Biological Effects of Shoreline Armoring in Puget Sound: Past Studies and Future Directions for Science

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Abstract. Human alteration of Puget Sound shorelines is extensive yet its biological consequences are largely unknown, in part because research and monitoring of the Puget Sound ecosystem (1) has usually not included anthropogenic disturbances such as shoreline armoring as explicit factors in sampling design and data analysis, (2) tends to not make direct measures of biological condition a top priority, and (3) has rarely sampled across the full range of natural physical and biological conditions within the system. Several recent site- and local-scale field studies have documented differences between modified and more natural beaches in terms of several biological attributes (for example, spatial extent and patch size of eelgrass; supratidal invertebrate abundance and assemblage composition; embryo condition of intertidally spawning fish; and taxonomic composition, size, behavior and diet in fish assemblages). Many of these results are equivocal and no large-scale biological field studies have resolved the uncertainty. However, combination and reanalysis of bird survey and shoreline attribute monitoring data from all of greater Puget Sound illustrate the value of landscape-scale studies focusing explicitly on biological responses to human influence across a range of natural ecological gradients (for example, season, year, oceanographic sub-basin, shoreform). Changes in the taxonomic composition of marine bird and waterfowl assemblages were related to urban land cover gradients along Puget Sound shorelines throughout greater Puget Sound, although specific effects of armoring itself were not detected. Together these studies demonstrate that armoring of Puget Sound shorelines affects abiotic attributes (for example, physical structure and microclimate), can adversely affect the biota at local scales, and suggest the potential for Sound-wide changes in biology as a result of shoreline armoring. But the cumulative, population and ecosystem level effects of armoring remain understudied and unknown. Expanded, systematic field studies that characterize biological attributes across a range of armoring, other anthropogenic disturbances, and natural ecological conditions (for example, geomorphology, exposure, landscape position) are necessary to improve our understanding and management of the biological effects of shoreline armoring in Puget Sound. Only one such study is planned for central Puget Sound but others increasingly are being proposed.

Introduction

Puget Sound is a large and ecologically diverse and dynamic fjord estuary system that has undergone major physical and biological transformation as a result of human activity (Bortleson and others, 1980; Collins and Sheikh, 2005; Ruckleshaus and McClure, 2007; Rice, 2007; Simenstad and others, 2010). At the interface between terrestrial and aquatic, and salt and freshwater environments, Puget Sound shorelines are a unique ecotone that is home to many species during at least part of their lives (Brennan and Culverwell, 2004). These include taxa that are the focus of considerable management, regulatory, and conservation concern: eelgrass (*Zostera marina)*, a dominant feature of the biota that provides habitat for many other species and significant detrital input to Puget Sound food webs; ESA-listed Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) and summer chum salmon (*O. keta*) that use estuarine shorelines for extended rearing as juveniles (Simenstad and others, 1982; Beamer and others, 2005); the small pelagic fishes (Pacific herring [*Clupea pallasii pallasii*], surf smelt [*Hypomesus pretiosus*], and sand lance [*Ammodytes hexapterus*]), all of which spawn on intertidal or subtidal Puget Sound shorelines (Penttila, 1995) and likely play key roles in the Puget Sound ecosystem as mid-level consumers and as prey for many species (Rice, 2007); and marine birds and waterfowl, several of which have undergone significant population declines in recent decades (Puget Sound Action Team, 2007).

Shoreline armoring is one of the more conspicuous and prevalent disturbances across the Puget Sound landscape (see Carman and Taylor, 2010), often cited as an important factor contributing to perceived declines in biological condition (Thom and Hallum, 1991; Thom and others, 1994; Ruckelshaus and McClure, 2007), yet few studies

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of its ecological consequences have been done, and still fewer conclusive data are available. This is consistent with the broader pattern in Puget Sound science of both limited biological monitoring and assessment in estuarine environments, and omission of anthropogenic stressors in sampling design and data analysis (Rice, 2007). Relying on random selection of sample locations in field studies, for example, is unlikely to encounter a representative range of anthropogenic disturbance simply because those disturbances are not randomly distributed.

With the partial exception of toxicology studies (see Puget Sound Action Team, 2007, and Rice, 2007, and references therein), biological monitoring in Puget Sound typically consists of tracking trends of single species abundance over time rather than evaluating the character of the biota along explicit human influence gradients. That is, we tend to ask, “How much is there and how is that changing over time?” rather than “What is out there and how does it reflect the various dimensions and degrees of human activity?” (Rice, 2007). Addressing this second type of question is critical for effective monitoring and assessment (Karr, 2006). Foundational studies (for example, Miller and others, 1980; Long, 1982) documenting the character of shoreline biota across natural ecological gradients are also rare and dated (but see Dethier and Schoch, 2005).

In addition to these common problems of focus and approach, the study of the biological effects of shoreline armoring presents considerable practical difficulties because of the heterogeneous and dynamic nature of shoreline environments, and the myriad combinations of material, elevation, and age of armored structures across diverse natural ecological contexts such as geomorphology, exposure, and landscape position (Williams and Thom, 2001; Simenstad and others, 2006). Extensive private ownership of shorelines in Washington State restricts access to shorelines and generates opposition to documenting adverse effects of armoring. Shoreline armoring also is typically one of many anthropogenic disturbances that often occur together; thus, isolating the effects (local and offsite) of armoring from a suite of individual stressors, evaluating its relative importance, and understanding cumulative effects at landscape and ecosystem scales is a major scientific challenge. All of these factors have slowed progress toward understanding the biological effects of shoreline armoring in Puget Sound.

The purpose of this paper is to briefly review the state of the science with respect to the biological effects of armoring in Puget Sound, including a summary of studies to date, and suggested directions for future research. Conceptual models of how shoreline armoring may affect coastal ecosystems in general, and the documented effects of armoring in systems outside of Puget Sound are reviewed elsewhere in this volume (for example, see Coyle and Dethier, 2010).

Puget Sound Studies

Several recent studies have addressed the biological effects of shoreline armoring within Puget Sound focusing on plants (Simenstad and others, 2008), invertebrates (Tonnes, 2008; Sobocinski, 2010), fishes (Rice, 2006; Toft and others, 2007; and see Toft and others, 2010), and birds (Rice, 2007). Although results are often equivocal, some clear patterns have emerged, and these studies provide useful foundation for future work by testing various methods, and by documenting biotic and abiotic attributes of armored and unarmored shorelines.

In a study of intertidal eelgrass landscape structure in Hood Canal and the eastern Strait of Juan de Fuca, Simenstad and others (2008) used extensively ground-truthed remote sensing to evaluate the spatial continuity and patch attributes of intertidal eelgrass across a range of natural and anthropogenic gradients, including drift cell position and shoreline armoring, respectively. Identifying relationships between the many potential effects proved complex. Natural beach geomorphology greatly affected eelgrass attributes, but extreme cases of shoreline armoring were identified as a potentially important effect on eelgrass landscape metrics. In addition, the authors suggest that their methods and approach may complement Sound-wide video transect surveys (Gaeckle and others, 2007), which are limited in their spatial resolution, and perhaps more importantly, do not factor in shoreline armoring or any other human influences in the sampling design.

Some of the clearest results documenting the biological effects of armoring have come from studies of supratidal invertebrates. Species richness and absolute abundance in benthic cores and fallout traps (compared between paired beaches) in central Puget Sound tended to be lower at the base of armored sites than on natural substrates (Sobocinski and others, 2010), but such differences were not apparent in a synoptic set of samples in the same study, possibly because of increased spatial variation in the synoptic versus paired samples, and the relatively high elevation of the bulkheads on the sites studied. This suggests that the extent of intertidal coverage of armoring is an important determinant of ecological effects. Armored beaches tend to have little or no wood, and less wrack, present on them (Tonnes, 2008; Sobocinski and others, 2010). Consequently, densities of talitrid amphipods, which are strongly related to the presence of driftwood and wrack (Tonnes, 2008), were orders of magnitude higher on unmodified than on modified beaches. One caveat to some of these results is the degree to which the armoring, or simply the removal of overhanging vegetation, affected the results (Rice, 2006; Tonnes, 2008).

Removal of armoring as part of ecological restoration actions seems to have beneficial effects on invertebrate assemblages. Ongoing monitoring of restoration projects at Olympic Sculpture Park and Seahurst Park in central Puget Sound (Toft 2009; Toft and others, 2008, and 2010) has documented, for example, increased taxa richness after armoring removal, and a convergence of assemblage composition on restored sites with that on unarmored reference sites. An expanded study of the Seahurst Park project that includes ten paired armored and unarmored sites will run from spring 2010 to winter 2013 (M. Dethier, oral commun., 2010).

Fish assemblage attributes associated with armoring in Puget Sound include changes in taxonomic composition, individual size distribution, behavior, and diet of fishes (Toft and others, 2007; Toft and others, 2010); and reductions in the abundance and condition of the embryos of surf smelt, a small pelagic fish that uses upper intertidal beaches to spawn (Rice, 2006). Changes in attributes of fish assemblages at armored sites seem to be related at least in part to beach slope and substrate type, and are more distinct the lower the armoring extends into the intertidal (Toft and others, 2007; 2010).

Because smelt embryos are affected by thermal and moisture conditions (Lee and Levings, 2007), microclimate conditions on the different beaches are the likely cause for the increased mortality on the altered beach, where, for example, summer substrate temperatures averaged nearly 5°C higher on the altered beach, and peak temperatures were 29°C on the altered beach versus 18°C on the natural beach. But while some site-level effects of shoreline modification in general are apparent, the degree to which the observed effects are specifically the result of armoring is less clear. Overhanging vegetation is commonly lost when a beach is armored and that loss likely is responsible for a significant portion of the changes in microclimatic (Rice, 2006; Tonnes, 2008) and biotic (Romanuk and Levings, 2003, 2006) conditions on armored beaches.

Moreover, because there is no evidence that Puget Sound fish populations are limited by shoreline rearing and spawning habitat (but see Beamer and others, 2005 for evidence of estuarine rearing habitat limitation in juvenile wild Chinook salmon), a better understanding of the population biology and status of Puget Sound fishes would be helpful in evaluating the true biological significance of shoreline armoring. For example, we have little information on the population status of most of the species potentially affected by shoreline armoring, let alone whether shoreline armoring is having a significant adverse effect on that status, or "how much" armoring it might take to be of serious concern. Better understanding of the physical attributes and spatial distribution of preferred spawning habitats of surf smelt, sand lance, and herring, and the relative importance of spawning habitat loss in the population dynamics of these species is a major knowledge gap.

In addition to these local- and site-level studies, a post-hoc analysis of aircraft-based marine bird surveys along shorelines provides an instructive example on how we might approach future research on armoring and other anthropogenic effects. Multiple populations of marine birds and waterfowl have undergone major declines in Puget Sound during recent decades (Puget Sound Action Team, 2007), presumably the result of many local and remote effects. Historical monitoring and assessment of these taxa did not attempt to relate changes in bird abundance or taxonomic composition to local environmental factors, including human influences such as the modification of shoreline ecosystems. The combination of aircraft-based bird census data with shoreline attribute data (Washington Department of Natural Resources, 2001), including land-cover data (Hepinstall-Cymerman and others, 2009), revealed that the taxonomic composition changes along anthropogenic gradients (Rice, 2007). For example, as the percentage of urban land cover alongshore increased, overall taxa richness declined, and the relative frequency of opportunistic and tolerant taxa such as large gulls, increased. Although no clear relationships between attributes of bird assemblages and shoreline armoring were apparent, this study demonstrates that, despite coarse lumping of disparate data sets across a large and heterogeneous natural landscape, relationships between integrative measures of biological condition and human activity can be detected, simply by framing the research question appropriately: that is, asking "What is out there and how does it reflect the various dimensions and degrees of human activity?" rather than just "How much is there and how is that changing over time?"

Conclusion

Despite widespread recognition of the potentially serious adverse biological effects of shoreline armoring, and several recent studies developing methods to study such effects and documenting impacts in Puget Sound, empirical evidence of biologically significant effects remains scarce, in part because of the lack of scientific studies focused explicitly on armoring effects, including underlying mechanisms. The study of the effects of shoreline armoring presents many challenges, but if our inferences about likely effects are correct, and armoring exists across over one third of the Puget Sound shoreline (Carman and Taylor, 2010), surely we should be able to detect those effects, and use that information to improve the understanding and management of Puget Sound ecosystems.

Several key efforts would be particularly informative:

- Conduct focused field studies on the biological and physicochemical character of armored and unarmored shorelines, alone and in combination with other anthropogenic disturbances. Subjects for biological response should include multispecies metrics in ecologically diverse taxa that are likely to be responsive to armoring, and amenable to scientific study. In addition to plants, supratidal invertebrates, fishes, and birds already mentioned here, consideration of effects on intertidal and subtidal infauna (see Dethier and Schoch, 2005, for an example of sampling methods and potential response variables) would be an informative focus. Because armoring effects may differ across the many local differences in, for example, substrate, exposure, shoreform, and landscape position, these studies should attempt to cover all major natural gradients. New shoreline typology (Shipman, 2008; McBride and others, 2009) and change analysis (McBride and others, 2005; Simenstad and others, 2010) can provide a useful basis for incorporating such factors into sampling design. Controlled, manipulative experiments such as restoration actions could provide invaluable insights into armoring effects and mechanisms.
- Seek opportunities to incorporate armoring and other forms of anthropogenic shoreline modification into existing monitoring and assessment programs such as those that are focused on vegetation (Gaeckle and others, 2007) and marine birds and waterfowl (Puget Sound Action Team, 2007).
- Improve our understanding of the population biology of key species of concern, such as small pelagic fishes. For example, characterizing physical attributes and spatial and temporal distribution of spawning habitats, and developing life cycle models for these species, would be useful tools in evaluating the true biological significance of shoreline armoring.

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