Completion Report

Cordell, Jeffrey

Period: 2/1/2012 - 1/31/2013
Project: R/OCEH-1 - *Integrating Intertidal Habitat into Seattle Waterfront Seawalls, Phase 2*

:: STUDENTS SUPPORTED

No Students Reported This Period

:: CONFERENCES / PRESENTATIONS

Seawall Habitat Forum, public/profession presentation, 20 attendees, 2012-06-04

Seattle Aquarium Aquaversity Training, public/profession presentation, 20 attendees, 2012-10-08

:: ADDITIONAL METRICS

K-12 Students Reached: 15

Orca Bowl student enrichment tour

Acres of degraded ecosystems restored as a result of Sea Grant activities: 0

Curricula Developed: 0

Resource Managers who use Ecosystem-Based Approaches to Management: 0

Volunteer Hours: 0

HACCP - Number of people with new certifications: 0

Cumulative Clean Marina Program - certifications: 0

:: PATENTS AND ECONOMIC BENEFITS

No Benefits Reported This Period

:: TOOLS, TECH, AND INFORMATION SERVICES

Description		Developed	Used	Names of Managers	Number of Managers
Habitat panel data for use by City of Seattle technical	**Actual** (2/1/2012 - 1/31/2013) :	0	1	City Consultant. Tetra Tech, Incorporated in replacement	1

advisors to design improvements for new city seawall. R/ES-66, R/OCEH-1	**Anticipated** (2/1/2013 - 1/31/2014) : 0	1	wall design.

:: HAZARD RESILIENCE IN COASTAL COMMUNITIES

No Communities Reported This Period

:: ADDITIONAL MEASURES

Safe and sustainable seafood

Number of stakeholders modifying practices
Actual (2/1/2012 - 1/31/2013) : 0
Anticipated (2/1/2013 - 1/31/2014) : 0

Number of fishers using new techniques
Actual (2/1/2012 - 1/31/2013) : 0
Anticipated (2/1/2013 - 1/31/2014) : 0

Sustainable Coastal Development
Actual (2/1/2012 - 1/31/2013) : 1
Anticipated (2/1/2013 - 1/31/2014) : 1
City of Seattle has adopted seawall habitat concepts from this Sea Grant research project in the design for the new Seattle seawall.
It is anticipated that these designs will be included in the actual construction of the seawall beginning winter 2013.

Coastal Ecosystems
Actual (2/1/2012 - 1/31/2013) : 0
Anticipated (2/1/2013 - 1/31/2014) : 0

:: PARTNERS

Partner Name: City of Seattle
Partner Name: City of Seattle (Department of Transportation)
Partner Name: EnvironIssues
Partner Name: Muckleshoot Indian Tribe
Partner Name: National Marine Fisheries Service (US DOC, type: government, scale: federal
Partner Name: Seattle Public Utilities
Partner Name: Suquamish Tribe
Partner Name: Tetra Tech, Inc.
Partner Name: University of Washington
Partner Name: US Army Corps of Engineers (DOD, Army, USACE)
Partner Name: US Fish and Wildlife Services (US DOI, FWS)
Partner Name: Washington State Department of Fish and Wildlife
Partner Name: Washington State Department of Natural Resources

:: IMPACTS AND ACCOMPLISHMENTS

Title: **Washington Sea Grant-sponsored research produces more habitat-friendly seawall designs**

Type: impact

Relevance, Response, Results:
Relevance: Seawalls protect urban infrastructure but degrade habitat for fish and other wildlife by transforming complex sloping shorelines into simplified vertical walls. The impending replacement of Seattle's seawall presented an opportunity to improve habitat for wildlife, including several salmon species that migrate through the area. Since little systematic research has been done on the habitat benefits of various seawall designs, any insights gained in Seattle might improve design elsewhere.
Response: Washington Sea Grant-supported scientists collaborated with the City of Seattle to design, install and monitor large-scale test panels at three locations along the Seattle waterfront. The research compared three types of relief (flat panel, sloped steps, and a "fin" pattern resembling protruding tire treads) and two surface textures (smooth and cobbled) to untreated seawall. The first phase documented the initial response of invertebrates and algae to the different designs, and a second provided additional monitoring.
Results: Second phase results corroborated initial findings: The relief panels (with steps and fins) supported more diverse communities than the existing seawall or flat panels. Some populations, such as mussels, reached densities on the flat panels resembling those in more natural habitats. Although initial results indicated that juvenile salmon found more prey on the relief panels, no consistent pattern emerged. As a result of this collaboration, Seattle will be the first city in the world to incorporate habitat panels into a large expanse of seawall. The city plans to monitor for several years after construction, generating the data needed to design future ecologically beneficial seawalls.

Recap:
Washington Sea Grant-funded research produces a new wildlife-friendly seawall design for Seattle, showing the way to better seawall design around the world.

Comments:
Primary Focus Area – OCEH (HCE)
Secondary Focus Area – COCC (SCD)

Associated Goals: Protect and restore marine, coastal and estuarine habitats (HCE Restore).
Assist coastal communities and marine-dependent businesses in planning and making decisions that provide local and regional economic benefits, increase resilience and foster stewardship of social, economic and natural resources (SCD Inter-relation).

Related Partners: *none*

:: PUBLICATIONS

Title: **"Habitat Research" interpretive panel at Waterfront Park, Seattle**

Type: Publication Year: 2012
Uploaded File: Habitat_panel.jpg.jpg, 5476 kb
URL: *none*

Abstract:
n/a

Citation:
Habitat Research. Interpretive Panel. Washington Sea Grant. 2012.

Copyright Restrictions + Other Notes:

Journal Title: *none*

Title: **Project Website**

Type: Internet Resources, Topical Websites Publication Year: 2013
Uploaded File: *none*
URL: https://sites.google.com/a/uw.edu/seattle-seawall-project/

Abstract:
n/a

Citation:
Seattle Seawall Habitat Enhancement Project. University of Washington, 2013. https://sites.google.com/a/uw.edu/seattle-seawall-project/

Copyright Restrictions + Other Notes:

Journal Title: *none*

:: OTHER DOCUMENTS

No Documents Reported This Period

:: LEVERAGED FUNDS

No Leveraged Funds Reported This Period

Rationale and Objectives

Marine biodiversity is a global conservation issue and has been negatively affected in coastal areas, where large declines are associated with the intense human uses of coastal habitat that include industry, seaports, and extraction of natural resources (Gray 1997). In temperate estuaries and coastal seas around the world, habitat loss is second only to exploitation as the cause of most species depletions and extinctions (Lotze et al. 2006). Marine shorelines around the world are being transformed as the demand for infrastructure increases, and shoreline alteration is projected to accelerate as populations along coastal areas grow and as the threat of sea level rise increases (Bulleri & Chapman 2010, Chapman & Underwood 2011).

One of the most common impacts arising from shoreline development is the replacement of natural beaches with armoring structures needed to preserve shoreline use. Of these, seawalls are the least complex, typically built of smooth vertical concrete slabs that often transform complex habitats into less heterogeneous substrata (Chapman & Underwood 2011). Seawalls typically support only some of the taxa that occur in natural rocky intertidal habitats because they lack the complexity of natural shorelines, resulting in altered recruitment, survival, densities, fecundity, and species interactions (Chapman & Bulleri 2003, Bulleri & Chapman 2010, Chapman & Underwood 2011, Klein et al. 2011). Seawalls have lower diversity, supporting fewer mobile species than rocky shores, but biological effects are also manifested in changes of density, size, and reproductive capability of the organisms (Chapman 2003, Bulleri & Chapman 2004).

One important difference between seawalls and natural rocky intertidal shorelines is the lack of habitat heterogeneity and complexity associated with slope, roughness, crevices, and overhangs. Slope and shade impact intertidal communities by affecting recruitment, thermal stress, desiccation, and survival (Wethey 1984, Menconi et al. 1999, Helmuth & Hofmann 2001, Blockley & Chapman 2006). Surface roughness (small-scale variations in the height of a surface) and crevices are important habitat features, especially as refuges from physical disturbance for invertebrates such as mussels, chitons, limpets, and snails (Bergeron & Bourget 1986, Faller-Fritsch & Emson 1986, Menconi et al. 1999, McKindsey & Bourget 2001, Moreira et al. 2007). Seawalls also have less space, a major limiting resource in rocky intertidal habitats, than natural hard substrata (Little & Kitching 1996, Raffaelli & Hawkins 1996). Limited space on seawalls creates more abrupt vertical zonation than naturally craggy, sloped rocky shorelines and may make organisms more vulnerable to increased competition and predation (Ivesa et al. 2010, Klein et al. 2011).

The introduction of seawalls into the coastal environment can be viewed as a major disturbance that is followed by a succession of species colonizing the new substratum. The mechanisms, trajectories, rates, and possible outcomes of succession, which are influenced by colonization, recruitment, and species interactions, have been well studied in the rocky intertidal zone (Branch 1986, Farrell 1988, 1991, McKindsey & Bourget 2001). A contemporary view of succession is that it can be altered by many biotic and abiotic factors, and that the outcome is not a stable state but rather results in a community subject to dynamic change (Farrell 1991). Communities with low species diversity may have a more predictable succession of species because there are fewer alternative communities possible (Farrell 1991). An initial colonization by ephemeral algae and sessile invertebrates gradually replaced by larger perennial algae is typical in rocky habitats (Dayton 1971, Farrell 1991, Chapman & Underwood 1998). It may, however, be more difficult to predict the rate of succession, which depends largely on the timing and number of the initial colonizers (Farrell 1991). It can take months or years for the assemblage in a clearing to converge with the surrounding intertidal assemblage (Dayton 1971, Farrell 1991, Chapman & Underwood 1998, Viejo et al. 2008).

Puget Sound is an estuarine fjord in Washington State, USA, in which shorelines are primarily glacial sediment beaches, embayments, and deltas, including mudflats and tidal marshes, with rocky coasts limited mostly to the northern and seaward margins of the Sound (Shipman 2008). Beaches in Puget Sound are being increasingly modified by the addition of hard substrata through armoring, intertidal fills, seawalls, groins and jetties, and overwater structures (Shipman 2008). In particular, urban bays have experienced large declines in natural shoreline, with 68% modified in King County, where Elliott Bay and the City of Seattle are located (WDNR 1999). Mixed gravel-cobble beaches originally characterized Elliott Bay with low- to high-bank bluffs to landward and low tide terraces to seaward. Currently there are over 3 kilometers of seawall along the Seattle central waterfront built adjacent to deep water resulting in very little remaining shallow sloping intertidal beach (WDNR 1999). Seattle's seawall is in disrepair and scheduled for replacement beginning in 2013, presenting a unique opportunity to evaluate alternative designs for seawalls that may support more natural levels of biodiversity and ecological function on urbanized shorelines.

Our objective was to determine whether ecologically engineered seawalls incorporating slope and texture could provide benefit to intertidal biota, specifically increasing invertebrate and algal taxa richness and abundance. To test this we deployed large test panels on the Seattle seawall that incorporated different types of relief and surface texture. Our experiment was designed to test the hypotheses that: (1) test panels had converged with the surrounding seawall by the end of our study (i.e. the test panels had been on the seawall long enough to have the same organisms as the unaltered seawall, such that they could be compared); (2) taxa richness (the number of different types of organisms) would be higher on panels with built-in slopes and texture than on less complex panels and the existing seawall; and (3) differences in the abundance of ecologically important and habitat-forming species would be associated with certain slopes and textures of the seawall panels. The test panels were deployed during winter 2007-2008, and sampling started in spring 2008. Phase 1 of the study was completed after two years of sampling, in 2010 and is described in a Master's thesis by Goff (2010). Here we summarize the Phase 1 data and present the findings of Phase 2 of the study, for which sampling occurred in 2010 and 2011, thus examining four years of field data from the experimental habitat panels.

Methods

Study area. The study site was the central waterfront of Seattle, Washington, USA, along the shoreline of Elliott Bay, located in central Puget Sound. Elliott Bay is a partly enclosed estuarine environment with inputs of freshwater from the Duwamish/Green River system. Although highly altered by urban and industrial development, the Duwamish River estuary and Elliott Bay are a migratory corridor and rearing habitat for several species of Pacific salmon (*Oncorhynchus* spp.) that utilize the habitat along Seattle's seawall. The study site spans a portion of the Seattle central waterfront seawall (Fig 1). Logistical constraints limited study locations, but three replicate locations were found within the study site that had very similar conditions of low freshwater influence, elevation of the toe of the seawall, orientation to sun and waves, and usable length for deploying experiments. With a southwest orientation, the seawall and its associated biota were subject to intense afternoon sun during summer low tides and exposure to wind, waves, and low temperatures in winter.

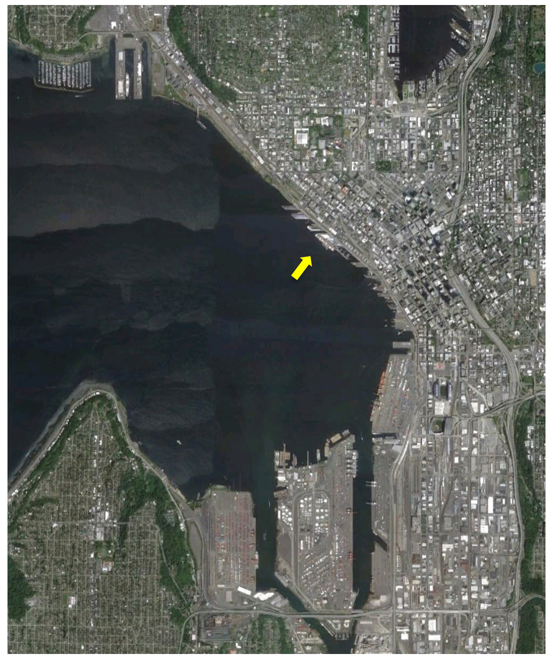


Figure 1. The Seattle Waterfront on Elliott Bay, showing the general location of the study area (arrow).

Study design. Test panel treatments included three panel designs (finned, stepped, and flat) (Fig 2) and two surface textures (smooth and cobble) (Fig 3) for a total of six treatments. Panels, approximately 1.5 m wide by 2.3 m high, were designed along with City of Seattle engineers, who managed their construction and deployment.

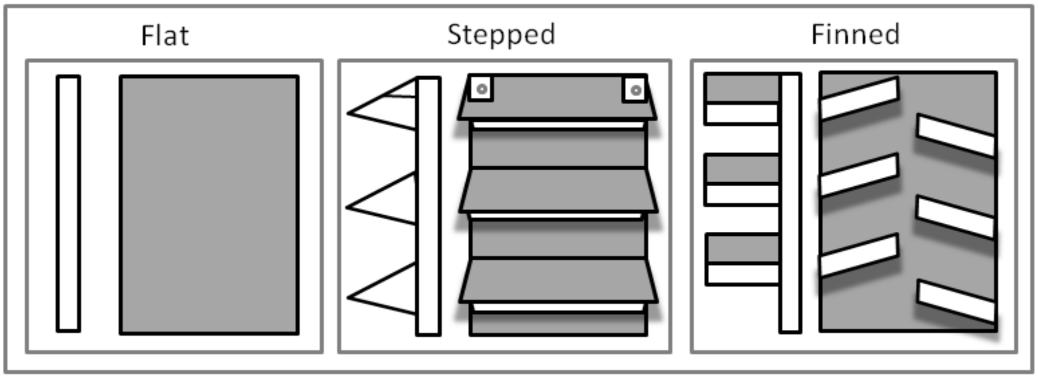


Figure 2. Schematic showing the three types of habitat panels deployed along the Seattle seawall.

Figure 3. Aerial photographs of three experimental locations along the Seattle waterfront, and the six types of treatment panels as they appeared several months after deployment.

All six types of ecologically engineered test panels were randomly installed at the three locations along the Seattle waterfront (Fig 3). Each location spans approximately 40 m of seawall such that the bottom of each panel was at approximately 0 m Mean Lower Low Water (MLLW). Reference (undisturbed original seawall) and control (pressure-washed seawall) sections were also randomly selected at each location when the panels were installed to provide a comparison to existing conditions and to a "time-zero" for evaluating succession and convergence.

Data collection

Sessile Organisms. In phase 1 of the project, sessile invertebrates and algae were quantified at monthly intervals May-August 2008 and in April, June, and August 2009. In phase 2, sessile invertebrates and algae were quantified in April and June 2010 and May and June 2011. Quadrat sampling was used to quantify biota at three panel elevations (in reference to MLLW): (1) "upper" from approximately 1.5 m to 2.3 m, (2) "middle" from approximately 0.7 m to 1.5 m, and (3) "lower" from approximately 0 m to 0.7 m. Three random quadrat locations were chosen at each elevation for a total of nine quadrats per panel. The same locations were sampled thereafter to provide a time series. Due to the size of the panels, the net area covered by the quadrats was a substantial portion of the total area. On step and fin panels, subsamples were taken from both vertical and sloped surfaces at each elevation and classified as such to enable separate analyses of different substratum angles. Areas on the underside of fins and steps were not sampled.

Quadrat sampling on a stepped panel.

Invertebrates and algae were visually scanned in 25-cm x 25-cm gridded quadrats to identify species and estimate percent cover (Murray et al. 2006). Invertebrates and algae falling within each of 25 regularly spaced grid cells within the quadrats were identified and a percent cover was estimated for the entire quadrat (Dethier et al. 1998). When a primary organism and an epibiont occupied the same space within a grid cell, for example green algae on a barnacle, both organisms were recorded. When necessary, representative specimens from outside the quadrat were collected for identification.

Epibenthic organisms. Epibenthic sampling was conducted in both phases of the study during the juvenile salmon outmigration period that occurs between April and July.

An epibenthic pump (14.8 cm diameter, 150-um mesh size) was used to collect mobile macro- and meiofaunal invertebrates from the surface of habitat test panels (Fig 4). The pump works by vacuuming invertebrates inside a cylinder of known volume from a known surface area of submerged substrate. The sampler has been modified to better fit the contours of the cobble relief surfaces of the test panels by adding a brush edge to the sampler bottom.

Epibenthic pump.

Stratified random sampling was conducted on the lower elevation (approximately 0' to 3' MLLW) of each habitat test panel. Epibenthic pump samples were collected to characterize species assemblage and density on both vertical and sloped surfaces (Fig 4). To minimize microhabitat variability, vertical and sloped strata were sampled separately (Raffaelli and Hawkins 1996). Sampling was conducted at three spots and combined into a composite sample. Sample locations were randomly stratified over vertical sections and over the lower step of the stepped panels, the lower two fins of the fin design panels, and the lower one-third of the flat panels. Samples were also collected from the lower one-third of the pressure-washed control area and from the reference area of pre-existing seawall, except at Clay Street where the lower sections of seawall had been removed during maintenance. At this site reference and control sections were sampled at the lowest possible elevation at approximately +3 feet MLLW).

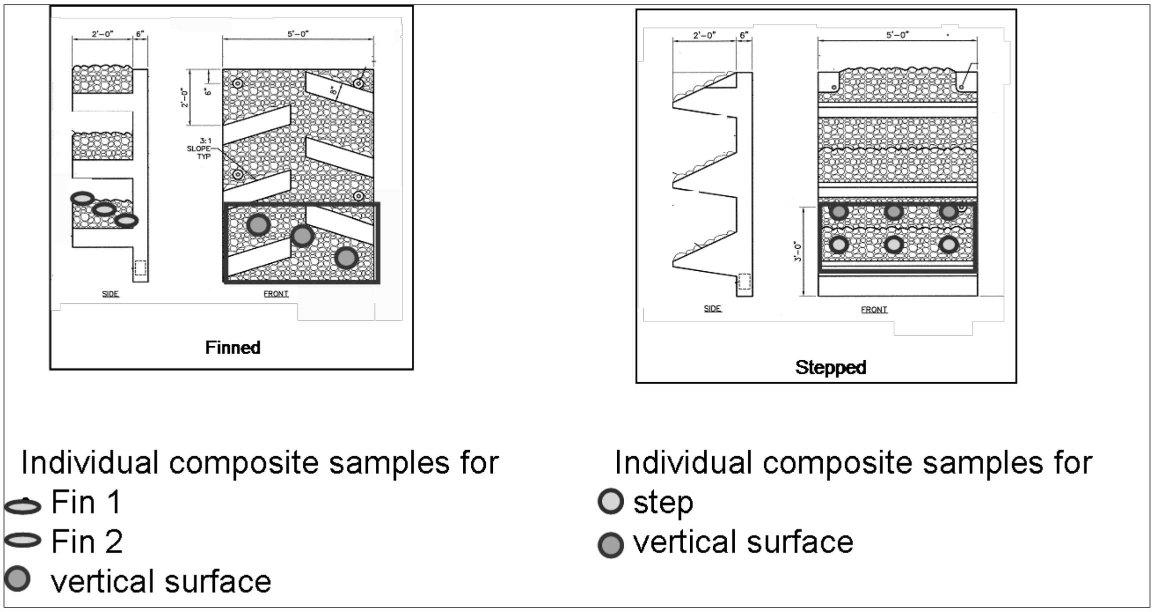


Figure 4. Schematic showing where epibenthic samples were taken on finned and stepped panels (right).

Epibenthic samples were fixed in 10% buffered formalin in the field. Invertebrate taxa from known salmon prey groups such as large harpacticoid copepods, gammarid amphipods, other peracarid crustaceans, and mobile polychaete worms were identified to species; other taxa were identified to family level or lower.

Data Analysis

Sessile organisms. Analyses of differences in the whole biotic assemblage on the panels were conducted using ANOSIM (Analysis of Similarity) tests in PRIMER v.6 on a Bray-Curtis resemblance matrix of square-root transformed data. We excluded taxa contributing less than 3% cover (Clarke 1993). ANOSIM pair-wise tests by whole panel type were used to measure similarity of assemblages of all engineered panels compared to reference sections of seawall. These pair-wise tests for each sampling event measured whether there was increasing overlap and convergence over the entire panel with alternative panel designs as well as control sections of seawall (Clarke 1993). ANOSIM produces a R-value and a p-value. We used $p < 0.05$ to indicate significant dissimilarity (lack of convergence); small R-values (below 0.4) were used as a conservative cut-off indicating that there was no meaningful difference between the reference and treatment panel (Clarke and Warwick 2001). We used the *R*-statistic to measure the convergence and divergence over the study period of the assemblages among different types of panels and the reference sections, and to determine whether panels had been in place long enough to develop differences in taxa richness, assemblage, and abundance. The species of algae varied from month to month, so we compared algal functional groupings to reduce temporal variance (Steneck & Dethier 1994).

Data on particular taxa and overall richness were also plotted graphically, with standard errors to provide an estimation of precision on the mean with N = 3 (Zar 2009). We examined density of limpets, and percent cover of the canopy forming alga *Fucus distichus* and the mussels *Mytilus* spp. We chose these three taxa because they were relatively abundant on the panels and are known to affect successional development and community composition. These metrics were tested at upper, middle, and lower elevations independently for differences associated with panel design features (slope and texture). In graphic plots, all quadrats within a given elevation were pooled to create averages of these taxa for vertical and sloped quadrats and for smooth and cobble quadrats at each replicate location, but standard error was calculated only on the average of the 3 replicate locations. A two-way fixed factor univariate ANOVA (Analysis of Variance) was conducted using percent cover or density data. Data were tested at upper, middle, and lower elevations independently for differences associated with panel design features, with angle of substratum (vertical and sloped) and surface treatment (cobble and smooth) as main factors. Raw data from quadrats (3 quadrats per elevation per panel at each of the 3 replicate locations) were used in the analysis and no averaging was done on these data prior to ANOVA tests. ANOVA assumptions of normality and equality of variances were assessed using q-q plots and box-plots using SPLUS v.8. No data transformations were deemed necessary. Because of the limited sample size available in this urbanized setting (N=3), all ANOVA tests have a degrees of freedom = 1. When significant differences were found using ANOVA, Tukey's *post hoc* test for multiple comparisons was used to identify specific differences between all possible pairs of means (Zar 2009).

Epibenthic organisms. Taxa richness was measured for all panel types and sampling events and then averaged among the three sites. Differences among taxa richness were tested using univariate two-way with interaction ANOVA for differences among sampling events and among panel designs and surfaces on untransformed data.

Densities for specific taxa that fell within three major groupings of juvenile salmonid prey (amphipods, harpacticoid copepods, and insects) were measured for all panel types and sampling events and then averaged among the three sites. Densities (+1) were transformed (log10) to manage zeros and satisfy parametric test assumptions. Differences among taxa richness values were tested with univariate two-way with interaction ANOVA for differences among sampling events and among panel designs and surfaces.

Major Findings

Sessile community dynamics and convergence. During the Phase 1 part of the study, a primary succession of algae and invertebrates developed on engineered panels, while the reference panel assemblage remained relatively stable and the control panels exhibited some succession after they were power-washed. Thirty-six taxa were identified in addition to bare space, barnacle scars, dead algae and dead barnacles across all sampling events. In early stages of colonization, the ecologically panels were almost completely covered with algae (over 80%) with small patches of bare space. The first algae to appear on the upper and middle elevations of panels consisted mainly of foliose forms with secondary contributions by green and brown microalgal biofilms (Fig 5). Dense mats of filamentous algae dominated the lower elevations. Invertebrates on the panels were limited to new barnacle recruits and small snails. In contrast, the reference panels had much smaller percent cover of algae. The reference panels also had more bare space, barnacles, snails and limpets, and dead algae and invertebrates. The power-washed control panels were colonized by species of both the pioneering assemblages found on the engineered panels and by some of the species found on the reference panels. However, by the end of Phase 1 studies, communities on all of the treatments were similar (Fig 5).

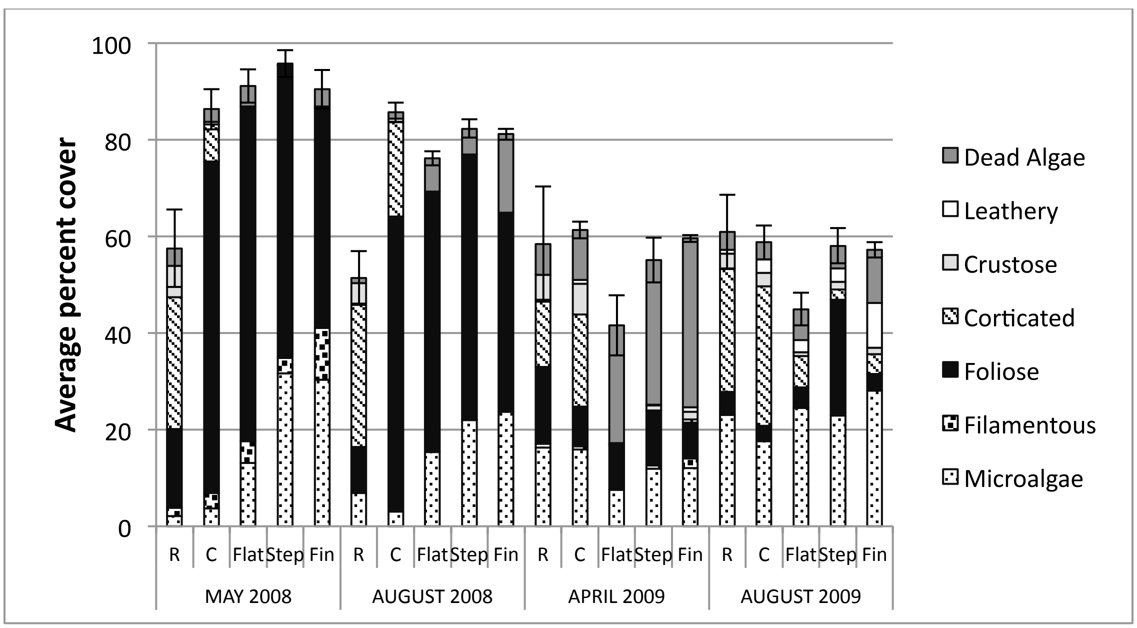


Figure 5. Average percent cover of algal types showing succession over the study period (±SE of the averages of the three replicate locations within the study site).

One of the goals of the Phase 1 study was to determine whether or not communities of organisms on the test panels had converged with those on the un-treated seawall. Showing convergence would mean that the subsequent comparisons and statistical tests of the test panels with the seawall would be more meaningful. The results indicated that the test panel communities had converged with those on the seawall (Fig 6).

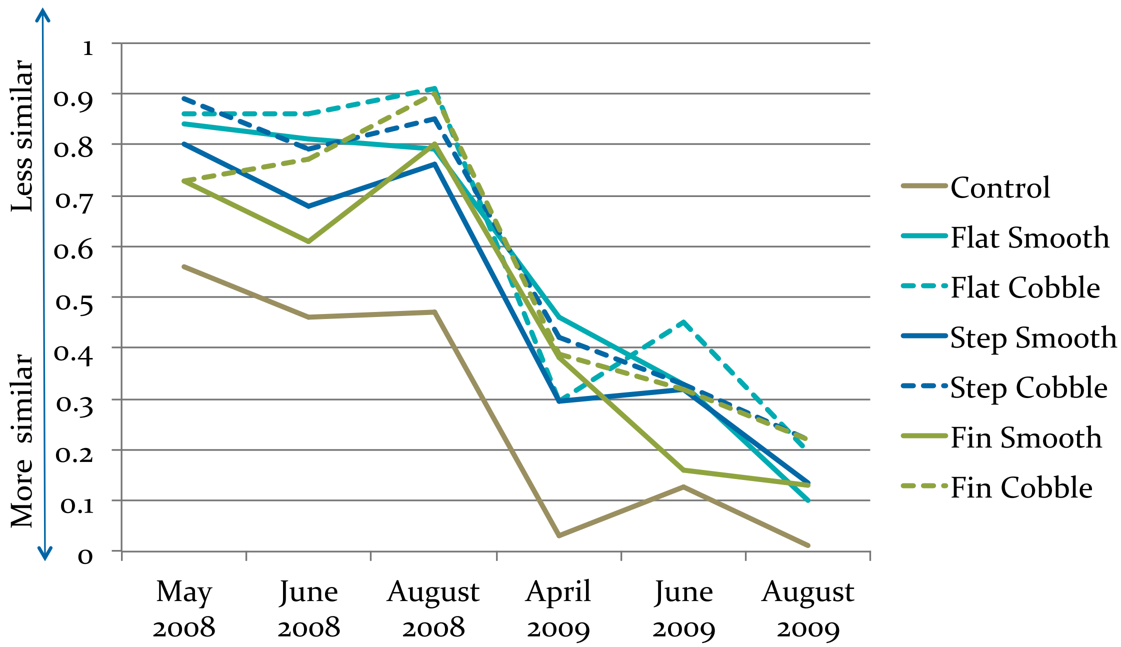


Figure 6. ANOSIM R values comparing panel treatments to reference seawall. R values < 0.4 indicate similar communities compared to reference sections of seawall.

Individual sessile species effects. Phase 1 studies showed that the engineered panels affected the three individual species of interest. Although assemblage composition of major taxa groupings was very similar among reference, control, and the habitat panels, differences associated with slope or surface texture were observed in abundance of *Fucus distichus*, limpets, and *Mytilus* mussels.

At the end of Phase 1 studies in August 2009, *Fucus distichus* was significantly more abundant on sloped surfaces (steps and fins) than on vertical surfaces at middle and lower elevations (Fig 6A). Surface treatment did not have a significant effect on mussels. Limpets were significantly more abundant on vertical surfaces in the upper and middle elevations of panels than they were on sloped surfaces (Fig. 6C). The upper elevation limpet densities were also affected by surface treatment, with significantly greater numbers on smooth surface treatments than on cobble (Fig 6D). The reverse was true at the lower elevations, with greater limpet densities on the cobble surface treatment. The cobble surface treatment was associated with significantly greater mussel coverage on engineered panels at all three elevations (Fig. 6F), but slope did not have a significant effect on mussels (Fig 6E).

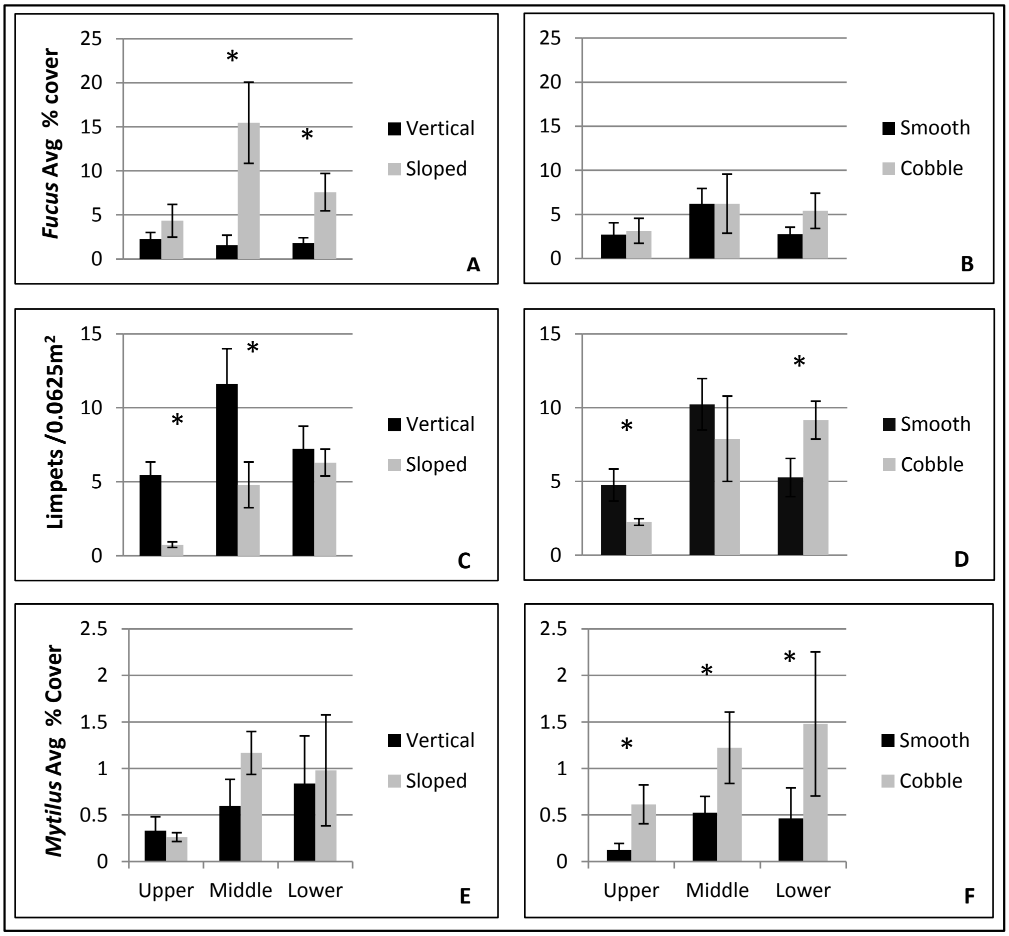


Figure 6. Abundances of three taxa at the end of Phase 1 study. Average percent cover of *Fucus distichus* by elevation, substratum angle (A), and surface treatment (B). Average limpet densities by elevation, substratum angle (C), and surface treatment (D). Average percent cover of *Mytilus* by elevation, substratum angle (E), and surface treatment (F). Error bars represent standard error. Asterisks indicate statistical significance at $p < 0.05$.

Phase 2 studies continued the monitoring of *Fucus*, mussels, and limpets. At the end of Phase 2, the results for *Fucus* and limpets were similar to those from Phase 1, though there were not as many significant differences (Fig 7). At the end of 2011, as at the end of 2009, *Fucus distichus* was more abundant on sloped steps and fins than on vertical surfaces at middle and lower elevations (Fig 7A). Limpets were again significantly more abundant on vertical surfaces in the upper elevations of panels than they were on sloped surfaces (Fig. 7C). The main difference between Phase 1 and Phase 2 results was in the percent cover of mussels. At the end of the Phase 2 study there were no significant differences in mussel cover based on surface texture

(Fig 7F), whereas in the Phase 1 part of the study, mussels were significantly more abundant on cobble surfaces.

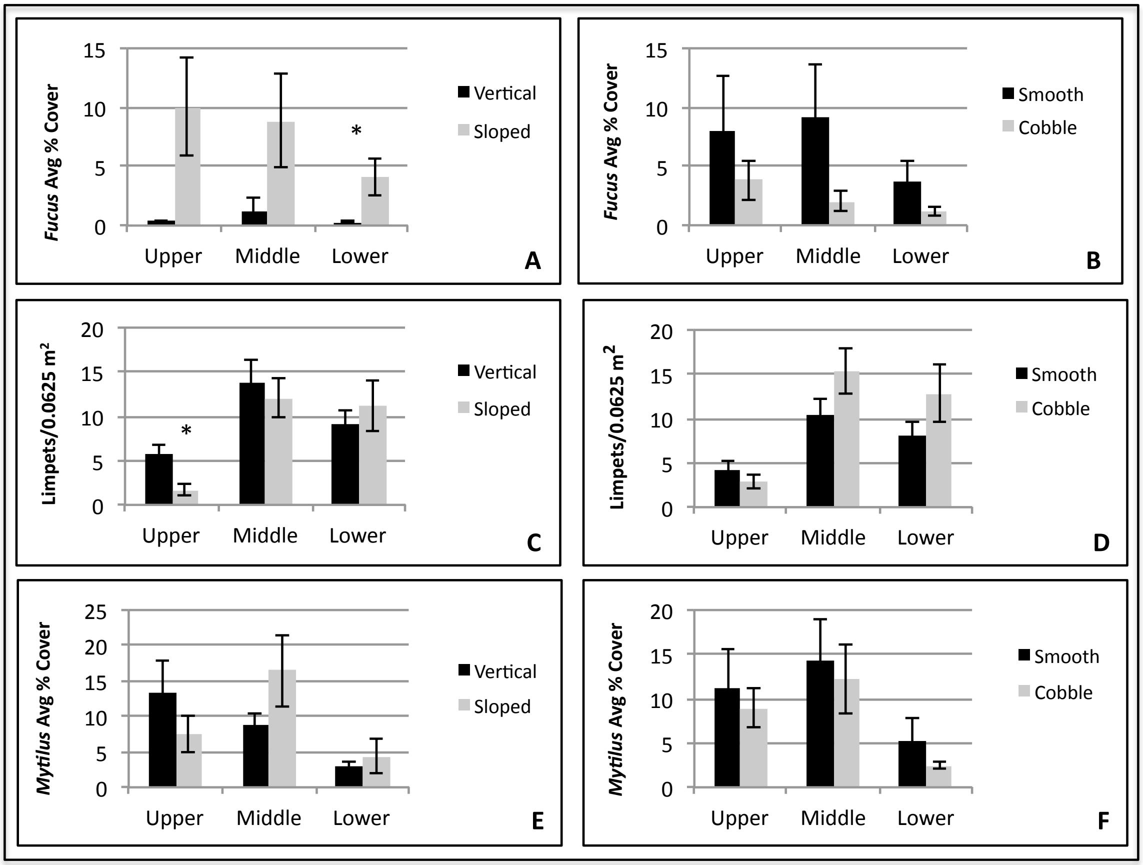


Figure 7. Abundances of three taxa at the end of Phase 2 study. Average percent cover of *Fucus distichus* by elevation, substratum angle (A), and surface treatment (B). Average limpet densities by elevation, substratum angle (C), and surface treatment (D). Average percent cover of *Mytilus* by elevation, substratum angle (E), and surface treatment (F). Error bars represent standard error. Asterisks indicate statistical significance at $p < 0.05$.

While there were no effects of substrate angle or texture on mussels at the end of the Phase 2 study, mussels were much more abundant on all of the panel treatments as compared to the control and references (Fig 8). Mussel cover increased greatly throughout the Phase 2 study and by the end of the study in June 2011, they were much more abundant on the habitat panels than they were at the end of the Phase 1 study in 2009.

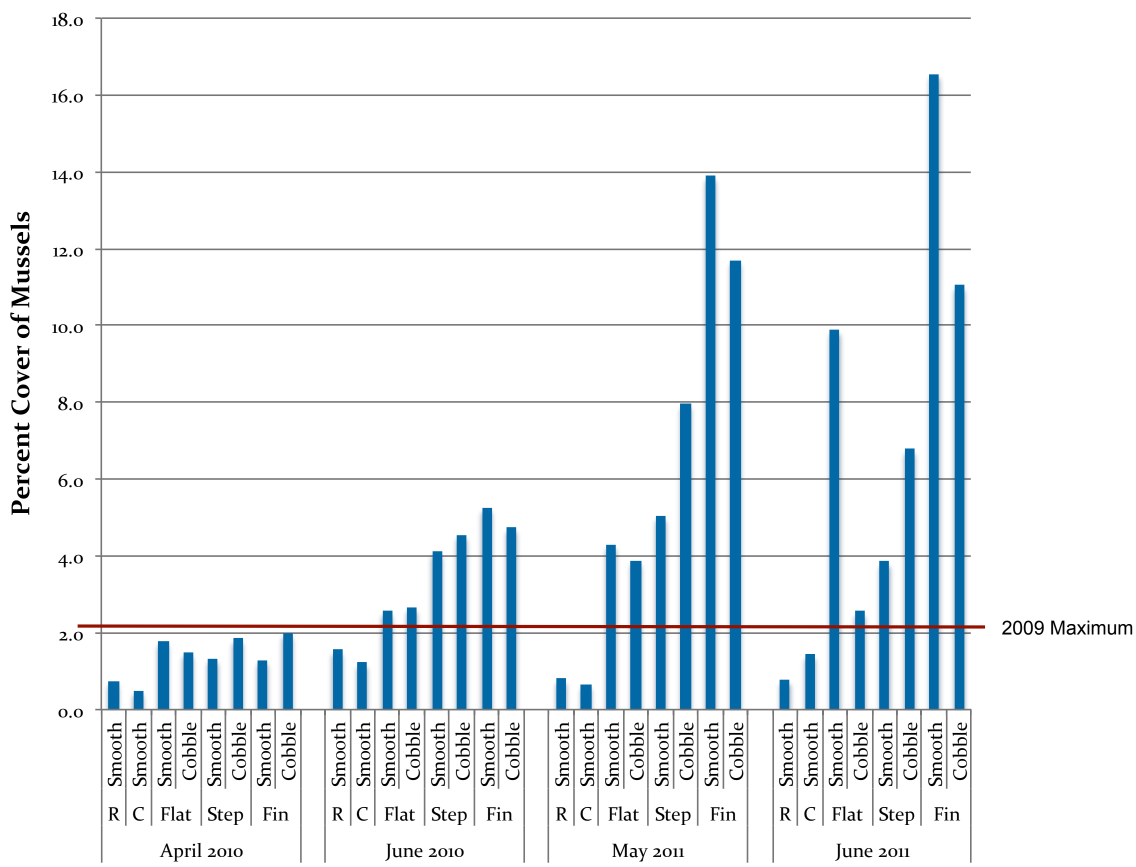
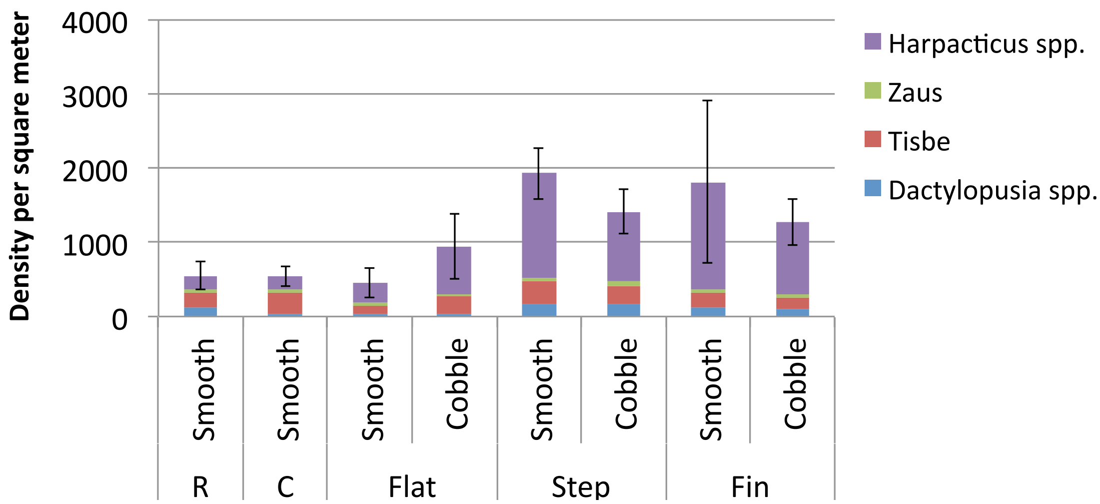


Figure 8. Phase 2 results of percent cover of mussels on reference (R), control (C), and habitat panel treatments. Horizontal line indicates the maximum percent cover of mussels found during Phase 1 study, 2008-2009.

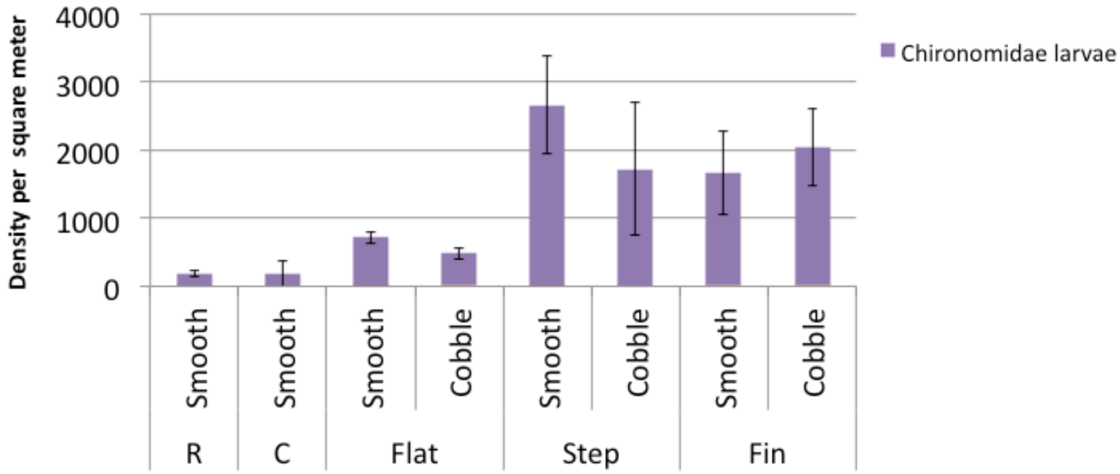
Epibenthic organism abundance. Phase 1 studies showed that the taxa of juvenile salmon prey collected by the epibenthic pump differed based on panel type. For the types of harpacticoid copepods commonly found in juvenile salmon diets, stepped and finned panels had significantly higher abundances compared to the control (Fig 9). The stepped and finned smooth treatments also had significantly higher abundances of these harpacticoids compared to the reference seawall and the un-textured smooth test panel.



	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	*	*	*	-				
Step Cobble	-	*	-	-	-			
Fin Smooth	*	*	*	-	-	-		
Fin Cobble	-	*	-	-	-	-	-	

Figure 9. Results from Phase 1 study showing average densities of harpacticoid copepods known to be common in the diets of juvenile salmon, on reference (R), control (C), and habitat panel treatments. Error bars represent standard error. The results were statistically significant for panel type, and the table shows where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).

Another group of juvenile salmon prey, chironomid flies (midges) were common in the samples and were significantly more abundant on stepped and finned panels than on the control or reference sections of seawall (Fig 10).



	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	*						
Flat Cobble	-	-	-					
Step Smooth	*	*	-	-				
Step Cobble	*	*	-	-	-			
Fin Smooth	*	*	-	-	-	-		
Fin Cobble	*	*	-	*	-	-	-	

Figure 10. Results from Phase 1 study showing average densities of chironomids (midges) a common prey item of juvenile salmon, on reference (R), control (C), and habitat panel treatments. Error bars represent standard error. The results were statistically significant for panel type, and the table shows where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).

For the Phase 2 analysis, data from all four years of sampling were expressed as total organisms per the lower (sampled) section of each panel. This was intended to make it easier to determine which panel type would yield the most overall benefit for juvenile salmon that feed on epibenthic organisms. When the data for epibenthic organisms from both phases of the project were examined in this way, the results were not as straightforward as for the Phase 1 results. There were large differences in assemblages and abundances of organisms across seasons and sampling years and among the different panels types (Figs 11, 12). For example, chironomid larvae were much more abundant in summer samples compared to spring samples, and were more abundant in Phase 1 samples than in Phase 2 samples. Also, the finding in Phase 1, of significantly more salmon prey at stepped and finned panels, was not evident when Phase 1 and Phase 2 data were analyzed together. There were no consistent differences in salmon prey between any of the panel types and the references and controls: the only instances in which statistically significant differences were found (based on ANOVA at alpha <0.05 with post-hoc Tukey tests) were (1) total salmon prey in spring 2008 was more abundant on the flat smooth panels than on the reference; (2) in summer 2009 chironomid larvae were more abundant on the stepped smooth panels compare to the controls and references; and (3) in summer 2011 chironomid larvae were more abundant on the finned cobble panels compared to the controls.

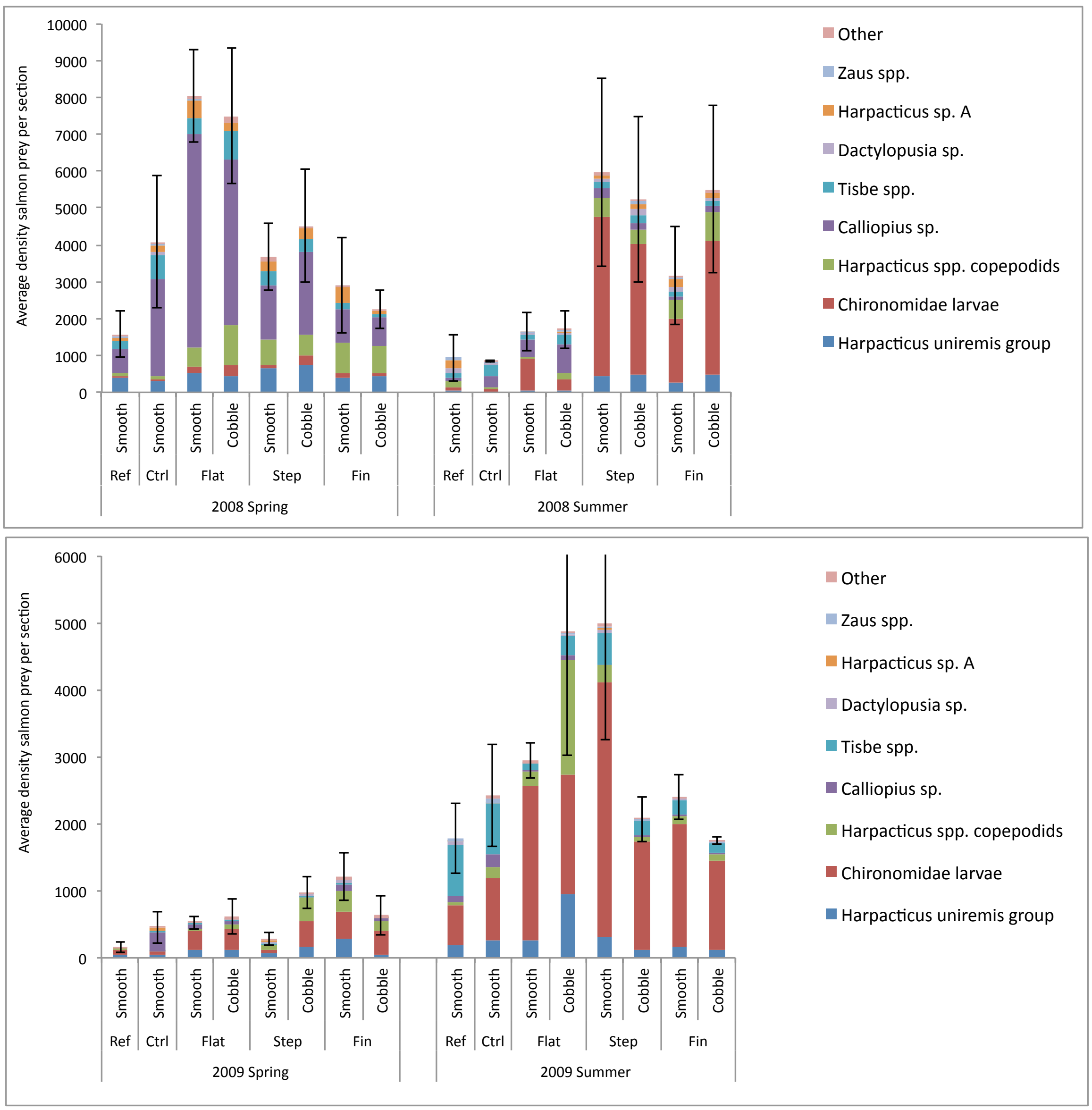


Figure 11. Results from 2008 and 2009 (Phase 1) epibenthic pump samples showing abundance of juvenile salmon prey taxa on the lower section of the reference, control, and habitat panel treatments. Error bars represent standard error.

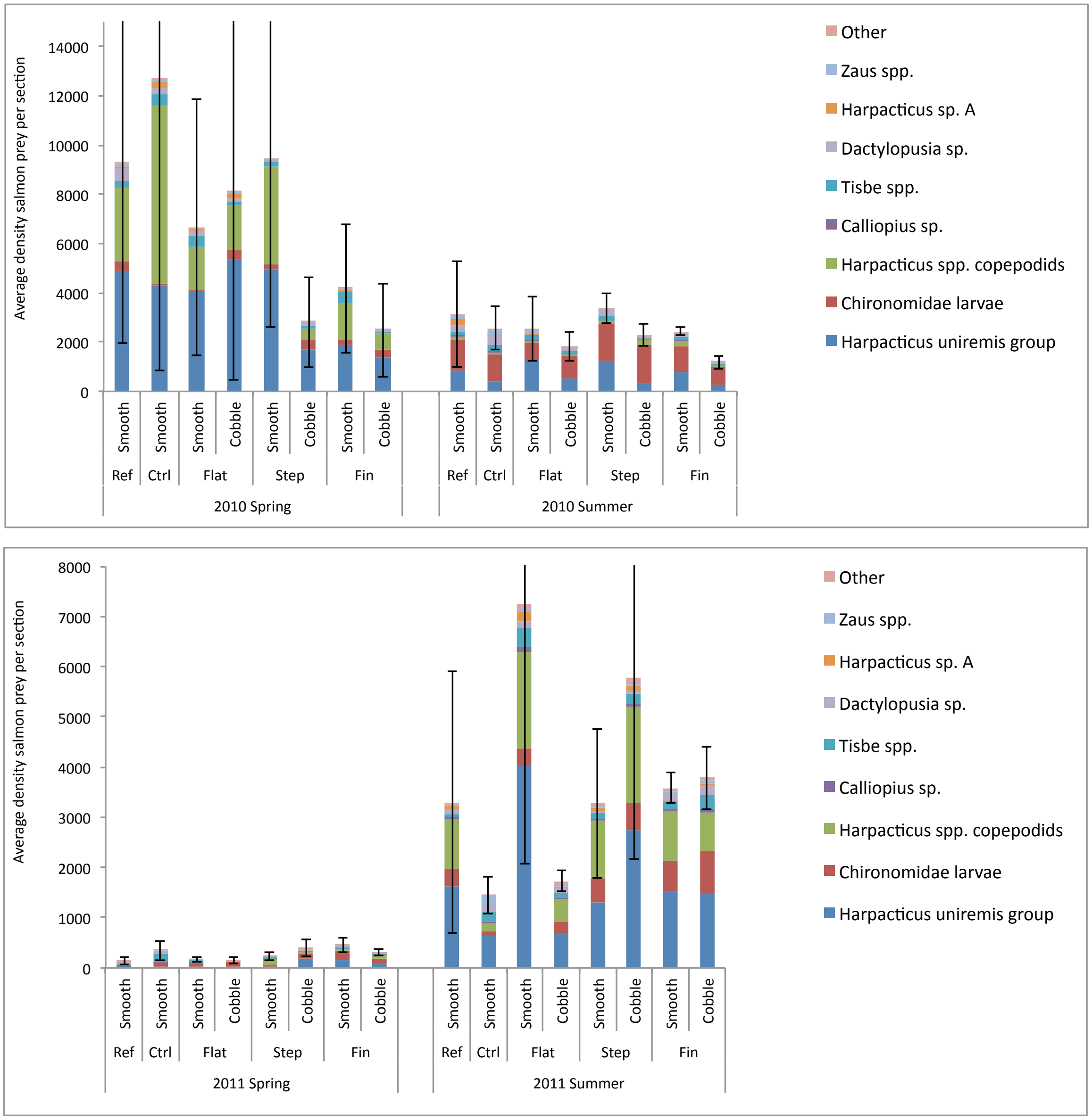
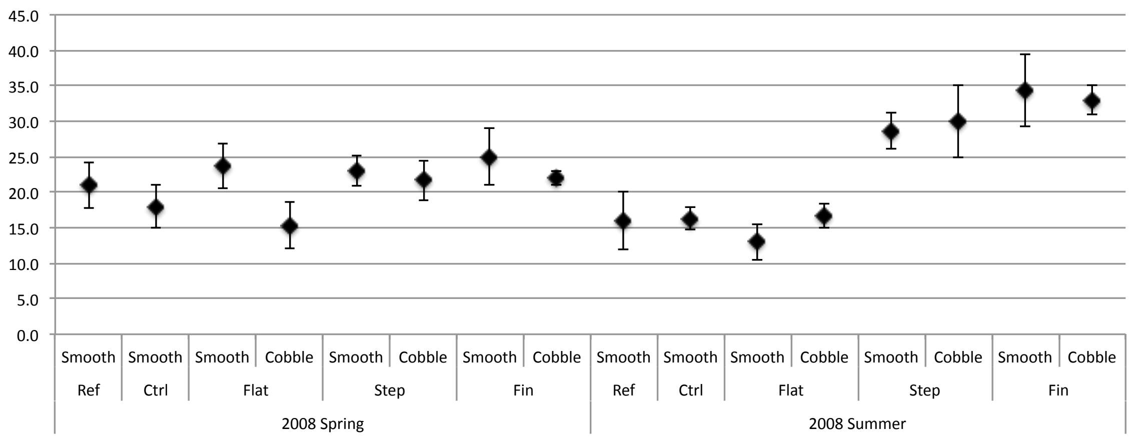


Figure 12. Results from 2010 and 2011 (Phase 2) epibenthic pump samples showing abundance of juvenile salmon prey taxa on the lower section of the reference, control, and habitat panel treatments. Error bars represent standard error.

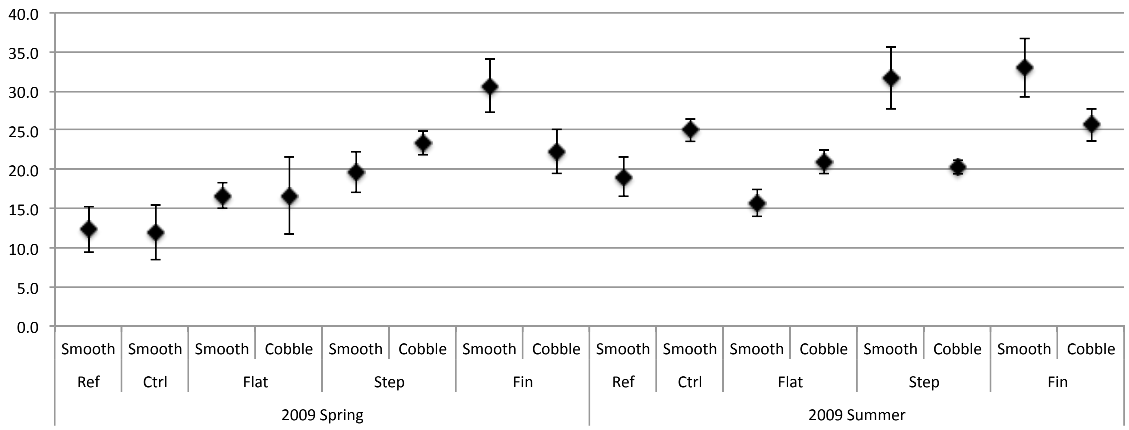
Epibenthic organism taxa richness. Average taxa richness (number of different types of organisms present) tended to be higher throughout both Phase 1 and Phase 2 studies on the stepped and finned panels compared to the flat panels and the references and controls (Figs 12-15). In many cases these differences were statistically significant (see tables associated with Figs 12-15). Also, taxa richness values were usually higher on the stepped and finned panels in the summer than they were on the same panels in the spring.



No significant differences

Summer 2008	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	-	-	-	-				
Step Cobble	*	-	*	-	-			
Fin Smooth	*	*	*	*	-	*		
Fin Cobble	*	*	*	-	-	*	-	

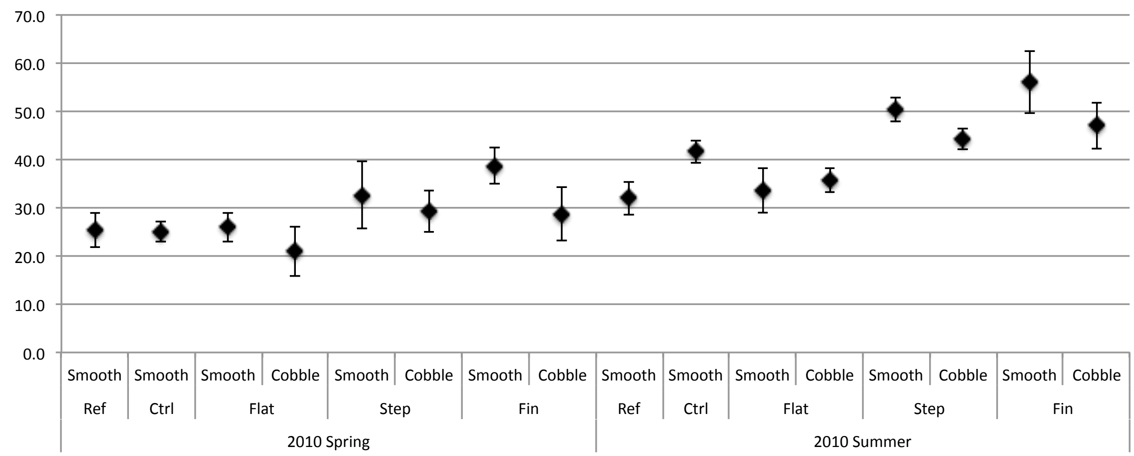
Figure 12. Results from 2008 (Phase 1) epibenthic pump samples showing average taxa richness on reference, control, and habitat panel treatments. Error bars represent standard error. The table shows where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).



Spring 2009	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	-	-	-	-				
Step Cobble	-	-	-	-	-			
Fin Smooth	*	*	-	-	-	-		
Fin Cobble	-	-	-	-	-	-	-	

Summer 2009	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	*	-	*	-				
Step Cobble	-	-	-	-	-			
Fin Smooth	*	-	*	-	-	*		
Fin Cobble	-	-	-	-	-	-	-	

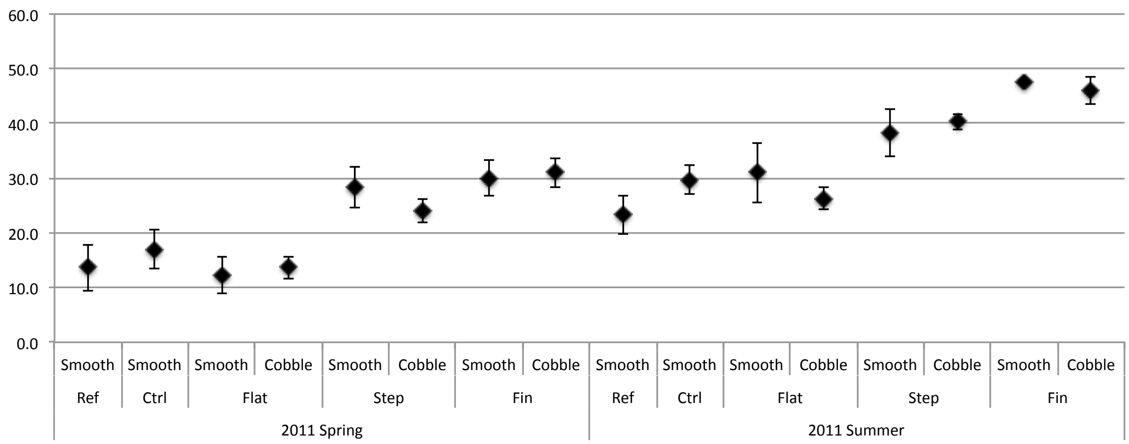
Figure 13. Results from 2009 (Phase 1) epibenthic pump samples showing average taxa richness on reference, control, and habitat panel treatments. Error bars represent standard error. The tables show where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).



No significant differences

Summer 2010	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	*	-	-	-				
Step Cobble	-	-	-	-	-			
Fin Smooth	*	-	*	*	-	*		
Fin Cobble	-	-	-	-	-	-	-	

Figure 14. Results from 2010(Phase 2) epibenthic pump samples showing average taxa richness on reference, control, and habitat panel treatments. Error bars represent standard error. The tables show where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).



Spring 2011	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	-	-	*	-				
Step Cobble	-	-	-	-	-			
Fin Smooth	*	-	*	*	-	-		
Fin Cobble	*	-	*	*	-	-	-	

Summer 2011	R	C	Flat Smooth	Flat Cobble	Step Smooth	Step Cobble	Fin Smooth	Fin Cobble
R								
C	-							
Flat Smooth	-	-						
Flat Cobble	-	-	-					
Step Smooth	*	-	-	-				
Step Cobble	*	-	-	-	-			
Fin Smooth	*	*	*	*	-	-		
Fin Cobble	*	*	-	*	-	*	*	

Figure 15. Results from 2010(Phase 2) epibenthic pump samples showing average taxa richness on reference, control, and habitat panel treatments. Error bars represent standard error. The tables show where specific treatment types were significantly different from each other (represented by an asterisk, and based on post hoc Tukey tests).

Summary and Conclusions

The potential ecological benefit of enhancing habitat complexity of seawalls and other marine structures is receiving increased attention (Glasby & Connell 1999, Davis et al. 2002, Chapman & Bulleri 2003, Airoldi et al. 2005, Chapman & Blockley 2009, Dyson 2009, Bulleri & Chapman 2010). The use of ecological criteria in seawall design may mitigate some negative impacts, while still serving societal needs for erosion protection and infrastructure support (Bulleri & Chapman 2010). In Sydney Harbor, Australia, seawall enhancements such as small tide pools resulted in significant increases of algal and sessile invertebrate species diversity, especially at higher elevations of the intertidal zone (Chapman & Blockley 2009, Browne & Chapman 2011). There, features such as crevices on seawalls can provide important microhabitats and slope along urbanized shorelines which can increase distribution, cover, and types of sessile and mobile invertebrates (Chapman 2003, Moreira et al. 2006, 2007, Chapman & Underwood 2011). It is, however, important to test the generality of the conclusions reached from the work in Sydney Harbour before general suggestions for management of urban waterways can be developed.

Our findings, from a different geographic region and type of embayment, corroborate that sloped surfaces and crevices on an urban seawall provided by more complex surface texture that benefit important intertidal organisms, and could be key components of future seawall design. Increased abundance of habitat-forming species such as *Fucus* and *Mytilus* added further complexity to the seawall, encouraging increased densities of epibenthic crustaceans and insect larvae that are prey for juvenile salmon that utilize Seattle's shoreline for migration and rearing habitat (Toft et al. 2007, Goff 2010). While many of the critical processes and functions of the original shoreline may be irreversibly lost due to shoreline armoring, such as sediment supply and natural hydrologic flow regimes, our study indicates that at least some ecological functions can be improved on highly modified shorelines.

Minimizing ecological impacts of seawalls has been identified as a priority, and a recent review of coastal infrastructure impacts underscores the urgent need of collaboration between engineers, managers, and ecologists to improve the habitat value of these structures (Bulleri & Chapman 2010). By collaborating with the City of Seattle and incorporating two elements of complexity (slope and crevices) into experimental panels along Seattle's seawall, we were able to demonstrate the potential for improving the habitat value of this structure for several important organisms. This study contributes to the mounting evidence that seawall habitat enhancements could help mitigate shoreline armoring impacts to urban intertidal communities.

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