Reversing Shoreline Armoring: Quantifying the Effectiveness of Restoration on Coastal Biota of Puget Sound

Timothy Seung-Chul Lee

A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Marine Affairs

University of Washington

2017

Committee:

Ryan P. Kelly

Jason D. Toft

Program Authorized to Offer Degree:

School of Marine & Environmental Affairs

University of Washington

Abstract

Reversing Shoreline Armoring: Quantifying the Effectiveness of Restoration on Coastal Biota of Puget Sound

Timothy Seung-Chul Lee

Chair of the Supervisory Committee:
Assistant Professor, Ryan P. Kelly
School of Marine & Environmental Affairs

Shoreline armoring is prevalent around the world with unprecedented human population growth and urbanization along coastal habitats. While armoring structures, such as riprap and bulkheads, are built to prevent beach erosion and protect coastal infrastructure from storms and flooding, such structures can deteriorate habitats for migratory fish species, disrupt aquatic-terrestrial connectivity, and reduce overall coastal ecosystem health. One question is whether armoring is reversible, allowing restoration via armoring removal and related actions of sediment nourishment and replanting of native riparian vegetation. Relative to armored shorelines, natural shorelines retain valuable habitats for macroinvertebrates and other coastal biota. Remarkably, few assessments of the responses of coastal biota to shoreline-armoring removal exist. Here, I use pre- and post-restoration data for five biotic measures (wrack % cover, saltmarsh % cover, number of logs, macroinvertebrate counts and richness) from a set of restored shorelines in Puget

Sound, WA, USA. I find that a broad suite of ecosystem metrics responds strongly and positively, and that these results are evident after less than a year. Restoration responses remain positive and statistically significant across different shoreline elevations and temporal trajectories. This meta-analysis suggests that removing shoreline armoring is an effective technique for restoration projects aimed at improving the health and productivity of coastal ecosystems, and these results may be applicable regionally and globally.

Acknowledgements

First and foremost, I would like to thank my thesis chair and advisor, Ryan Kelly for his dedication, humor insight, and thorough guidance during my two years at UW, as well as introducing me to a research project that I became truly passionate about. During my first year in SMEA, Ryan asked me one of the most important questions that all students with scientific research ambitions should constantly think about: what excites you about the world? In other words, what gets you up in the morning? I knew I was broadly interested in coastal ecosystems, but I still did not have the answers to Ryan's questions. All that changed when in winter 2016, Ryan announced that there was a possible thesis project on anthropogenic impacts of coastlines. That is when Jason Toft comes in.

I cannot express how grateful I am for having worked with Jason, who introduced me to the coastline research and the effects of urbanization on their ecosystems. Shortly after meeting with Jason in early 2016, I then realized that the impact of urban growth on coastal ecosystems is the subject that gets me up in the morning, and that I would like to continue researching coastal ecosystems as a career. I would like to thank Jason for introducing me to his years of work, the importance of protecting coastlines' living resources, and finally, accepting me as part of the team dedicated to best understand and manage coastal resources under immense population growth pressures. Jason has provided his insight, guidance, and sense of humor both in and out of field, and I am honored to have worked with him as a student and a colleague.

There are many others to thank for at UW, including the rest of the faculty at SMEA (Eddie Allison, Patrick Christie, Nives Dolsak, Dave Fluharty, Terrie Klinger, Tom Leschine, Marc Miller), whose teachings piqued my interests in policy elements of sciences and encouraged me to look for bigger picture and integrate elements of both social and natural sciences. I would also like to thank Tiffany Dion for her endless dedication to help all the SMEA students in any way possible, and I know I could not have completed my degree requirements in timely manner without her immense help. I also would like to thank Jackie Chapman and Suanty Kaghan for providing any administrative assistance whenever possible. I sincerely thank Jennifer Ruesink for setting time to meet with me throughout the past year to provide valuable feedback on my thesis methods and structure. I also thank Ray Webster for setting time to meet with me in person to provide valuable feedback on my statistics and discuss quantitative methods for current and future directions. As a teaching assistant for two years at UW, I am also thankful for the following individuals as I believe working with them made me realize I greatly teaching more than ever: Tim Billo, Mikelle Nuwer, Yen-Chu Weng, Joyce LeCompte-Mastenbrook.

I also would like to thank my cohort of awesome students in SMEA for their friendship and creating a fun atmosphere within SMEA year-round. I thank Chris Hart and Jimmy Kralj not only for their awesomeness as fellow colleagues under Ryan’s advising group, but also for providing their feedback as peers during our weekly advising meetings. I also would like to thank many friends within and outside of UW because I know my life wouldn’t be enjoyable without you all.

I am thankful for my family for their perpetual love and support: my parents, Charles and Hannah Lee, and my brother Kenny Lee. Finally, I cannot express how grateful I am for my amazing girlfriend, Quynh Nguyen, for always being there for me, whether in person or in spirit. I could not have had an exciting and joyous life in Seattle without you. Did I forget Lucy, the best four-legged friend/running companion one could ask for? I love you all.

Dedication

To memory of my dear friend Romain Chateau, who never ceased to make me laugh and raise my spirits even during the hardest times

Table of Contents

INTRODUCTION

Worldwide, shorelines adjacent to bodies of fresh and saltwater are facing among the fastest urbanization and population growth than other geographic regions (Neumann et al. 2015). Coastal regions have always experienced high immigration rates because of their ease of access to domestic and international shipping, military and defense uses, tourism, access to recreational activities, access to valuable ecosystem services, and employment opportunities (Millennium Ecosystem Assessment (MEA) 2005; Gittman et al. 2015; Neumann et al. 2015). About 17% of the world's population lives within 100 kilometers from the coastlines and half of the world's major city centers are located within 50 kilometers from coasts (Millennium Ecosystem Assessment (MEA) 2005). Many of these heavily populated coastal regions are in low-lying elevations; in 2000 these low-elevation coastal zones comprised nearly 11% of the world's total coastal population, but by 2060, it is estimated that the population in these low-elevation coastal zones will be as great as 1.4 billion, or 12% of the world's population (Neumann et al. 2015).

Coastal infrastructure and urban centers are exposed to various hazards including storms, large waves, flooding, sea level rise, and erosion (Jones and Hanna 2004; McGranahan, Balk, and Anderson 2007). As a response, many coastal communities have established hardened structures such as bulkheads, jetties, riprap revetments and seawalls, a practice commonly called "shoreline armoring" (Chapman 2003; Bulleri and Chapman 2010; Chapman and Underwood 2011; Heerhartz et al. 2014; Gittman et al. 2015). In some large urban centers such as San Diego Bay, Chesapeake Bay, Sydney Harbor, and Hong Kong's Victoria Harbor, over 50% of shorelines have been armored, and the continuing growth of coastal immigration and urbanization is expected to increase the rate of shoreline armoring (J. L. D. Davis, Levin, and Walther 2002; Dugan et al. 2008; Lam, Huang, and Chan 2009; Patrick, Weller, and Ryder 2016). In the United

States alone, about 14% of the lower 48 states' shorelines are armored, and 64% of these armored shorelines are adjacent to estuaries and coastal rivers (Gittman et al. 2015).

Armored shorelines overall are associated with lower biodiversity and abundance of an array of vegetation cover, invertebrate and fish species (Dugan et al. 2008; Morley, Toft, and Hanson 2012; Peters, Yeager, and Layman 2015; Gittman, Peterson, et al. 2016). These shorelines can accelerate beach erosion as waves are rapidly reflected from armored structures (Heatherington and Bishop 2012; Gittman, Scyphers, et al. 2016). They can also reduce overall ecological health of coastal ecosystems by degrading shallow intertidal habitats which are valuable for survival of juvenile fish and aquatic invertebrates (Gittman, Peterson, et al. 2016). Armored shorelines can also disrupt the gradual transition between terrestrial and aquatic habitats as the gradual shoreline slope is abruptly steepened, which in turn can result in reduction of salt marsh habitats and reduction of submerged aquatic vegetation. Similarly, armoring also reduces the beaches' ability to retain woody debris and "wrack" or organic matter deposition on shorelines. This loss of organic and inorganic debris can affect the aquatic-terrestrial food web, including fishes, macroinvertebrates associated with wrack and vegetated habitats, and birds (Bozek and Burdick 2005; Dugan et al. 2008; Heerhartz et al. 2014; Harris, Strayer, and Findlay 2014; Heerhartz and Toft 2015; Dethier et al. 2016; Wensink and Tiegs 2016).

In recent years, alternatives to shoreline armoring and restoration approaches with armoring removal have emerged to simultaneously protect coastal urban infrastructure and restore ecological health (J. L. Davis et al. 2015; Gittman, Peterson, et al. 2016; Bilkovic et al. 2017). For example, the creation of marsh sills in lieu of armoring shorelines has been implemented in North Carolina (Bilkovic and Mitchell 2013), restoring oyster reefs have been implemented in

Chesapeake Bay (Lawless and Seitz 2014), and restoring red mangrove colonization on riprap revetments have been established in Biscayne Bay, Florida (Peters, Yeager, and Layman 2015). The number of studies assessing the effectiveness of armoring removal on coastal ecosystems have been limited; nevertheless, such studies have demonstrated that these restored shorelines can host higher abundances and diversity across different taxonomic groups. For example, marsh sills have higher abundance and diversity of fish and bivalves in shorelines of North Carolina (Gittman, Peterson, et al. 2016) and introducing native riparian vegetation and logs after armoring removal can facilitate rapid response of macroinvertebrate assemblages in shorelines of Puget Sound, Washington (Toft, Cordell, and Armbrust 2014).

In Puget Sound, WA, USA, there has been recent momentum to restore its armored shorelines through removal of armoring structures, nourishment of sediments, re-planting native riparian vegetation and distribution of logs and woody debris (Toft, Ogston, et al. 2013; Heerhartz et al. 2014). Such restoration efforts in the Puget Sound are driven by the need to protect Pacific salmon species such as endangered populations of Chinook Salmon (*Oncorhynchus tshawytscha*), whose juveniles use shallow intertidal areas as nursery habitats (Munsch, Cordell, and Toft 2016). Macroinvertebrate prey, both aquatic and terrestrial, are vital part of coastal food webs and changes in their population can detrimentally impact food availability for many fish species in these ecosystems (Sobocinski, Cordell, and Simenstad 2010). Furthermore, salmon hold cultural, ecological, and economic importance to the region (Rhodes et al. 2006; Munsch, Cordell, and Toft 2015). Therefore, it is essential to ask whether shoreline restoration in the service of local ecosystems is having its intended effect, and to date, relatively little such analysis has been done.

In this meta-analysis, my objective is to determine how coastal biota respond when armored shorelines are restored through armoring removal, beach grading, and planting native vegetation. I assess their responses across a) monitored shorelines, b) coastal biota type, c) shoreline elevations, and d) trajectory in time. Understanding these post-restoration dynamics can enhance knowledge of the recovery success of other restored shorelines regionally and globally.

MATERIALS & METHODS

Study Sites & Sources of Data

The Puget Sound is a fjordal estuarine ecosystem that comprises the southern part of the Salish Sea and encompasses over 30,000 km^2 in the Pacific Northwest overlapping Washington, USA and British Columbia, Canada. This ecosystem is primarily composed of cold-temperate waters, river deltas, and shorelines mainly composed of sediments mixed with clay, sand, mud, and gravel originating from receded glaciers. Continued erosion of coastal bluffs contributes this sediment mix into the beaches of Puget Sound (Shipman 2001). More than a quarter of the 4,000 kilometers of shorelines in Puget Sound are armored (Puget Sound Partnership 2016).

I assessed six restored shorelines in Puget Sound to determine coastal biota responses (Figure 1). These shorelines were restored to 1) improve habitat for nearshore fish including juvenile salmon, 2) improve connectivity between terrestrial and aquatic habitats, and 3) increase macroinvertebrate counts and diversity. These restored shorelines from north to south were Cornet Bay (CB) of Deception State Park on Whidbey Island, Powel Property (PP) on Bainbridge Island, Salmon Bay Natural Area (SBNA) which is downstream from the Hiram

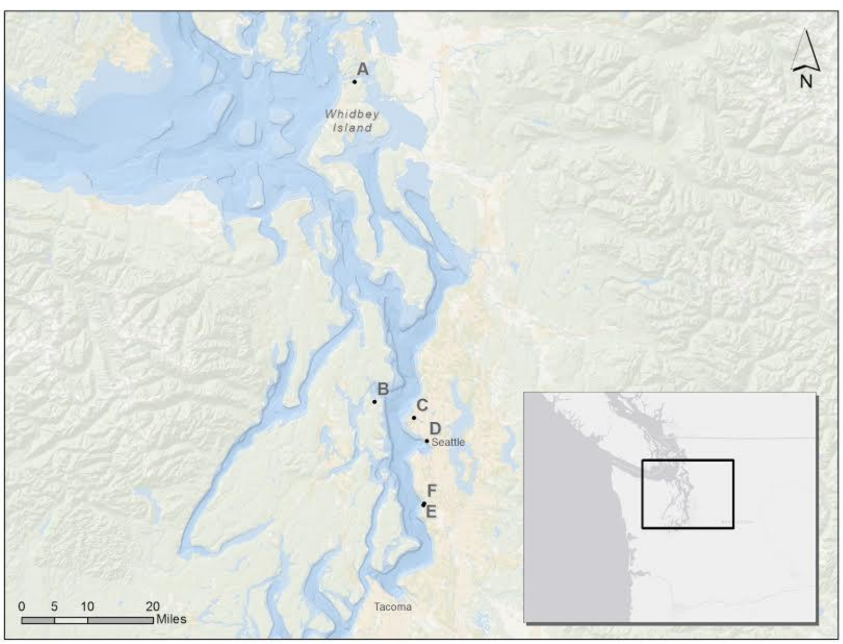

Figure 1 Map of the Puget Sound and the restored shorelines used for the meta-analysis. A = Cornet Bay, B = Powel Property, C = Salmon Bay Natural Area, D = Olympic Sculpture Park, E = Seahurst Park I (restored 2005), F = Seahurst Park II (restored 2014)

M. Chittenden Locks of Seattle, Olympic Sculpture Park (OSP) in downtown Seattle, and two locations in Seahurst Park in the city of Burien, WA (SHP I and II that were restored in 2005 and 2014, respectively) (Figure 1, Table 1). All sites were formerly armored with bulkhead and riprap, and SBNA also had an overwater structure (Figure 2). These shorelines were restored from 2005 - 2014 (Table 1) (Toft, Cordell, et al. 2013; Toft, Ogston, et al. 2013; Toft, Cordell, and Armbrust 2014; Adams, Padgham, and Toft 2015; Dethier et al. 2016; Toft 2016; Cordell et al. 2017).

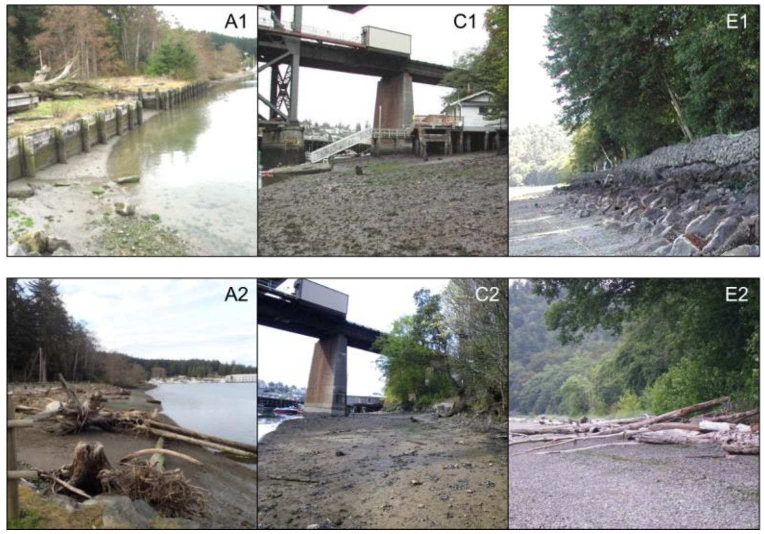

Figure 2 Three of the six restored shorelines used for this meta-analysis. Frames A1, C1, and E1 show shorelines armored prior to their respective restorations and frames A2, C2 and E2 show shorelines in their restored state. Left to right: Cornet Bay (A1 & A2), Salmon Bay Natural Area (C1 & C2), Seahurst Park I (E1 & E2).

Table 1 Shorelines used for the meta-analyses by pre-restoration year monitored, restoration year, post-restoration monitoring years and the types of coastal biota monitored (Abbreviations: CB = Cornet Bay, PP = Powel Property, SBNA = Salmon Bay Natural Area, OSP = Olympic Sculpture Park, SHP I = Seahurst Park restored in 2005, SHP II = Seahurst Park Restored in 2014, PR = pre-restoration, Rest. = restoration, W % = wrack % cover, L # = number of logs, SM % = saltmarsh % cover, MIC = macroinvertebrate counts, MIR = macroinvertebrate richness, Elev. = shoreline elevation sampling).

Site	PR Year	Rest. Year	Post-Restoration Monitoring Year							Coastal Biota Monitored					Elev.	Reference
			<1	1	2	3	4	5	10	W %	L #	SM %	MIC	MIR		
CB	2012	2013	-	X	-	-	-	-	-	X	X	-	X	X	-	Dethier et al. (2016)
PP	2012	2012	-	X	X	-	-	-	-	-	-	X	-	X	X	Adams et al. (2015)
SBNA	2004	2010	X	-	X	-	-	-	-	-	-	-	X	X	-	Toft, Cordell et al. (2013)
OSP	2005	2006	-	X	-	X	-	X	-	-	-	-	X	X	-	Toft, Ogston et al. (2013) Cordell et al. (2017)
SHP I	2004	2005	-	X	-	X	-	X	X	-	-	-	X	X	X	Toft et al. (2014) Toft (2016)
SHP II	2010	2014	-	X	-	-	-	-	-	-	-	-	X	X	X	Toft (2016)

Five major types of coastal biota were monitored before and after restoration, with some sites monitored up to ten years after restoration (Table 1). Survey data included counts and richness of macroinvertebrates for both terrestrial and aquatic groups, wrack % cover, number of logs, and % saltmarsh cover. Three shorelines were also monitored at two different shoreline elevations (Table 1).

Quantitative Analysis

To measure the effectiveness of shoreline restoration on coastal biota, I used Cohen's *D* Effect Size (Cohen 1992). This effect-size statistic has been widely used, for example to measure stream engineering on increasing salmon abundances, pine forest restoration on native understory vegetation, and invasive vegetation removal on restoring native woody plants (Taylor, Smith, and Haukos 2006; McGlone, Springer, and Laughlin 2009; G. B. Stewart et al. 2009). Cohen's *D* is calculated with the following equation:

$$D = \frac{(\mu_A - \mu_B)}{\sigma}$$

where μ_A is the mean value of measured variable (e.g., counts, richness, percent cover) after restoration, μ_B is the mean value of measured variable before restoration, and σ is the pooled standard deviation. Although values of *D* are likely to vary with context, as a general guideline, when *D* less than 0.2, the restoration is considered to have had no effect, while 0.2 to 0.8 indicate moderate effect, and 0.8 or greater indicates substantial effect (Rosnow, Rosenthal, and Rubin 2000).

I calculated *D* for the following four major categories: 1) restored shorelines, 2) monitored coastal biota, 3) shoreline elevation, and 4) trajectory in time or post-restoration years. For the restored shorelines category, I calculated the effect sizes of all the respective coastal biota monitored for each shoreline individually. For the monitored coastal biota, I calculated the effect sizes for the five types of coastal biota: wrack % cover, number of logs, saltmarsh cover, macroinvertebrate counts and macroinvertebrate richness. For the shoreline elevation, I calculated effect sizes for the elevation at the base of the armoring and at the elevation where armoring formerly stood. And finally, for the trajectory in time I calculated effect sizes for the six post-restoration monitoring years. To test for statistical significance of D, I performed one-sample two-tailed t-tests ($\alpha = 0.05$), comparing the observed data against the null hypothesis (H_0: $\mu = 0$). Where comparing the means of two different elevations, I used a two-sample two-tailed t-test.

RESULTS

All the six shorelines demonstrated positive responses with the mean effect size varying between 1.07 and 1.79 (Figure 3); four of the six shorelines had statistically significant responses (Figure 3). Among sites and elevations, all five coastal biotic measures showed similarly positive effects, although not all significantly so (Figures 4 and 5). Mean effect sizes differed between the two elevations ($p < 0.002$).

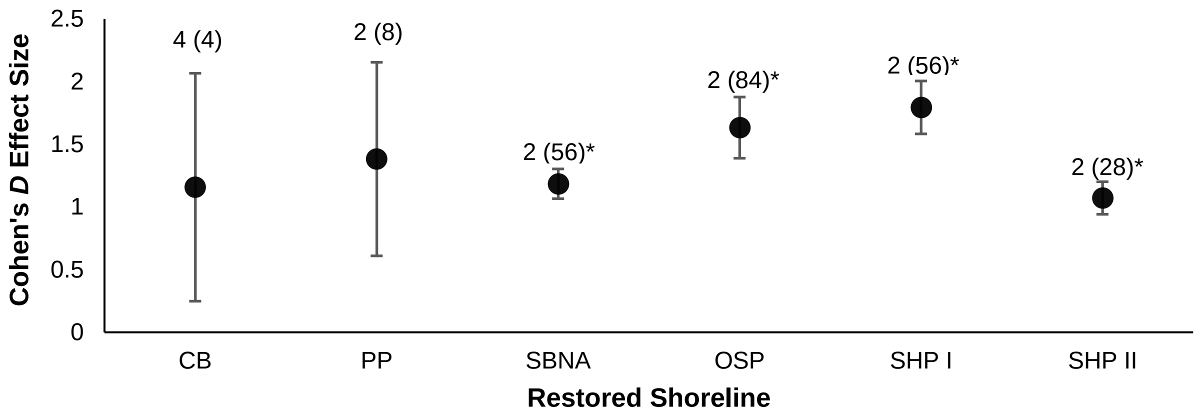

Figure 3 Cohen's *D* Effect Sizes (±SE for error bars) across six restored shorelines of the Puget Sound used for this meta-analysis. Data labels show the number of coastal biota types monitored and the sample sizes (the number of effect sizes for each shoreline). Shoreline effect sizes with asterisks were significantly different from zero (SBNA: $t_{0.05(2),54} = 9.9$, $p < 0.001$, 95% CI = 0.95, 1.43; OSP: $t_{0.05(2),83} = 6.69$, $p < 0.001$, 95% CI: 1.14, 2.12; SHP I: $t_{0.05(2),55} = 8.49$, $p < 0.001$, 95% CI = 1.37, 2.22; SHP II: $t_{0.05(2),27} = 8.23$, $p < 0.001$, 95% CI: 0.8, 1.34).

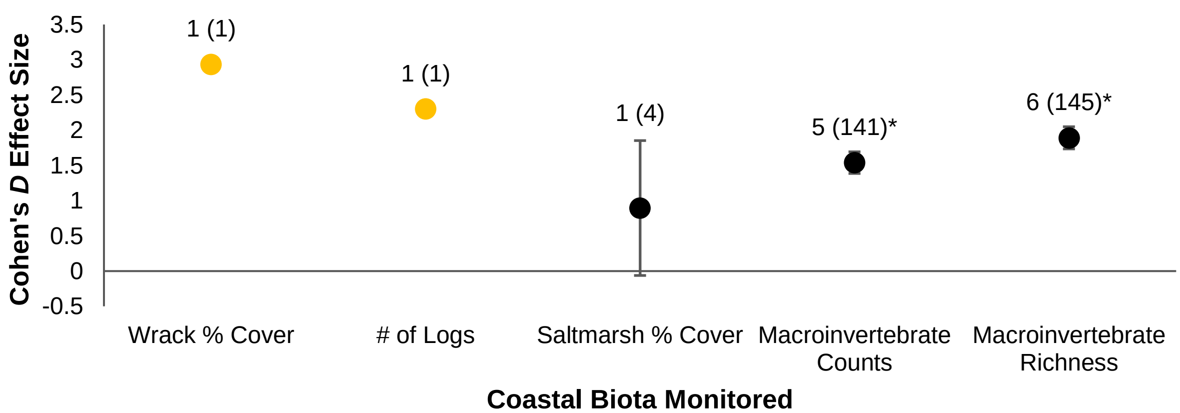

Figure 4 Cohen's *D* Effect Sizes (±SE for error bars) by five major types of coastal biota monitored. Data labels show number of restored shorelines each coastal biota was monitored and the sample sizes (the number of effect sizes for each biota type). Coastal biota labeled in orange were not integrated for individual t-tests due to lack of replicates. Coastal biota effect sizes with asterisks were significantly different from zero (Macroinvertebrate Counts: $t_{0.05(2),140} = 10$, $p < 0.001$, 95% CI: 1.23, 1.84; Macroinvertebrate Richness: $t_{0.05(2),144} = 12.01$, $p < 0.001$, 95% CI: 1.58, 2.20).

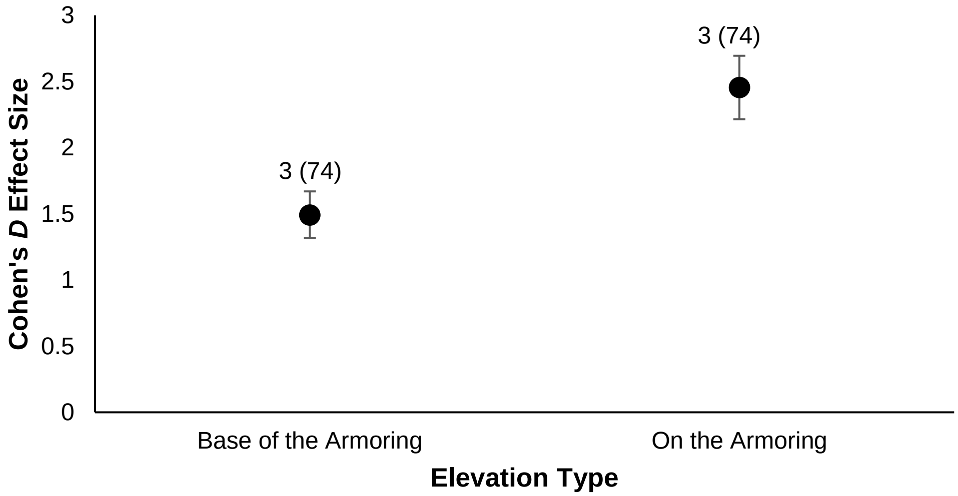

Figure 5 Cohen's *D* Effect Sizes (±SE for error bars) by elevation monitored. Data labels show the number of restored shorelines and the sample sizes (the number of effect sizes for each elevation type). Both elevations' effect sizes were significantly different from zero (Base of the Armoring: $t_{0.05(2),73} = 8.44$, $p < 0.001$, 95% CI: 1.14, 1.85; On the Armoring: $t_{0.05(2),73} = 10.24$, $p < 0.001$, 95% CI: 1.98, 2.93).

All the post-restoration years monitored demonstrated positive and statistically significant responses ($p < 0.001$ for all post-restoration years), with year 10 showing the greatest positive response ($\bar{X} = 3.34$) and year <1 showing the lowest ($\bar{X} = 1.07$) (Figure 6).

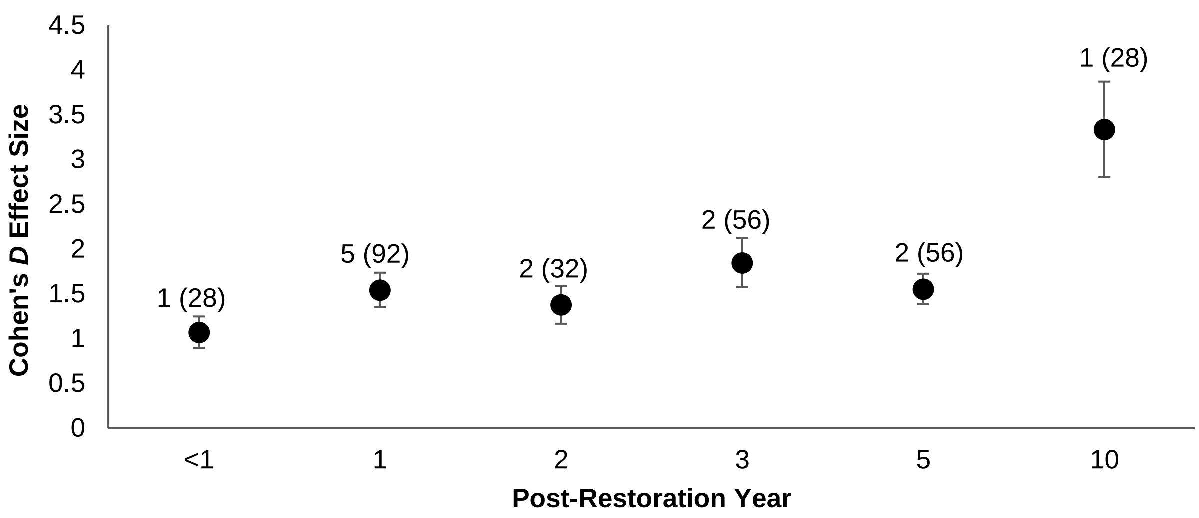

Figure 6 Cohen's *D* Effect Sizes (±SE) by post-restoration years monitored. Effect sizes reflect comparisons between pre-restoration and post-restoration for each respective post-restoration year monitored. Data labels show the number of restored shorelines and sample sizes (the number of effect sizes for each post-restoration year monitored). Effect sizes of all post-restoration years were significantly different from zero (Year <1: $t_{0.05(2),27} = 6.07$, $p < 0.001$, 95% CI: 0.71, 1.43; Year 1: $t_{0.05(2),91} = 8.02$, $p < 0.001$, 95% CI: 1.16, 1.93; Year 2: $t_{0.05(2),31} = 6.5$, $p < 0.001$, 95% CI: 0.95, 1.81; Year 3: $t_{0.05(2),55} = 6.71$, $p < 0.001$, 95% CI: 1.30, 2.40; Year 5: $t_{0.05(2),55} = 9.2$, $p < 0.001$, 95% CI: 1.22, 1.89; Year 10: $t_{0.05(2),27} = 6.25$, $p < 0.001$, 95% CI: 2.24, 4.43).

DISCUSSION

Armoring removal can yield significantly positive responses of coastal biota. All four major effect categories (restored shorelines, coastal biota, shoreline elevation, and trajectory in time) indicated substantially positive responses (effect size > 0.8; Rosnow et al. 2000). Furthermore, there was clear evidence that coastal biota responded within a year after restoration, with subsequent post-restoration years maintaining biotic and abiotic gains. Of the five major types of coastal biota, recovery was strongest for macroinvertebrates; the responses of wrack cover, number of logs and saltmarsh cover were also positive but with smaller sample sizes and therefore weaker statistical inferences.

My findings of strong significant responses of macroinvertebrate were consistent with previous work focused on individual marine sites (Toft et al. 2013; Toft, Cordell, and Armbrust 2014) and other aquatic habitats, most of which are primarily in freshwater ecosystems. Some extensive macroinvertebrate response studies come from restoring rivers and channelized streams, in which increasing habitat complexity via restoration has been shown to support greater abundance and diversity of macroinvertebrates (Korsu 2004; Muotka and Syrjänen 2007; Miller, Budy, and Schmidt 2010). In addition to rivers and streams, previous work also found that wetlands, when restored or newly created, are quickly colonized by macroinvertebrates, but more so by those with greater dispersal capability such as aerial insects (Brown, Smith, and Batzer 1997; T. W. Stewart and Downing 2008). Like the previous research in other aquatic systems, this meta-analysis showed that overall, macroinvertebrate responses in coastal ecosystems are positive and substantial, which in turn can enhance prey availability for migratory fishes and seabirds and improve ecosystem health as a whole (Dugan et al. 2003; Heerhartz and Toft 2015).

Overall, I found that coastal biota is capable of responding positively immediately to shoreline restoration through armoring removal across multiple post-restoration years. Based on studies in other systems assessing biota recovery after restoration of channelized streams, saltmarsh habitats, and oyster reefs, the trajectory found in this meta-analysis suggests that such strong recovery responses shortly after restoration are common (Warren et al. 2002; Miller, Budy, and Schmidt 2010; La Peyre et al. 2014). This is not always the case, as Muotka and Syrjänen (2007) and Korsu (2004) found that after restoration of channelized streams, the initial abundances and diversity of macroinvertebrates drop significantly. In Muotka and Syrjänen's study, macroinvertebrate recovery is not pronounced until 4-6 years, but the variability appears to stabilize after 8 years (Muotka and Syrjänen 2007). Nevertheless, Miller et al's meta-analysis of river restoration projects (2010) found that macroinvertebrates do recovery rapidly within a year after restoration, suggesting that responses of macroinvertebrates to restoration can vary across habitats and restoration types.

Through this meta-analysis I also found that coastal biota that were directly affected by armoring (higher shoreline elevation) responded more positively than the biota that were indirectly affected (lower shoreline elevation). Similarly, Toft et al. (2014) found that coastal biota at lower elevations that were below the footprint of armoring did not respond to shoreline armoring removal as strongly as that in higher elevations where armoring had been directly placed. No existing studies have assessed direct and indirect effects of restoration in coastlines associated with armoring removal. However, previous restoration work on ecological responses to dam removal in rivers found that biota within sections of rivers directly affected by dam impoundment can respond positively within days to a few years; these biota parameters include but are not limited to native riparian plant re-colonization and re-colonization of lotic organisms

(Hart et al. 2002). Rivers upstream that were indirectly affected by dam impoundment may not experience full recovery of aquatic-terrestrial ecosystem linkages until years to decades after the dam removal (Hart et al. 2002). In contrast, previous work on ecological responses to removal of dikes in estuarine tidal wetlands found that habitats seaward, or those that are indirectly affected by dikes, are just as likely to respond positively to dike removal as the habitats inland, or those that are directly affected by dikes in terms of marsh vegetation, benthic macroinvertebrate, fish and other megafauna recovery as tidal wetland sinuosity increases (Hood 2004). While I found that coastal biota responds more positively in restored habitats that were directly affected by armoring, responses to restoration may vary across different coastal environments.

One of the challenges in this meta-analysis was sample size limitation. Through this meta-analysis I also found that wrack % cover, saltmarsh % cover and the number of logs did respond positively to shoreline restoration, but their responses were based on limited sample sizes. Therefore, it cannot be generalized that similar responses might be observed in other shorelines restored through similar means, as small sample sizes can increase error rate and potentially distort response interpretations (Raudys and Jain 1991). It is important to note that wrack % cover can increase abundances and diversity of macroinvertebrates, facilitate saltmarsh growth, and support megafauna such as seabirds (Dugan et al. 2003; Chapman and Roberts 2004; Smith 2007; Harris, Strayer, and Findlay 2014; Heerhartz et al. 2014). Natural shorelines have higher woody debris counts and densities than armored shorelines, and these can enhance and retain wrack % cover but also reduce beach erosion (Angradi et al. 2004; Eamer and Walker 2010; Harris, Strayer, and Findlay 2014; Heerhartz et al. 2014). Based on the existing knowledge of wrack, saltmarsh, and logs in healthy coastlines, it is essential to increase the geographical scope and sample sizes of these coastal biota types to assess the successful recovery of restored coastal ecosystems.

Coastal biota recovery to armoring removal may also be hindered or facilitated by abiotic variables and their responses to restoration. Per Dethier et al. (2016), beach profiles and sediment grain size may change slowly to armoring installations, which suggests that these two variables may respond slowly across seasons to years after armoring removal. Furthermore, responses of sediment change, such as increasing or decreasing deposition, may also effect recovery patterns of biota. Lower shoreline elevations are also more susceptible to disturbances by hydrological and oceanographic processes, which in turn may prevent rapid recovery of its associated coastal biota (Harris, Strayer, and Findlay 2014).

Finally, the responses of coastal biota that were observed in this meta-analysis may be attributed to “passive” ecosystem management post-recovery. The passive approach does not require further action to be taken after a restoration is complete (Simenstad, Reed, and Ford 2006). Instead, it encourages disturbances to occur, which can potentially influence the recovery trajectory of ecosystem components. Shorelines are exposed to frequent disturbances such as wave contact, flooding, and storm-related events (Gittman, Scyphers, et al. 2016). Disturbances caused by high-wave surges and other storm-related events can enhance recovery by depositing wrack along shorelines, which can enhance habitats for grazing arthropods and even saltmarshes (Dugan et al. 2003; Chapman and Roberts 2004). The combination of disturbances and recoveries enhanced by various oceanographic processes has the potential to elicit positive responses within coastal biota for years after initial restoration.

CONCLUSIONS

This meta-analysis assessed coastal biota's responses at six restored shorelines in Puget Sound across biota type, shoreline elevation, and time-since-restoration, finding strong and uniformly positive responses to armoring removal. Although long-term monitoring is necessary to thoroughly assess recovery trajectories and resilience of shoreline ecosystems (Warren et al. 2002; Gittman, Scyphers, et al. 2016), this study demonstrated that shoreline restoration can prompt rapid positive responses of some coastal biota. However, even with these pronounced results, reversing shoreline armoring is a management challenge. Coastal habitats around the world are facing urban growth unlike ever before (Gittman et al. 2015). In the United States, shoreline armoring is primarily driven by development of residential properties, attempts to improve domestic and international shipping traffic, and protection against storm events (Gittman et al. 2015). With nearly half of the world's population expected to live within 100 kilometers from shorelines by 2030, it is safe to assume that the armoring will continue to increase within and outside the United States in the next few decades (Millennium Ecosystem Assessment (MEA) 2005; Gittman et al. 2015; Gittman, Scyphers, et al. 2016).

Shorelines without armoring can be natural erosional barriers. For example, large woody debris protects from beach erosion but also enhances wrack accumulation, which in turn can enhance saltmarsh growth and improve aquatic-terrestrial connectivity (Chapman and Roberts 2004; Eamer and Walker 2010; Heerhartz et al. 2014). Removing shoreline armoring and improving aquatic-terrestrial connectivity is not only beneficial to the ecosystem but also can help coastal communities and livelihoods, as many ecosystem components that are harvested (such as fishes) rely on ample availability of macroinvertebrate prey for survival. Interestingly, it was found that in coastal residential communities, increasing armoring can be triggered by a chain reaction; as one community member implements armoring adjacent to his or her property, nearby neighbors will adopt the same practice (Scyphers, Picou, and Powers 2014). Nevertheless, many homeowners recognize environmental impacts of shoreline armoring and expressed preference for natural shoreline structures, as they can be aesthetically appealing and have many ecological benefits (Scyphers, Picou, and Powers 2014).

It is therefore critical for policymakers to consider numerous benefits of shoreline armoring removal before undertaking new shoreline development. While removal of armoring is not feasible in all cases due to financial or safety concerns, it is clear from this study that restoring armored shorelines can potentially benefit coastal ecosystem health and coastal populations with increasing availability of ecosystem services. Existing and newer shoreline management policies should consider the innumerable benefits of natural shorelines for coastal populations, properties, and its associated ecosystems. Such policies can encourage homeowners and other stakeholders to embrace restored shorelines since these habitats can simultaneously protect properties, coastal populations, biodiversity, and retain ecosystem services.

REFERENCES

Adams, J., B. Padgham, and J.D. Toft. 2015. "Habitat Restoration: Bainbridge Island Nearshore." Tacoma, WA.

Angradi, T.R., W.E. Schweiger, D.W. Bolgrien, P. Ismert, and T. Selle. 2004. "Bank Stabilization, Riparian Land Use and the Distribution of Large Woody Debris in a Regulated Reach of the Upper Missouri River, North Dakota, USA." *River Research and Applications* 20: 829–46.

Bilkovic, D.M., and M.M. Mitchell. 2013. "Ecological Tradeoffs of Stabilized Salt Marshes as a Shoreline Protection Strategy: Effects of Artificial Structures on Macrobenthic Assemblages." *Ecological Engineering* 61: 469–81.

Bilkovic, D.M., M.M. Mitchell, M.K. La Peyre, and J.D. Toft. 2017. *Living Shorelines: The Science and Management of Nature-Based Coastal Protection*. 1sted. Boca Raton, FL: CRC Press.

Bilkovic, D.M., and M.M. Roggero. 2008. "Effects of Coastal Development on Nearshore Estuarine Nekton Communities." *Marine Ecology Progress Series* 358: 27–39.

Bozek, C.M., and D.M. Burdick. 2005. "Impacts of Seawalls on Saltmarsh Plant Communities in the Great Bay Estuary, New Hampshire USA." *Wetlands Ecology and Management* 13: 553–68.

Brown, S.C., K. Smith, and D.P. Batzer. 1997. "Macroinvertebrate Responses to Wetland Restoration in Northern New York." *Environmental Entomology* 26 (5): 1016–24.

Bulleri, F., and M.G. Chapman. 2010. "The Introduction of Coastal Infrastructure as a Driver of Change in Marine Environments." *Journal of Applied Ecology*.

Bulleri, F., M.G. Chapman, and A.J. Underwood. 2005. "Intertidal Assemblages on Seawalls and

Vertical Rocky Shores in Sydney Harbour, Australia." *Austral Ecology* 30: 655–67.

Chapman, M.G. 2003. "Paucity of Mobile Species on Constructed Seawalls: Effects of Urbanization on Biodiversity." *Marine Ecology Progress Series* 264: 21–29.

Chapman, M.G., and D.E. Roberts. 2004. "Use of Seagrass Wrack in Restoring Disturbed Australian Saltmarshes." *Ecological Management and Restoration* 5 (3): 183–90.

Chapman, M.G., and A.J. Underwood. 2011. "Evaluation of Ecological Engineering Of 'armoured' shorelines to Improve Their Value as Habitat." *Journal of Experimental Marine Biology and Ecology* 400: 302–13.

Cohen, J. 1992. "A Power Primer." *Psychological Bulletin* 112 (1): 155–59.

Cordell, J.R., J.D. Toft, S. Munsch, and M. Goff. 2017. "Benches, Beaches, and Bumps: How Habitat Monitoring and Experimental Science Can Inform Urban Seawall Design." In *Living Shorelines: The Science and Management of Nature-Based Coastal Protection*, edited by D.M. Bilkovic, M.M. Mitchell, M.K. La Peyre, and J.D. Toft, 421–38.

Davis, J.L., C.A. Currin, C. O'Brien, C. Raffenburg, and A. Davis. 2015. "Living Shorelines: Coastal Resilience with a Blue Carbon Benefit." *PLOS ONE* 10 (11): 1–18.

Davis, J.L.D., L.A. Levin, and S.M. Walther. 2002. "Artificial Armored Shorelines: Sites for Open-Coast Species in a Southern California Bay." *Marine Biology* 140: 1249–62.

Dethier, M.N., W.W. Raymond, A.N. McBride, J.D. Toft, J.R. Cordell, A.S. Ogston, S.M. Heerhartz, and H.D. Berry. 2016. "Multiscale Impacts of Armoring on Salish Sea Shorelines: Evidence for Cumulative and Threshold Effects." *Estuarine, Coastal and Shelf Science* 175: 106–17.

Dugan, J.E., D.M. Hubbard, M.D. McCrary, and M.O. Pierson. 2003. "The Response of Macrofauna Communities and Shorebirds to Macrophyte Wrack Subsidies on Exposed

Sandy Beaches of Southern California." *Estuarine, Coastal, and Shelf Science* 58S: 25–40.

Dugan, J.E., D.M Hubbard, I.F. Rodil, D.L. Revell, and S. Schroeter. 2008. "Ecological Effects of Coastal Armoring on Sandy Beaches." *Marine Ecology* 29: 160–70.

Eamer, J.B.R., and I.J. Walker. 2010. "Quantifying Sand Storage Capacity of Large Woody Debris on Beaches Using LiDAR." *Geomorphology* 118: 33–47.

Gittman, R.K., F.J. Fodrie, A.M. Popowich, D.A. Keller, J.F. Bruno, C.A. Currin, C.H. Peterson, and M.F. Piehler. 2015. "Engineering Away Our Natural Defenses: An Analysis of Shoreline Hardening in the US." *Frontiers in Ecology and the Environment* 13 (6): 301–7.

Gittman, R.K., C.H. Peterson, C.A. Currin, F.J. Fodrie, M.F. Piehler, and J.F. Bruno. 2016. "Living Shorelines Can Enhance the Nursery Role of Threatened Estuarine Habitats." *Ecological Applications* 26 (1): 249–63.

Gittman, R.K., S.B. Scyphers, C.S. Smith, I.P. Neylan, and J.H. Grabowski. 2016. "Ecological Consequences of Shoreline Hardening: A Meta-Analysis." *BioScience* 66 (9): 763–73.

Harris, C., D.L. Strayer, and S. Findlay. 2014. "The Ecology of Freshwater Wrack along Natural and Engineered Hudson River Shorelines." *Hydrobiologia* 722: 233–45.

Hart, D.D., T.E. Johnson, K.L. Bushaw-Newton, R.J. Horwitz, A.T. Bednarek, D.F. Charles, D.A. Kreeger, and D.J. Velinsky. 2002. "Dam Removal : Challenges and Opportunities for Ecological Research and River Restoration." *BioScience* 52 (8): 669–82.

Heatherington, C., and M.J. Bishop. 2012. "Spatial Variation in the Structure of Mangrove Forests with Respect to Seawalls." *Marine and Freshwater Research* 63: 926–33.

Heerhartz, S.M., M.N. Dethier, J.D. Toft, J.R. Cordell, and A.S. Ogston. 2014. "Effects of Shoreline Armoring on Beach Wrack Subsidies to the Nearshore Ecotone in an Estuarine Fjord." *Estuaries and Coasts* 37: 1256–68.

Heerhartz, S.M., and J.D. Toft. 2015. “Movement Patterns and Feeding Behavior of Juvenile Salmon (Oncorhynchus Spp.) along Armored and Unarmored Estuarine Shorelines.” *Environmental Biology of Fishes* 98: 1501–11.

Hood, W.G. 2004. “Indirect Environmental Effects of Dikes on Estuarine Tidal Channels: Thinking outside of the Dike for Habitat Restoration and Monitoring.” *Estuaries* 27 (2): 273–82.

Jones, K., and E. Hanna. 2004. “Design and Implementation of an Ecological Engineering Approach to Coastal Restoration at Loyola Beach, Kleberg County, Texas.” *Ecological Engineering* 22: 249–61.

Korsu, K. 2004. “Response of Benthic Invertebrates to Disturbance from Stream Restoration: The Importance of Bryophytes.” *Hydrobiologia* 523: 37–45.

La Peyre, M.K., A.T. Humphries, S.M. Casas, and J.F. La Peyre. 2014. “Temporal Variation in Development of Ecosystem Services from Oyster Reef Restoration.” *Ecological Engineering* 63: 34–44.

Lam, N.W.Y., R. Huang, and B.K.K. Chan. 2009. “Variations in Intertidal Assemblages and Zonation Patterns between Vertical Artificial Seawalls and Natural Rocky Shores: A Case Study from Victoria Harbour, Hong Kong.” *Zoological Studies* 48 (2): 184–95.

Lawless, A.S., and R.D. Seitz. 2014. “Effects of Shoreline Stabilization and Environmental Variables on Benthic Infaunal Communities in the Lynnhaven River System of Chesapeake Bay.” *Journal of Experimental Marine Biology and Ecology* 457: 41–50.

McGlone, C.M., J.D. Springer, and D.C. Laughlin. 2009. “Can Pine Forest Restoration Promote a Diverse and Abundant Understory and Simultaneously Resist Nonnative Invasion?” *Forest Ecology and Management* 258: 2638–46.

McGranahan, G., D. Balk, and B. Anderson. 2007. "The Rising Tide: Assessing the Risks of Climate Change and Human Settlements in Low Elevation Coastal Zones." *Environment and Urbanization* 19 (1): 17–37.

Millennium Ecosystem Assessment (MEA). 2005. "Ecosystems and Human Well-Being: Synthesis." Washington, DC.

Miller, S.W., P. Budy, and J.C. Schmidt. 2010. "Quantifying Macroinvertebrate Responses to In-stream Habitat Restoration: Applications of Meta-analysis to River Restoration." *Restoration Ecology* 18 (1): 8–19.

Moreira, J., M.G. Chapman, and A.J. Underwood. 2006. "Seawalls Do Not Sustain Viable Populations of Limpets." *Marine Ecology Progress Series* 322: 179–88.

Morley, S.A., J.D. Toft, and K.M. Hanson. 2012. "Ecological Effects of Shoreline Armoring on Intertidal Habitats of a Puget Sound Urban Estuary." *Estuaries and Coasts* 35: 774–84.

Munsch, S.H., J.R. Cordell, and J.D. Toft. 2015. "Effects of Seawall Armoring on Juvenile Pacific Salmon Diets in an Urban Estuarine Embayment." *Marine Ecology Progress Series* 535: 213–29.

———. 2016. "Fine-Scale Habitat Use and Behavior of a Nearshore Fish Community: Nursery Functions, Predation Avoidance, and Spatiotemporal Habitat Partitioning." *Marine Ecology Progress Series* 557: 1–15.

Muotka, T., and J. Syrjänen. 2007. "Changes in Habitat Structure, Benthic Invertebrate Density, Trout Populations and Ecosystem Processes in Restored Forest Streams: A Boreal Perspective." *Freshwater Biology* 52: 724–37.

Neumann, B., A.T. Vafeidis, J. Zimmermann, and R.J. Nicholls. 2015. "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global

Assessment." *PLOS ONE* 10 (3): 1–34.

Patrick, C.J., D.E. Weller, and M. Ryder. 2016. "The Relationship Between Shoreline Armoring and Adjacent Submerged Aquatic Vegetation in Chesapeake Bay and Nearby Atlantic Coastal Bays." *Estuaries and Coasts* 39: 158–70.

Peters, J.R., L.A. Yeager, and C.A. Layman. 2015. "Comparison of Fish Assemblages in Restored and Natural Mangrove Habitats along an Urban Shoreline." *Bulletin of Marine Science* 91 (2): 1–15.

Peterson, M.S., B.H. Comyns, J.R. Hendon, P.J. Bond, and G.A. Duff. 2000. "Habitat Use by Early Life-History Stages of Fishes and Crustaceans along a Changing Estuarine Landscape: Differences between Natural and Altered Shoreline Sites." *Wetlands Ecology and Management* 8: 209–19.

Puget Sound Partnership. 2016. "Puget Sound Partnership: Shoreline Armoring." www.psp.wa.gov/vitalsigns/shoreline_armoring_indicator1.php.

Raudys, S.J., and A.K. Jain. 1991. "Small Sample Size Effects in Statistical Pattern Recognition: Recommendations for Practitioners." *IEEE Transactions on Pattern Analysis and Machine Intelligence* 13 (3): 252–64.

Rhodes, L.D., C. Durkin, S.L. Nance, and C.A. Rice. 2006. "Prevalence and Analysis of Renibacterium Salmoninarum Infection among Juvenile Chinook Salmon Oncorhynchus Tshawytscha in North Puget Sound." *Diseases of Aquatic Organisms* 71: 179–90.

Rosnow, R.L., R. Rosenthal, and D.B. Rubin. 2000. "Contrasts and Correlations in Effect-Size Estimation." *Psychological Science* 11 (6): 446–53.

Scyphers, S.B., J.S. Picou, and S.P. Powers. 2014. "Participatory Conservation of Coastal Habitats: The Importance of Understanding Homeowner Decision Making to Mitigate

Cascading Shoreline Degradation." *Conservation Letters* 8 (1): 41–49.

Seitz, R.D., R.N. Lipcius, N.H. Olmstead, M.S. Seebo, and D.M. Lambert. 2006. "Influence of Shallow-Water Habitats and Shoreline Development on Abundance, Biomass, and Diversity of Benthic Prey and Predators in Chesapeake Bay." *Marine Ecology Progress Series* 326: 11–27.

Shipman, H. 2001. "Beach Nourishment on Puget Sound: A Review of Existing Projects and Potential Applications." *Puget Sound Research*, 1–9.

Simenstad, C., D. Reed, and M. Ford. 2006. "When Is Restoration Not? Incorporation Landscape-Scale Processes to Restore Self-Sustaining Ecosystems in Coastal Wetland Restoration." *Ecological Engineering* 26: 27–39.

Smith, S.M. 2007. "Removal of Salt-Killed Vegetation during Tidal Restoration of a New England Salt Marsh: Effects on Wrack Movement and the Establishment of Native Halophytes." *Ecological Restoration* 25 (4): 268–73.

Sobocinski, K.L., J.R. Cordell, and C.A. Simenstad. 2010. "Effects of Shoreline Modifications on Supratidal Macroinvertebrate Fauna on Puget Sound, Washington Beaches." *Estuaries and Coasts* 33: 699–711.

Stewart, G.B., H.R. Bayliss, D.A. Showler, W.J. Sutherland, and A.S. Pullin. 2009. "Effectiveness of Engineered in-Stream Structure Mitigation Measures to Increase Salmonid Abundance: A Systematic Review." *Ecological Applications* 19 (4): 931–41.

Stewart, T.W., and J.A. Downing. 2008. "Macroinvertebrate Communities and Environmental Conditions in Recently Constructed Wetlands." *Wetlands* 28 (1): 141–50.

Taylor, J.P., L.M. Smith, and D.A. Haukos. 2006. "Evaluation of Woody Plant Restoration in the Middle Rio Grande: Ten Years After." *Wetlands* 26 (4): 1151–60.

Toft, J.D. 2016. “Benthic Macroinvertebrate Monitoring at Seahurst Park 2015: Year 10 Post-Restoration of South Seawall Removal and Year 1 of North Seawall Removal.” Burien, WA.

Toft, J.D., J. Cordell, C. Levy, E. Morgan, and E. Armbrust. 2013. “Salmon Bay Natural Area: Restoration Aquatic Monitoring.” Seattle, WA.

Toft, J.D., J.R. Cordell, and E.A. Armbrust. 2014. “Shoreline Armoring Impacts and Beach Restoration Effectiveness Vary with Elevation.” *Northwest Science* 88 (4): 367–75.

Toft, J.D., A.S. Ogston, S.M. Heerhartz, J.R. Cordell, and E.E. Flemer. 2013. “Ecological Response and Physical Stability of Habitat Enhancements along an Urban Armored Shoreline.” *Ecological Engineering* 57: 97–108.

Warren, R.S., P.E. Fell, R. Rozsa, A.H. Brawley, A.C. Orsted, E.T. Olson, V. Swamy, and W.A. Niering. 2002. “Salt Marsh Restoration in Connecticut: 20 Years of Science and Management.” *Restoration Ecology* 10 (3): 497–513.

Wensink, S.M., and S.D. Tiegs. 2016. “Shoreline Hardening Alters Freshwater Shoreline Ecosystems.” *Freshwater Science* 35 (3): 764–77.