Anticipated Effects of Sea Level Rise in Puget Sound on Two Beach-Spawning Fishes

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Introduction

The shoreline of Puget Sound provides habitat for many species, including surf smelt (*Hypomesus pretiosus*) and Pacific sand lance (*Ammodytes hexapterus*); two fishes that spawn in the intertidal zone. Surf smelt and Pacific sand lance (hereinafter sand lance) are key parts of the Puget Sound food web (Simenstad and others, 1979), providing food for many sea birds, marine mammals and fishes, including economically and culturally important Pacific salmon (*Oncorhynchus* spp.). By integrating climate change predictions and their expected effects on intertidal geological processes and subsequent ecological processes, we hope to inform policies to protect surf smelt and sand lance spawning habitat while addressing legitimate private property concerns regarding shoreline armoring.

Shoreline armoring might be the most important threat to surf smelt and sand lance spawning habitat (Thom and others,1994), and a little studied threat to sand lance winter rearing habitat (Quinn, 1999). Griggs and others (1994) and Williams and Thom (2001) identify many detrimental effects of shoreline armoring, and more than one-third of Puget Sound's shoreline is armored (Puget Sound Water Quality Action Team, 2002), including many locations where surf smelt and sand lance spawn. Since 1974 shoreline armoring has been regulated where spawning has been documented. However, many beaches have not been surveyed and the spawning behavior of sand lance was not well known until 1989 (Penttila, 1995), so much of the shoreline of Puget Sound was armored prior to regulation or documentation of beach spawning. Furthermore, existing regulations do not consider cumulative or off-site impacts of armoring, cannot prohibit armoring in most cases (see Carman and others, 2010), and do not address likely future environmental conditions such as higher sea level.

Sea level is expected to rise substantially in this century, which likely will profoundly affect the structure and function of the Puget Sound ecosystem (National Wildlife Federation, 2007). As sea level rises the spatial extent of intertidal beaches might contract, which would reduce the extent of intertidal habitat and thus the amount of suitable spawning habitat. Where the upward extent of beach migration is limited by shoreline armoring (Griggs and others, 1994; Griggs, 2005), loss of spawning habitat might be exacerbated (Thom and others, 1994). However, the question of whether sea level rise will result in a loss of surf smelt and sand lance spawning habitat on armored shorelines has not been addressed quantitatively. Our goals were (1) to describe the geographic and temporal distribution of surf smelt and sand lance spawning in Puget Sound, including discontinuities in occurrence and egg abundance; (2) to describe associations between beach elevation and egg abundance; and (3) to determine the potential for spawning habitat contraction and egg loss as a result of sea level rise on armored beaches.

In this paper, we address our goals by describing some results and conclusions (1) of a long-term survey to detect beach spawning in Puget Sound, (2) of a one-year survey of beach spawning density on Camano Island, WA, and (3) of the first year of a study of the spatial distribution of eggs on central Puget Sound intertidal beaches.

Study Methods

Puget Sound Survey

To describe the geographic and temporal distribution of surf smelt and sand lance spawning occurrence we analyzed survey data collected by the Washington Department of Fish (WDFW) since 1972. These data included visual observation of egg presence and results of analyses of standard samples consisting of four subsamples of about 500 mL of the upper approximately 5 cm of substrate that were collected about 6 m apart at approximately +10 ft mean lower low water (MLLW). Sampling locations were selected haphazardly, to maximize efficiency at detecting presence of spawning. The Washington Department of Natural Resources has delineated and mapped morphologically homogeneous shorelines and maintains a GIS

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layer (Washington State Department of Natural Resources, 2010, Washington ShoreZone Inventory at http://www.dnr.wa.gov/ResearchScience/Topics/AquaticHabitats/Pages/aqr_nrsh_inventory_projects.aspx) that identifies them. We plotted spawning sample results onto Washington ShoreZone Inventory beaches. Some ShoreZone beaches were sampled more than once. Surveyed beaches were attributed with presence of surf smelt or sand lance spawning if one or more samples detected their eggs. Spawning absence was attributed to beaches where all samples failed to detect eggs. Spatial patterns of spawning were presented graphically using a GIS, and frequency of spawning occurrence is described by tallying data by survey and ShoreZone beach.

Camano Island Survey

To describe the spatial and temporal distribution of surf smelt and sand lance egg abundance, we conducted surveys every 2 weeks from September 2007 through August 2008 at 51 locations on Camano Island, Washington. Samples were collected at locations that were evenly spaced around the island. Sampling procedures were similar to those used for the Puget Sound survey. In this preliminary analysis, we summarized egg counts by location and through time for both species.

Intertidal Egg Distribution

To describe the distribution of eggs relative to beach elevation we collected samples at approximately 4, 6, 8, and 10 ft above MLLW on 28 beaches in central Puget Sound. Each sample consisted of 4 subsamples of 500 mL, similar to the standard samples collected in the Puget Sound survey. Subsamples were taken 6 m apart from the top approximately 5 cm of sediment. Samples were collected in 2005 and 2006 to assess the sufficiency of the sampling method developed by WDFW (Moulton and Penttila, 2001; Krueger and others, 2007). Sampling locations were selected haphazardly as part of the Puget Sound survey.

To assess the likely effect of sea-level rise on forage fish spawning on armored beaches, we estimated the proportion of eggs likely to be lost as a result of a range of potential sea-level rise scenarios. We assume that the morphology (for example, shape and substrate) of armored beaches will remain unchanged as sea level rises. We used estimates of sea-level rise of 0.13 to 0.69 m (5.1 to 27.3 in.) within this century made by the Intergovernmental Panel on Climate Change (2001) and used by the National Wildlife Federation (2007) to guide analysis. Because expectations for sea-level rise are highly uncertain for specific locations and differ among locations (National Wildlife Federation, 2007), we estimated loss of eggs as a proportion of beach lost. Beach elevations were standardized between MLLW and mean higher high water (MHHW) plus 1.5 ft. We used the latter elevation as a conservative (that is, high) estimate of the elevation of shoreline armoring, because data describing the elevation of armoring was not available. To describe the distribution of egg abundance in relation to beach elevation, we fit a 2-parameter gamma distribution to each of the 13 (of 28) beach locations that had sufficient data. We then calculated the cumulative gamma distribution over all sites using proportions of surf smelt eggs and standardized beach elevations. The cumulative density function estimates the proportion of eggs lost as a result of sea level rise on armored beaches as a proportion of the beach is lost as a result of sea- level rise, given no change of beach morphology. That is, given the difference between MLLW and MHHW + 1 ft, estimates of sea level rise can be used to estimate the proportion of beach inundated and subsequently the proportion of eggs lost on a beach.

Results

Puget Sound Survey

Surf smelt and sand lance have broad geographic distributions, and spawn throughout much of Puget Sound (fig. 1). More than 20,000 samples have been collected to document spawning locations (Washington Department of Fish and Wildlife, 2010, at http://wdfw.wa.gov/mapping/salmonscape). Surf smelt eggs were found in 6,574 samples and sand lance eggs were found in 1,540 samples. To date, 3,689 of 6,956 ShoreZone beaches have been surveyed. Spawning by one or both species was observed on 37 percent of sampled beaches. Spawning by both species is spatially discontinuous. Spawning by either surf smelt or sand lance has not been detected on many sampled beaches where habitat seems suitable.

Camano Island Survey

On Camano Island, surf smelt and sand lance egg abundance was highly variable among locations and through time within a year (Quinn and others, 2009). Most of the surf smelt eggs were collected from 20 percent of the locations sampled during a few late summer and early fall sampling sessions. Similarly, most sand lance eggs were collected at a few locations during a few early winter sampling sessions. Surf smelt eggs were much more abundant than sand lance eggs on Camano Island, but eggs of both species were found at many locations (Quinn and others, 2009).

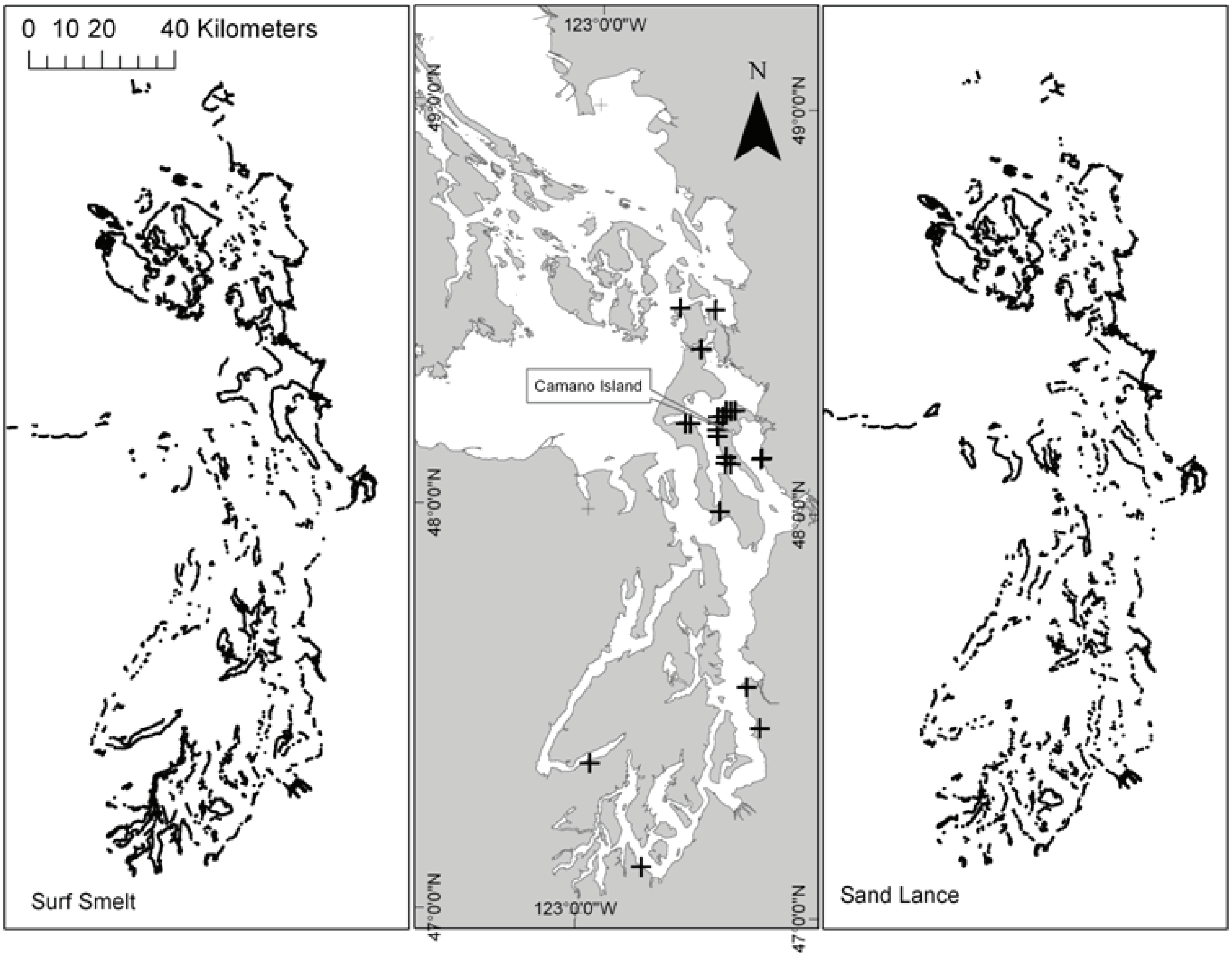

Figure 1. Geographic distribution of samples with observations of surf smelt (left) and sand lance (right) occurrence in Puget Sound. Large + indicates sampling locations (center) where data describing the relation between surf smelt egg density and beach elevation were collected.

Intertidal Egg Distribution

Only 13 locations had sufficient data on surf smelt to fit gamma distributions to quantify the relation between egg abundance and beach elevation. Locations with the highest number of eggs tended to have those eggs at higher elevation than at other sites (fig. 2) and on most beaches a high proportion of eggs were found at high beach elevations (fig. 3). Only 2 locations had sufficient data for sand lance to fit gamma distributions to quantify the relation between egg abundance and beach elevation, precluding subsequent analysis (Krueger and others, 2009). Sand lance seem mostly to spawn at lower elevations in the intertidal zone than do surf smelt. Examination of the cumulative gamma distribution suggests that on beaches where the tidal range plus 1.5 ft is about 10 ft, the low estimate of sea level rise (about 5.1 in.) will inundate about 3.5 percent of beaches and 5 percent of surf smelt eggs, whereas the high estimate of sea level rise (about 27.3 in.) will inundate about 23 percent of the beach and about 75 percent of surf smelt eggs (fig. 3).

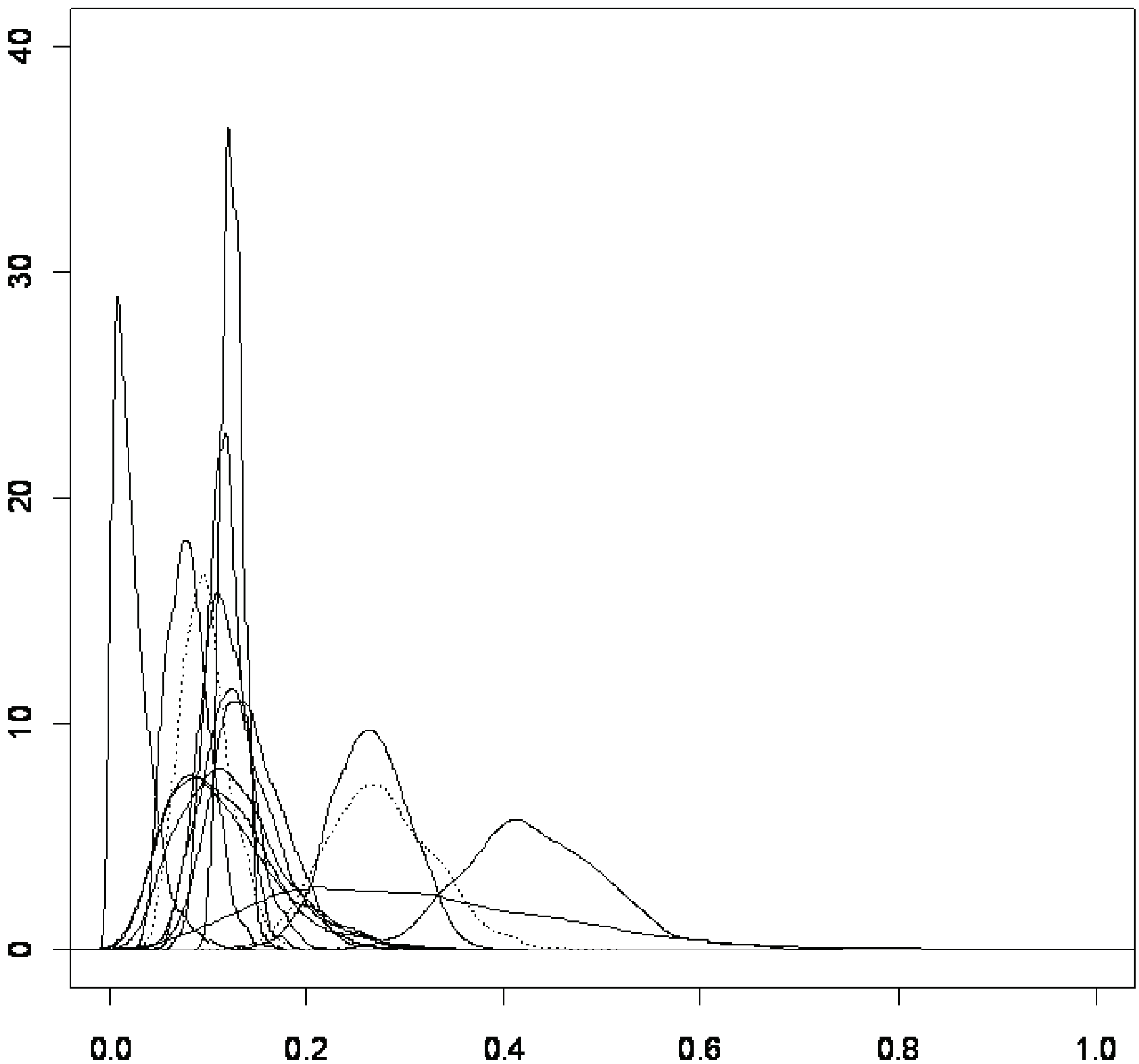

Figure 2. Gamma distributions that describe the relation between surf smelt (n = 13 beaches, solid lines) and Pacific sand lance (n = 2 beaches, dashed lines) egg density and beach elevation. Beach elevation (x-axis) is standardized between 0 (MHHW + 1.5 feet) and 1 (MLLW). Egg density (y-axis) is presented as a percentage of the total number of eggs collected at each beach.

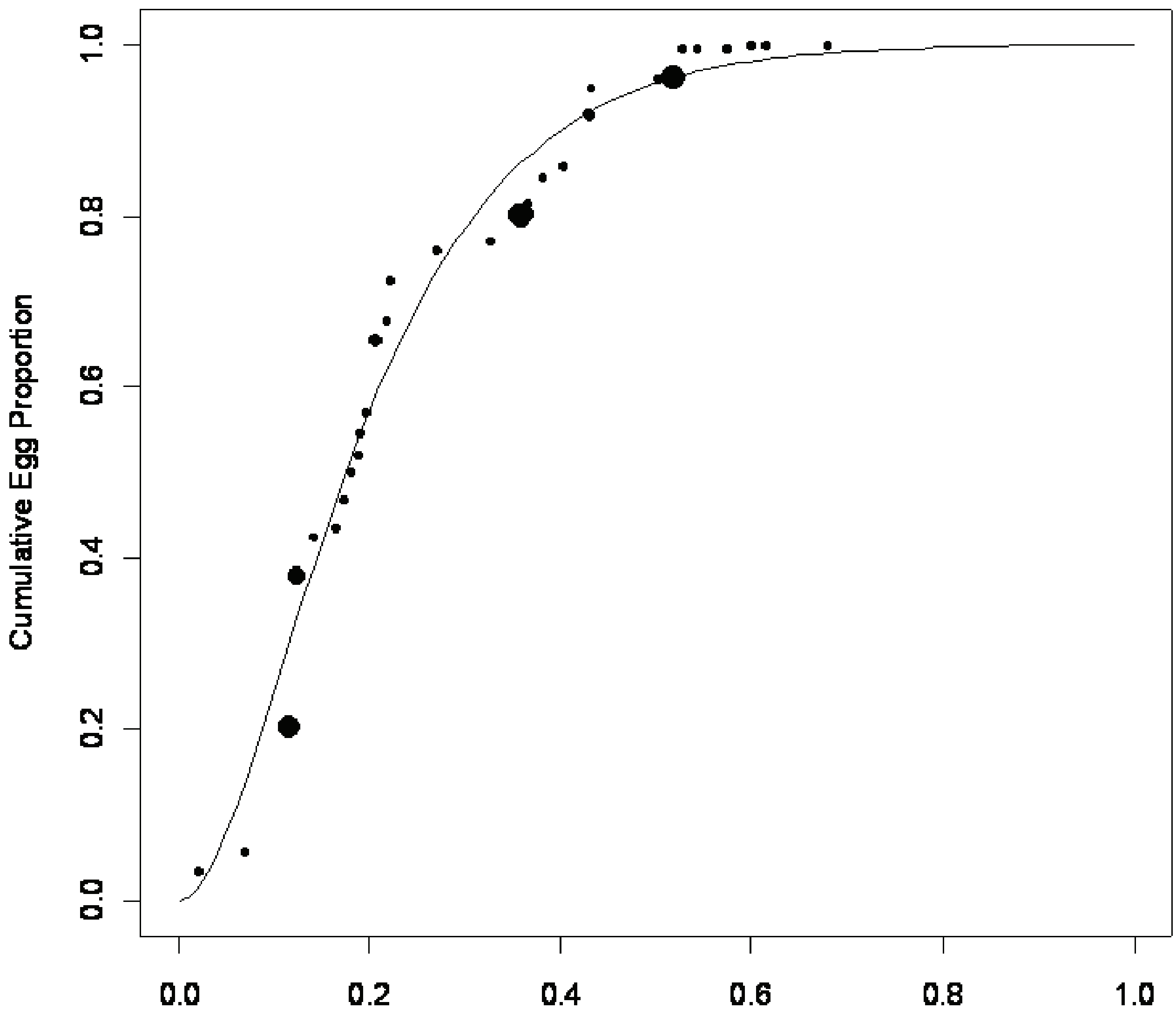

Figure 3. Cumulative gamma distribution describing the proportion of surf smelt eggs found (y-axis) in relation to beach elevation. Beach elevation (x-axis) is standardized between 0 (MHHW + 1.5 feet) and 1 (MLLW). Points identify the position of samples in relation to the fitted line. Larger points identify two samples. Note that loss of a small proportion of the higher beach elevation (for example, 0 to 0.2) affects a large loss of eggs (about 55 percent of those found on the beach). These analyses assume that armoring is at MHHW + 1.5 feet and that beach morphology is static.

Discussion

Maintaining abundant surf smelt and sand lance in Puget Sound is a conservation imperative, but current regulations do not consider cumulative or off-site impacts of armoring, cannot prohibit armoring in most cases (see Carman and others, 2010), and do not address likely future environmental conditions such as sea-level rise. Conserving surf smelt and sand lance is an opportunity to proactively manage for expected environmental conditions by integrating knowledge of geological and ecological processes into policy decisions that address legitimate private property concerns. Although much remains to be learned about Puget Sound beaches, the effects of management actions, and the ecology of surf smelt and sand lance, sufficient information is available to provide sound advice to policy makers and to suggest precautionary management.

The broad geographic distribution of surf smelt and sand lance in Puget Sound likely requires different management actions among regions where environmental conditions, fish behavior, and population structure differ. Robards and others (2002) found differences in the growth and abundance of populations of sand lance in Cook Inlet, Alaska, that were subject to different environmental conditions, and Moore and others (2008) describe some patterns of oceanographic properties in Puget Sound that likely affect fish growth, abundance, and behavior. The presence of several populations (stocks) in Puget Sound seems likely a result of observed differences in spawn timing among locations and consistent timing of spawning at some locations. Small discrete populations have been found for similar species at a similar spatial extent (Bradbury and others, 2008), but their delineation is an unaccomplished prerequisite for efficient monitoring and management in Puget Sound. Further, within Puget Sound, regional differences in effective fetch and tide range and local differences in beach morphology (Finlayson, 2006) suggest that the effects of practices such as shoreline armoring differ among locations. Management of beaches and species should account for these spatial patterns.

Monitoring and management should also account for the spatial and temporal discontinuity of spawning. Observed discontinuity likely is a result of differences in environmental conditions, population size, and sampling errors (Angermeier and others, 2002). Spawning surf smelt and sand lance seem to have preferred sediment sizes on beaches (Penttila, 1995), and adult and juvenile sand lance have sediment size preferences (Haynes and others, 2008) that might affect where spawning occurs. Although predicting the effects at a location is difficult, shoreline armoring can coarsen beach sediment (Kraus and McDougal, 1996) and cause degradation, possibly making beaches less suitable for spawning. Management to establish and maintain large populations of these species should ensure abundant suitable spawning sediment.

Discontinuity might be a result of small population size. The abundance of these species is not known, but such information is necessary for monitoring and management. False absence sampling errors also can produce observed discontinuity. The sampling procedure used to collect most of our spawning data has a low false absence error rate (Krueger and others, 2007), suggesting that most observed absences are correct. However, it should not be assumed that the locations of spawning do not change. Although repeated selection of a beach for spawning has been observed for surf smelt (D.E. Pentilla, written commun.) and Japanese smelt (*Hypomesus japonicas*, Hirose and Kawaguchi, 1998), capeline (*Mallutus villosus*), another beach spawning fish, has altered its geographic distribution of spawning in Newfoundland, Canada, in response to changing water temperature (Nakashima and Wheeler, 2002). Changing environmental conditions might affect where and when spawning occurs. Research that better describes the spatiotemporal distribution of spawning will facilitate more efficient management, but failure to detect spawning should not preclude conservation of beaches that might be suitable for spawning now or in the future.

Spawning surf smelt, and perhaps sand lance, have strong preferences for specific beach elevations (Krueger and others, 2007) and among beaches where spawning is observed, the number of eggs often differs by several orders of magnitude (Quinn and others, 2009). These patterns have profound monitoring and management implications. Importantly, spawning success might be disproportionate to the length or area of beach affected by armoring or other disturbance. That is, loss of spawning on a small proportion of beaches might affect a large loss of spawning if the disturbed beaches have many eggs. We know little about the relative importance of specific beaches for spawning; therefore, precautionary management that assures suitable spawning habitat on known and likely spawning beaches is warranted. Further, impacts to a small part of the upper beach might result in a large loss of eggs because surf smelt eggs are most abundant at high beach elevations.

Sea-level rise is likely to cause substantial loss of surf smelt spawning habitat on beaches with armored shorelines because armoring prevents beach migration inland (Griggs and others, 1994), thereby reducing the area of beach with elevations preferred for spawning. On some beaches loss of surf smelt spawning habitat is likely to occur soon with moderate sea level rise because many eggs are deposited at high beach elevations (fig. 3). Estimates of sea-level rise suggest that on beaches with armored shoreline substantial surf smelt spawning habitat might be lost in the next few decades and most spawning habitat might be lost by 2100.

Several limitations of our study should be noted to prevent misapplication of our results. First, our beach spawning elevation and beach form data likely do not fully describe conditions on many Puget Sound beaches because our data are from few beaches that are mostly in central Puget Sound. Second, sufficient data to describe the distribution of sand lance eggs in relation to beach elevation are not available because data were not collected during their peak spawning period (that is, winter). The effects of sea-level rise and shoreline armoring on sand lance might be similar to those we describe for surf smelt, but we have little data to support that conjecture. Also, because we use a surrogate to estimate the elevation of shoreline armoring we might have underestimated the effect of sea-level rise on spawning where armoring is below our surrogate elevation. Further, our analyses did not account for likely changes to beach profiles or sediment size likely to occur with elevated sea level. Failure to account for these effects might underestimate the effect of sea-level rise and shoreline armoring on spawning habitat. Finally, estimates of sea-level rise are uncertain, especially for specific locations (Mote and others, 2008). We used a range of sea-level rise estimates to address this problem. Because we make conservative assumptions (for example, beach profile and substrate remain suitable) for our analyses, our detection of substantial loss of spawning habitat likely is robust.

Our analyses suggest that addressing shoreline armoring effects on beach morphology and surf smelt and sand lance spawning habitat is an important and urgent management concern. Loss of beach spawning habitat as a result of sea-level rise and shoreline armoring is likely to be widespread because much of the shoreline of Puget Sound is already armored and the desire to armor shorelines is expected to increase as additional shoreline is developed (Quinn, 2010) and as sea level rise speeds beach migration (Griggs and others, 1994; Johannessen and MacLennan, 2007). Further, the discontinuous geographic distribution of spawning occurrence and egg abundance suggest that loss of a relatively small number of spawning beaches might have a large detrimental effect on egg abundance. Importantly, some regulatory protection of surf smelt and sand lance spawning habitat exist, but those measures fail to take into account the expected environmental change and spatiotemporal variation in spawning. Further, existing regulatory protection fails to consider the cumulative or off-site effects of projects and provides no ability to deny projects for single-family residences, even if the project might exacerbate losses on other beaches. Effective conservation of surf smelt and sand lance should address such regulatory shortcomings.

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