Multiscale impacts of armoring on Salish Sea shorelines: Evidence for cumulative and threshold effects

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Abstract

Shoreline armoring is widespread in many parts of the protected inland waters of the Pacific Northwest, U.S.A, but impacts on physical and biological features of local nearshore ecosystems have only recently begun to be documented. Armoring marine shorelines can alter natural processes at multiple spatial and temporal scales; some, such as starving the beach of sediments by blocking input from upland bluffs may take decades to become visible, while others such as placement loss of armoring construction are immediate. We quantified a range of geomorphic and biological parameters at paired, nearby armored and unarmored beaches throughout the inland waters of Washington State to test what conditions and parameters are associated with armoring. We gathered identical datasets at a total of 65 pairs of beaches: 6 in South Puget Sound, 23 in Central Puget Sound, and 36 pairs North of Puget Sound proper. At this broad scale, demonstrating differences attributable to armoring is challenging given the high natural variability in measured parameters among beaches and regions. However, we found that armoring was consistently associated with reductions in beach width, riparian vegetation, numbers of accumulated logs, and amounts and types of beach wrack and associated invertebrates. Armoring-related patterns at lower beach elevations (further vertically from armoring) were progressively harder to detect. For some parameters, such as accumulated logs, there was a distinct threshold in armoring elevation that was associated with increased impacts. This large dataset for the first time allowed us to identify cumulative impacts that appear when increasing proportions of shorelines are armored. At large spatial and temporal scales, armoring much of a sediment drift cell may result in reduction of the finer grain-size fractions on beaches, including those used by spawning forage fish. Overall we have shown that local impacts of shoreline armoring can scale-up to have cumulative and threshold effects -- these should be considered when managing impacts to public resources along the coast.

1. Introduction

Anthropogenic alteration of shorelines is a worldwide phenomenon as a significant proportion of population growth is in coastal communities. Types of shoreline development are diverse, ranging from simply building houses overlooking the water to completely altering the shore by covering it with fill or structures. The Salish Sea, which includes all the inland marine waters of British Columbia (Canada) and of Washington State (USA), has shorelines that range from virtually pristine beaches to concrete-covered commercial ports. In the face of increasing coastal urban growth and sea level rise, effective management of our shorelines requires understanding both functions of natural beaches and the scales at which we are impacting them (Arkema et al., 2013; Harris et al., 2015).

One of the most prevalent forms of coastal development in the Salish Sea and worldwide is shoreline armoring, comprising various artificial means of stabilizing banks and bluffs that might otherwise erode and endanger infrastructure. A recent conservative estimate of armored shoreline in the continental US is 14% (Gittman et al., 2015). Local, mostly biological, effects of shoreline armoring are well known for some types of embayments and marshes (e.g., Bozek and Burdick, 2005; Chapman and Underwood, 2011) and open-coast sandy beaches (e.g., Dugan et al., 2008; review by Nordstrom, 2014), and recently for the gravel-sand beaches of Puget Sound (Sobocinski et al., 2010; Heerhartz et al., 2014). Armoring locally reduces retention of logs and wrack (algae, seagrass, leaf litter, and other organic and inorganic debris left by ebbing tides) and the invertebrate communities that inhabit this detritus. It can also have indirect effects on seabird and shorebird use (Dugan et al., 2008) as well as abundance and diversity of large mobile invertebrates (Chapman, 2003). Potential spawning locations for beach-spawning forage fish, such as surf smelt (*Hypomesus pretiosus*), are reduced when armoring covers the high shore, and egg mortality increases when beach temperatures are raised by shoreline modifications (Rice, 2006). These trophically important fish may also be negatively impacted in cases where armoring coarsens the sediment due to local winnowing of finer grain sizes (Penttila, 2007; Quinn et al., 2012; Fox et al., 2015; Greene et al., 2015). By changing the nearshore habitats encountered by juvenile migrating salmon, armoring affects their diets (Munsch et al., 2015) and possibly residence time (Heerhartz and Toft, 2015).

Considerable study of physical impacts of armoring on beaches has been conducted, although the results are contradictory. In some circumstances, interactions of sediment impoundment, wave reflection, and alterations to nearshore water currents may alter beach scour, mobilization of sediment, and recovery from storms. In theory, these processes may result in narrower, steeper, and coarser-grained beaches (Pilkey and Wright, 1988; Bozek and Burdick, 2005; Nordstrom, 2014). One clear effect is that passive erosion (e.g., caused by relative sea level rise) causes narrowing of armored shorelines because the upper beach is prevented from migrating inland. In contrast, whether active erosion is induced by seawalls is still argued (reviews by Kraus and McDougal, 1996; Ruggiero, 2010); few long-term studies have been attempted but generally do not show a definitive armoring effect (e.g., Griggs et al., 1994; Griggs, 2010). Modeling work (e.g., Ruggiero, 2010) suggests that contradictions seen in the literature may stem from variation among study systems in key physical parameters, in particular the relative elevation of the seawall and the morphology of the beach and nearshore, including their slopes.

Even for the more consistent biological impacts of armoring, translating local effects to a landscape scale is challenging because of the myriad other natural and anthropogenic factors that affect shoreline processes. The signal to noise problem is particularly large in inland waters such as the Salish Sea because of the complexities of underlying geology, shoreline shape, freshwater input, wave fetch, orientation to prevailing winds, nearshore bathymetry, and sources of sediments, vegetation, and organisms. In most of the world, beach sediments derive predominantly from rivers. On sandy shorelines, these sediments are jealously retained with groins, and millions of dollars are spent annually to replenish beaches where natural sources have been locked up by dams (Berry et al., 2013). Although numerous rivers empty into the Salish Sea and a few of them create large deltas, much of the riverine sediment is deposited in deep fjord-like basins rather than building beaches. Instead, most beach-building sediment comes from erosion of bluffs (Keuler, 1988). It follows that “locking up” these sediments by armoring shorelines should have large-scale and long-term impacts, including cumulative effects if few sediment sources are left unaltered (reviewed by Berry et al., 2013; Nordstrom, 2014). However, demonstrating cumulative effects, e.g. changes that continue to worsen with additional armoring, is notoriously difficult -- especially if changes appear gradually, as is likely with many geomorphic processes. In Europe, extensive coastal armoring is thought to have contributed to broad-scale steepening of the shoreline (Taylor et al., 2004), but many other processes could be important.

In the southern part of the Salish Sea (in Washington State), which includes Puget Sound, extensive shoreline armoring has accompanied the last 100 years of development along the greater Everett-Seattle-Tacoma urban corridor, and is thought to significantly impair nearshore ecosystem processes (Simenstad et al., 2011). While local effects have recently been documented (e.g., Sobocinski et al., 2010; Heerhartz et al., 2014), broader or cumulative impacts have not. This uncertainty stymies managers and regulators who lack compelling data that would provide the “best available science” to inform guidelines. Pressures to relax armoring regulations stem from the need to protect valuable infrastructure from erosion, especially with risk exacerbated by sea level rise. Sociological studies show that decisions by a few homeowners to armor their shoreline often triggers neighbors to do the same, leading to cascading local impacts (Scyphers et al., 2015). In addition to such possible cumulative effects, regulators are particularly interested in which types or locations of armoring have greater impacts than others, and whether there are thresholds that trigger these impacts. Samhouri et al. (2010) define an ecological threshold as a point at which small changes in environmental conditions produce large (non-linear) responses in ecosystem state. For example, ecological thresholds have been associated with habitat fragmentation (e.g., Andrén, 1994) and edge effects (Toms and Lesperance, 2003). One possible threshold that may apply to shoreline armoring is the extent that structures encroach on the beach. In addition, slow and delayed “latent impacts” (Coverdale et al., 2013) may exist but are very difficult to detect, especially given signal-to-noise problems.

Previous studies by our research team have focused on local impacts of shoreline armoring in central and southern Puget Sound (Heerhartz et al., 2014 and 2015). We dealt with among-site ‘noise’ by use of a paired sampling design, focusing our surveys on nearby, physically-paired, armored and unarmored beaches. Here we broaden our geographic scale to test whether the documented biological effects of armoring exist on beaches in the Salish Sea north of Puget Sound. We also test whether any physical impacts are detectible, because our previous work in central and southern Puget Sound found few differences in quantified physical parameters that were correlated with armoring. The northern region has more bedrock shorelines and different oceanographic characteristics, so we anticipated that there would be some regional differences in beach parameters. Based on our own localized studies and on literature from other systems (e.g., open-coast beaches), we hypothesized that: 1) Armoring-associated reduction of logs, wrack, and invertebrates would be consistent across regions in paired-beach analyses; 2)

These associations would be increasingly clear when armoring is lower on the beach face; 3) By examining a large range of sites, the predicted pattern of armoring altering beach slope and sediment coarseness might be detectible; and 4) Such geomorphic signals would be most distinct where extensive stretches of armoring have "locked up" more sediment sources in an area. To address these questions, we discuss regional patterns but ignore the huge beach-to-beach variation in geomorphic conditions, to be discussed elsewhere (A.N. McBride, pers. comm.).

2. <u>Methods</u>

2.1 Sites

Our analyses include data from 65 pairs of armored and unarmored beaches in the inside marine waters of Washington State, from the southern extent of Puget Sound to the Canadian border (Figure 1). The data thus encompass three oceanographic regions: South (6 site pairs), landward of a sill at the Tacoma Narrows; Central (23 site pairs), inside Puget Sound proper, south of a sill at Admiralty Inlet; and North (36 site pairs), outside of the Sound but within the Salish Sea. The south sites and to a lesser extent the central ones are influenced by constrained water exchange caused by the sills, and by freshwater input from several rivers. The north sites have greater oceanic flushing but have substantial seasonal freshwater input from several large rivers, especially the Fraser in Canada and the Skagit in Washington. The primary sediment composition on our study beaches was a mix of sand and gravel predominantly derived from glacial and interglacial deposits, delivered to beaches via episodic bluff erosion, and distributed by longshore transport (Shipman, 2010). Wave energy regime and local geology are then the primary drivers of beach sediment character and gradient in the Salish Sea. Pairs of beaches were within the same drift cell (independent zone of littoral sediment transport from source to deposition area) and same component of that drift cell (erosional or depositional). The 65 pairs were within 49 different drift cells (out of over 600 in the Washington state portion of the Salish Sea). These 49 cells ranged from 1.8 to 60.4 km long, and varied from 0 to 99% armored.

Sites had armoring at different elevations and of different types (e.g., concrete seawalls, stone riprap, retaining walls of wood pilings). Paired beaches were matched as closely as possible in terms of geomorphic setting and geology of the bluff, aspect to prevailing winds and sun, wave exposure, and nearshore bathymetry. Beaches in a pair were always nearby; mean distance between members of a pair was 383 m, maximum distance was 1 km. All field data reported here were collected in summer (June to Aug.); central and south sites were surveyed in 2010-2012, north sites in 2012-2013.

2.2 Biological Surveys

Data collection followed procedures described in Heerhartz et al. (2014). Briefly, at all sites we placed a 50 meter shore-parallel transect high on the shore near the wrack zone; this line was used for both biological and sediment sampling. We define beach wrack as organic matter consisting of detached and stranded algae, seagrass, and terrestrial debris. We surveyed the most recent line of beach wrack and avoided older and usually more desiccated wrack. Armored beaches lacking wrack and logs were surveyed at the highest elevation where natural beach sediments were present (i.e., at the toe of armoring). At 10 randomly selected points we estimated the percent cover of each type of wrack (i.e., seagrass, algae, or terrestrial-source), and noted the most abundant types of algae. At 5 of these points we collected samples of wrack and the top 2.5 cm of sediment using a 15-cm diameter benthic corer, and quantified the number of logs (less or greater than 2 m length). We also measured the width of the log line perpendicular to shore. In the lab, wrack samples were sorted into types, dried, and weighed. All invertebrates were extracted (using 106 micron sieves) from the wrack, and identified and counted using a dissecting microscope; talitrid "beach-hopper" amphipods and other crustaceans were identified to genus, and other invertebrates to family (except oligochaetes, which were not identified beyond class). Invertebrate-dense samples were split with a Folsom Plankton Splitter and abundances were back-calculated. For analyses, all parameters were averaged (percent covers) or summed (biomasses, invertebrate counts) across the transect (n = 5 for wrack core and log samples, n = 10 for wrack percent covers).

2.3 Geomorphic Survey Methods

We characterized sediment grain sizes from the wrackline from three to five of the core samples by sieving dried sediments smaller than 16 mm through progressively finer sieves (1/2 phi intervals) using a RoTap shaker, and weighing the amount retained in each sieve. Coarser sediments (cobbles) were individually measured. Elevations of wracklines were measured; because these differed within and among pairs, sediments were not all collected from the same elevation on the beach. In addition, we assessed grain sizes, with lower precision, along a transect at Mean Low Water (MLW: ca. +1 m above MLLW). At three randomly selected points we used a 50×50 cm quadrat to estimate percent cover of cobbles (> 6 cm), pebbles (4 mm - 6 cm), granules (2-4 mm), sand (< 2 mm), and mud (smooth) at the surface and at 5 cm subsurface. The two sets of estimates were averaged for per-quadrat proportions.

Beach profiles were obtained on low tides using a laser level and stadia rod or RTK-GPS, measuring from the top of the berm or toe of the eroding bluff (on unarmored beaches) to elevations approaching mean lower low water (MLLW), depending on the tide. On armored beaches the profiles were measured from the lowest elevation on the armoring structure to MLLW. Beach slope was calculated for the upper portion of each beach from the wrack line to ~0.6 vertical meters above local MLW. This section was consistently in the active sediment transport zone of the foreshore (an area of similar energy) of our beach transects. See Supplementary Material for additional methods and data sources.

Due to the fjord-like shape and complex bathymetry of the Salish Sea, the magnitude of the vertical tidal range varied greatly from our northern to southern sites. Mean tidal range varied from 1.39 to 3.19 m, and the elevation of the mean higher high water (MHHW) datum varied from 2.39 (in the north) to 4.32 m (far inside Puget Sound) above MLLW. To standardize our elevation measurements in relation to tidal range and enable us to meaningfully assess impacts of armoring emplaced at various elevations, we calculated a “relative encroachment” (RE) metric by subtracting the elevation of armoring or toe of bluff from the MHHW datum for each beach. Datum information for nearby sites was obtained from: http://tidesandcurrents.noaa.gov/; in some cases it was necessary to interpolate between distant stations. Positive RE values indicated that the toe (of armoring or bluff) was lower than MHHW, and negative values were higher. RE at our study sites are reported in vertical feet, and ranged from -5.1 ft (= -1.55 m) to +7.0 ft (= 2.14 m), with a mean of -0.33 ± 0.16 ft SEM (standard error of the mean) (= - 0.10 m ± 0.05 SEM).

We tested whether the proportion of the drift cell that was armored (hereafter referred to as DCA: data from various sources) would generate cumulative armoring impacts, for example by blocking increasing proportions of sediment sources. Variables that could be affected by large-scale and long-term impacts of armoring might show these effects, including some parameters where local and short-term impacts were not seen. Of particular interest was testing our hypotheses of a correlation between sediment grain size or beach slope and DCA.

2.4 Statistical Analyses

We assessed local impacts of armoring using paired t-tests, taking advantage of our sampling design to compare the differences between mean values of each measured response parameter at each pair of beaches. Parameters tested are listed in Table 1.

We tested larger-scale effects of RE and DCA on response variables of interest using a mixed effects model. For all analyses "Site" was defined as a random effect and RE or DCA as a fixed effect. Each "Site" had two sampled beaches, the armored beach and its unarmored pair. In this setting the model is allowed to vary the intercept for each "Site," therefore accounting for both within site and among site variation, i.e. acknowledging that sites are representative of Salish Sea beaches and were randomly selected. For models testing counts of wrack invertebrates (either summed, or separately for particular taxa) or components of wrack mass we used a generalized mixed effects model with a quasi-Poisson distribution using the glmmPQL function in the MASS package in R (Venables and Ripley, 2002; R Development Core Team, 2014). A quasi-Poisson distribution was chosen over a Poisson distribution to account for overdispersion and to adequately fit biological count data. For all model fits, residual plots and fitted values were examined, and all appeared reasonable considering the inherent variability of the dataset. For models testing the effect of RE or DCA on percent cover or proportion data (including wrack cover and sediment grain sizes) we used a normal linear mixed effects model with "Site" as the random effect on arcsine-square root transformation of the response variable, as is common with such data to improve normality. The mixed effects models testing the effect of DCA all showed high correlation between the fixed effect and the random effect of Site (Supplemental Table 1). This was expected since each member of a Site existed in the same drift cell by design. Because of the difficulty of deciding what constitutes an independent test, and lack of agreement in the literature on adjusting alpha levels for multiple testing (e.g., Hurlbert and Lombardi, 2003, 2012), we present *p* values as reported by individual tests, and interpret our results conservatively.

Some regression analyses showed non-linear changes in the response variable, suggesting a threshold or breakpoint. For these we applied segmented (piecewise) regression to search for statistically significant two-segment relationships; these can be common in ecological systems and are characterized by an abrupt change in a response variable at some point ("threshold") in an independent variable (Toms and Lesperance, 2003; Samhouri et al., 2010). Our analyses used an approach based on Crawley (2007) (see Supplementary Material). All univariate analyses were run in R (R Development Core Team, 2014).

We used permutational multivariate analysis of variance (PRIMER v6 with PERMANOVA+; Clarke and Gorley, 2006; Anderson et al., 2008) to test for differences in sediment grain sizes between armored and unarmored beaches (type as fixed factor) with sites as replicates (pair as random factor). Multivariate relationships between environmental predictor variables and wrack sample invertebrate assemblages were investigated using distance-based linear modeling (DISTLM) conducted using the step-wise selection procedure to minimize the Akaike information criterion (AIC). These analyses partition the multivariate variability of the invertebrate assemblages along best-fit axes and then test the environmental variables that are most closely related to these axes.

3. Results

3.1 Regional Differences

Although we were interested in testing for armoring effects on beach parameters that might exist despite regional variation, the physical backdrop for testing such local impacts includes regional differences in bluff geology and shoreline geomorphology. There are fundamental geologic differences among regions that result in variation in bluff material (Fig. 2). The north region experienced advance and retreat of glaciers so that surface morphology reflects the zone of ice grinding on bedrock; the exposed sediment in the central region transitions to a glacial outwash zone; and the sediment deposits in the south are dominated by outwash that was at the front edge of the ice. These influences are also seen in sediment grain sizes at the wrackline of the study beaches (Fig. 2). Grain size distributions were quite consistent between armored and unarmored beaches within a region, but some differed among regions; in particular, very coarse gravel and very coarse sand were more abundant at the central sites (in the outwash zone), medium sand was particularly abundant at the north sites, and coarse gravel in the south. Sediments at MLW also showed no obvious armoring effect in the paired analysis but had some regional differences, with pebbles and granules more abundant in the south (Suppl. Fig. 1).

Characteristics of the chosen sites varied among regions for some physical parameters but not others. The large-scale parameter of wave fetch impacting each beach did not vary with treatment but was lower in the south (Fig. 3). Drift cell lengths were greatest in the north and shortest in the south, but with substantial variance within all regions (Suppl. Fig. 2). The DCA (proportion of the drift cell armored: Suppl. Fig. 2) of the drift cells containing our study sites were very different among regions, highest in the urbanized and heavily-armored central region (mean 69% ± 5% SE armored) and much lower in the north (24 ± 3%) and south (25 ± 15%). Beach width was reduced consistently by armoring but showed no regional pattern (Fig. 3). Elevation of the toe of the bluff/armoring showed both a treatment effect, with armoring moving the toe to a lower elevation, but also a regional effect because of the much greater tidal range in the south region. The toes of unarmored bluffs are much higher above MLLW in the south than the north (Fig. 3) because of this factor. Our calculated relative encroachment metric (RE) accounted for this background difference (see Methods). In all regions armored beaches 'encroached' upon Mean Higher High Water relative to unarmored beaches (Fig 3); this difference was least in the north, showing that armoring is generally not emplaced as low on the shore in that region, and greatest in the south. RE values for unarmored beaches were similar among regions.

Some of the abiotic and biotic parameters that respond locally to armoring (see below) also varied among regions (Fig. 3, 4). Numbers of logs stranded on the beach were much higher at unarmored beaches but were most abundant in the central region and least in the south; the same pattern was seen in width of the log line (data not shown). Shade from overhanging vegetation likewise was always higher at unarmored beaches but was most abundant (and most different with armoring) at the south sites (Fig. 3). Algal and seagrass wrack biomasses were much greater at the north sites, and there was some variation in the types of wrack found there; seagrass was much more common (Fig. 4), reflecting the local abundance of large seagrass meadows in the region. Algal types were not weighed separately in the wrack samples, but we did record the most common component in each; in all regions, ulvoid algae were the most common (in 80- 85% of samples in all regions), but *Fucus* spp. was more common in the north samples (most common alga in 13% of the samples, versus only 1% in the central and south). The north part of the Salish Sea contains a high proportion of bedrock, the preferred substrate of *Fucus*, whereas there is little such habitat in the central and south regions (Fig. 2).

Invertebrates in the wrackline samples showed surprising and largely unexplained differences among regions. This was seen especially in the abundances of talitrid amphipods, oligochaetes, and nematodes, all of which were very patchy at the north sites but often 2-10 times more abundant than at the central or south sites (Fig. 4). For the amphipods, these differences stemmed largely from very abundant juveniles (unidentified talitrids) and adults in the genus *Traskorchestia*, with lower numbers of adults in the genus *Megalorchestia* (Fig. 4). Factors affecting amphipod assemblages (all three groups) were examined with multivariate analyses, testing how well a wide range of 'independent' variables (grain sizes, amounts and types of wrack, RE, shade, etc.) can predict the types and abundances of amphipods. The best DISTLM analysis produced an r^2 of only 0.32, with 11 predictor variables included. More amphipods of all types were found with more wrack mass and fewer with high RE and high DCA, but all correlations between individual amphipod taxa and individual factors were very weak (r^2 values <0.05). Total wrack mass was correlated with total amphipods over all beaches, but not strongly ($r^2 = 0.19$). When the wrack was mostly terrestrial there were almost no amphipods, but when the wrack was mostly marine the numbers ranged from zero to over 10,000 among five core samples.

Of the other wrackline arthropods, Collembola varied highly within and among regions; in particular some of the south sites had very large numbers, but these showed no correlations with amounts of any type of wrack. Insects (primarily Diptera larvae and adults) tended to be more abundant in the north (Fig. 4). Insect numbers showed no correlations with algal mass but a positive correlation with terrestrial wrack mass ($r^2 = 0.16$ for all beaches), especially for armored beaches ($r^2 = 0.25$).

3.2 Sound-Wide Patterns in Paired Analyses

As was found in the central-south regions (Heerhartz et al., 2014, 2015), when data from the north sites were included in a 65-pair sound-wide analysis, armoring had clear Sound-wide impacts on a number of parameters on the upper shore (Figs. 3 and 4, Table 1). Unarmored beaches within a pair were wider (overall means and SE Armored 27.3 ± 1.8 m, Unarmored 33.7 ± 1.9 m), and extended higher up the shore (Armored 3.03 ± 0.07 m above MLLW, Unarmored 3.77 ± 0.08 m), but we found no paired differences in slope of the upper shore (Armored 0.115 ± 0.0002, Unarmored 0.110 ± 0.0001). This slope metric is not sensitive to small-scale armor-induced scour. Unarmored beaches had far more shade from overhanging vegetation (Armored 12.5 ± 3.2%, Unarmored 41.7 ± 4.8%), more stranded drift logs (Armored 0.7 ± 0.2, Unarmored 6.7 ± 0.5), and a wider log line (Armored 0.6 ± 0.1 m, Unarmored 5.2 ± 0.4 m). More wrack also accumulated on unarmored beaches, with this pattern holding true for all the measured components of algae, seagrass, and terrestrial plant material (visible by region in Fig. 4). All these differences except slope were significant in paired t-tests (*p* values < 0.01, Table 1).

However, for the invertebrates found in the wrack, some of these patterns were not consistent with the more localized study of Heerhartz et al. (2015). Armored beaches had reduced numbers of amphipods and insects only in the central and south regions (Heerhartz et al., 2015); when the north beaches were included, neither of these paired *t*-tests was significant (Fig. 4, Table 1). The exceptions were numbers of Collembola, which varied highly among regions but overall were more common at unarmored beaches, and the relatively uncommon talitrid amphipod genus *Megalorchestia*, also more abundant at unarmored beaches (Fig. 4). Worms involved in decomposition of the wrack (oligochaetes and nematodes) showed no overall armoring effect (Fig. 4, Table 1).

Grain size distributions of sediment at the wrack line were generally consistent between pairs of sites (visible by region in Fig. 2), even though the “wrackline” sediments were usually sampled from lower elevations at armored beaches (with wrack stranded at the toe of the armoring). We found no differences in any sediment grain sizes in paired t-tests (*p* values > 0.15, Table 1). In the mid shore (MLW), where sediments were collected at the identical elevation on armored and unarmored beaches, there was again no effect of armoring on grain sizes (Table 1, Suppl. Figure 1).

3.3 Thresholds and Cumulative Impacts

We tested for the relative roles of armoring emplaced lower on the shore and of increasing amounts of armoring within drift cells by regressing RE and DCA against the suite of dependent variables (amounts of wrack of different kinds, counts of invertebrates in the wrackline, numbers of logs, etc.). These regressions generally had the form expected from the pairwise analyses, for example declines in logs, wrack, and invertebrates occurred with larger encroachment of armoring on the beach, but few had r^2 values > 0.10 (data not shown). Often the scatterplots were ‘wedge-shaped’ (e.g., Fig. 5, Suppl. Fig. 3). For example, Fig. 5 shows that low-shore-armored beaches always had few logs or little wrack, whereas unarmored or high-shore-armored beaches had highly variable amounts. These plots thus were indicative of the large number of interdependent parameters causing variation in the measured shoreline variables, e.g., wrack abundance at the time of measurement was affected by many factors other than encroachment.

Based on the appearance of some scatterplots, we used segmented regression to test for thresholds in the number of logs on a beach in relation to relative encroachment (Fig. 5). Our analysis found that there was a breakpoint in the relationship at a relative encroachment of 1.44 feet (SE +/- 1.37 ft), where the regression changed from a non-significant slope of -0.31 (+/- 0.70) to a significant slope of -1.34 (+/- 0.27) ($p < 0.0001$) (Fig. 5). In other words, beaches with armoring low on the shore had far fewer logs than expected based on the relationship between number of logs and RE for beaches where the armoring was farther up the shore. Thus RE = 1.44 ft constitutes a threshold of relative encroachment below which logs are virtually excluded from a beach. This model was compared to a simple linear regression of total logs against RE using AIC and r-squared values; these were almost identical, with segmented AIC at 723.6 ($r^2 = 0.26$) and simple regression at 722.2 ($r^2 = 0.25$). These comparisons suggest that both models are similar in their ability to describe the data, but in terms of data useful to managers, it is helpful to present the segmented model and threshold. Other scatterplots and segmented regressions suggested similar relationships for the amount of wrack (Suppl. Fig. 3) but were not significant.

Our 65 pairs of sites varied greatly in the degree of armoring present (DCA) in the drift cells where they were located (Suppl. Fig. 2). Of particular interest at this larger spatial scale was testing our prediction that there would be an effect of alongshore extent of armoring on sediment grain sizes or beach slope, which showed no armoring signal at the local, paired t-test scale. Our mixed-effects regressions showed clear effects of DCA on a number of grain sizes (Table 1). Figure 6 illustrates these patterns with DCA-extent binned (4 categories) so that the whole grain size spectrum can be shown at once. Regardless of their local armoring status, beaches in the more-extensively armored drift cells (“High” in Fig. 6) had significantly higher proportions of coarse sediments, especially very coarse gravel (32-64 mm), and significantly lower proportions of fine sand (125-250 µm) and medium sand (250-500 µm) (Table 1). Multivariate analyses testing the suite of all grain sizes together showed a highly significant relationship with DCA (1-way PERMANOVA, $p = 0.0001$). To be certain that these grain-size differences were not biased by the generally lower elevation of “wrackline” samples at armored beaches, we ran a simple linear model (without the Site term and thus not mixed-effects) on DCA versus grain sizes (arcsin sqrt transformed) using data from just the unarmored beaches (visible in Fig. 6). Even with the smaller sample sizes (half the N beaches), there was still a significant association of higher DCA with an increased fraction of very coarse gravel ($p = 0.0002$), and decreased medium sand ($p = 0.006$). Other grain sizes were not statistically related to armoring.

We also analyzed sediments from the mid-shore (MLW) at all beaches, although for this elevation we had less precise data on grain sizes (from estimates using quadrats in the field) (Fig. 6). Mixed-effects regressions showed no significant effects of DCA on any grain sizes at this lower elevation.

Because DCA varied with region (Suppl. Fig. 2), as did the proportions of different sediment sizes on the beaches (Fig. 2), we were concerned that the relationship between DCA and grain size might be biased, i.e. driven by some other independent variable that differed among regions. To address this, we examined the underlying geological material (categories in Fig. 2) of the bank or bluff in each drift cell and found that not surprisingly, DCA varied with bluff material -- the most armoring occurred in drift cells dominated by loose sediment (that would presumably require more stabilizing), and the least armoring in bedrock areas. A 2-factor ANOVA on the proportion of very coarse gravel (the fraction with the strongest relationship to degree of armoring) with factors of underlying material (6 types) and DCA (4 levels, binned as in Fig. 6) showed that gravel was significantly associated with DCA ($p < 0.0001$), but not with underlying bluff material ($p = 0.21$), with no significant interaction ($p = 0.08$). Thus one interpretation of this analysis is that although underlying geological material in the bluff must ultimately affect the amount of gravel on the beach, the regional pattern is more closely related to the degree of armoring in the drift cell.

The slope of the upper beach also varied with DCA. This test was run with only 54 pairs of beaches (see Suppl. Methods). Beaches on more-armored drift cells (regardless of local armoring) had slightly but significantly steeper slopes than those in less-armored drift cells (Table 1, $p = 0.0028$, data not illustrated); mean slope was 10% at low-DCA beaches and 15% at high-DCA areas. Unexpectedly, relative encroachment had a small but significant ($p = 0.045$) effect in the opposite direction; beaches with greater encroachment of armoring were slightly flatter than those with less encroachment. This may relate to heavily-encroached beaches having scour in front of armoring, which would lead to a reduced near-armor slope (A.N. McBride pers. comm.).

The proportion of the drift cell armored was also directly or indirectly associated with several biological parameters. Mixed-effects regressions showed that DCA had a significant negative effect on some wrack mass parameters, and also on total numbers of wrack invertebrates and Collembola (Table 1).

4. Discussion

4.1 Local and Regional Effects

As was found in our previous sampling over a smaller geographic region (Sobocinski et al., 2010; Heerhartz et al., 2014, 2015), a variety of response variables, especially those associated with the upper shore, differed between paired armored and unarmored beaches across the southern part of the Salish Sea. Parameters locally reduced by armoring included width and shadiness of the beach, and log and wrack accumulation on the upper shore. Many of the invertebrate taxa that inhabit the wrack or live under logs were also less abundant with armoring. Most of these patterns were visible throughout our large study area even though there were substantial underlying regional differences. Northern beaches had more algal and seagrass wrack; the abundance of bedrock in the north that supports large algal populations likely contributed to the available algal wrack mass, as did seagrass from very large seagrass beds in Padilla Bay and on large river deltas. The lesser encroachment of armoring in the north also presumably allowed more wrack to accumulate. Northern shorelines have been settled and altered more recently than the central region, and regulation of armoring elevation has become stricter with time. The northern sites also had lower overall proportions of their drift cells armored (DCA); this could be due to the greater awareness of shoreline impacts in this later-developed region, and/or to the larger proportion of bedrock in the drift cells reducing the need for shoreline stabilization.

For some biotic parameters there was an association with armoring either on local or broader spatial scales, while for others the regional, geomorphic, or other sources of variation obscured such potential patterns. The larger masses of wrack (especially algal) in the north were occupied by higher densities of amphipods, nematodes, and oligochaetes, while more insects were associated with larger amounts of terrestrial wrack. Somewhat surprisingly, numbers of insects showed no relationship with the amount of overhanging vegetation (percent shade).

Collembolans showed a regional pattern driven by high densities in a few southern sites, but did not correlate with any type of wrack.

The very large regional variation in talitrid amphipod abundances and their inconsistent response to armoring likely relate to unexplored behavioral responses of these important wrack inhabitants. *Megalorchestia* was the only amphipod taxon to show a consistent sensitivity to armoring across regions (seen also by Dugan et al., 2003), and to respond significantly to relative encroachment of armoring on the beach. This genus tends to burrow in sand high on the shore (Pelletier et al., 2011; Dugan et al., 2013) and to be sensitive to sediment textures (Viola et al., 2013). *Traskorchestia,* in contrast (likely including most of the "juvenile talitrids" counted) burrows less and is more likely to move around the beach, shelter in wrack, and survive submersion for extended periods (Koch, 1989). They may concentrate in lower wrack when the tide is out but (in the absence of armoring) move to higher elevations to avoid being submerged at high tide. Our wrack samples were taken at variable times relative to the tidal level and under many different weather conditions, and we did not track age or field-moisture content of the wrack; such static sampling may have affected our ability to accurately measure these highly mobile organisms.

Our tests of armoring-associated effects lower on the shore were inconclusive. Sediment analyses at Mean Low Water showed no differences between paired beaches. We also tested for a biotic response to hypothesized changes in sediment texture in the abundance or species richness of juvenile clams, but found no patterns (Dethier, unpubl.). Our mid-shore samples were physically removed from armoring by an average of ~30 m across the beach face, meaning that direct armor effects such as from wave reflection were unlikely. Long-term indirect effects such as gradual loss of finer sediments from the beach face could impact the mid shore but were not detected in our data.

4.2 Broader-Scale Patterns

For some parameters that we hypothesized would be affected by armoring, the local, paired-beach scale was mismatched to the larger-scale processes that likely control these parameters. This was particularly true for geomorphological parameters such as beach profiles (e.g., slope). One likely explanation is that armoring impacts "smear" among members of a sampled pair; for example, if an unarmored beach has sediment naturally eroding onto the shore, some of the sediment is likely to get carried to the nearby armored beach even if that beach is, on average, “updrift”. Conversely, changes to wave energies and sand supply caused by a large stretch of armoring could impact sediment processes on a nearby unarmored beach. Important contextual parameters such as age of the armoring often could not be ascertained due to poor historical record keeping. Even with our large sample sizes we had insufficient replication to test hypotheses related to different types of armoring, for example vertical concrete versus sloped riprap.

Our ability to test for relationships between armoring and various response parameters was also compromised by the interactions between space and time, and geomorphology and biology. Testing hypotheses about armoring effects on sediment grain sizes and beach slopes, for example, was not possible until we had data encompassing drift cells with a large range of armoring – and for those conditions to have been present for long enough that finer sediments had time to gradually winnow out of armored beaches. In addition, there are potential geomorphic factors not considered in our analysis, and a definitive cause and effect relationship is yet to be determined. Differences in upper-shore sediment grain sizes were not detected at the paired beach scale but were significant when examined at a large geographic scale. We interpret this regional-scale analysis to suggest that there is a reduction of sediment input resulting from armoring large proportions of drift cells. In turn, this appears to have long-term, cumulative geomorphological effects, such that proportions of fine sediments are reduced, leaving behind coarser ones. Even at this scale, cumulative armoring effects were relatively subtle, and statistically significant only for the grain sizes at the ends of the size spectrum. As in sandy beach ecosystems (Berry et al., 2014), this cumulative effect may reduce the ecological resilience of Puget Sound beaches, where sediment supply is already episodic. Grain sizes then affect numerous biological parameters such as suitability for spawning surf smelt (Penttila, 2007), and the numbers and types of invertebrates in the wrack zone and elsewhere on the beach (e.g., Viola et al., 2013; Heerhartz et al., 2015). The predominance of wedge-shaped plots in our analyses (e.g., Fig. 5, Suppl. Fig. 3) attests to the large numbers of factors affecting all of our measured parameters; abundances of wrack invertebrates, for example, are likely influenced not only by the amount and type of wrack itself, but the elevation of the wrack on the shore, the porosity of the sediment, and the region.

Lower elevations of shoreline armoring, calculated as relative encroachment over the beach, showed a clear negative association with most beach parameters at both local and larger spatial scales. For some of these parameters, such as number of accumulated logs, segmented regressions demonstrated that there was a distinct threshold elevation below which armoring seemed to have dramatic impacts; a similar pattern was seen in total wrack mass. In each case, the threshold was ca. 1 - 2 vertical feet below MHHW. Armoring below this elevation, which is no longer permitted for new construction in Washington State, was associated with substantially greater differences in measured parameters than armoring higher on the beach. This elevation thus may constitute a "utility threshold" (Samhouri et al., 2010) to be targeted by management actions or restoration to obtain the most significant beneficial changes in ecosystem functions.

Our study has documented both obvious and more subtle effects of armoring on Salish Sea shorelines, including those detectable at diverse spatial and temporal scales as summarized in Figure 7. Some differences, such as reduced wrack accumulation on armored beaches, could be seen at local spatial scales (paired beaches) and probably would be observable within days of armor installation. Wrack is delivered to beaches on almost every high tide, and stranding of this material is clearly reduced in front of armoring, especially when the structure is relatively low on the shore. At the other end of the spatial and temporal spectrum, the hypothesized geomorphic responses such as slope and grain size distributions were not visible at the paired-beach scale, where they are obscured by the numerous processes that impact local beaches on both short and long-term time scales. These responses likely require both a large extent of armoring and substantial time of sediment reworking to create a signal that is detectable over the natural geomorphic variability.

Exact positions of responses related to armoring on the space and time axes in Figure 7 are only approximate, and some are context-dependent or only weakly supported. Forage fish spawning, placed at intermediate scales of space and time (Fig. 7), could actually be affected rapidly and locally if armoring covers spawning beaches, or slowly and only at very broad scales in the case of gradual population decline due to large-scale loss of appropriate sand grains for egg attachment. Our previous studies have suggested that shoreline armoring has some effect on abundance and behavior of terrestrial birds (Heerhartz, 2013) and juvenile salmon (Toft et al., 2013; Heerhartz and Toft, 2015), but since these organisms are highly mobile and use large stretches of shoreline, distinguishing population responses to armoring is very difficult. Mobile organisms in general present similar problems with regard to conservation (Runge et al., 2014; Rolet et al., 2015). Juvenile salmon migrating alongshore on their way to the ocean encounter the entire spectrum of armored and natural beaches, so attributing effects on diet, fitness, and survival to one factor such as armoring requires manipulative studies such as holding fish in a small area to measure local feeding rates (Toft et al., 2007; Toft et al., 2013). Armoring located in juvenile fish habitats likely changes the character of the wrack and invertebrates therein, as well as overhanging vegetation and insects, all of which may alter behavior or feeding of the fish.

While our study did not directly address restoration efforts, our observations combined with site-specific data from armor-removal projects within the Salish Sea (e.g., Toft et al., 2014) suggest that many of the armoring impacts we observed may be reversible. In some cases, beach functions may be at least partially restored by modification of shore structures and may not require complete removal (Berry et al., 2013; Nordstrom, 2014). Our data suggest that moving armoring higher on the shore may restore some ecological functions while still protecting infrastructure. Recovery of beach characteristics and functions may follow the same temporal patterns illustrated in Figure 7. Wrack can return quickly when armoring has been removed and there is physical space on the upper shore for it to accumulate; colonization by arthropods and other decomposers is likely to follow quickly if there are local sources of colonists. Terrestrial birds will probably visit restored spaces quickly, once invertebrate food becomes available, and rapid juvenile salmonid use of a restored beach has already been demonstrated at a site in Puget Sound (Toft et al., 2013). If sediments are appropriate for spawning forage fish, or if armoring removal is accompanied by beach nourishment with appropriate sediment, then egg-laying may occur during the next spawning season; but even spawning on appropriate sediment is unpredictable in space and time (e.g., surf smelt: Penttila, 2007). These biotic changes may happen on relatively short temporal scales, for example seasonally, rather than taking years over which some armoring impacts may develop. Recovery of geomorphic parameters such as beach shape and pre-armoring sediment grain sizes will depend on sediment sources, whether from updrift, upslope, or artificial delivery.

Multiscale spatial and temporal impacts of armoring are also likely to be seen on open-coast sandy beaches or other systems such as armored estuarine marshes. On sandy beaches, the effects of armoring on wrack accumulation and on other trophic levels have been well studied (e.g., Dugan et al., 2008). A relatively unique feature of Pacific Northwest beaches is extensive windrows of beach logs, but these may have some parallel in marsh vegetation that can only develop when armoring is absent or very high on the shoreline (Bozek and Burdick, 2005). As in the Salish Sea, on both sandy beaches and marshes the direction of drift (e.g., longshore currents, estuarine outflow) should affect the location and spatial scale of armoring impacts because the accumulation of both sediments and organic matter are important in those ecosystems. Geomorphic effects of armoring on open beaches or marshes are similarly likely to be slow or highly episodic, depending on types of sediment sources and their proximity, as well as variations in wave energy. The degree to which sediment sources are locked up, either by extensive alongshore armoring or by dams on riverine sources, may have cumulative effects; investigating possible thresholds in the interactions between sediment budgets and marsh health or beach geomorphology would be useful but temporally challenging.

In conclusion, our broad study covering a wide range of beaches and drift cells with different types, elevations, and degrees of armoring has allowed us to quantify hitherto elusive patterns of impacts of armoring on beach processes. Armoring alters beach conditions from the local to the sound-wide scale, with its effects likely emerging on time scales that range from immediate to years or decades. In the Salish Sea, there is great variation among beaches and regions in upper-shore parameters such as logs, wrack, and invertebrates, but in many cases an armoring signal overrides these complex processes, and broad associations are visible. The changes in the geomorphic character of beaches towards steeper and coarser conditions appear to be slow and subtle, but ultimately can ramify to impact beach functions, including supporting forage fish use and altering the infauna. The elevation of armoring on the shore clearly does make a difference to numerous functional characteristics, and at least in the case of log accumulation, there is a threshold for this effect. Our data also suggest that adding more armoring within drift cells may lead to cumulative impacts on several geomorphic and biological parameters. The mechanisms that might cause these cumulative effects, for example starving the beaches of sediment supply or altering local hydrodynamics, require further investigation.

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Table 1. Summary of statistical tests.

	Paired t-tests		RE			DCA		
Description	**pvalue**	**direction**	**pvalue**	**Direction**	**Test type**	**pvalue**	**Direction**	**Test type**
Beach Width	0.0104	U > A						
Beach Slope	ns		0.0453	neg	C	0.0028	pos	C
Shade on upper shore	<0.0001	U > A						
Number of logs	<0.0001	U > A						
Width of log line	<0.0001	U > A						
Wrack Terrestrial Percent Cover	<0.0001	U > A	< 0.0001	neg	B	ns		B
Wrack Algae Percent Cover	0.0012	U > A	0.0002	neg	B	ns		B
Wrack Total Percent Cover	<0.0001	U > A	< 0.0001	neg	B	ns		B
Wrack Total Mass	<0.0001	U > A	< 0.0001	neg	A	0.0074	neg	A
Wrack Algae Mass	0.00773	U > A	< 0.0001	neg	A	0.0247	neg	A
Wrack Terrestrial Mass	0.00013	U > A	< 0.0001	neg	A	ns		A
Wrack Total Invertebrates	ns		0.0001	neg	A	0.0051	neg	A
Wrack Total Amphipods	ns		0.003	neg	A	ns		A
Wrack Total Insects	ns		< 0.0001	neg	A	ns		A
Wrack Total Collembola	0.00759	U > A	0.0001	neg	A	0.0293	neg	A
Wrack Oligochaeta + Nematoda	ns							
Wrack Megalorchestia	0.0002	U > A						
Very Coarse Gravel	ns		ns		B	0.0001	pos	B
Coarse Gravel	ns		ns		B	ns		B
Medium Gravel	ns		ns		B	ns		B
Fine Gravel	ns		ns		B	ns		B
Very Fine Gravel	ns		ns		B	ns		B
Very Coarse Sand	ns		ns		B	ns		B
Coarse Sand	ns		ns		B	ns		B
Medium Sand	ns		ns		B	0.0042	neg	B
Fine Sand	ns		ns		B	0.0008	neg	B
Fines	ns		ns		B	ns		B

Notes: Type of test: A = Mixed-effect ANOVA on quasi-Poisson data; B = Mixed-effects on arcsin sqrt transformed data; C = normal linear mixed effect model. ‘ns’ = non-significant. ‘neg’ and ‘pos’ refer to the direction of effect of the parameter on the response variable, e.g. large RE is associated with low wrack cover.

Figure Captions

Figure 1. Map of the Washington State portion of the Salish Sea, showing study site locations and major cities. Each pair of beaches (armored and unarmored) is represented by a dot. North sites are represented by letters, Central by #1-25, and South by #26-31. Basemap data courtesy of Washington Dept. of Ecology (WA State Basemap, Place Names) http://www.ecy.wa.gov/services/gis/data.htm and Washington State Dept. of Transportation (Shoreline) http://www.wsdot.wa.gov/mapsdata/geodatacatalog/

Figure 2. Upper panel: Regional differences in geological materials comprising bluffs at the study sites. Lower panel: averaged sediment grain-size distributions (proportions) in samples from the wrack line (samples sieved in the lab). Sample sizes: North = 36 pairs of beaches, Central = 23 pairs, South = 6 pairs.

Figure 3. Physical parameters measured at all beaches. Bars are means and one SE. Sample sizes as in Fig. 2.

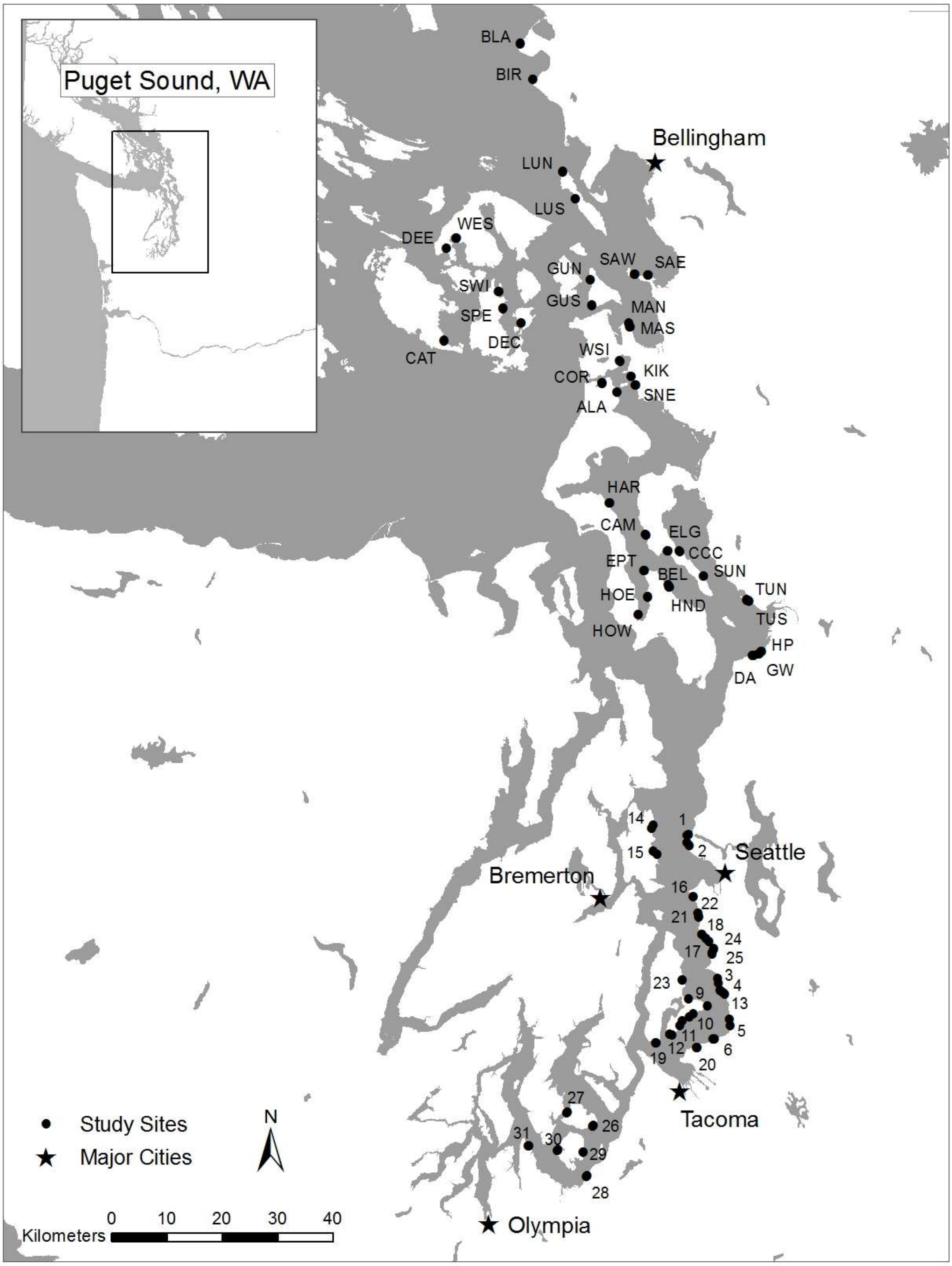
Figure 4. Abundances of types of wrack and organisms in wrack cores by region and treatment (armored vs unarmored). Bars are means and one SE of the summed elements. North = 36 pairs of beaches, Central = 23 pairs, South = 6 pairs.

Figure 5. A segmented regression of the number of logs per transect relative to encroachment of bluff or armoring below MHHW. Regression lines incorporate both unarmored beaches (open circles), and armored beaches (filled circles).

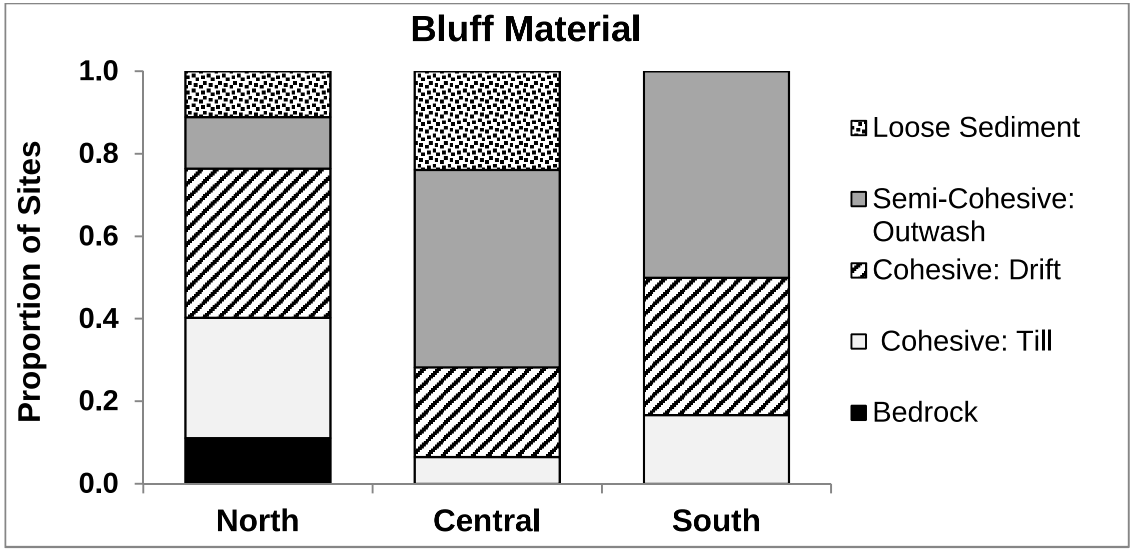
Figure 6. Proportions of sediment grain sizes at the Wrack line (upper panel) and at Mean Low Water (lower panel) in drift cells with different degrees of armoring (Low DCA = 0-0.2 proportion armored, Medium Low = 0.2-0.5, Medium High = 0.5-0.8, and High = 0.8-1.0). We split these proportions somewhat unevenly to allow for similar site replication within each bin, and also to highlight the impacts of particularly low and particularly high amounts of armoring in the drift cell. Sediments from the Wrack line were dry-sieved in the lab; sediments at MLW were

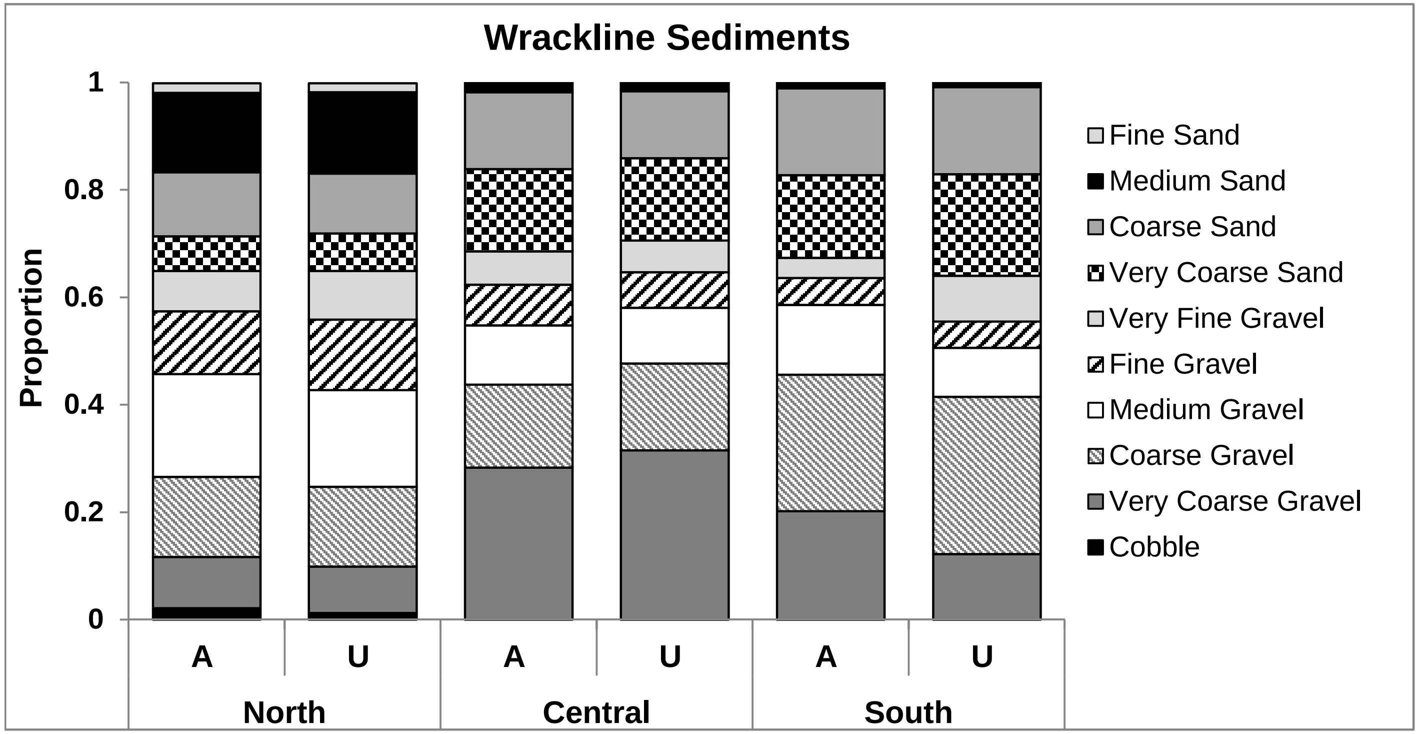
estimated in quadrats on the beach. Some of the MLW bars do not sum to 1.0 because of small amounts of hardpan or mud present. For each of the bars (A and U) in each DCA category, the N beaches = Low 20, Med Low 24, Med High 12, High 9.

Figure 7. Temporal and spatial scales at which different types of impacts of armoring can be detected. Impacts in dashed boxes are hypothesized but not thoroughly demonstrated. Speed of responses following restoration (armor removal) may follow the same temporal and spatial patterns.

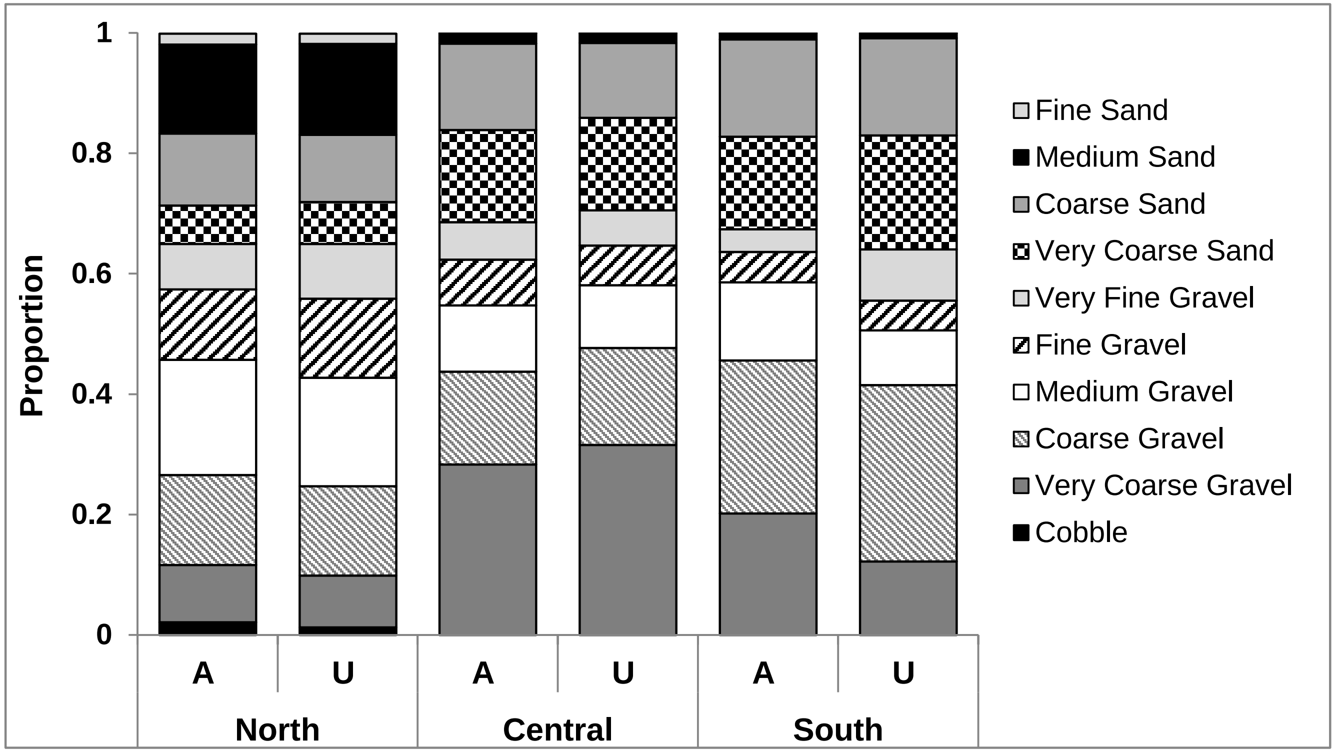


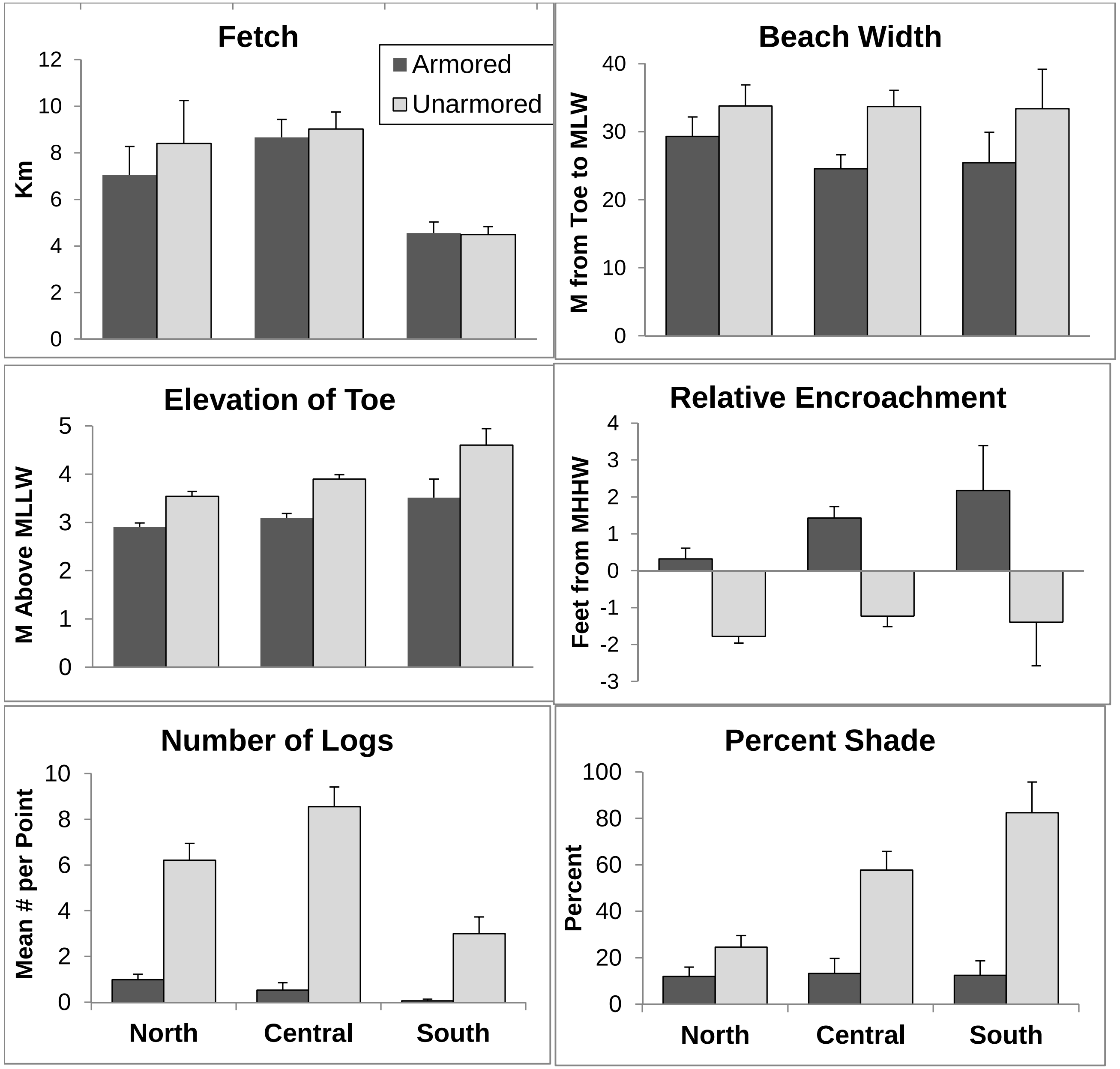
Puget Sound, WA
BLA
BIR
Bellingham
LUN
LUS
WES
DEE
SAW
SAE
GUN
SWI
GUS
SPE
MAN
MAS
DEC
CAT
WSI
KIK
COR
SNE
ALA
HAR
CAM
ELG
CCC
EPT
BEL
SUN
HOE
HND
TUN
TUS
HOW
HP
GW
DA
14
1
15
2
Seattle
Bremerton
16
22
21
18
24
17
25
23
3
4
9
13
10
5
11
12
6
19
20
Tacoma
27
26
31
30
29
28
Olympia
Study Sites
Major Cities
N
0
10
20
30
40
Kilometers

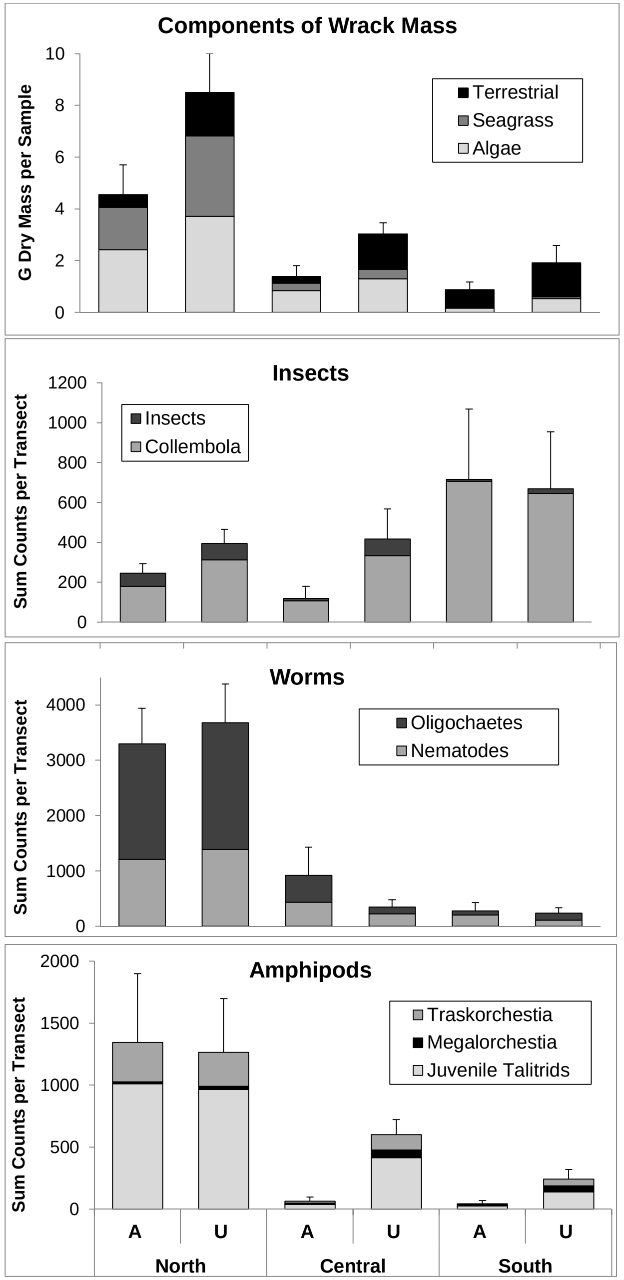

Bluff Material
Proportion of Sites
1.0
0.8
0.6
0.4
0.2
0.0
North
Central
South
Loose Sediment
Semi-Cohesive: Outwash
Cohesive: Drift
Cohesive: Till
Bedrock


Wrackline Sediments
Proportion
1
0.8
0.6
0.4
0.2
0
A
U
A
U
A
U
North
Central
South
Fine Sand
Medium Sand
Coarse Sand
Very Coarse Sand
Very Fine Gravel
Fine Gravel
Medium Gravel
Coarse Gravel
Very Coarse Gravel
Cobble

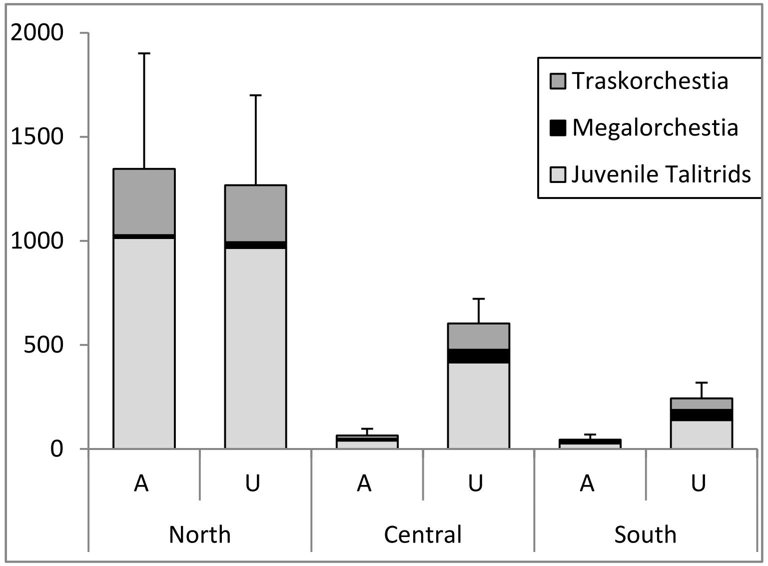
		Cobble	Very Coars	Coarse Gra	Medium G	Fine Gravel	Very Fine G	Very Coars	Coarse San	Medium Sa	Fine Sand
North	A	0.021488	0.095282	0.149155	0.191365	0.116851	0.075414	0.064057	0.119268	0.148119	0.017663
	U	0.01284	0.086154	0.148256	0.180283	0.131376	0.09069	0.069545	0.111773	0.151088	0.016959
Central	A	0	0.283364	0.154279	0.110103	0.075864	0.0623	0.152821	0.143533	0.017358	0.000318
	U	0	0.315728	0.161272	0.103893	0.066134	0.058702	0.153456	0.124483	0.015947	0.000316
South	A	0	0.202206	0.254028	0.129773	0.050142	0.037794	0.153949	0.161581	0.009792	0.000591
	U	0	0.122422	0.292684	0.091002	0.049337	0.084941	0.189321	0.161718	0.008178	0.000292

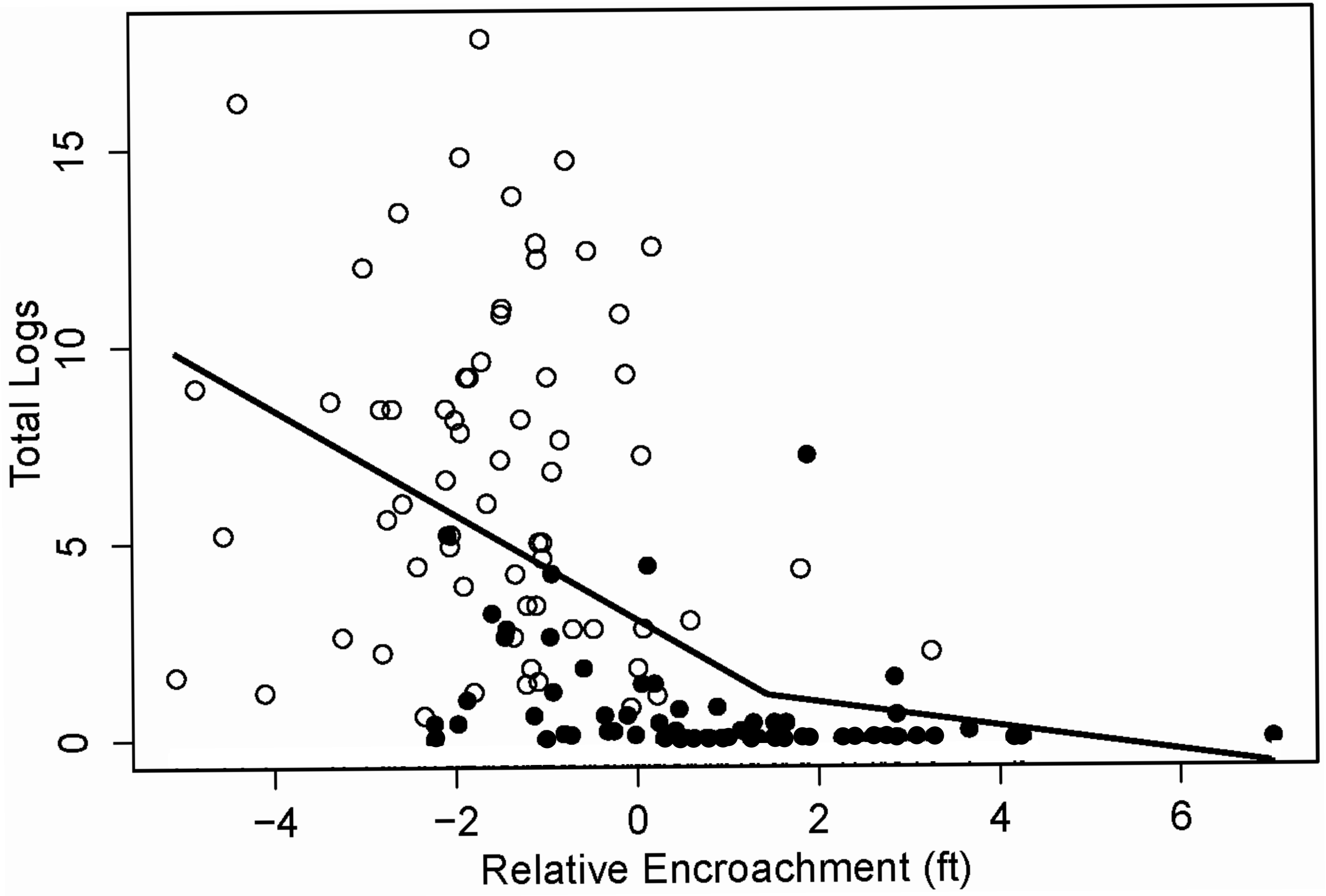


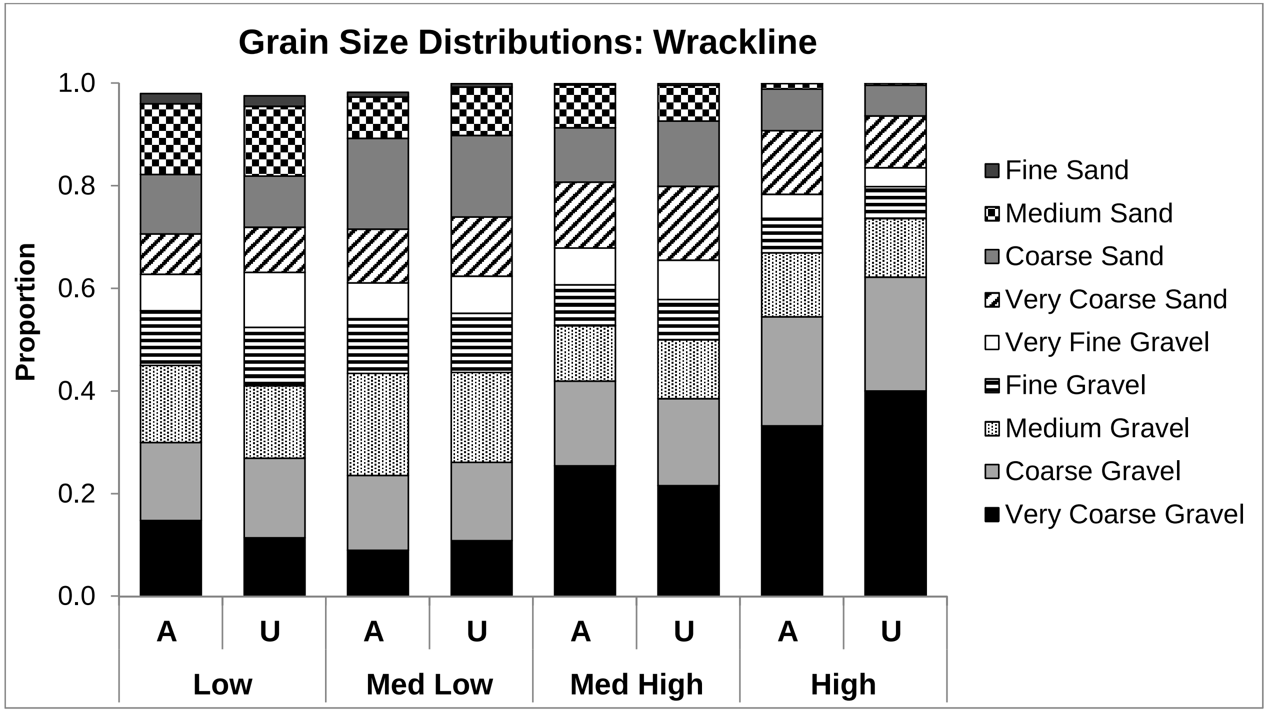

Fetch
Armored
Unarmored
Km
0
2
4
6
8
10
12
Beach Width
M from Toe to MLW
0
10
20
30
40
Elevation of Toe
M Above MLLW
0
1
2
3
4
5
Relative Encroachment
Feet from MHHW
-3
-2
-1
0
1
2
3
4
Number of Logs
Mean # per Point
0
2
4
6
8
10
North
Central
South
Percent Shade
Percent
0
20
40
60
80
100
North
Central
South

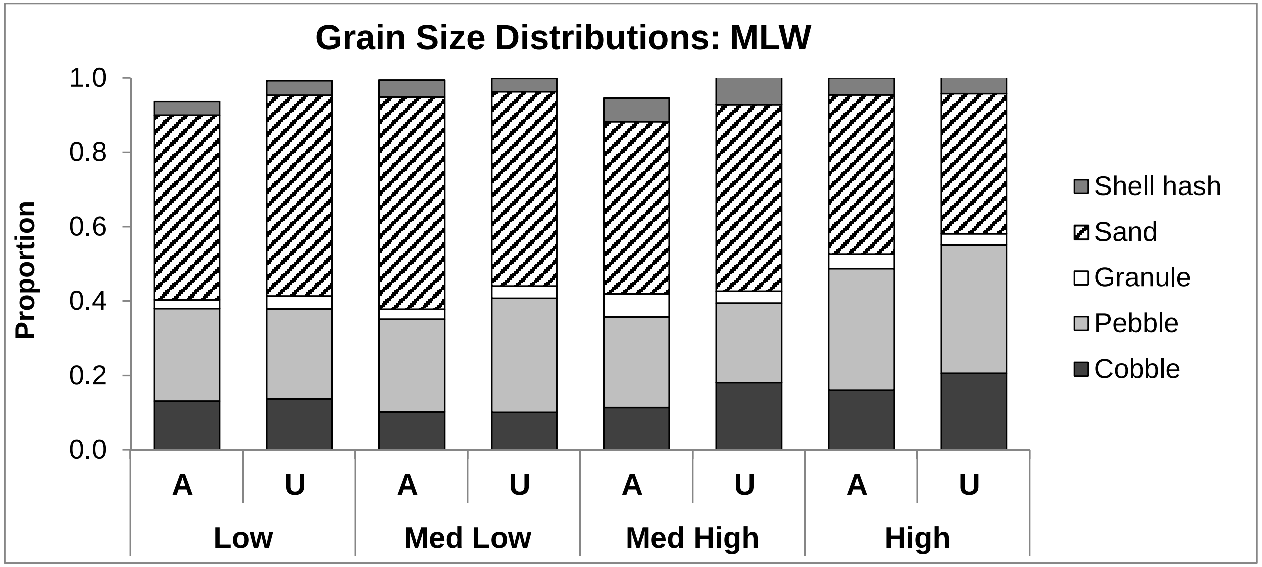

Components of Wrack Mass
G Dry Mass per Sample
0
2
4
6
8
10
Terrestrial
Seagrass
Algae
Insects
Sum Counts per Transect
0
200
400
600
800
1000
1200
Insects
Collembola
Worms
Sum Counts per Transect
0
1000
2000
3000
4000
Oligochaetes
Nematodes
Amphipods
Sum Counts per Transect
0
500
1000
1500
2000
Traskorchestia
Megalorchestia
Juvenile Talitrids
A
U
A
U
A
U
North
Central
South

		Juvenile Ta	Megalorch	Traskorche	se of summed amphipods
North	A	1013.556	14.55556	317.0556	555.049
	U	966.1111	27	273.9444	432.0206
Central	A	40.2971	10.01449	14.65217	32.55651
	U	416.2536	60.74457	125.538	119.734
South	A	26.08333	11.83333	7	24.45452
	U	138.7083	49.79167	55.33333	75.61202




Total Logs
0
5
10
15
−4
−2
0
2
4
6
Relative Encroachment (ft)


Grain Size Distributions: Wrackline
Proportion
1.0
0.8
0.6
0.4
0.2
0.0
A
U
A
U
A
U
A
U
Low
Med Low
Med High
High
Fine Sand
Medium Sand
Coarse Sand
Very Coarse Sand
Very Fine Gravel
Fine Gravel
Medium Gravel
Coarse Gravel
Very Coarse Gravel

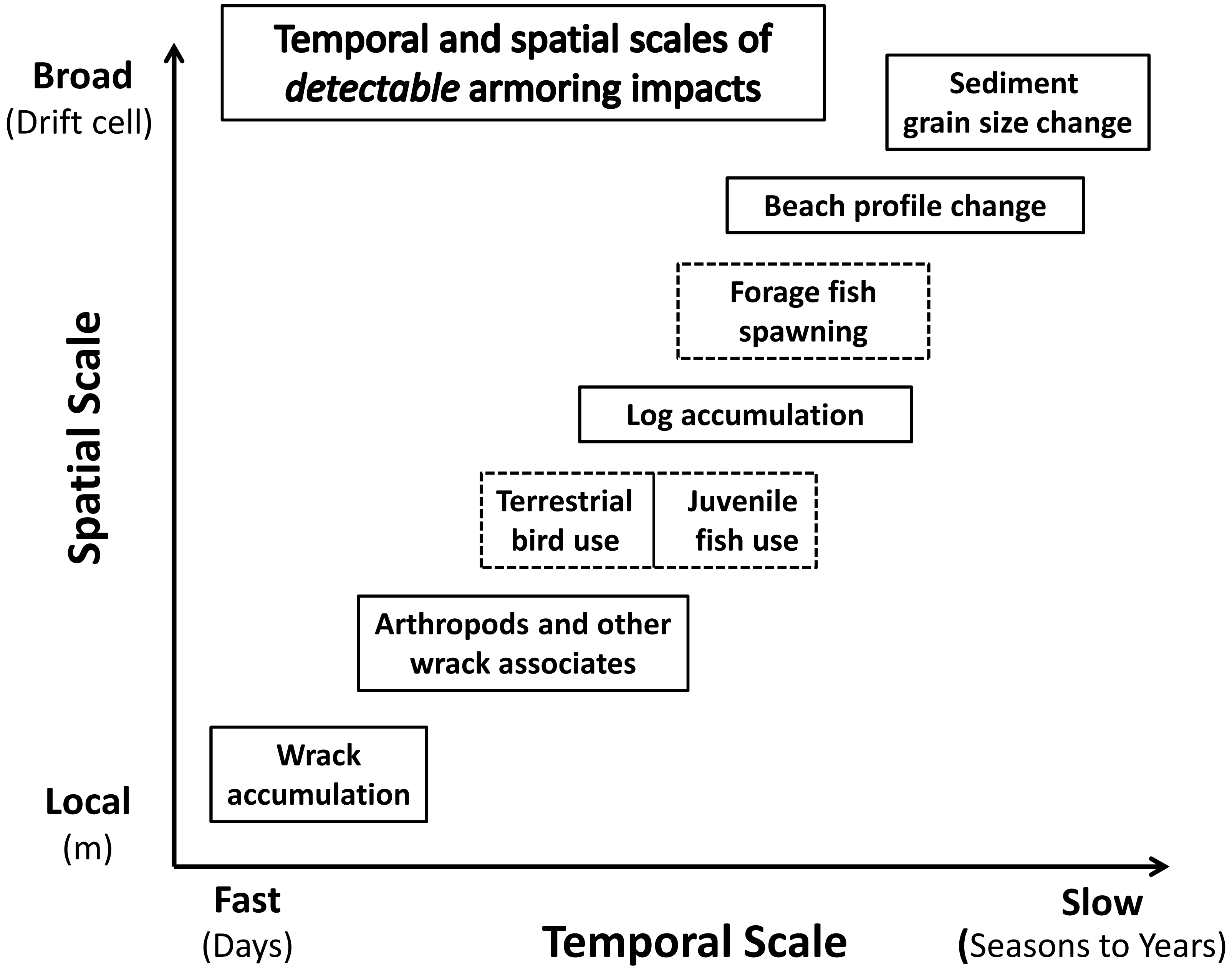

Grain Size Distributions: MLW
Proportion
1.0
0.8
0.6
0.4
0.2
0.0
A
U
A
U
A
U
A
U
Low
Med Low
Med High
High
Shell hash
Sand
Granule
Pebble
Cobble

Sediments at Wrackline

		Very Coars	Coarse Gra	Medium G	Fine Gravel	Very Fine	Very Coars	Coarse San	Medium Sa	Fine Sand
Low	A	0.147945	0.15229	0.150261	0.106661	0.070686	0.078953	0.115797	0.137712	0.019542
	U	0.114452	0.155417	0.140489	0.114065	0.107334	0.087705	0.09964	0.135933	0.020694
Med Low	A	0.089794	0.145919	0.199104	0.106303	0.069984	0.104732	0.176887	0.080753	0.009099
	U	0.108878	0.152796	0.175193	0.115191	0.0721	0.115617	0.158459	0.094424	0.006778
Med High	A	0.254745	0.16495	0.107665	0.0801	0.071897	0.127873	0.106228	0.083483	0.002895
	U	0.216148	0.169108	0.115094	0.0786	0.076468	0.143977	0.127238	0.069655	0.003509
High	A	0.332212	0.21277	0.124939	0.067408	0.046495	0.124167	0.080937	0.010688	0.000312
	U	0.400213	0.221983	0.114468	0.061955	0.036658	0.10138	0.059399	0.003812	9.73E-05

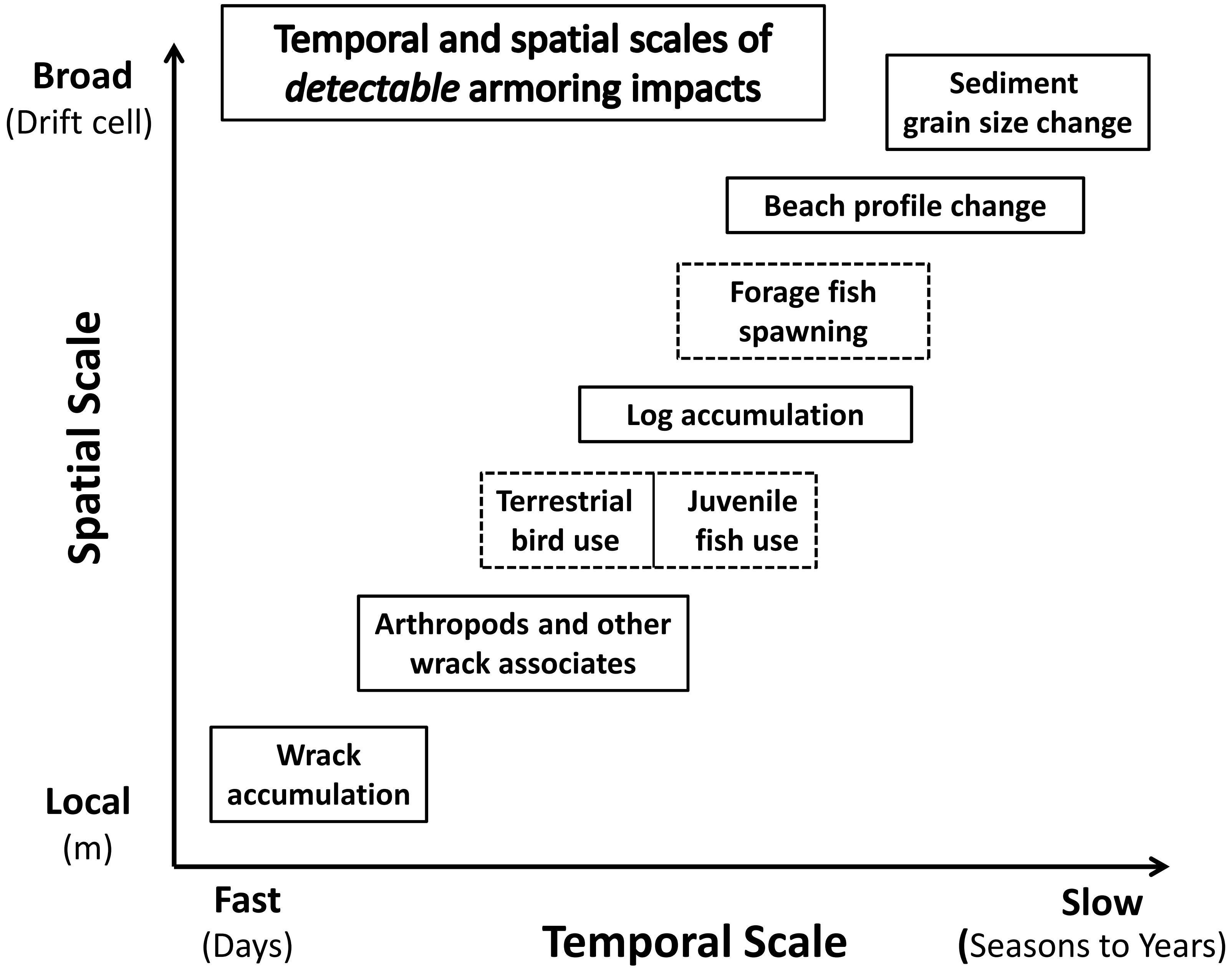
Sediments at MLW

		Cobble	Pebble	Granule	Sand	Shell hash
Low	A	0.13	0.25	0.02	0.50	0.04
	U	0.14	0.24	0.03	0.54	0.04
Med Low	A	0.10	0.25	0.03	0.57	0.05
	U	0.10	0.31	0.03	0.52	0.04
Med High	A	0.11	0.24	0.06	0.46	0.06
	U	0.18	0.21	0.03	0.50	0.08
High	A	0.16	0.33	0.04	0.43	0.05
	U	0.21	0.35	0.03	0.38	0.05


Temporal and spatial scales of *detectable* armoring impacts
Broad
(Drift cell)
Spatial Scale
Local
(m)
Sediment grain size change
Beach profile change
Forage fish spawning
Log accumulation
Terrestrial bird use
Juvenile fish use
Arthropods and other wrack associates
Wrack accumulation
Fast
(Days)
Temporal Scale
Slow
(Seasons to Years)

Highlights for Dethier et al., “Multiscale impacts…”

- Logs, wrack, and high-shore invertebrates decline with shoreline armoring.
- Armoring emplaced further down the beach face has progressively greater impacts.
- Documented threshold responses with elevation are relevant for habitat managers.
- In drift cells with extensive armoring, beaches have coarser sediment.
- Detection of geomorphic beach changes requires large spatial scales of observation.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