshore unit lines, were created. Offshore lines were used to calculate average depths 50 m offshore for each alongshore unit. Associated bathymetry length segments (BL), 50-m buffer widths (B), and bathymetric depths (D) were used in equations to determine change in alongshore segment length given a change in sea level (step 4, Figure 3). Shoreline slope, σ (°), was assumed to be uniform per shoreline segment and was approximated for both emerging and submerging shorelines by Equation (1):

$$\sigma = \arctan\left(\frac{D}{B}\right) \quad (1)$$

Step 3: Land and Sea-Level Change for a 100-Year Time Interval

For the 2008 ShoreZone database, shoreline change was projected for a 100-year period. Projections to the year 2108 were based on two factors taken together: (1) an assumed steady-state rate of isostatic rebound (current uplift rate is expected to continue for more than 100 y; R. Motyka and C. Larsen, *personal communication*) spatially interpolated from the 72 observation sites and (2) sea-level rise using a mean rate of 0.20 cm yr^{-1} (Bittermann *et al.*, 2013) that was presumed uniform across the entire region. Values from the resulting raster of projected change were combined to assess and compare change across study communities. Year 2108 projected sea-level change was either higher (+) or lower (–) than current depth (Figure 1).

Step 4: Determining Shoreline Segment Change

Change in alongshore segment length was conducted by geometric analysis facilitated by using a buffer (GIS buffer segment length and estimates of shoreline horizontal change; Figure 3). Length of predicted shoreline advance or retreat (horizontal displacement) z per shoreline segment was calculated by geometric analysis of similar triangles (Figure 3). Similar triangles have the same shape, same slope, and equal angles but different sizes; therefore, corresponding sides all having the same ratio. The calculation of z uses change in relative sea level (step 3) h, the 50-m buffer width B, and the bathymetric depth at the buffer D (Figure 3):

$$z = h\left(\frac{B}{D}\right) \quad (2)$$

Length of the new shoreline segment x + AL was approximated by Equation (3) (Figure 3):

$$x = \mathrm{AL} + (\mathrm{BL} - \mathrm{AL})\frac{h}{D} \quad (3)$$

where, AL is the initial shoreline segment length, and BL is the buffer shoreline segment length.

For rising sea level h is positive, and for falling sea level h is negative. Shoreline segment x depends on whether sea level is expected to rise or fall and whether the initial shoreline segment length is greater or lesser than the buffer length (bay or peninsula shape, respectively). Thus, if relative sea level is going up, converging shorelines such as bays and inlets have shoreline segments that increase in length (Figure 3, segment 1), whereas on peninsulas, length segments typically decrease in length (Figure 3, segment 3). If shoreline segments are in a bay and the land rebounds, the shoreline segment often decreases in length (Figure 3, segment 2). If the shoreline segment is on a peninsula and the land is rebounding, the shoreline segment will often increase in length (Figure 3, segment 4). For straight shorelines, there is little or no change in shoreline segment (Figure 3, segment 6).

Step 5: Summarizing Benthic Species Information and Linking It to Physical Attributes

Future length of the five species biobands (inferred butter clam habitats, blue mussels, eelgrass, red algae, and canopy kelp) and five substrate types (estuary/mud, fans, sediment, sediment/rock, and rock, as categorized by Harper and Morris, 2014, tables 9, 11, and 12) was determined/inferred by summing the alongshore segment lengths. To assess the amount of exposure or degree of shoreline protection quantitatively for each community, exposure categories were related to fetch distances (Table 3). Fetch is the distance traveled by wind or wave across open water and thus is positively correlated with wave energy reaching the shoreline. In addition to assuming uniform slope for each individual alongshore length segment, no change was assumed for fetch, substrate type, or species type for each shoreline segment over the 100-year prediction interval because analyses of these alterations were not in the scope of this research.

Table 3. *Definitions of exposure (adapted from ShoreZone).*

Maximum Fetch (km)	Length for Analysis (km)	Description of Exposure
< 1	1	Very protected
1–10	10	Protected
10–50	50	Semiprotected
50–500	500	Semiexposed
>500	1000	Exposed

Step 6: Field Verification

To confirm ShoreZone designations and estimates of slope, a random group of six sites was selected from each community. Selected shoreline length segments were accessed by float plane, boat, driving, or walking. At each site, slope gradient was measured with a hand level and dominant shoreline species were identified. Fieldwork included estimates of eelgrass density (shoots m^{-2}) where present. Validation was not used to change database; rather, it was used to assess project limitations.

Statistical Analysis

Mean slope values for substrate slope and fetch for both species and substrates were weighted by the length of each substrate type. Associations among substrate, slope gradient, fetch, and species for the six communities were assessed with repeated analysis of variance measurements. If significant, Tukey honest significance tests were conducted (p = 0.05). Northern (Yakutat, Hoonah, and Angoon) and southern (Kake, Klawock, and Kasaan) communities were also compared. Regression analysis evaluated the role of one or more variables for predicting species occurrence, and 95% confidence intervals were determined where appropriate. All statistical analyses were performed by R 2.7 (R Core Development Team, 2008).

RESULTS

Integrating sea-level rise and isostatic rebound resulted in a predicted change in sea level for the year 2108, ranging from a 1.8-m drop in Yakutat to a 0.2-m rise in Kasaan. Approximately 150 km of coastline in the vicinity of Klawock (<0.02% of Klawock community shoreline; Figure 1) had a change of 0 km.

Current Substrate and Slope of Alongshore Segments

Overall, rock and rock/sediment segments accounted for 38% of the shorelines for all northern communities combined (Angoon, Hoonah, and Yakutat) and 59% of the shorelines in the south (Kake, Klawock, and Kasaan). Estuarine segments accounted for 20% of the shorelines in the north and 18% in the south. Fans and sediment segments accounted for 42% of the shorelines in the north and 22% of the shorelines in the south. Mean slope, derived from bathymetric measurements for mud, fans, sediment, rock/sediment, and rock-dominated shorelines was 0.93°, 3.1°, 6.3°, 7.4°, and 13.6°, respectively, with significant differences in slopes of dominant shoreline sub-

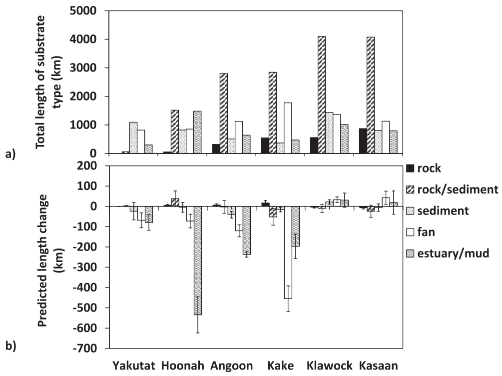

Figure 4. Substrate types (a) presently in the vicinity of six SE Alaska communities and (b) of 100-yr estimates of substrate type change. Note that communities are listed from north to south from the left to right side of the graph. Error bars represent 95% confidence intervals.

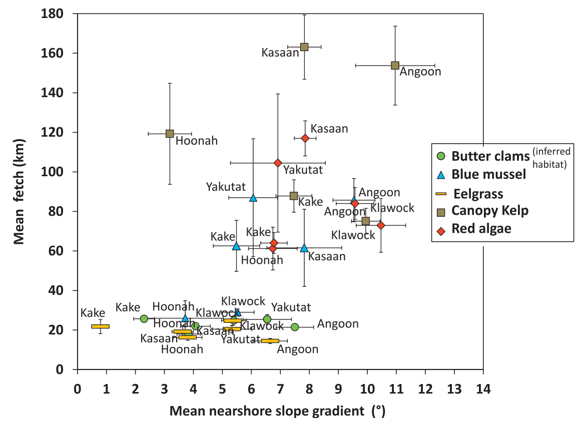

Figure 5. Relationship between mean fetch and slope gradient for benthic species. Error bars represent 95% confidence intervals.

strates ($p < 0.001$ for all comparisons). For community comparisons of mean slope, the Angoon rock substrates (15.6°) were significantly steeper than Kake rock substrates (11.6°, $p < 0.0001$); Klawock had significantly steeper mud substrates (2.6°) than all other communities except Yakutat (1.5°, $p < 0.001$), and Klawock had steeper sediment/rock substrates (6.8°) than Kake (4.6°), Hoonah (6.4°), and Kasaan (5.6°, $p \leq 0.03$). Kake had a lower fan slope (1.8°) than all communities (range 2.9°–7.9°, $p < 0.0001$; Figure 4a, Table 4).

Slope and Fetch Relationships for Species

Mean slope ranged from 0.8° for eelgrass-lined shorelines to 10.9° for kelp shorelines, with all slope and species comparisons significantly different ($p < 0.0001$), except between eelgrass and inferred butter clam habitats ($p = 0.28$) and red algae and kelps ($p = 0.16$; Figure 5, Table 5). For eelgrass, inferred butter clam, blue mussel, red algae, and kelp habitats, mean fetch ranged from 12 km for eelgrass to 163 km for kelp, with all fetch distances significantly different ($p < 0.0001$), except for eelgrass and inferred clam habitats ($p = 0.95$; Table 5). Kake had a significantly lower mean slope gradient for eel grass and butter clams than all other communities ($p < 0.0005$; Figure 5). The Hoonah kelp slope was lower than all other communities ($p < 0.0005$). No differences in red algae or blue mussel slopes were found across communities.

Alongshore Substrate Future Length Change

Overall, the most common future predicted alongshore substrate type was rock/sediment, and the most changed substrate alongshore length was estuary/mud and fan substrates (Figure 4b). Alongshore length losses of estuary/mud and fans for Yakutat, Hoonah, Angoon, and Kake ranged from 40 to 445 km and 32 to 392 km, respectively. Hoonah was predicted to lose approximately 30% of its current estuary/mud alongshore length. Kake, predicted to lose approximately 22% of its alongshore fan length, was also expected to gain 4 km (<1% increase) of rock alongshore length. Angoon was predicted to lose 35% of its estuary/mud alongshore length. Klawock and Kasaan were predicted to gain 33 and 13 km of sediment substrates, respectively, accounting for <1% loss of current alongshore length.

Current Species Type/Substrate Association and Estimated Future Change

In general, eelgrass was found more often in association with sediment substrates in Yakutat, mud substrates in Hoonah, and fan substrates in Kake (Figure 6). Inferred butter clam habitats were more often associated with fans and less with sediment in Kake than in other communities. Blue mussels, unlike other species, were present on all substrate types but were primarily associated on fans at Yakutat and Kake and on rock/sediment at Hoonah, Angoon, Kake, and Klawock. Red algae occurred more on rock and rock/sediment substrates in southern communities than northern communities. Canopy kelp was associated with rock and rock/sediment substrates in Angoon and Kasaan. In Hoonah and Klawock, canopy kelp was found on multiple substrates, even mud substrates. No canopy

Table 4. *Relative sea-level change with mean slope and fetch of substrates at study communities for the ShoreZone database.*

Community	Sea-Level Change (m)	Slope (°)	Mean Slope (°) Rock	Sed/Rock	Sediment	Fan	Mud	Fetch (km)	Fetch (km) Rock	Sed/Rock	Sediment	Fan	Mud
Yakutat	1.58	5.2	—	11.3	7.7	4.7	1.5	98.1	—	460**	119	104	9.9
Hoonah	1.03	4.5	11.8	6.4	6.4	2.9	1.0	39.9	150	62	26	34	12.7
Angoon	0.48	8.9	15.6**	8.9	7.8	7.5	1.7	58.9	156	59	39	34	12.6
Kake	0.21	5.7	11.6	5.9	4.6	1.8**	2.1	54.4	93	55	41	34	19.1
Klawock	–0.18	7.7	12.8	8.6	6.8	4.1	2.6**	43.4	63	50	30	31	13.8
Kasaan	–0.16	6.7	12.0	7.0	5.6	2.7	1.0	78.5	203**	73	22	30	19.6*

*Sed denotes sediment. Values are significantly different at *0.001 < p < 0.05 and **p < 0.001.*

Table 5. *Mean slope and fetch of species at study communities.*

Community	Mean Slope (°)					Fetch (km)				
	Kelp	Red Algae	Mussels	Clams	Eelgrass	Kelp	Red Algae	Mussels	Clams	Eelgrass
Yakutat	—	6.9	6.1	6.5	5.3	—	105	89	25	20
Hoonah	3.2**	6.7	5.5	4.1	3.8	119	61	29	22	16
Angoon	10.9	9.6	9.5	7.5	6.6	154	84	86	21	14
Kake	7.5	6.8	5.5	2.3**	0.8**	88	64	63	26	22
Klawock	9.9	10.5	3.7	5.4	5.4	75	73	26	25	25
Kasaan	7.8	7.9	7.8	3.8	3.6	163	117	61	18	19

*Values are significantly different at *0.001 < p < 0.05, **p < 0.001.*

kelp was indicated in the ShoreZone database for Yakutat. Eelgrass alongshore bioband lengths currently ranging from 50 to 150 km in Kake, Hoonah, Yakutat, and Angoon were predicted to be reduced from 10 to 20 km (Figure 7a,b) by year 2108, a total loss of 14%. Specifically, eelgrass losses of 10%, 10%, 15%, and 33% are estimated, respectively, for Yakutat, Hoonah, Angoon, and Kake. Increases of eelgrass length up to 5–10 km were predicted for Klawock and Kasaan, representing a 2%–3% increase. Over 85 km of inferred butter clam alongshore length was predicted to disappear in the future, accounting for an approximately 13% reduction of its current range. Mean alongshore inferred clam habitat reductions constitute losses of approximately 10%, 6%, 9%, and 22%, respectively, for Yakutat, Hoonah, Angoon, and Kake. In general, canopy kelp and red algae shoreline lengths were found to be greater in southern communities than northern communities (158–397 *vs*. 0–109 km for kelp, respectively; 300–410 *vs*. 41–310 km for red algae, respectively, for Klawock and Kasaan *vs*. Yakutat and Hoonah).

Field Verification

In general, fieldwork verified ShoreZone designations and slope calculations, substrates, and species, with several notable exceptions. Clam occurrence, inferred by ShoreZone query alone, indicated likely clam presence on sediments and fans in protected and semiprotected locations only (ShoreZone, 2014), but fieldwork verified clam occurrence on other substrates, notably mud and rock/sediment substrates. Abundant clam habitats at multiple sites having rock/sediment mixtures were found. Canopy kelp, not indicated in the ShoreZone database for the Yakutat study community, was observed at several shorelines having rock/sediment substrates. In Klawock and Hoonah, some shoreline segments had both eelgrass and kelp, features not indicated in the ShoreZone database. Eelgrass was not apparent in some locations, as indicated in the ShoreZone database. For example, although ShoreZone indicated eelgrass as being "continuous," fieldwork indicated eelgrass populations to be extremely sparse, with densities averaging <10 eelgrass shoots m^{-2}. It is possible that eelgrass density has changed considerably in the 8 years since ShoreZone data was last collected.

DISCUSSION

Using the ShoreZone database, isostatic rebound rate, sea level rise rate, and a simple set of calculations, it was determined that both emergence and submergence of the land resulted in disproportionately greater alongshore length unit changes for low-slope gradient shorelines located within protected bays and estuaries, with less change predicted for rocky exposed peninsulas. In SE Alaska, sea-level fall—occurring at much greater rates than sea level-rise—will have the greatest significance to alongshore species, including clams and eelgrass. It was determined that land emergence, resulting in extensive shoreline land exposure, has greater consequences for protected bay coastlines, where shallow protected bays are transitioning to meadows, with less change expected for straight, steeper, rocky shorelines. These transitions are clearly seen in both recent land ownership records (*e.g.*, 96-y transition, Juneau Borough, Figure 8) and paleo records (Carlson and Baichtal, 2015; Pendea *et al*., 2010; Spiess, 2017). In contrast to arctic Alaskan communities facing issues associated with thawing permafrost and extensive coastal erosion (*e.g.*, Jorgenson, Shur, and Pullman, 2006; Larsen *et al*., 2008), SE Alaska is an area undergoing change, where some community adaptation is possible given the occurrence of species in a variety of substrates and slopes.

Resources most and least sensitive to alterations by future sea-level change, as identified by this simple geometric or bathtub approach, are most applicable to rock, rock/sediment, and protected shorelines (estuaries/mud), areas accounting for

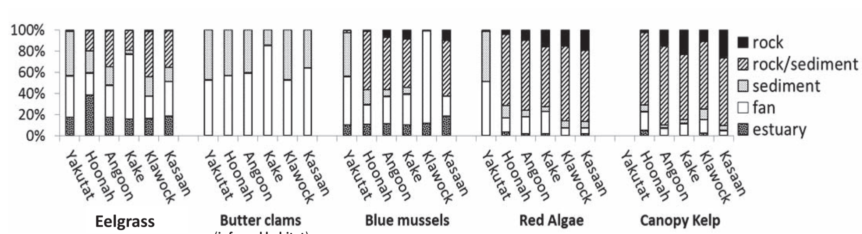

Figure 6. Barplots of substrate/species relationships.

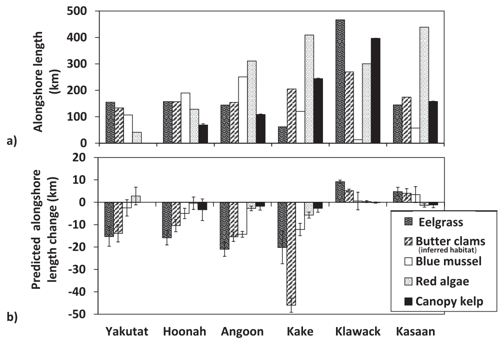

Figure 7. Barplots of (a) length of habitat type and (b) predicted change in species type per community. Error bars represent 95% confidence intervals.

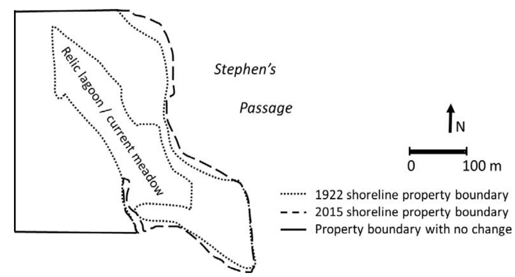

Figure 8. Record of 93-y coastal change for a property on Admiralty Island, SE Alaska. Rapid isostatic rebound (>25 mm y^{-1}) resulted in 1 km of alongshore length loss with conversion of a 3-ha lagoon to a meadow (adapted from City and Borough of Juneau land use survey records, U.S. Survey 1285, located in Section 2 and 3, Township 42 south, Range 65 east).

65% of the alongshore length examined (60% of northern communities and nearly 80% of southern communities). Blue mussels, found on the greatest range of substrate types and slopes, appear to be resilient to coastal change. Likewise, similar to Thieler and Hammar-Klose (1999), steep, rocky, fjord-like coastlines—locations abundant with red algae and canopy kelps—were found to be most resilient. A <3% change was predicted for red algae and canopy kelps; an indication that sea level change poses little threat to seaweed populations. Today, as in the past, seaweed is an important part of peoples' diets (De Laguna, 1972; Turner, 2003). In contrast, sites dominated by clams and eelgrass, with predicted >10% alongshore length unit loss (a conservative estimate, excluding alongshore fans), were found most vulnerable, particularly if located in protected (low fetch) shorelines with shallower slope. Angoon, a community with steeper shorelines, has a 1600-year-long record of butter clam use (Moss, 1993).

Currently, eelgrass distribution is extensive in SE Alaska, likely surpassing the sum of combined shorelines of Oregon and Washington (420 km total *vs.* >1000 km for study sites alone in SE Alaska; Berry *et al.*, 2001; NOAA, 2015; ShoreZone, 2014), and eelgrass supports healthy fish populations (Plummer *et al.*, 2013). Prediction of eelgrass reduction may be slightly counterbalanced by the predicted 5 km total increase of alongshore eelgrass length in Kasaan and Klawock, a prediction supported by predicted regeneration success in Padilla Bay, Washington, where coastlines are also being inundated by rising seas (Kairis and Rybczyk, 2010).

As others have found (*e.g.*, Lindstrom, 2009; Schoch, Albert, and Shanley, 2014), this use of the NOAA ShoreZone database helped to assess current and inferred trends in alongshore bioband length, including eelgrass, butter clam, and red algae habitats, giving insight to possible community coastal adaptation and conservation strategies. Fieldwork indicated that inferred presence of butter clams with the ShoreZone-directed online query (ShoreZone, 2014) would benefit from inclusion of combinations of bedrock and sediment mixtures (coastal classes 11–20; Harper and Morris, 2014). Further understanding of species resilience could be gained by assessing relationships between sediment particle size and species. Inferred clam presence on a range of slopes and fetch distances indicates that community stewardship programs aimed at fostering greater clam densities could strategically focus efforts on steeper shorelines to adapt to losses on coastline with lower slopes. Additionally, now, as in the past, community members could foster greater clam densities along steeper bedrock/sediment shorelines by building clam gardens, a practice used to enhance butter clam production in locations having rock/sediment substrate mixtures (Groesbeck *et al.*, 2014; Moss and Wellman, 2017). Moreover, although slow changes in alongshore lengths of coastal resources attributed to isostatic rebound might not be particularly noticeable to community members, there is certainly community awareness of a recent increase in sea otter (*Enhydra lutris*) populations and resulting loss of clams by otter predation (Kake and Hoonah community members, *unpublished communications*; U.S. Fish and Wildlife Service, 2014). Communities could strategize on measures to protect long-term alongshore clam habitats by focusing efforts on habitats that are both steeper and most readily protected from sea otter predation.

Although this analysis employs a simple bathtub approach with assumed steady-state rate sea-level rise, it provides a starting point for more in-depth assessments of shoreline alterations from isostatic rebound and variable sea-level rise rates. Such studies are warranted given associations among glacier retreat, increased ocean temperature, and sea-level rise rate (Meier *et al.*, 2007). Furthermore, examination of likely changes in uplifted and submerged substrates, particularly for fans and exposed sediment shorelines (accounting for approximately 35% of shorelines studied: 40% of northern communities and 20% of southern communities), is needed given the dynamic nature of sediment transport processes, including longshore drift, wave action, stream deposition, and erosion by tidal surge (Zervas, 2005). More comprehensive work is needed for these sites. Although not in the scope of this research, alongshore species occurrence may also be altered by future water clarity, urbanization, and overharvest. For example, glacial recession in SE Alaska will ultimately be associated with less turbid runoff (Hood and Berner, 2009), facilitating greater light transmittance through the water and enabling eelgrass establishment (Olesen and Sand-Jensen, 1994; Thom *et al.*, 2008), particularly along SE Alaska coastlines in communities such as Yakutat, where coastlines are currently inundated by turbid runoff from the Hubbard Glacier. Also, herring eggs collected from eelgrass, kelp, and hemlock boughs, currently considered one of the top five traditional and cultural harvested foods in SE Alaska (Wolfe, 2004), are compromised by loss of eelgrass from shoreline disturbance and changes in food webs associated with overfishing (Baden *et al*., 2003, 2012; Orth *et al*., 2006), particularly herring overharvest during the sac roe commercial harvest (Thornton, 2015) for the product, *Kazunoko*, consumed in sushi restaurants. Further work is needed to investigate innovative adaptation strategies, including restoration and creation of ancient clam gardens, and the role of sea otters on food webs. Finally, indigenous tribal groups most threatened by alterations in traditional and cultural gathering patterns are the people most able to distinguish environmental changes that will have consequences for the rest of the Earth (Folkestad *et al*., 2005; Green and Raygorodetsky, 2010; Watt-Cloutier, 2014).

CONCLUSIONS

In SE Alaska, isostatic rebound, more than sea-level rise, has the potential to alter access to and abundance of coastal benthic species. The simple geometric analysis presented here provides a first step for illuminating impacts of retreating sea level on coastal benthic species. Most change is predicted for low-gradient sloped shoreline habitats within protected bays and small estuaries with habitats dominated by eelgrass, clams, and blue mussels. Only minor change was predicted for red algae and canopy kelps, species typically found on rocky coastlines. Field observations of species, particularly blue mussels, on a range of exposures, substrates, and slopes were indicative of species resilience to coastline change. Furthermore, when located on steeper slopes, eelgrass and clam habitats had less predicted alongshore habitat length reduction. Knowledge of likely biologic shifts informs community action and resource management aimed at sustaining traditional and cultural food gathering opportunities. For example, given that steeper habitats are more resistant to shoreline change, community adaptation strategies aimed at promoting growth of eelgrass or clams may benefit by focusing activities on steeper habitats having a mix of substrates. Research findings have relevance to the coastal communities of SE Alaska and other temperate coastal communities undergoing isostatic rebound. Finally, adaptation to coastline change and future accessibility to shoreline resources for traditional and cultural gathering is compounded by other community concerns, including pollution, paralytic shellfish poisoning, ocean acidification, and overharvest.

ACKNOWLEDGMENTS

This research was supported by funding from Western Wildland Environmental Threat Assessment Center and Pacific Northwest Research Station Civil Rights Action Group Grants. We are grateful for discussions, editing, and advice by Barbara Schrader, Sonia Ibarra, Wendel Raymond, Ryan Bellmore, Rachel White, Lee Benda, Jeff Freymueller, Roman Motyka, and Jim Baichtal. We are also grateful for the peer review comments by the anonymous reviewers and the work that Dr. Christopher Makowski and the editing team at the *Journal of Coastal Research* (JCR) has done.

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