

The Impact of Shoreline Armoring on Supratidal Beach Fauna of Central Puget Sound

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Abstract

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The purpose of this study was two-fold: (1) to assess the biological role of the supratidal zone, and (2), to evaluate how the biological structure changes when the shoreline is armored.

In order to study impacts of shoreline structures on invertebrate assemblages, two sampling regimes were employed: paired and synoptic sampling. Paired sampling was intended to compare altered and natural spatially discrete beach stretches at four paired sites. At each site, shoreline modifications extended below MHHW, and therefore, eliminated the supratidal zone. Percent cover quadrats, sediment grain size cores, benthic infaunal cores, and insect fallout traps were collected. Paired sampling showed natural beach sites to have more deposited wrack. Natural beach sites were predominantly composed of medium-grained mixed sand, while altered beach stretches were dominated by gravel, suggesting that shoreline armoring coarsens sediments. Benthic infauna from sediment cores at both natural and altered sites generally had low taxa richness and patchy organism distribution. Oligochaetes and nematodes were numerically dominant in all samples. Other taxa, including talitrid amphipods, insects, and collembolans were significantly more abundant at natural beach stretches; crustaceans were significantly more abundant at altered beach stretches. The insect assemblage, measured with fallout traps, was highly diverse, including over 100 taxa, but individual samples were marked by numerous rare species and many zero counts. Taxa richness was higher at natural beach sites. Dominant taxa included: chironomids, other dipterans, talitrids, homopterans, coleopterans, and collembolans. As with the benthic infauna, talitrids were significantly more abundant at natural beach stretches.

Benthic infauna was collected and analyzed at twenty-six synoptic sampling sites, with and without shoreline armoring, on two dates. All shoreline structures in this sampling were above MHHW. Little difference between invertebrate assemblages at armored and non-armored sites existed, though nonmetric multidimensional scaling (NMDS) plots showed vegetation to influence assemblage structure.

Shoreline armoring decreases abundance and taxa richness in both benthic infaunal invertebrate and insect assemblages in the supratidal zone. The impacts of shoreline modifications are most profound when they are installed below MHHW and where backshore vegetation has been removed. This study begins to draw linkages between the terrestrial and marine system via this zone by assessing invertebrate assemblages, although many relationships are still unknown. Identifying and quantifying these associations is the next step in analyzing the contribution of the supratidal zone to the Puget Sound nearshore ecosystem.

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Introduction

Background

Shoreline habitat integrity is of growing concern in urbanizing areas. In Puget Sound, Washington, the shoreline is highly valued; it serves as a gateway for recreational boating and shipping, a source for commercially viable finfish and shellfish, and a platform for urban and suburban development. Management of the shoreline is often site-specific, resulting in a wide variety of shoreline modifications, the cumulative biological impacts of which are unknown (Emmett et al. 2000). In Puget Sound, much research has shed light on chemical pollution (Brown et al. 1999; Landahl et al. 1997; Macdonald and Crecelius 1994) and physical changes (Canning and Shipman 1995; Macdonald et al. 1994) resulting from urbanization, but little focus has been placed on the biological impacts of shoreline development and the resulting habitat alteration (Emmett et al. 2000; Levings and Thom 1994; Myers 2001). Coastal development often results in the installation of revetments, bulkheads, or other structures intended to stabilize shoreline property, specifically beaches. As shoreline development infringes on Puget Sound beaches, understanding the impact to intertidal biota at the nexus of the terrestrial and marine environments is necessary for effective management. This study aims to determine the effects of shoreline armoring on upper beach fauna in central Puget Sound.

Puget Sound is a polyhaline fjord, located in western Washington, USA. This water body opens to the Pacific Ocean via the Strait of Georgia and the Strait of Juan de Fuca and is considered to be part of the Georgia Basin, a region encompassing the metropolitan areas of Vancouver, British Columbia (Canada) and Seattle, Washington (Levings and Thom 1994). Extensive freshwater input from several large river systems, including the Fraser, Skagit, Snohomish, Duwamish, Puyallup, and Nisqually rivers creates a mixed salinity environment, though most of Puget Sound has salinity of 26-32 ppt. The Sound has a moderately to steeply sloping mixed-substrate shoreline, nourished primarily by sediments (e.g., glacial till) eroding from shoreline bluffs (Canning and

Shipman 1995; Downing 1983). This inland-sea supports a wide variety of flora and fauna, including top level predators such as harbor seals, orca whales, and numerous species of birds and finfish, including five species of Pacific salmon.

Increasing shoreline development, beginning with the Burlington Northern Railroad construction from Seattle northward in the late 1800s, and continuing with rapid population growth, has led to a decline in physically intact, natural shoreline and coastal wetlands in Puget Sound (Levings and Thom 1994). Approximately one third of the Puget Sound shoreline is modified, mostly in and around the greater Seattle metropolitan area in King (68% modified), Pierce (54% modified), and Snohomish (75% modified) counties (WDNR 1999). Primary modifications include bulkheads and rip-rap revetments. This has resulted in significant shoreline and intertidal habitat disruption from the installation of piers, docks, shoreline revetments, and ports (Levings and Thom 1994; Nightingale and Simenstad 2001). In addition to habitat loss, chemical contaminants, excessive nutrient input, over-harvesting of fish and invertebrate species, and freshwater and sediment diversions, are among anthropogenic impacts threatening Puget Sound and other developed estuaries (Emmett et al. 2000; Kennish 2002).

Research has shown that changes in physical structure and function, including coarsening of sediments, deflection of wave energy, and increasing erosion along the unaltered shore, result from shoreline modifications in the marine environment (Canning and Shipman 1995; Douglass and Pickel 1999; Inman and Brush 1973; Macdonald et al. 1994; Nordstrom 1989). Shoreline modifications, and specifically bulkhead and rip-rap armoring, produce many physical alterations: the removal of backslope vegetation and large wood, introduction of new material dissimilar from the natural substrate, and the replacement of beach with hard and/or vertical surfaces (Fig. 1). Consequently, these structures have the potential to eliminate or significantly change the natural intertidal zone, especially when modifications are installed at or below mean higher high water (MHHW). Other shoreline modifications may include the installation of piers, bulkheads, jetties, fill, and boat ramps. Structures such as piers and docks may produce greater adverse effects than shoreline revetments, because they intrude further into the

marine environment (Haas 2002; Nightingale and Simenstad 2001). Because physical and chemical processes (wind and wave energy, sediment grain size, salinity, tide height, pH, etc.) drive biological structure and function in the intertidal zone (Kozloff 1983; Miller 1996; Ricketts et al. 1985; Sousa 1985), a change in biota is expected in cases where shoreline armoring occurs (Attrill et al. 1999; Christensen et al. 1996; Peterson et al. 2000; Spalding and Jackson 2001).

The cumulative biological impact of shoreline development is unknown, though of increasing concern. As development encroaches on the intertidal zone, marine resources are likely to be adversely impacted. The nearshore* area is highly productive, especially in areas rich in organic detritus and harboring eelgrass (*Zostera marina*), and serves as habitat for a diversity of organisms at all trophic levels (Kozloff 1983; Schoch 1999). Additionally, the nearshore zone serves as a refuge and rearing ground for numerous fish species (Beck et al. 2001; Christensen 1978; Mattila et al. 1999). In Puget Sound, several species of Pacific salmon (*Oncorhynchus* spp.) rear in nearshore marine areas (Thorpe 1994), though the extent of beach use is little studied compared to that of estuarine marsh and eelgrass habitats, which have been shown to be of high importance for juveniles (Healey 1981; Shreffler et al. 1992; Tanner et al. 2002). Birds and small mammals have also been shown to utilize the intertidal zone in other regions (Brown and McLachlan 1990; Navarrete and Castilla 1993; West et al. 2002), though the extent of this function in Puget Sound is unknown.

In Puget Sound, chinook salmon (*Oncorhynchus tshawytscha*) are of particular interest because they were listed as “threatened” under the Endangered Species Act in March of 1999 (NOAA 1999). Though once a viable commercial species here, chinook salmon populations have rapidly declined and have been extirpated from many native spawning habitats (Ecology 2003; WDFW 1998; WDOE 2003). Both freshwater and estuarine nearshore habitat loss, with the associated loss of rearing opportunity for

* *Nearshore*, for the purposes of this document, is defined as the intertidal zone, including the supratidal, through the photic zone, to a depth of approximately -20m MLLW.

juvenile salmon, are among the factors implicated in this decline (Healey 1982; Knudsen et al. 2000; Levings and Thom 1994; Simenstad et al. 1982; Simenstad and Cordell 2000; Smith et al. 1998).

Relative to estuarine migration corridors associated with specific river systems, the role of Puget Sound marine shorelines in the life history and ecology of outmigrating juvenile salmonids is little studied. This is of particular importance for “ocean-type” salmonids, which are those fish that out-migrate to estuarine or marine waters at a small size, soon after emerging from the gravel in freshwater; “stream-type” fish are those which rear in freshwater systems for extended periods. It is known that Pacific salmon exhibit numerous life history types and that ocean-type salmonids, specifically chum (*O. keta*), pink (*O. gorbuscha*), and chinook salmon, rely extensively on estuarine and nearshore marine habitats for refuge and feeding (Healey 1980; Healey 1982; Kaczynski et al. 1973; Shreffler et al. 1992; Simenstad et al. 1982). It has been hypothesized that these fish similarly use Puget Sound shorelines before migrating off-shore (Williams and Thom 2001). Recent research[†] has shown relative abundance of unmarked (wild) ocean-type chinook salmon to be higher closer to the beach, while marked (hatchery) fish were collected in increasing abundances offshore, in Skagit Bay, Washington. These data suggest that wild fish have protracted use, in time and space, of the intertidal fringe (i.e., the nearshore zone from MLLW to MHHW), emphasizing the importance of this zone for rearing (Rice et al. 2003).

The extent to which ocean-type fish feed on terrestrial and marine derived prey produced specifically along marine shorelines is unknown, though existing literature (Brodeur 1989, 1991; Brown et al. 1987; Healey 1981; Kaczynski et al. 1973; Levings et al. 1983; Moulton 1997) suggests that terrestrial insects can be an important prey resource for these fish during the early marine stage of their seaward migration. A recently compiled matrix from previous dietary studies on chinook, coho, and chum

[†] Unpublished data collected by NOAA/NMFS Northwest Fisheries Science Center and Skagit System Cooperative, presented by C.A. Rice, NOAA/NMFS, at Georgia Basin/Puget Sound Research Conference, Vancouver, BC, Canada, April 2003.

salmon from Hood Canal, and Commencement Bay, Duwamish Head, Skagit Bay, and Shilshole Bay, in Puget Sound, indicates that terrestrial insects and intertidal amphipods are some times important dietary components throughout Puget Sound[‡]. Additionally, fish diet analysis from chinook salmon caught at Puget Sound marine beaches, performed coincident with this study, showed a high proportion of gammarid amphipods and insects, specifically Diptera, Homoptera, and Psocoptera in chinook salmon stomachs (Fig. 2)[§].

The extent to which shoreline alterations disturb intertidal biological processes in general, and salmon habitat in particular, is relatively unclear. It is well documented that shoreline modifications result in many physical alterations (see previous discussion of shoreline armoring and associated literature). Consequently, when modifications are installed at or below MHHW, they may eliminate much or all of the supratidal zone, a potential source for prey items specifically associated with wrack or shoreline vegetation.

The supratidal zone^{**} is defined as the area above MHHW, influenced by splash and extreme high tides, generally 3.2 m and higher (above MLLW) in central Puget Sound (Carefoot 1977). This zone is a unique but little-studied ecotone, having largely escaped notice of both marine and terrestrial ecologists (Attrill et al. 1999). As the ecotone bridging the two systems, it possesses some properties common to both and is a dynamic zone of great importance in energy exchange and nutrient flux in the greater nearshore ecosystem (Polis and Hurd 1996; Zimmer et al. 2002). Supratidal ecology is driven by both terrestrial and marine processes including marine wrack deposition, terrestrial leaf litter input, sediment deposition from bluff erosion, deposition of large wood (both from longshore currents and direct input from the upland), recycling and decomposition of organic detritus, and export of organisms to the nearshore food web (Fig. 3). Among the physical factors affecting the ecology of this zone are: exposure, fetch, tidal current and height, drift cell dynamics, and sediment grain size.

[‡] J. Cordell, University of Washington, personal communication

[§] Data to be included in a report to King County, Washington, Department of Natural Resources and Parks

^{**} Both *supratidal* and *supralittoral* are terms used to refer to this zone. Because this research was conducted in a marine intertidal system, the term *supratidal* is used.

Vegetation in and adjacent to the supratidal zone provides habitat for insects (Allan et al. 2003) and other invertebrates and shades the beach, maintaining moisture and temperature thresholds essential for spawning forage fish (Penttila 2000; Rice 2003) and marine crustaceans (Koch 1989), as well as other beach dwelling invertebrates (Pennings et al. 2000). The supratidal zone also serves as a source for marine derived nutrients entering the terrestrial system through decomposition of deposited marine wrack (Polis and Hurd 1996).

Beach wrack—the agglomeration of organic debris deposited by an ebbing tide—is an important supratidal component on sandy shores. Material for beach wrack can be derived from marine (e.g., *Ulva* spp. and *Zostera* spp.) or terrestrial (e.g., leaf litter and wood) sources. Man-made flotsam can also become incorporated into wrack assemblages. Wrack functions as a microhabitat by providing shelter, food, and moisture necessary for many intertidal invertebrates, especially amphipods, isopods, and insects (Colombini et al. 2000; Dobson 1976; Jedrzejczak 2002a; McGwynne et al. 1988; Pank 1997). These organisms are important in the biogeochemical cycling of marine material (Jedrzejczak 2002b; Polis and Hurd 1996), and are prominent consumers in the detritus-based food web.

Because wrack is often patchy and ephemeral, based upon tidal inundation, swamping, desiccation, and availability of material, the communities associated with it tend to be short-lived and highly motile. Jedrzejczak (2002b) described a patterned succession of *Zostera marina* wrack colonization in the Baltic Sea, with talitrid amphipods, adult dipterans, and coleopterans occupying wrack mats within the first few hours to days, followed by meiofauna in subsequent days. Wrack, along with wood and other organic debris, can be a source for the detritus-based nearshore food web. Colonization of wrack by scavengers, infauna, and ultimately bacteria and diatoms, is an important process in maintaining energy exchange between the terrestrial and marine systems (Colombini et al. 2000; Dobson 1976; Dugan et al. 2000; Jedrzejczak 2002b; McGwynne et al. 1988).

Much research in both lacustrine and riverine systems has focused on the importance of aquatic/terrestrial riparian ecotones in facilitating energy exchange between terrestrial and aquatic habitats and providing physical structure to the shore zone (Castelle et al. 1994; Likens 1985; Naiman et al. 2000). These physical functions of littoral and riparian zones are well documented and include: stabilizing banks, providing shade that minimizes water temperature fluctuations, supporting wildlife, nutrient cycling, maintaining water quality, and contributing terrestrial organic matter to the aquatic environment. It has been hypothesized that many of these physical functions are equally important in the Puget Sound marine system (Williams 2001; Williams and Thom 2001).

While the physical functions of the marine riparian zone in Puget Sound have been studied (Canning and Shipman 1995; Macdonald et al. 1994; Shipman 1998), much less is known about the biological processes because most previous studies conducted in Puget Sound have been shoreline inventories, mapping projects, or outfall studies, each with specific management goals (Berry et al. 1998; Williams 2001). The purpose of this study is twofold: (1) to assess the biological role of the supratidal zone, specifically with respect to potential salmonid prey resource occurrence and abundance; and (2) to evaluate how the biological structure and function change when the shoreline is armored.

Approach

This study assesses invertebrate assemblages in the supratidal zone, and describes how those assemblages differ at sites with shoreline modifications, specifically bulkheads and rip-rap retaining structures. Invertebrates, as secondary consumers, are at the foundation of the Puget Sound nearshore detritus-based food web. Changes in invertebrate assemblages, as a result of anthropogenic activity, may have cascading impacts at higher trophic levels (e.g., fish and/or birds) (Kitchell et al. 1994; Romanuk and Levings 2003b). In order to evaluate the biological role of the supratidal zone and the impact of shoreline armoring, I posed the following hypotheses and objectives:

H₁: There is no difference in benthic invertebrate species composition and abundance between natural, unarmored beaches and beach stretches with shoreline modifications

Objective: Collect and analyze benthic organisms from paired sites to quantify differences in benthic biota between natural and modified beach stretches

H₂: Supratidal insect assemblages are consistent in species composition and abundance between natural, unarmored beaches and beach stretches with shoreline modifications

Objective: Collect and analyze insects from fallout traps at paired sites to determine the extent of insect assemblages associated with supratidal vegetation (both wrack and marine riparian vegetation)

H₃: Sediment grain size is consistent between natural, unarmored beaches and beach stretches with shoreline modifications

Objective: Collect and analyze sediment cores from paired sites for grain size differences associated with shoreline armoring

H₄: Organic debris, such as large wood, wrack, and leaf litter, is found with the same frequency at altered and natural beach sites

Objective: Use percent cover quadrats to estimate the occurrence of organic debris at paired altered and natural beach sites

H₅: Differences between supratidal benthic invertebrate communities at natural and altered beach sites are detectable over a broad spatial scale

Objective: Collect and analyze benthic organisms from synoptic sampling events covering a large area to quantify the occurrence, distribution, and abundance of benthic invertebrates in the supratidal zone

Shoreline development inherently impacts the boundary between the marine and terrestrial systems, while extending into each to varying degrees. I utilized two sampling schemes, paired sampling and synoptic sampling, to achieve a comparison between sites with and without shoreline armoring. Paired sampling was intended to compare spatially discrete beach stretches, where shoreline modifications extended below MHHW, eliminating the supratidal zone; synoptic sampling was used to gain an understanding of supratidal biota over a broader spatial scale, where all sampling was performed at a consistent elevation (i.e., shoreline modifications were higher than MHHW, allowing for a standardized comparison between natural and altered sites).

In order to standardize sampling and enhance data comparability, much of the methodology for this study was derived from the Estuarine Habitat Assessment Protocol (Simenstad et al. 1991). By quantifying invertebrates at both armored and natural beach stretches, I intended to describe and measure the effects of shoreline armoring on upper intertidal and supratidal biota. Field work commenced in September 2000 with a pilot study, and was completed in 2002. This study is part of continuing research initiated and supported by the King County, Washington, Department of Natural Resources and Parks, and the United States Army Corps of Engineers.

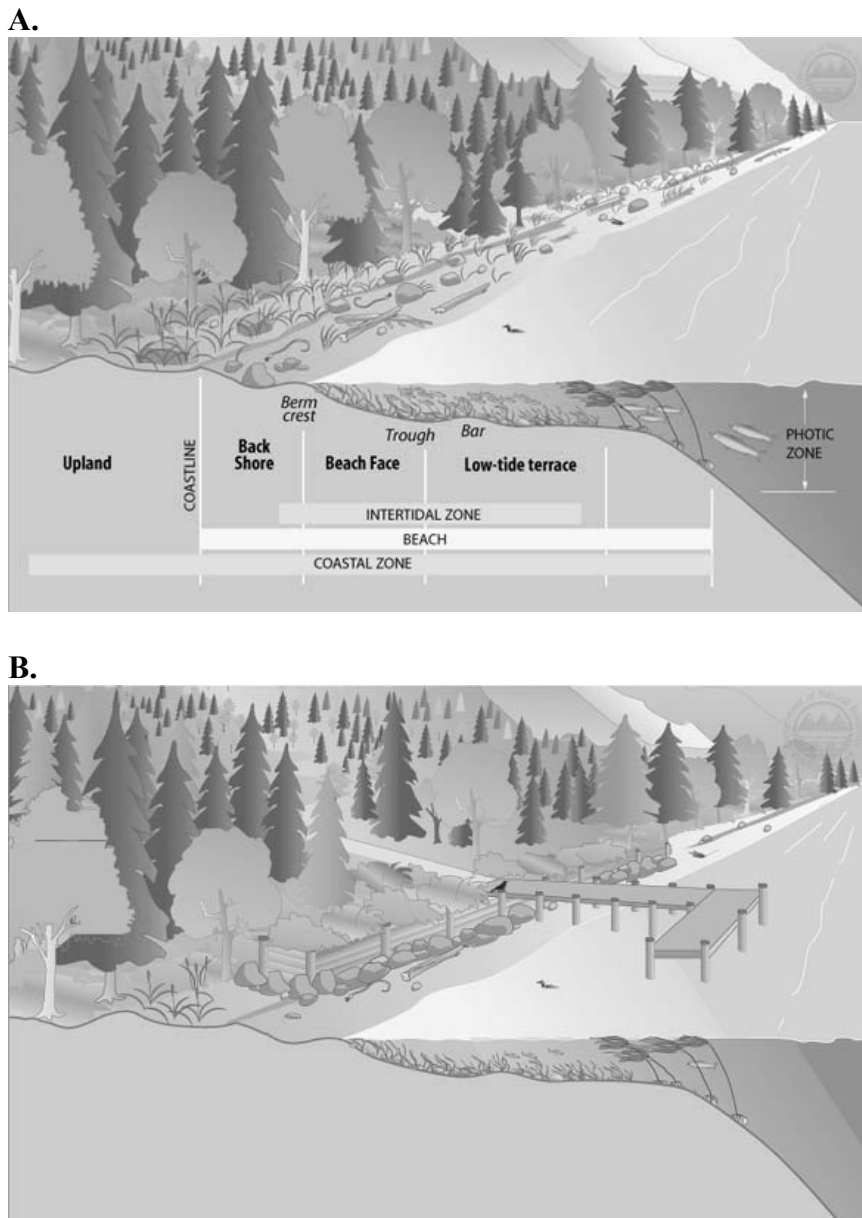


Figure 1. Schematic of supratidal zone and changes associated with shoreline armoring, A.) depicting a natural beach stretch, with intact backshore vegetation and accumulation of large wood and wrack and B.) depicting the same shoreline post-armoring. Note in B.) the removal of riparian zone and backshore and the intrusion of the structure into the intertidal zone, dropping the land/sea interface along the revetment to a range below MHHW. Graphic courtesy of King County Department of Natural Resource and Parks.

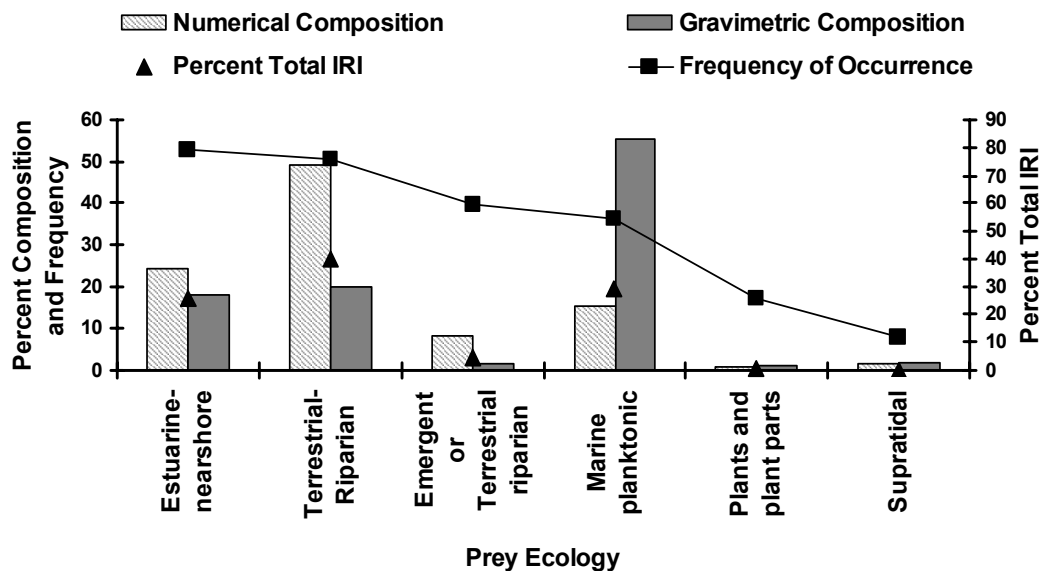


Figure 2. Dietary analysis from chinook salmon (n=218) collected by King County DNRP at Puget Sound beaches in 2001. Bars refer to percent composition by number (light gray) or weight (dark gray). Triangles indicate percent total IRI (Index of Relative Importance, a metric which accounts for occurrence and both numeric and gravimetric percent composition of prey, (Pinkas et al. 1971)). Drift insects fall under terrestrial riparian or emergent prey and gammarid amphipods are considered estuarine-nearshore prey. The supratidal category refers only to talitrid amphipods.

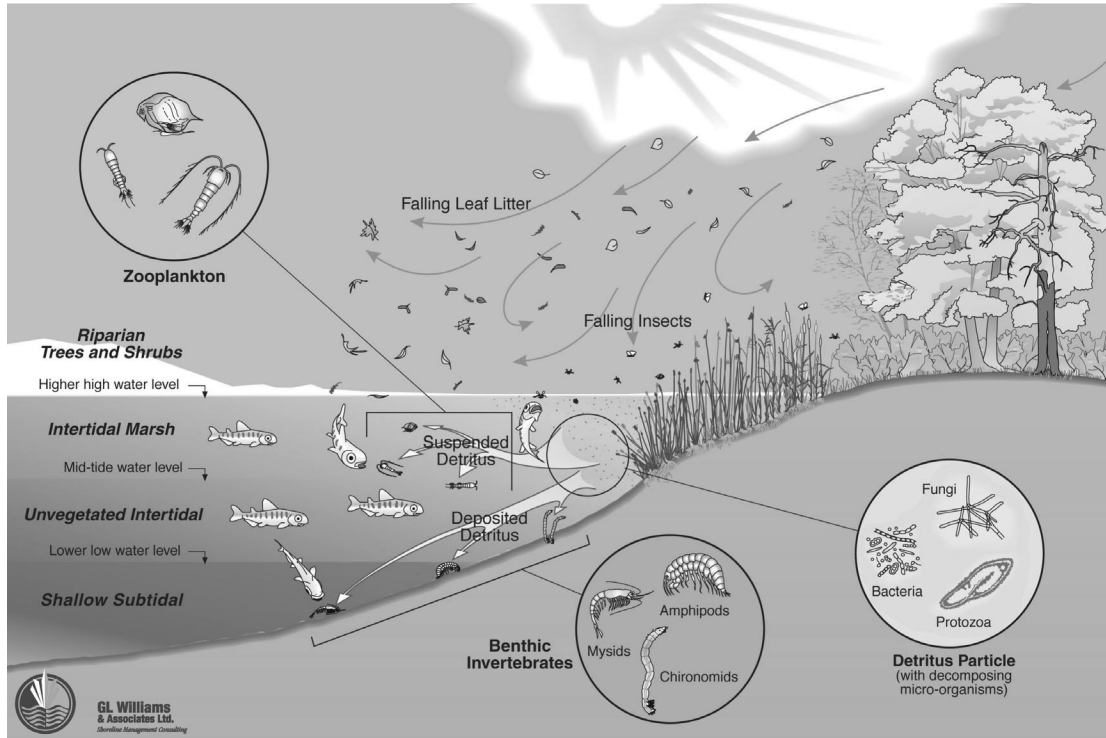


Figure 3. Natural processes in the supratidal zone, including deposition of leaf litter and drift insects from backshore vegetation. Graphic credit, Gary Williams, G.L. Williams and Associates.

Paired Sampling

Introduction

By assessing benthic invertebrate and insect occurrence and abundance, sediment grain size, and organic debris presence at paired beach stretches, this study sought to describe how the supratidal zone is impacted by shoreline modifications at discrete paired locations (see *Introduction, Approach*, null hypotheses H_1-H_4). Deposition and movement of organic debris and sediments are largely driven by wind, waves, and currents, all physical properties associated with the nearshore ecosystem (Nordstrom 1992). Paired sites, in close spatial proximity, were selected for this study to minimize the effects of these physical properties. Puget Sound contains numerous drift cells, which function as semi-contained littoral drift systems, each with a source and sink for beach sediments (Wallace 1988). By using paired sites, with both beaches contained within the same drift cell, the variation in physical characteristics between the paired beaches is reduced.

This paired sampling regime, while beneficial in terms of minimizing spatial differences, is inherently biased in that benthic infauna and sediments are sampled at differing tidal elevations within the pairs. All sites selected for this study had shoreline revetments installed below MHHW at the altered beaches. Therefore, sampling at altered sites was at a lower tidal elevation than at natural sites because shoreline structures precluded sampling at a consistent higher elevation. The intrusion into the intertidal zone by man-made structures has eliminated the natural supratidal ecotone along these beaches and shifted the land/sea interface to an elevation below MHHW.

Because of the known limitations of this sampling regime, a synoptic sampling of benthic invertebrates was also conducted (see section IV, Synoptic Sampling). Despite the biases inherent in the paired sampling study, the design was intended to elucidate armoring-induced differences in biota when shoreline structures intrude into the intertidal zone, a common occurrence in central Puget Sound.

Site Description

Four sites were selected for the paired sampling regime, which had altered and natural beaches adjacent to each other (Table 1, Fig. 4). The sites included in this study are mainly comprised of the beach type described as “open estuarine intertidal habitats,” with “mixed-coarse,” “gravel,” or “sand” substrates (Dethier 1990). The exception is the Dockton Beach site, located in Quartermaster Harbor (between Vashon and Maury Islands), which consists of “partly enclosed estuarine mud.” Puget Sound is unusual in that it is a deep, well-mixed basin, with moderately high energy, relative to a deltaic estuary. The estuarine beaches in this study lack severe exposure, as seen on Washington’s outer coast, but are subject to physical processes such as wind, waves, current, long-shore current, and swell, not typical of more enclosed estuarine systems (Nordstrom 1992).

Richmond Beach (RBP) is the most northerly of the paired sample sites. It is a westward-facing, moderately sloping beach, currently used as a park by the City of Shoreline. While much of the surrounding shoreline is a bulkheaded railroad grade dating from the late 1800s, a 0.5-km portion of the beach is not bulkheaded, with an intact supratidal zone and upland grass/shrub vegetation between the beach and the railroad grade. I used the center 50-m stretch of this portion of the beach as the natural beach and a bulkheaded stretch 0.5 km to the south as the altered beach at this site. The interface of the intertidal zone and the rip-rap at the altered stretch is at approximately +2.5 m (MLLW) in elevation. No vegetation is present within 50 m of the shoreline at the altered site.

Carkeek Park (CKP) is also a westward-facing, moderately sloping beach located just north of Meadow Point. Like Richmond Beach, Carkeek Park is surrounded by bulkheaded shoreline, with a small relict piece of unmodified shoreline that was used as the natural beach in this study. The outlet of Piper’s Creek, a salmon-spawning stream, lies to the south of this beach and the remaining vegetation is mostly grass with patchy shrub vegetation. This beach is owned by the City of Seattle and is heavily used for recreation. A bulkheaded stretch 0.25 km north of the natural stretch was used as the

altered stretch. The only vegetation present within 75 m of the shore along this beach was invasive scotch broom (*Cytisus scoparius*) along the railroad tracks. The interface of the intertidal zone and the rip-rap at the altered site is at approximately +2.4 m elevation.

Seahurst Beach (SHB) is a westward-facing, moderately sloping beach owned by the City of Burien, and is located north of Three Tree Point. The park includes a section of highly modified shoreline stretching north from the parking area to an education center and fish hatchery. Shoreline modifications in this area include groins, bulkheads, and rip-rap, and an unnamed salmon-bearing stream discharges just south of the parking area. Vegetation is set back 50 m from the shore due to the presence of a promenade, and includes large deciduous trees, shrubs, and some conifers. The altered stretch is at the southern end of this modified portion, and is comprised of rip-rap gabion baskets, with the land/water interface at about +2.6 m elevation. Vegetation is similar to other parts of the park and is set back 25 m along this stretch of beach, separated from the shoreline armoring and beach by a walking path. The natural beach is 1.2 km of unmodified shoreline located south of the park boundary. Because of the absence of the railroad grade south of Seattle, this beach could be considered the most intact of those sampled, with abundant overhanging vegetation (mostly western red cedar, *Thuja plicata*) and deposits of large wood in the supratidal zone.

The fourth site, Dockton Beach (DBP), is located in Quartermaster Harbor, an embayment formed by Vashon and Maury Islands. This site is different from the others because it is in a low-energy system and the intertidal zone is comprised of finer sediments than the other three sites. MHHW is slightly higher (+3.8 m MLLW) in Quartermaster Harbor than for other sites in this study. The site is north-facing and is part of a park/marina complex, operated by King County. The altered beach lies near the parking area and is bulkheaded, with deciduous vegetation set back 75 m. The interface of the seawall and the intertidal zone is approximately +2.3 m. The natural beach stretch is located to the east of the altered stretch and includes overhanging vegetation originating from backshore bluffs abutting the high-tide line. Much of this vegetation is sloughing from the bluffs and resides in the intertidal zone.

The four sites selected for this study are at least partially public lands. While sites were chosen for their physical attributes, inherent differences exist between sites. Because not all sites in central Puget Sound with shoreline modifications were measured for feasibility, I cannot establish how representative of the Puget Sound shoreline the selected sites are.

Methods

Sampling Timing and Frequency

Puget Sound has a mixed semi-diurnal tidal regime, and I chose to sample during spring high tides because these tides had more impact on the supratidal zone. Sampling was performed bi-weekly, from late March to early June 2001, to capture spring tide events with higher high tides greater than +10 feet (MLLW). Natural and altered beach segments at each site were sampled on the same day, immediately after the onset of the ebb tide.

Site Characterization

At each site, I qualitatively recorded beach characteristics, including tide level at the time of sampling (using predicted tide charts), upland and adjacent land use (e.g., undeveloped, commercial, residential), beach gradient (slight, shallow, moderate, steep), type and amount of riparian vegetation, backshore slope (high, medium, low bluff), amount of shade (% of transect expected to be shaded during mid-day on a sunny day), relative amount of large wood (none, some, moderate, extensive), substrate size (clay, silt, sand, etc.), and type of modification present.

Transects

Random samples were taken along a 50-m transect tape that was placed along the most recent high-tide wrack line. Transects within each treatment remained constant throughout the course of the study. Along each transect, I collected the following: percent cover of organic debris from ten observation quadrats, five benthic infaunal cores, three sediment grain size cores, and five insect fallout trap samples (Fig. 5). Transects for altered beach sites were located immediately below the shoreline

modifications, with elevations for each site recorded. Elevations were extrapolated from local tide predictions using *Tide Tool 2.1 for Palm Handhelds*[®] and Nobeltec/Nautical Software's *Tides and Currents*[®] software, for Des Moines, Quartermaster Harbor, and Meadow Point locations, based on predicted tide level at a given time. Due to weather conditions, actual tidal elevations may have deviated up to one foot from the predicted tides.

Percent Cover Quadrats

I randomly selected ten sampling points, corresponding to meter marks, for 0.3-m² visual estimation quadrats. In each of these, I assessed percent cover (0-100%, with 5% increments) and composition of wrack, wood, leaf litter, sand, cobble, and rip-raprap.

Benthic Fauna Cores

At five randomly selected stations along the transect, I collected sediment cores to a depth of 15 cm. The corer used was a metal cylinder 10 cm in diameter, with a sample area of 78.5 cm². In the laboratory, the samples were fixed with ≈10% buffered formalin and shaken to assure all animals were preserved. After several days of fixation, rocks and heavy debris were removed by hand and rinsed. The animals were elutriated from the remaining sediment by decanting the water through a 0.5-mm sieve. The samples were preserved in 70% isopropyl alcohol infused with the biological stain rose bengal.

In the laboratory, animals were identified and enumerated using an illuminated dissecting microscope. All animals were identified to the lowest practicable taxa, ranging from phylum for many of the infaunal worms to species for the gammarid amphipods.

Grain Size Cores

Core samples for sediment grain size were the same volume as the benthic cores and were collected adjacent to the 1st, 3rd, and 5th benthic core samples. They were frozen until analysis. Gravimetric dry sieve analysis was completed on all samples, after Folk (1964). Grain size was classified according to the Wentworth Scale (Wentworth 1922). Size distribution was entered into a uniformity coefficient (C_u), the ratio of D_{60} to D_{10} , whereby D_{60} is the soil diameter at which 60% of the sample by weight is finer than and

D_{10} is the same measurement at 10%, $C_u = \frac{D_{60}}{D_{10}}$. This metric is used to determine how evenly distributed the sediments are. A sample with a C_u of less than two is considered to be uniform in distribution (Lambe and Whitman 1979).

Insect Fallout Traps

I deployed insect fallout traps to collect terrestrial insects originating in supratidal and backslope vegetation. Five insect fallout traps were set out for 20 hours prior to the transect sampling time. The traps consisted of 30-cm x 20-cm x 15-cm plastic tubs filled with 3-5 cm of soapy water, and were randomly placed along the transect, above the influence of tides (approximately 3.8-4.2 m). Traps at natural and altered beaches were placed at the same tidal elevation. The collected invertebrates were sieved through a 0.106-mm sieve and preserved with 70% isopropanol in the field. Insects were identified (usually to family level) using an illuminated dissecting microscope and enumerated.

Data Analysis

All data were organized in Microsoft Excel XP[®]. Preliminary data exploration and statistical analyses were performed in Excel, using the Data Analysis tool. SPSS v.11.5 for Windows[®] was used for subsequent data analysis, including all analysis of variance (ANOVA) testing. Two software packages were used for all multivariate analysis: PC-ORD for Windows v.4.25[®] (nonmetric multidimensional scaling and indicator species analysis) and Primer for Windows v.5[®] (similarity measures and cluster analysis).

Data from benthic infaunal cores and insect fallout traps were analyzed using the same procedure. All abundance data were sorted in Excel. Taxa occurring in less than 10% of the samples collected were grouped into larger taxonomic groups for analysis (e.g., talitrids, dipterans, etc.). For benthic infaunal cores, all taxonomic groups were analyzed; however, for insect fall-out traps, only taxa considered to be important salmonid prey items or occurring specifically in the supratidal zone were selected, due to the high number of rare taxa.

Data were log transformed [$b_{ij} = \log(x_{ij} + 1)$] prior to statistical analyses, except where noted. This transformation compresses high values and spreads out lower values by expressing the values as orders of magnitude (McCune and Grace 2002). The natural log transformation was used to address the violation of assumptions of normality and skewness in the ANOVA. Boxplots showing original and log-transformed data for selected taxa (Fig. 6) show that patterns within the data are preserved, while noise is reduced with the natural log transformation.

Abundance data were plotted in Microsoft Excel and then analyzed using a univariate 3-factor analysis of variance (ANOVA, (Zar 1999)) in SPSS, using the General Linear Model tool. Factors in the analysis were site, beach treatment (type), and sampling date and the interaction effects between them (Fig. 7). Post-hoc tests for analyses of site and date discrepancies were run in SPSS using the Tukey “honestly significant difference” test (Multiple Comparisons, Tukey, (Zar 1999)). Unless noted otherwise, $\alpha = 0.05$ was the critical p-value in assigning statistical significance.

Count data for benthic infaunal cores were post-processed using multivariate nonmetric multidimensional scaling (NMDS, (McCune and Grace 2002)), to account for all taxonomic levels in the sample distribution. NMDS was performed in PC-ORD according to the algorithm established by Kruskal (1964) and adjusted by Mather (1976). The Bray-Curtis dissimilarity measure (also known as the Sorenson distance measure) was used for this analysis:

$$D_{i,h} = \frac{\sum_{j=1}^p |a_{ij} - a_{hj}|}{\sum_{j=1}^p a_{ij} + \sum_{j=1}^p a_{hj}}$$

where D is the dissimilarity between items i and h . The nearest-neighbor approach was used for hierarchical clustering, prior to NMDS analysis. In PC-ORD, the “autopilot” mode was used to perform the analysis; starting coordinates were selected at random by the software, and five runs were performed with real data (20 runs with randomized data in the Monte Carlo simulation).

After NMDS analysis was performed, a post-hoc indicator species analysis was performed using PC-ORD. This analysis is modeled after Dufrene and Legendre's method and aims to find the most characteristic species (taxa) in a group (Dufrene and Legendre 1997).

In two cases (one case each for benthic cores and fallout traps), samples could not be obtained due to the advancing tide, resulting in unequal sample sizes between altered and natural sites. Preliminary analysis was run to determine how the software (SPSS) would handle unequal sample sizes in an ANOVA, and little difference was noted when the set in question was removed. SPSS uses the harmonic mean in the general linear model function when sample sizes are uneven.

Results

Percent Cover Quadrats

Wrack was usually present in nominal quantities and was limited to a thin strand-line, never comprising more than 15% of the cover (Fig. 8). Wrack consisted primarily of eelgrass (*Zostera* spp.) and ulvoid algae (*Ulva* spp.); other algae such as *Porphyra* spp., *Enteromorpha* spp., and unidentified red and brown alga species were also present, in small amounts. Large wood was most prevalent at the SHB-Natural site and rarely occurred at the other three sites. Leaf litter was a minor component at all sites.

DBP was the only site that showed no significant differences between altered and natural beaches for any one of the organic debris variables, but no sites showed significant differences for all three variables (Table 2). In all cases, post-hoc tests determined that neither sample date, nor site, were factors confounding the model, except for the analysis for woody debris, in which case SHB was an anomalous site. When the dates and sites were pooled, (Fig. 9), the results from paired sample *t*-tests were significant, despite high variances, for all three variables: wrack, $p=0.00$; woody debris, $p=0.02$; leaf litter, $p=0.04$, showing natural sites to have a higher occurrence of organic debris.

Benthic Infauna

Benthic cores collected at the supratidal zone in central Puget Sound had low abundances and diversity of organisms. The data set was characterized by patchy distributions, many zeros, and few dominant taxa, typical of biotic community samples (McCune and Grace 2002). Only two infaunal worm taxa, oligochaetes and nematodes, were cosmopolitan, occurring in greater than 90% of the samples collected (Fig. 10). Additionally, it was not uncommon to find oligochaete and nematode densities varying by an order of magnitude or more; they were often found in hundreds per core, or up to several thousand per square meter. Only nine other taxa had a frequency of occurrence of more than 10%, and were often found in very low densities (75-400/m²). These findings were consistent among all four paired sites, at both natural and altered stretches.

Taxa richness was consistent with previous studies of sandy-substrate fauna (Flemer et al. 2002; Shimek 1992), with fewer than 15 taxa found in any one sample. For all sites combined, the mean number of taxa per sample was less than 8, with all natural and altered beaches combined averaging 8.6 and 6.9 taxa, respectively. When sites were analyzed individually with paired sample *t*-tests, only two natural sites, RBP and SHB had significantly higher taxa richness than their paired altered sites (RBP, $p=0.00$ and SHB, $p=0.02$) (Fig.11).

Because of the low frequency of occurrence and density of most organisms, broader taxonomic groupings were utilized for statistical analysis of count data (Table 3). In the benthic infauna core data set, the log transformation was used to emphasize the importance of informative taxa, such as talitrids and insects, and minimize the noise associated with abundant but variable taxa, such as nematodes and oligochaetes.

Univariate Analyses

Densities of five of the seven taxonomic groupings (Talitridae, Arthropoda, Insecta, Crustacea, and Collembola) were significantly different between altered and natural beach stretches (i.e., “type” result was significant) (Table 4). Natural beaches had higher densities of Talitridae (henceforth referred to as “talitrids”), arthropods, insects, and collembolans, while altered beaches had higher densities of crustaceans. There were

no statistically significant differences between infaunal oligochaetes and nematodes at natural and altered beaches (i.e., “type” result is not significant). However, for both taxonomic groups, site DBP proved anomalous, and therefore interaction factors are significant. Date was not a significant factor for either taxon.

Collembolans (“springtails”), a common but highly variable taxon, were significantly denser at natural sites. Although patchier than collembolans, arthropods and insects were also significantly more dense at the natural sites (Table 4). As with infaunal worms, site DBP was different from the other sites for collembolans; but not for arthropods or insects. Although the ANOVA identified date as a significant factor for these groups, post-hoc tests showed that in each case one date was different from the others, but the date difference varied between taxa.

Significant differences between sites and beach type were greatest for gammarid amphipods of the family Talitridae (“beach hoppers”); they were denser at natural beach sites than at altered sites (Fig. 12). The predominant species of talitrid found in benthic cores was *Megalorchestia pugettensis*, though two unidentified species of the genus *Traskorchestia* were also found. Densities at all sites were found to be significantly different in post-hoc tests, and one sampling date (June) was found to be significantly different from all other dates. As with other taxa, site DBP was different from the rest. When sites were evaluated independently for density of talitrids at altered and natural beaches using paired sample *t*-tests, the densities were not significantly different at site DBP ($p=0.208$), or CKP ($p=0.057$), though the *p*-value for the latter could be considered borderline (Fig. 13).

The only taxonomic group that had significantly higher densities at altered as compared to natural beaches was Crustacea, a group that consisted of strictly marine organisms in this study (Fig. 14). Interaction factors were not detected, but significant differences were found for both site and type factors, with site DBP different from the others (Table 4).

Multivariate Analyses

Because interactions are known to occur between taxa, NMDS multivariate analysis was utilized so that all taxa could be entered into the model simultaneously. Each data point was given a unique identifier (six-letter, one-number code, e.g. CKPNAT3) and then categorized in a dissimilarity matrix. The results from this measurement were first graphed in a hierarchically clustered dendrogram (Fig. 15) before the NMDS analysis. The dendrogram resulting from cluster analysis shows a distinct grouping of samples, with the most strongly defined groups containing samples from: a) natural beaches at three sites (CKP, RBP, SHB); b) both altered and natural beaches at DBP; and, c) altered beaches at three sites (CKP, RBP, SHB). Two samples from site CKP were outliers. This dendrogram is inclusive; no outliers or samples lacking fit were omitted.

The results from NMDS (Fig. 16) were much the same as from the cluster analysis, with natural sites forming one cluster, altered sites forming another, and all samples from site DBP being isolated in space from the other samples. A two-dimensional solution proved to have the best fit, with 42 iterations in the final model and a final instability of 0.0036. The final stress for the 2-dimensional solution was 11.8 (or 11.8%), a result that falls within the fair to good assessment, as per standard rules of thumb (McCune and Grace 2002), established by Kruskal (1964), and modified by Clarke (1993)^{††}.

This analysis reconfirms what the univariate ANOVA results suggested, that supratidal benthic infauna at the DBP site are different from the other sites, and that natural beach samples are dissimilar in taxa from altered samples. The NMDS plot shows benthic infauna from site SHB (both altered and natural) to be most similar throughout all sample points, often overlapping or lying in close proximity.

Based on relative density and frequency of occurrence, talitrids were highly indicative of natural beaches, as was shown by post-hoc indicator species analysis. Other

^{††} NMDS analysis results in a “stress” level which can be used as an indicator of the integrity of the model.

taxa influencing the model (i.e. those with high indicator values and low p-values, as reported from a Monte Carlo simulation) included: Arthropoda, Insecta, and Crustacea.

Grain Size Cores

At all sites, grain size ranged from gravel to fines (silt and clay, with diameter $<62.5\mu\text{m}$). Sediments were dominated by gravel ($<2000\mu\text{m}$ diameter) at altered beaches and medium sand ($<250\mu\text{m}$ diameter) at natural beaches (Fig. 17). The only site with very fine sand or silt (sediments with grain size diameter $<62.5\mu\text{m}$) was site DBP (Fig. 18). At all sites, the sediments were poorly-sorted, with high uniformity coefficients. Only site DBP-Natural is considered to be well-sorted, while the others have mixed sediment composition (Table 5). All natural beaches are more uniform (lower C_u) than altered beaches, with the exception of RBP, where $C_u = 4$ at both sites. It should be noted that distribution coefficients are approximate, since sediments are lumped into bins of a wide size range for analysis.

Insect Fallout Traps

With few exceptions, insect fallout traps were marked by numerous taxa with low occurrence and abundance and few ubiquitous taxa. Organisms ranged from benthic invertebrates, such as talitrid amphipods and oniscoid (terrestrial) isopods, to 13 orders of insects, including winged and crawling forms.

In all, the insect fallout traps captured 105 taxa, though only 21 taxa (19%) were represented in more than 10% of the samples collected (Table 6, Fig. 19). The majority of taxa were rare, with 45 taxa occurring in less than 2% of all samples collected. Number of taxa per site ranged from 22 (SHB-Altered) to 61 (SHB-Natural), with an average of 39.9 taxa per site, and a significant difference (paired sample t -test, $p=0.021$) between the 29.8 average at altered stretches, and 50 average at natural beaches. When partitioned by sampling date, only one sample (CKP, Date 1/March) had more taxa at the altered than the natural beach; another sample (RBP, Date 1/March) had even numbers of taxa. All other samples showed the natural beach to be more taxa rich (Fig. 20). Three-factor

ANOVA showed that differences in site, type, and date were highly significant ($p < 0.00$) and post-hoc tests showed site CKP to be most different from the others.

Dipterans, collembolans, and talitrids were the most dense taxa (Fig. 21). Site SHB-Natural had the greatest taxa richness and the greatest difference in density and diversity between altered and natural beaches.

The most numerous organisms were collembolans, which occurred in 67% of all samples, with an average abundance of eight per sample ($132/m^2$). When compared using a three factor ANOVA ($p = 0.024$, for type, data log transformed), they were significantly more dense at natural beach sites.

Dipterans appeared in 98% of the samples analyzed, with members of the family Chironomidae being most prevalent and abundant. Dipterans were the most diverse order in the samples, with 30 different families. However, half of these families had fewer than five representatives, when all samples were combined. Other prominent families within the order Diptera included: Cecidomyiidae, Ceratopogonidae, Dolichopodidae, Empididae, Muscidae, Phoridae, Psychodidae, Psyllidae, Sphaeroceridae, Tethinidae, and Tipulidae. Tethinids are a known beach fauna, commonly associated with decaying marine wrack and detritus in the Pacific Northwest (Borror et al. 1981); while other families contain species with diverse ecologies and habitat requirements. Though tethinids occurred in just 10% of the samples, they were more prevalent at natural beaches (Fig. 22). They were not found at DBP but were commonly found at RBP (in 26% of the samples).

ANOVA was conducted for both chironomids and dipterans (which included Diptera families, except Chironomidae). Because skewness and kurtosis were not severe for either taxa, but the variances were large, raw abundance data as well as log transformed data were used for ANOVA. Results show there to be significant factor and interaction effects (Table 7), suggesting that the distribution of dipterans is highly dependent on site, beach type, and sampling date. These taxa are distributed widely, and the patterns are not consistent across sites (i.e., site CKP shows a higher abundance for both Diptera and Chironomidae at the altered site, though the sum total indicates that

both taxa are more numerous at natural sites). In both cases, the results are similar for raw and log transformed data, though higher r^2 values indicate that log transformed data for Diptera and raw data for Chironomidae are better fits, respectively.

In addition to insects and spiders, talitrid amphipods of several species—*Megalorchestia pugettensis* and *Traskorchestia* spp., probably the common species *T. traskiana* and/or *T. georgiana*^{‡‡}—were caught in the fallout traps. Unlike the benthic core samples, where *M. pugettensis* was the dominant talitrid, *Traskorchestia* spp. were more common in the traps. This difference between cores (taken at MHHW) and fallout traps (set above the influence of tides) suggests either that the two genera occupy different beach strata or that one genus is more mobile. While some overlap did occur, the more robust *M. pugettensis* seem to prefer lower tidal elevations. For ANOVA analysis, all talitrids were combined. ANOVA showed highly significant differences ($p < 0.00$) in site, type, and date for talitrids, though the interaction between the three factors was not significant. Post-hoc tests showed that site SHB was significantly different from all others and that the first sampling date (March) was different than the other dates. In all cases, natural beaches had significantly higher densities than altered beaches (Fig. 23); however, the magnitude of variance shows that these animals were patchy, both in space and time.

Insect orders Homoptera and Psocoptera were selected for further analysis because these insects appeared in relatively high numbers in chinook salmon diets collected at these and other similar sample sites in Puget Sound,^{§§} although the prey consumed by the fish could have occurred over a broader spatial and temporal scale than covered in the beach sampling. Psocoptera, one of the top prey items numerically (30-50 psocoptera per stomach was not uncommon in chinook diets) were rare in the insect fallout traps (six psocopterans were collected at all sites). Statistical analysis of psocopterans was not performed because of the low occurrence and abundance.

^{‡‡} C. Staude, University of Washington, Friday Harbor Labs, personal communication

^{§§} Data to be included in a report to King County, Washington, Department of Natural Resources and Parks

Homoptera occurred in 35% percent of the fallout trap samples. Eight homopteran families were represented in the traps, though 78% were from three family groups: Aphididae, Psyllidae, and Cicadellidae. At two sites, CKP and DBP, homopterans were more dense at altered beaches, but at SHB and RBP, they were more numerous at natural beaches (Fig. 24). ANOVA based on the raw data indicated no significant difference between altered and natural beaches ($p=0.174$), and the site*type interaction was marginally non-significant ($p=0.054$). However, the results were opposite when the same analysis was performed using log transformed data (to account for the violation of assumptions). The site factor was significant ($p=0.025$), with homopterans being more abundant at natural beaches, and the site*type interaction was not significant ($p=0.408$). In both cases, the fifth sampling date (June) was different from the others and accounted for significant results in site and all date interactions.

Both the original taxa and a smaller set of family groups were analyzed using the same hierarchical cluster analysis as in the benthic infaunal core analysis (Bray-Curtis dissimilarity measure, nearest neighbor method). The resulting dendrograms showed few patterns in either case (Fig. 25), and further multivariate analyses were not conducted.

Discussion[CAS2]

Shoreline armoring removes and degrades an ecologically unique ecotone by altering physical habitat through sediment coarsening, vegetation removal, and decreased organic detritus accretion. In turn, ecologically important invertebrates are disturbed or reduced in the supratidal zone.

Previous studies (Boesch 1973; Mannino and Montagna 1997) have suggested that sediment size structures benthic communities. However, sediment size gradients are often confounded by other physical gradients (salinity, spatial distribution, pore water, tidal elevation, etc.) and the relative importance of the link between grain size alone and species richness remains unknown (Braziero 2001). Sediments in this study were of similar size across all sites, but differed between altered and natural beach stretches. Grain size differences may be important in that they are related to energy intensity at

each beach. However, shoreline armoring alone has drastically changed the intertidal zone at the altered beach stretches in this study, so armoring and sediment size may be unavoidably interrelated in this sampling design (i.e., comparison of sediment and resulting fauna across different grain sizes would be best carried out in a controlled setting where other physical disturbances are absent).

It is not surprising that Dockton Beach (DBP) differs in benthos composition from other sites, because the physical attributes of this site are quite different. Lower wave energy may contribute to the lack of explicit difference between samples at the altered and natural beaches at this site. Without extensive disturbance from waves or ship wakes, the physical changes induced by shoreline armoring (e.g., scouring, turbulence) are likely to be less intense, resulting in less difference in invertebrate assemblage between beach types^{***}. The sediments at this site, being finer than at the other sites and with a higher organic content, may further contribute to differences in benthic communities between this site and the others.

As in previous studies of benthic fauna in the upper-intertidal zone, the samples collected for this study were comparatively depauperate of organisms (Attrill et al. 1999; Shimek 1992) with only infaunal worms common and abundant. Because of the physical stressors of the supratidal zone—desiccation, exposure, limited inundation—it follows that fewer organisms are adapted to inhabit the benthos in this zone (Carefoot 1977; Garrison 1996; Kozloff 1987; Ricketts et al. 1985). However, the exception is talitrid amphipods, which are well-adapted to this zone and may be an ideal taxon for beach comparisons.

Talitrids were universally present in both benthic infaunal cores and insect fallout traps at natural beaches, but were nearly absent at altered sites. While not the most abundant organisms from either sampling type, talitrid amphipods, also known as “beach-hoppers,” are specialists in the supratidal zone, occupying a distinct ecological niche (Pank 1997). Though their ecology is semi-terrestrial, talitrids are considered marine

^{***} H. Shipman, Washington State Department of Ecology, personal communication

crustaceans and they rely heavily on the deposition of marine wrack for food and shelter, thus, their unique concentration in the supratidal.

At all sites, the percent cover of wrack was greater at natural beach stretches than at altered beaches. Wrack serves as habitat for many beach-dwelling creatures, including staphylinid beetles and talitrid amphipods (Colombini et al. 2000; Moore and Legner 1973; Oakden 1996; Pank 1997). Amphipods will descend to the wrack zone in the evening and consume wrack in quantities equal to or greater than their body weight (Pank 1997), serving as a conduit for energy and nutrient exchange in the nearshore ecotone (McLachlan et al. 1981; Polis and Hurd 1996). This study was conducted in the spring, when wrack deposition is ordinarily low; differences between site-types may be more profound during periods of high wrack deposition, such as the fall when leaf litter is present or after winter storm events.

Talitrid distribution was patchy (e.g., densities of 3/m² on one occasion and 360/m² on a subsequent sampling date at the same site), though it was not uncommon to find them in densities of up to several thousand per square meter, (e.g., benthic cores from Seahurst Beach). They were often found in natural beach infaunal core samples, and the strength of the results from indicator species analysis on these samples suggests that this taxon was driving the NMDS model output. While not necessarily a predictive tool, indicator species analysis explains what is guiding the statistical model and it can suggest taxa of interest for future sampling efforts. A perfect indicator taxon should be “faithful” (always present in a sample group) and “exclusive” (never occurring in other groups) (McCune and Grace 2002).

In this study, talitrid density was tightly correlated with natural beach type. As the supratidal interface is pushed to lower elevations, these organisms apparently face increased marine exposure that they are not adapted to. In addition, as shoreline armoring replaces sand and gravel shores with concrete and rock structures, it is likely that these animals lose essential sand habitat. Given that talitrids are adapted to the supratidal zone, removal of beach in this zone by installation of shoreline modifications (specifically bulkheads) presents a significant disruption and loss of their habitat.

Because shoreline armoring lowers the interface between land and sea, it follows that more marine organisms, such as crustaceans, would be found at altered beach sites. Results from the NMDS model show this to be the case, with an assemblage shift with shoreline armoring, toward fewer talitrids, insects, and collembolans (organisms that are terrestrial-dependent) and more marine crustaceans. The data strongly suggest that this is the result of lowering the land/sea interface replacing sandy sediments with hard substrate. The removal of shoreline vegetation which often accompanies shoreline armoring, also changes the physical structure of this zone by creating hotter, drier habitats, and removing vegetation-dependent organisms, such as insects.

Ecologists generally note that patchiness and high occurrences of zeros are common in community ecology (Dufrene and Legendre 1997; McCune and Grace 2002). McCune and Grace, in particular, suggest that the data often create a “dust-bunny distribution” when plotted in multidimensional space, with samples being clustered around the juncture of the axes; the insect fallout trap data set (like the benthic fauna data) followed this pattern. This was probably due to the ecological and taxonomic diversity found. With over one hundred taxa, including isopods, amphipods, arachnids, diplopods, and numerous insect taxa, these results are not surprising.

Interestingly, few of the insects commonly associated with wrack (i.e., wrack specialists) were collected in the insect fallout traps. The dipteran families Tethinidae, Ephydriidae, Sciomyzidae, Coelopidae, and Helcomyzidae are all shore specialists (Borror et al. 1981; Dobson 1976). With the exception of Tethinidae, these families were rare or absent in the fallout trap samples. This finding is perhaps attributable to the lack of proximity between the fallout traps (+4-5 m) and the wrack zone (+3.4-3.8 m), which in some cases was up to a distance of 10 m at both natural and altered beaches.

While insect fallout traps did collect a variety of insect taxa, it is also likely that this sampling methodology failed to collect certain species (e.g., non-flying insects such as ground beetles). Other sampling methods used in similar insect assessment studies included: pitfall traps, kick sampling, sticky tape, and nets (Caceres and Soluk 2002; Dufrene and Legendre 1997; Russel and Wilson 2001; Williams and Hamm 2002). A

combination of these methodologies may yield truer representation of insects living in this zone versus those caught during a spatio-temporally explicit sampling period, as in this study. Because some taxa found in fish stomachs (presumably eaten in the nearshore marine system) were absent in the fallout traps (e.g., psocopterans), the point of origin of the insects consumed is still unknown; the amount of insect drift that originates in this zone and becomes available to fish remains to be determined. Freshwater outflow may import some of these prey items to the nearshore zone, while others may be blown in from other upland areas or carried some distance by wind events (Caceres and Soluk 2002; Russel and Wilson 2001).

Invertebrate sampling at paired sites clearly showed shoreline-armoring induced assemblage differences. Shoreline modifications that encroach on the intertidal zone and remove the supratidal zone, as in this study, may be detrimental to the nearshore food web by removing important organisms, such as talitrid amphipods and insects.

Table 1. Sampling sites, coordinates, dates sampled, and land/sea interface elevations. Interface elevations are in meters above MLLW. MHHW is used for natural beach stretches.

Site Location	Code	Coordinates	Dates Sampled	Type	Interface Elevation
Richmond Beach	RBP	47.45.41.7N	3/24, 4/8, 4/25, 5/6, 6/7	Natural	3.5 m
		122.22.59.4W		Altered	2.5 m
Carkeek Park	CKP	47.71.19.7N	3/25, 4/9, 4/22, 5/8, 6/8	Natural	3.5 m
		122.37.79.3W		Altered	2.4 m
Seahurst Beach	SHB	47.28.23.5N	3/24, 4/8, 4/25, 5/6, 6/7	Natural	3.6 m
		122.22.02.5W		Altered	2.6 m
Dockton Beach	DBP	47.37.16.3N	3/27, 4/11, 4/23, 5/10, 6/4	Natural	3.8 m
		122.45.04.9W		Altered	2.3 m

Table 2. Percent Cover ANOVA results are given for all sites. Bold values indicate significant results for beach type (altered/natural). Variables with asterisks were significant when log transformed.

Site	Variable	Type Sig.
CKP	Wrack	0.05
	Wood	0.161
	Leaf Litter	0.316
DBP	Wrack	0.542
	Wood	0.975
	Leaf Litter	*0.835
RBP	Wrack	0.01
	Wood	0.047
	Leaf Litter	0.111
SHB	Wrack	*0.077
	Wood	0.016
	Leaf Litter	0.04

Table 3. Benthic core taxonomic groups used for statistical analyses.

Talitridae <i>Megalorchestia pugettensis</i> <i>Traskorchestia spp.</i> Unk. and Juv. Talitridae	Insecta Diptera (mostly Chironomidae) Coleoptera (mostly Staphylinidae) Hymenoptera (mostly Formicidae) Isoptera Thysanoptera Unk. Insecta
Crustacea Leptocheilia spp. Ostracoda Haracticoida Isopoda (Flabellifera)	
Nematoda	Arthropoda (Misc.) Acari Diplopoda Arachnida
Oligochaeta	
Collembola	

Table 4. Paired benthic core ANOVA results. Asterisks indicate significant results. For *Type* factor, letters indicate which beach type had higher abundances, N=Natural, A=Altered.

Factor	Taxa						
	Talitridae	Nematoda	Oligochaeta	Arthropoda	Crustacea	Insecta	Collembola
Site	*	*	*		*	*	*
Type	* N			* N	* A	* N	* N
Set	*			*		*	*
Site*Type	*	*	*				*
Site*Set	*	*				*	*
Type*Set	*	*		*		*	
Site*Type*Set	*	*	*			*	*

Table 5. Sediment grain size uniformity coefficients for paired benthic sediment cores.

Site	Type	d60 Category	d60	d10	Uniformity Coefficient
CKP	ALT	Very Coarse Sand	1000	125	8
	NAT	Coarse Sand	500	125	4
DBP	ALT	Very Coarse Sand	1000	125	8
	NAT	Medium Sand	250	125	2
RBP	ALT	Very Coarse Sand	1000	250	4
	NAT	Coarse Sand	500	125	4
SHB	ALT	Gravel	2000	125	16
	NAT	Coarse Sand	500	125	4

Table 6. Taxa occurring in greater than 10% of paired insect fallout trap samples, with group used for analysis in the right column.

Acari	
Arachnid	Other
Cecidomyiidae	
Ceratopogonidae	
Chironomidae	
Dolichopodidae	
Empididae	
Muscidae	
Phoridae	
Psychodidae	
Psyllidae	
Sphaeroceridae	
Tethinidae	
Tipulidae	Diptera
Sminthuridae	
Isotomidae	Collembola
Ptiliidae	
Staphylinidae	Coleoptera
Thysanoptera	Thysanoptera
Traskorchestia spp.	Talitridae

Table 7. ANOVA results for dipterans and chironomids from paired insect fallout trap samples. LN is log transformed data.

Taxa	Diptera	Diptera-LN	Chironomidae	Chironomidae-LN
Site	0.000	0.000	0.000	0.000
Type	0.000	0.000	0.003	0.040
Set	0.000	0.000	0.005	0.040
Site*Type	0.000	0.000	0.000	0.000
Site*Set	0.002	0.000	0.000	0.000
Type*Set	0.000	0.000	0.188	0.809
Site*Type*Set	0.199	0.194	0.000	0.019
Adjusted R² of Model	0.448	0.497	0.457	0.371

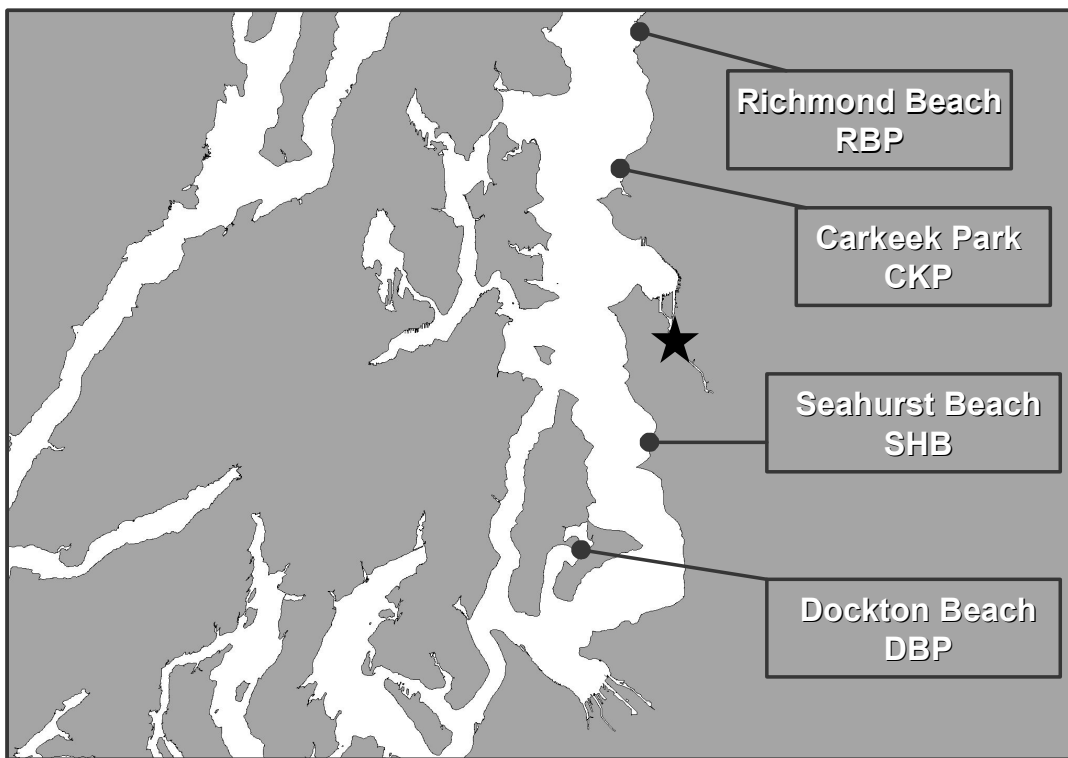


Figure 4. Paired sampling sites in Puget Sound, WA. Seattle is represented by the star.

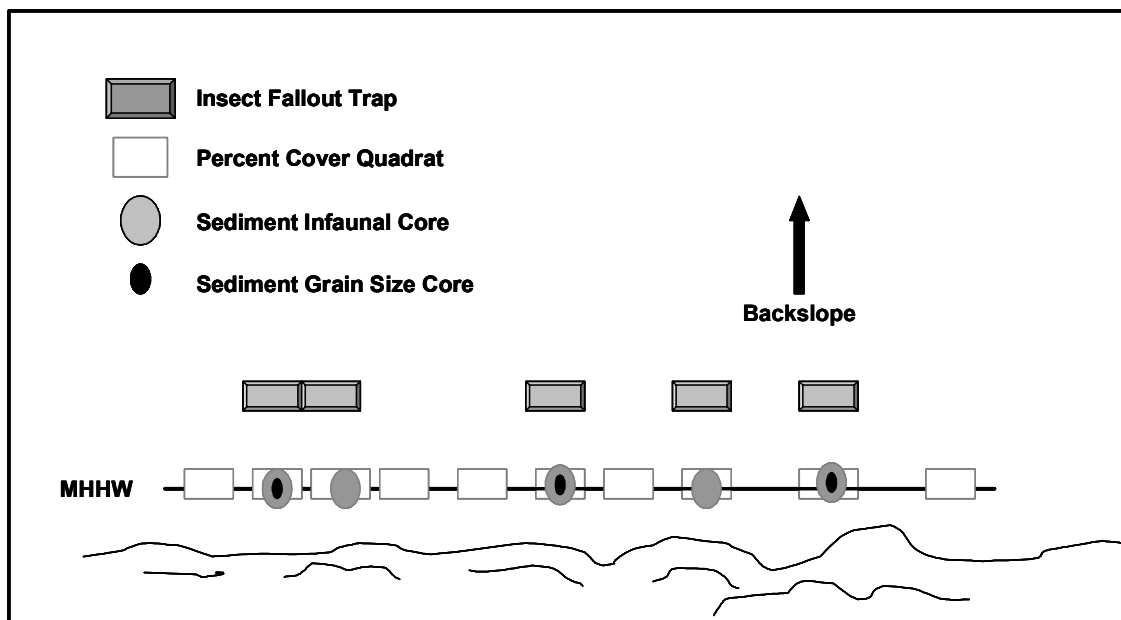
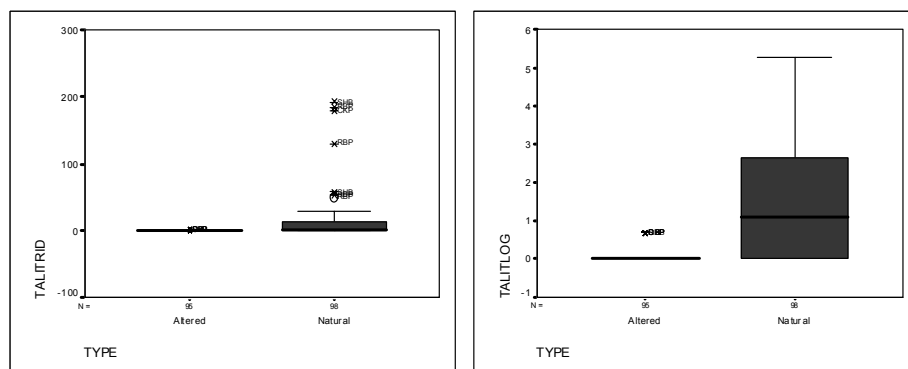
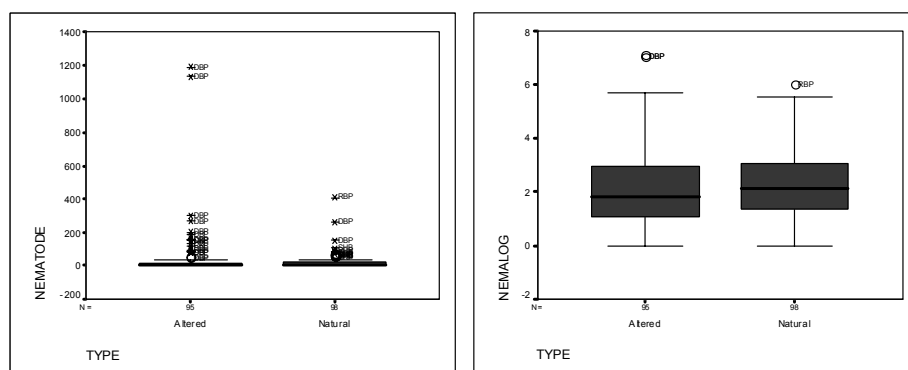


Figure 5. Schematic showing layout of transect and sampling stations.

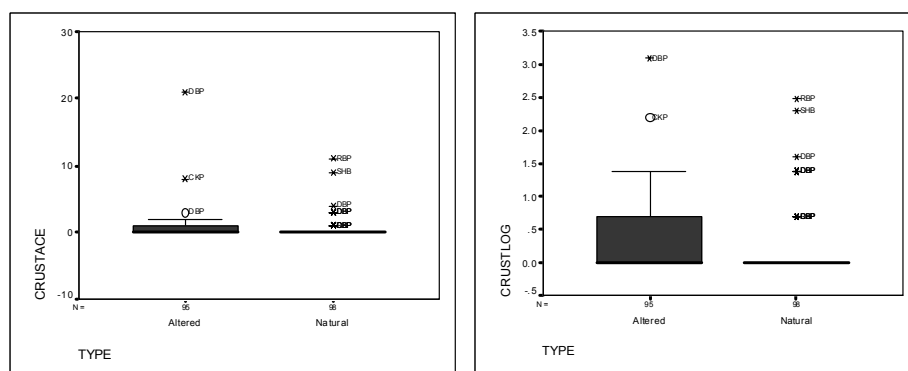
A. Talitridae



B. Nematoda



C. Crustacea



Raw Data

Log-Transformed Data

Figure 6. Boxplots showing raw data (left column) and log-transformed data (right column) for three different taxa, A.) talitrids, B.) nematodes, and C.) crustaceans. Within each boxplot, the left bar represents altered sites and the right bar represents natural sites, the black horizontal bar represents the median, the box and error bars show the interquartiles, and outliers are shown as individual points.

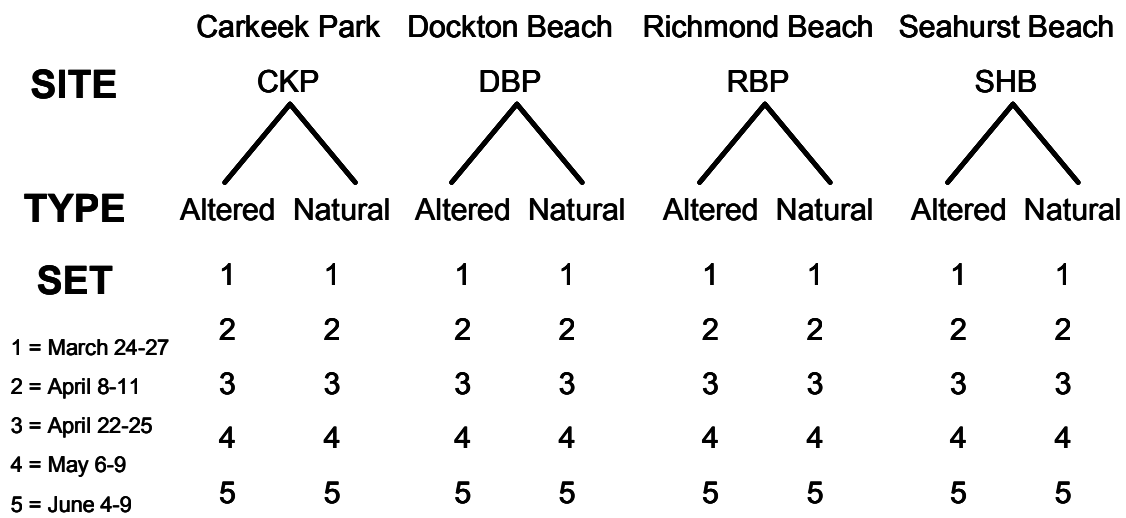


Figure 7. Schematic of sampling design and factors for analysis, site, type, and date.

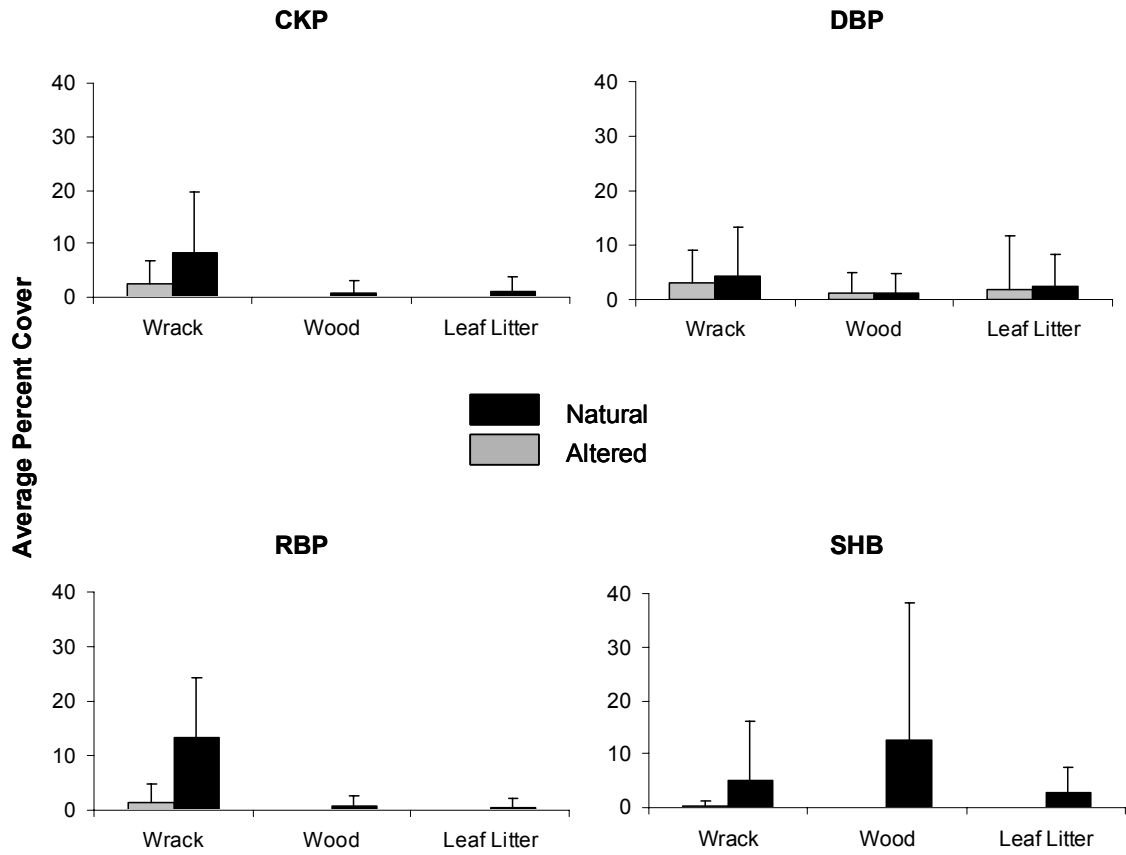


Figure 8. Percent cover quadrats for each site, with organic debris variables on the x-axis. All dates were pooled and error bars equal one standard deviation. See Fig. 4 for site abbreviations.

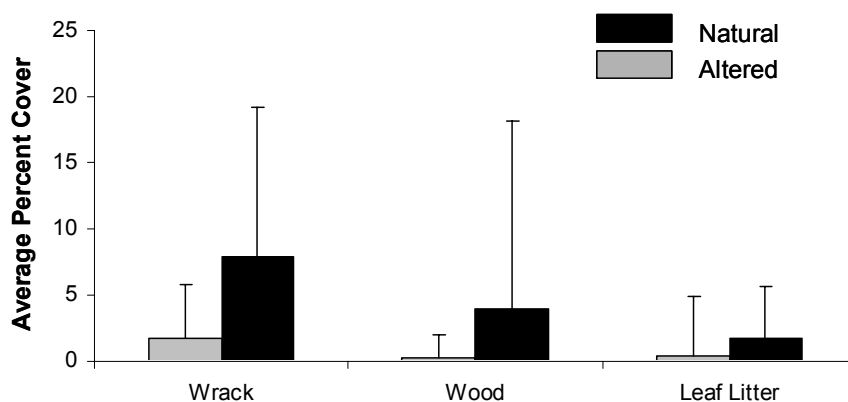


Figure 9. Percent cover quadrats for all sites grouped, with organic debris variables on the x-axis. Error bars represent one standard deviation. Paired sample *t*-tests resulted in p-values <0.05 for all categories.

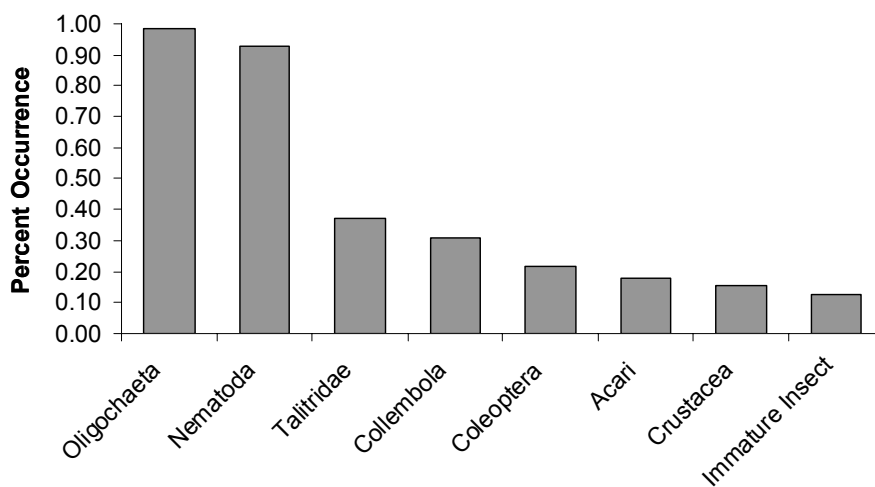


Figure 10. Benthic infaunal core percent frequency of occurrence across all samples, with taxa occurring in greater than 10% of the samples on the x-axis.

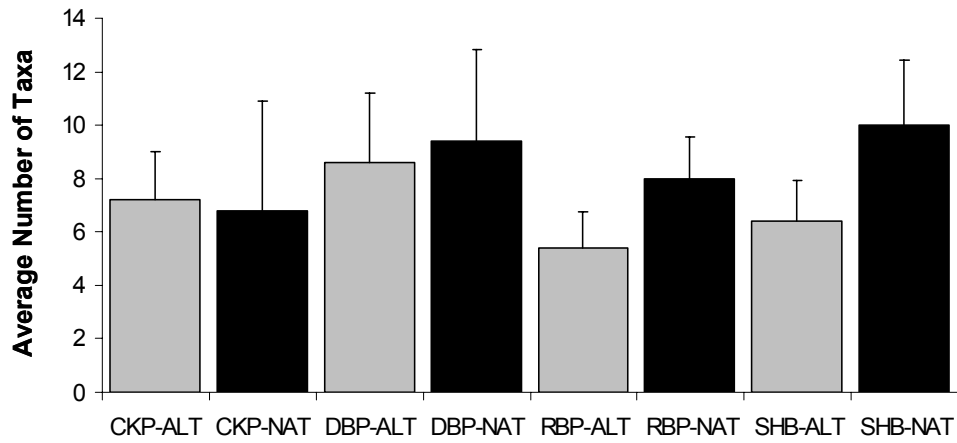


Figure 11. Paired benthic core taxa richness, with site on the x-axis. Only sites RBP and SHB have significantly different taxa richness, when compared using paired sample *t*-tests. Error bars represent standard deviations from all sampling dates. See Fig. 4 for site abbreviations.

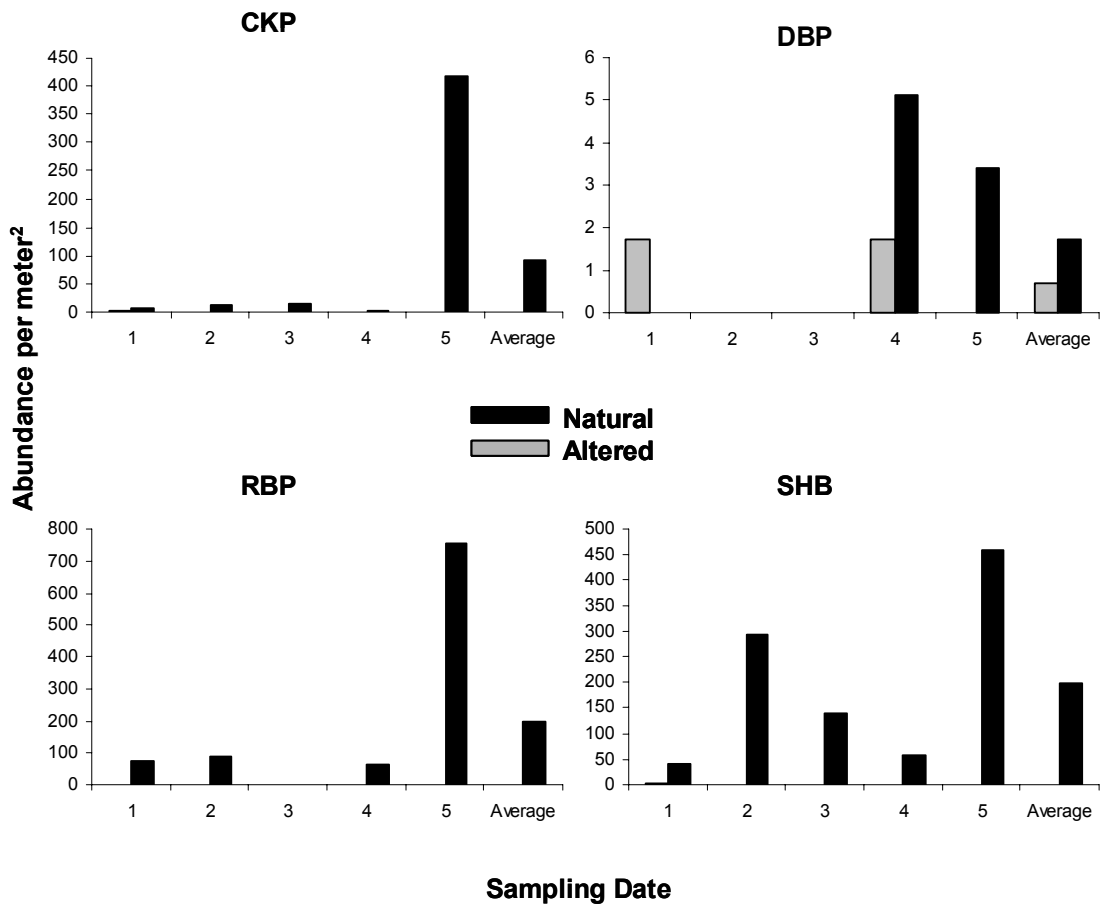


Figure 12. Paired benthic core talitrid density (abundance per square meter) at the four sampling sites (note varying scales, especially at DBP).

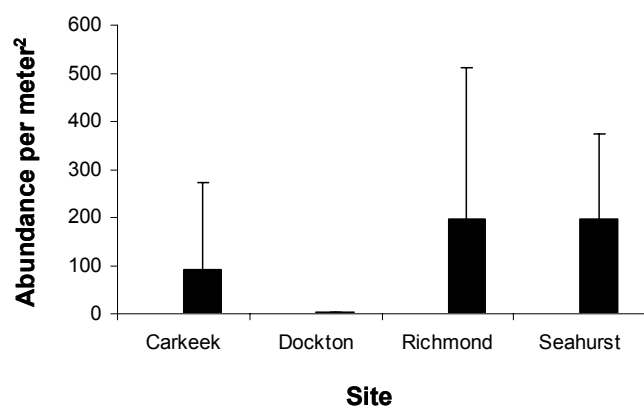


Figure 13. Talitrid density (abundance per square meter) at each paired site, averaged over all sampling dates. Averages at altered beaches are below one animal per square meter.

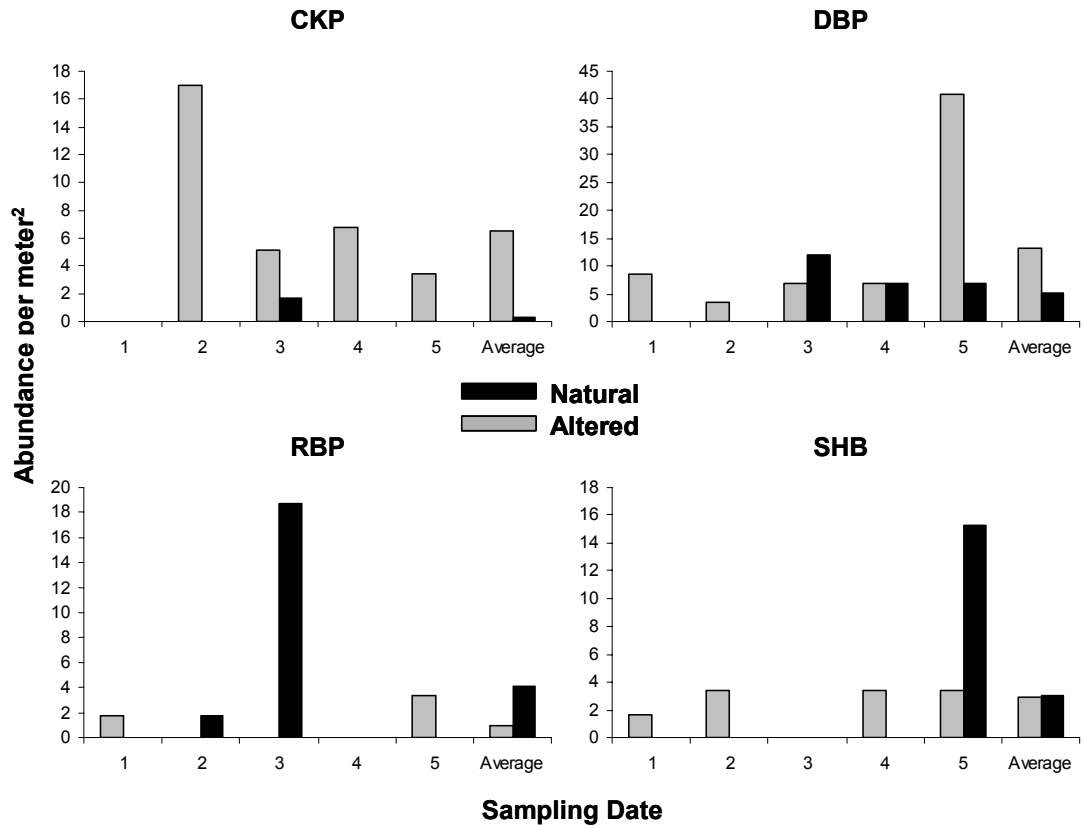


Figure 14. Paired benthic core crustacean density (abundance per square meter) at the four sampling sites (note varying scales, especially at DBP). See Fig. 4 for site abbreviations.

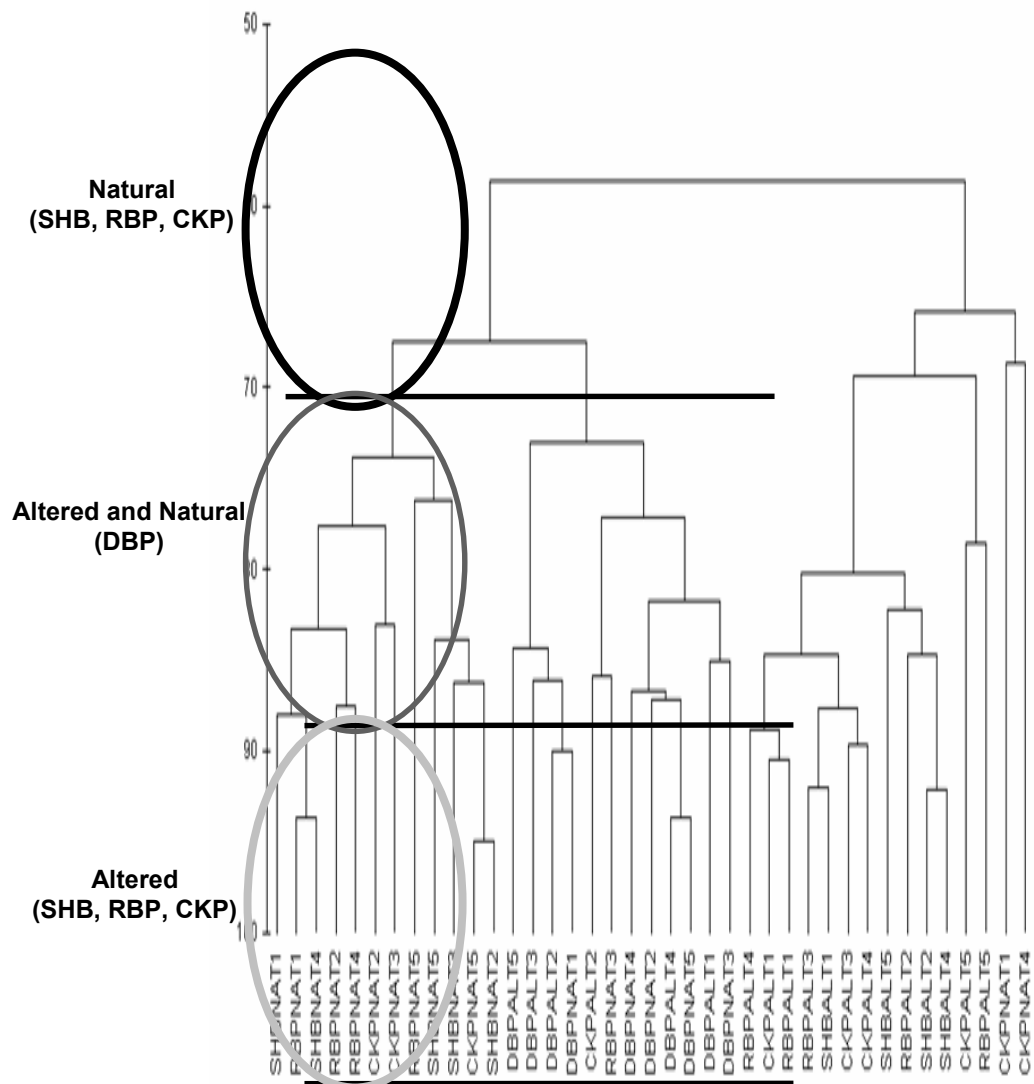


Figure 15. Hierarchically clustered dendrogram for paired benthic core samples. Distances were calculated using the Bray-Curtis (Sorenson) dissimilarity measure and the nearest neighbor method on log-transformed data. Ovals show three major groups as described.

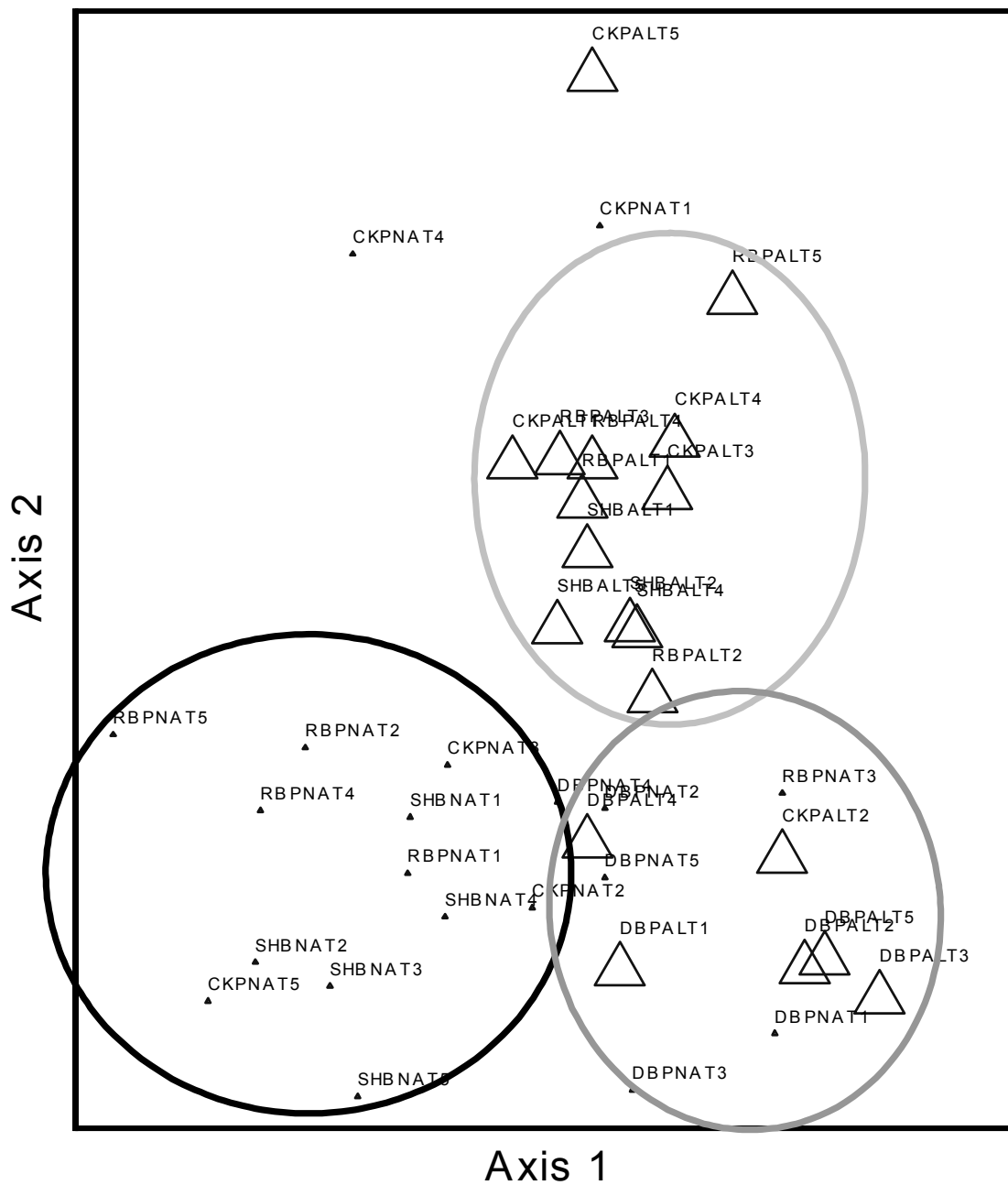


Figure 16. NMDS plot showing paired benthic core samples in three clusters: natural treatments from SHB, RBP, and CKP in black (lower left); altered treatments from SHB, RBP, CKP in light gray (upper circle); and both treatments from DBP in dark gray (lower right). Large triangles indicate altered treatments and small triangles indicate natural treatment.

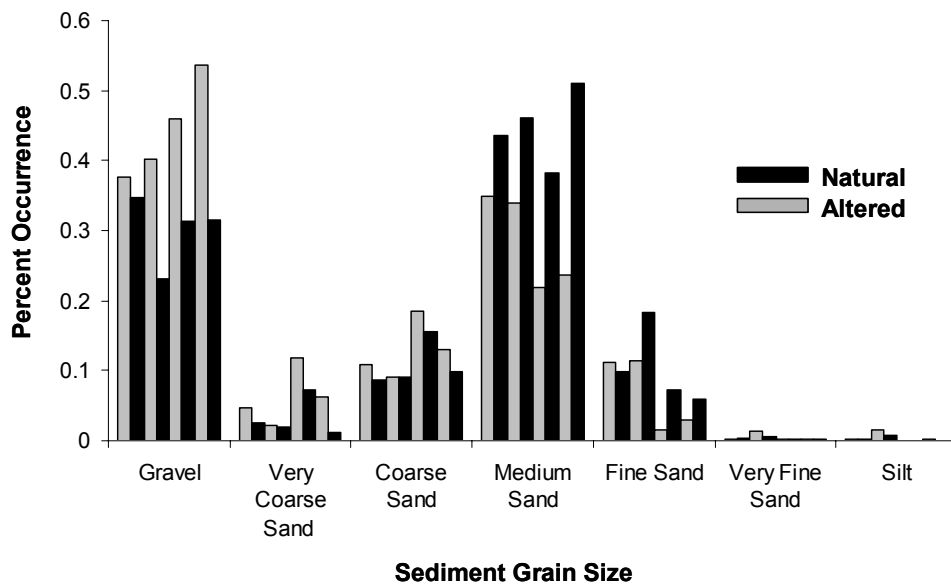


Figure 17. Sediment grain size from paired benthic cores. Each bar represents the average percent occurrence at a site. Medium sand dominates supratidal substrates at natural beaches and gravel dominates at altered beaches.

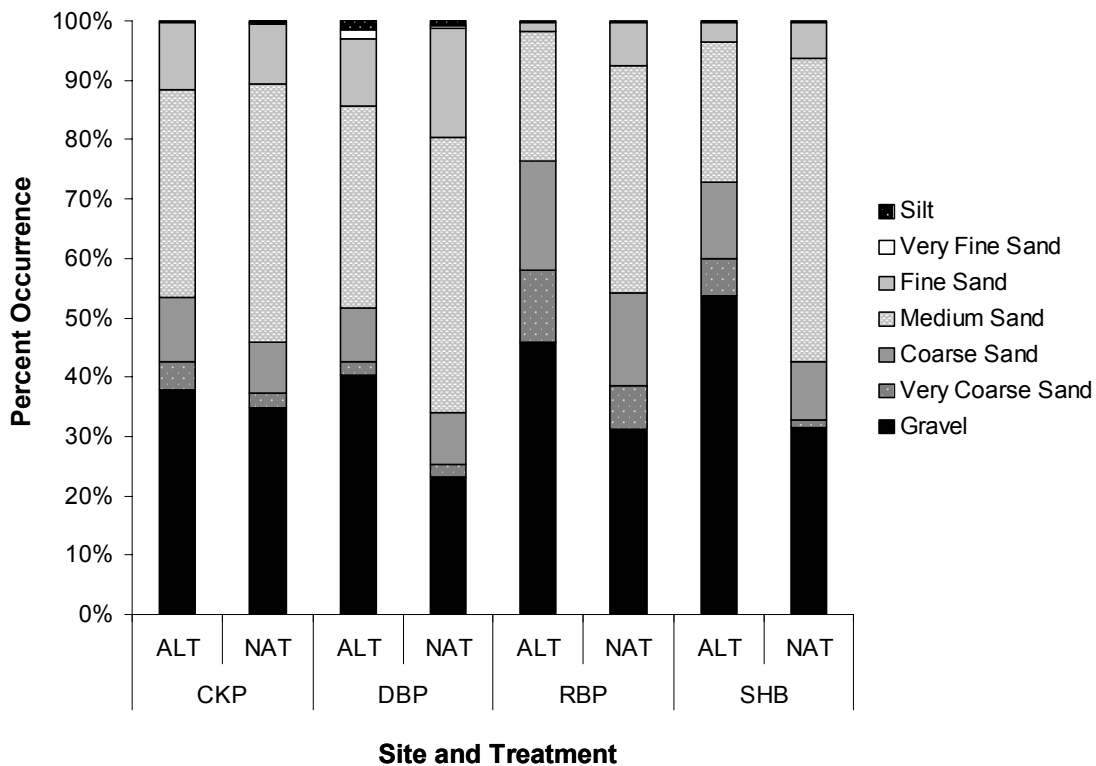


Figure 18. Distribution of sediment grain size at each site and beach type. Only site DBP (both treatments) has very fine sand or silt.

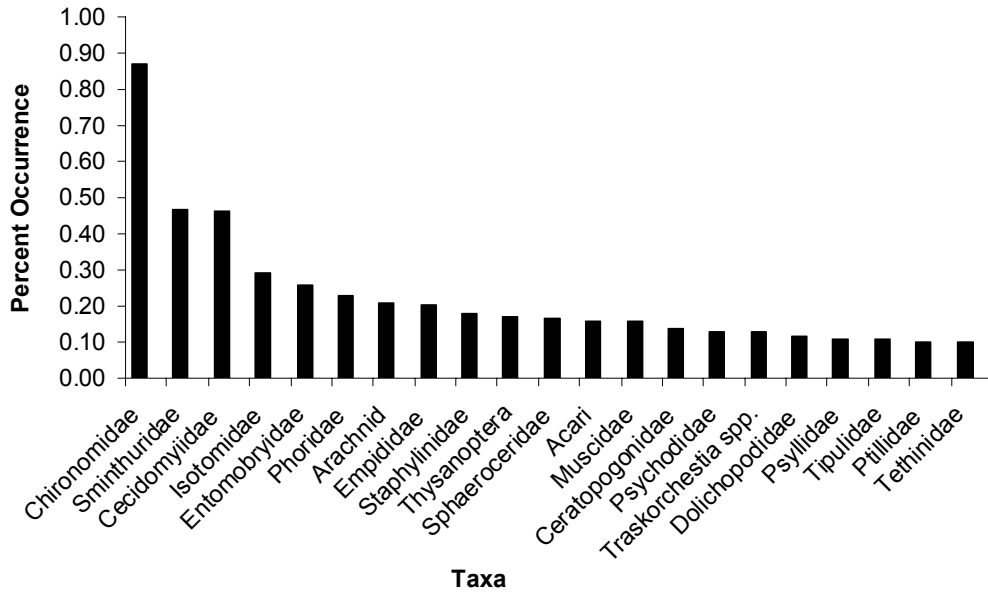


Figure 19. Percent occurrence for insect fallout trap samples. Only taxa occurring in greater than 10% of the samples collected are shown.

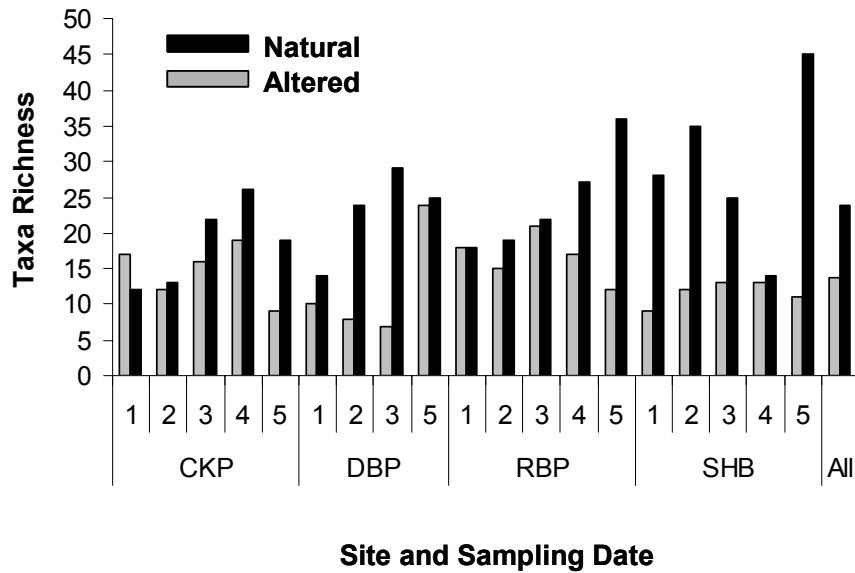


Figure 20. Insect fallout trap taxa richness at each site and sampling date. An average of all sites appears on the far right.

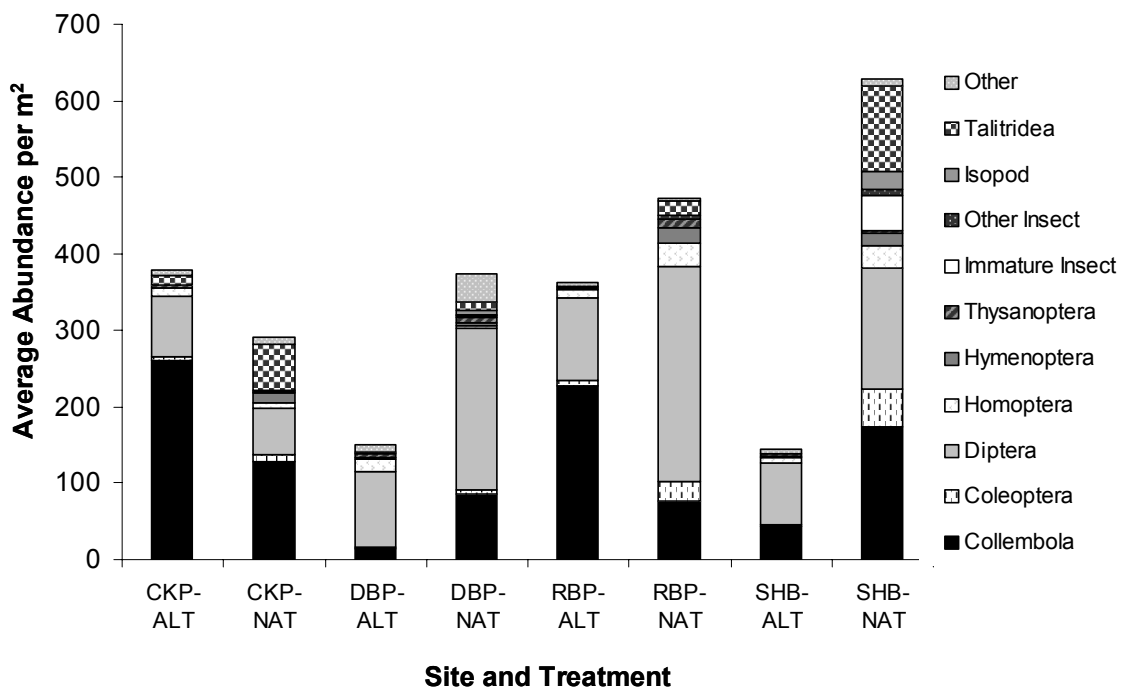


Figure 21. Relative density (abundance per square meter) of the most common taxa from paired insect fallout traps, per site and treatment.

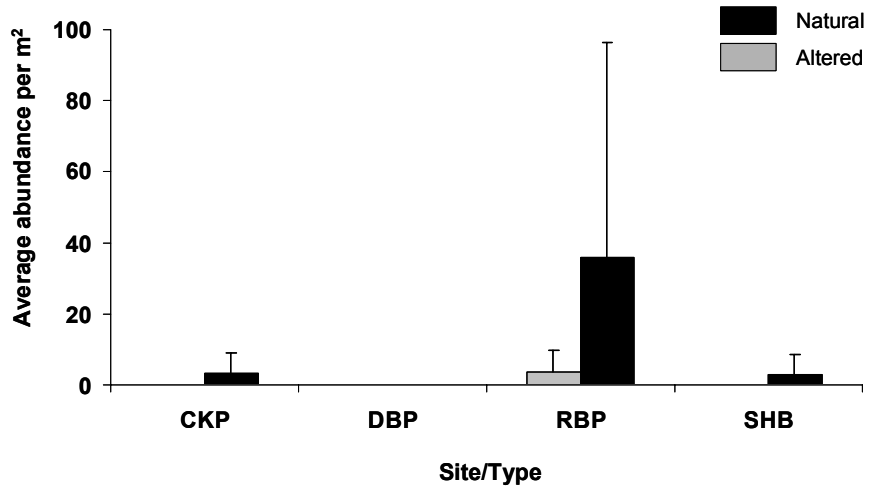


Figure 22. Average density (abundance per square meter) of tethinid flies from insect fallout traps at each paired site.

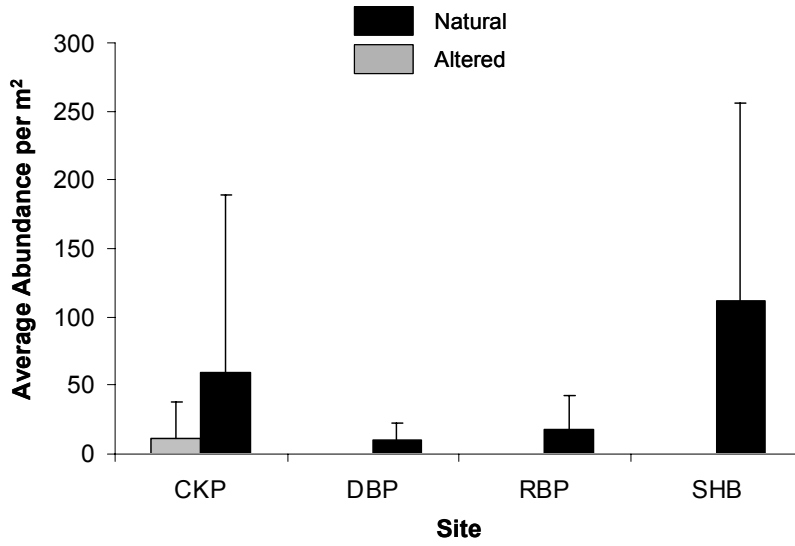


Figure 23. Paired insect fallout trap talitrid density (abundance per square meter) at each site.

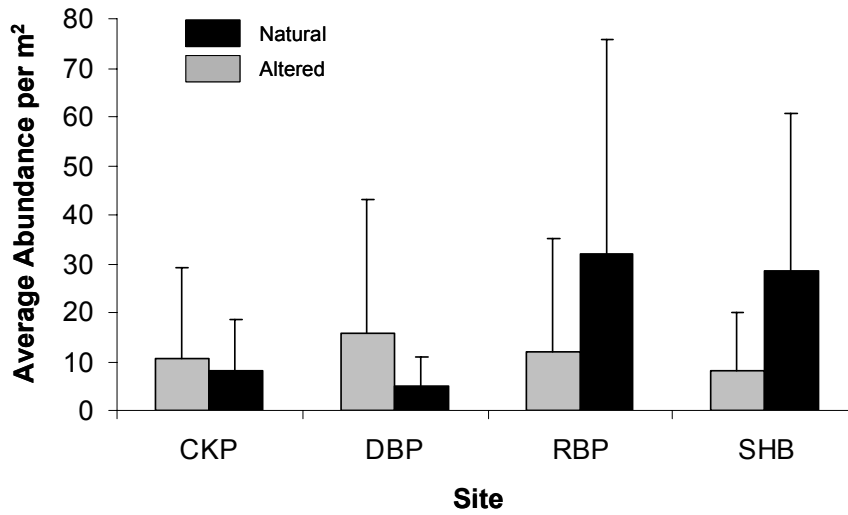


Figure 24. Paired insect fallout trap homopteran density (abundance per square meter) at each site.

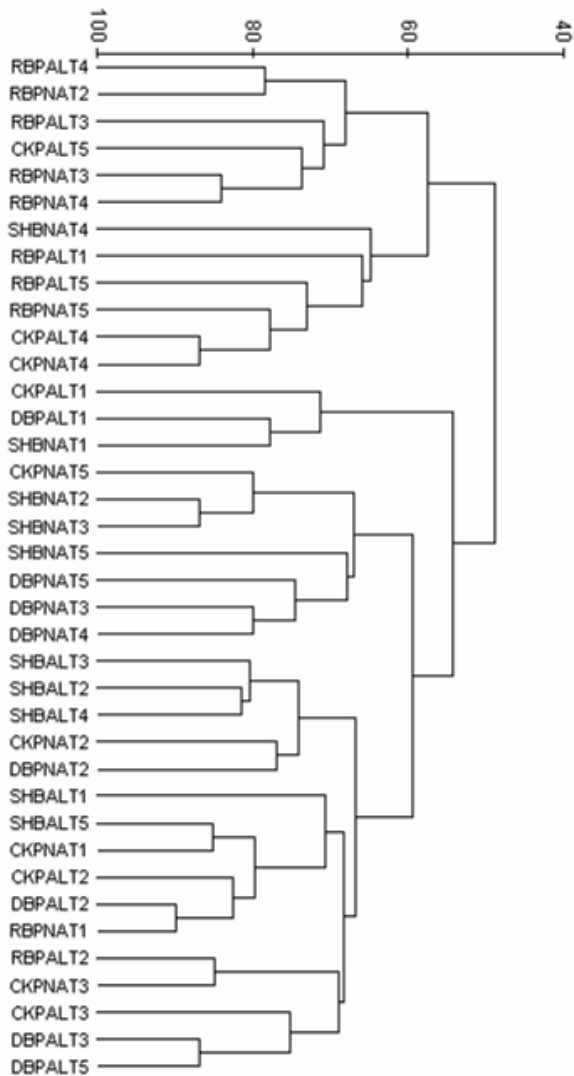


Figure 25. Hierarchically clustered dendrogram for insect fallout trap samples. Similarity between samples is shown, using the Bray-Curtis dissimilarity measurement. Each sample is coded with a 3-letter site code followed by ALT (altered) or NAT (natural) and a number corresponding to the sampling date.

Synoptic Sampling

Introduction

Most shoreline modifications in Puget Sound were installed to control erosion caused by bluff undercutting or steep slope failure (Macdonald et al. 1994). In many cases, bulkheads, rip-rap barriers, and other shoreline modifications have been installed below MHHW to protect eroding shoreline property; in these cases, the supratidal zone has been eliminated. However, some shoreline modifications have been installed higher than MHHW, especially in the case of single family residences, and may have different impacts on supratidal ecology. Reflected wave energy and sediment changes may impact invertebrate communities even in cases where modifications are above MHHW. This study was intended to evaluate benthic invertebrate distribution and abundance at a constant elevation, over a broad spatial scale at armored and unarmored sites, and to complement the paired sampling component of this study, which utilized spatially discrete sites with differing elevations.

Site Descriptions

During June of 2001, I conducted a pilot survey of Puget Sound beaches by boat to determine the feasibility of a synoptic sampling plan using only beaches with shoreline modifications at elevations greater than +4 m MLLW. This criterion was established to complement the paired sampling sites, because those natural and altered beach stretches had differing supratidal interface heights (see section III, Paired Sampling, *Site Description*). In addition to selecting sites which allowed for sampling at a constant elevation (MHHW), sites spanning an area of approximately 120 square miles were selected to evaluate spatial differences that may occur in the central Puget Sound basin.

I sampled twenty six sites between Tacoma and Mukilteo, on both the east and west sides of Puget Sound (Fig. 26). Sites were haphazardly selected in an effort to spatially stagger altered and natural sites and only included sites with high-elevation shoreline modifications, which were selected opportunistically. Because the eastern shoreline of Puget Sound, north of Seattle, is armored by the Burlington Northern

Railroad, sites on Blake, Vashon, and Whidbey Islands were included; however, distances to the Kitsap peninsula and Bainbridge Island precluded including them in the study. The sites selected were of mixed shoreline types, with and without shoreline modifications, including bulkheads and rip-rap revetments, and had varied backshore vegetation. Most of the altered sites were single family residences or municipal parks.

Methods

I conducted synoptic sampling twice, once prior to wrack deposition in July and once in September 2001. The latter date was selected to capture invertebrates associated with *Ulva* spp., which experiences late summer blooms (Nelson 2001), and eelgrass wrack; both *Ulva* spp. and eelgrass (*Zostera* spp.) are dislodged by early fall storms, entrained, and deposited on beaches during high wind events. The September sampling date was chosen opportunistically in calm weather following a storm. However, it should be noted that peak wrack accumulation generally occurs during the mid-winter months.

For both dates, sampling occurred on two consecutive clear days to minimize any variation caused by weather. Sampling was conducted at a standard elevation using the strand-line from the previous higher-high tide for standardization. Tides for both events were similar, approximately +3.6 m MLLW.

Of the 26 sites selected, 10 were natural beach stretches and 16 had shoreline modifications. There were 10 sites with backshore vegetation and 16 sites where vegetation was lacking. Vegetation did not necessarily correspond with shoreline type, as some natural beaches lacked vegetation and some altered beaches were vegetated (Table 8). A site was considered vegetated if trees or shrubs were intact within 50 m of the beach, though not necessarily overhanging. Very little wrack was present during the July sampling, and most of the wrack on the beach during the September event was *Ulva* spp., though some eelgrass was present.

For this survey, five benthic core replicates were collected haphazardly, to a depth of 10 cm using a standard 19.6-cm² PVC corer^{†††}. In the laboratory, samples were fixed with 10% formalin infused with rose bengal dye. At each site, I noted the GPS position was noted and qualitative data about the site/beach stretch (e.g., backslope vegetation, shade, beach slope, substrate type, and wrack) were recorded. Information about the wrack included composition and an index of wrack abundance (using a qualitative scale of 0-5, with 5 being abundant wrack) was noted in the laboratory for the second sampling set.

Samples were sorted in the lab by elutriation, and decanted through a 0.5-mm sieve before being identified and enumerated under a dissecting microscope. Taxonomic groups were analyzed as for the paired samples, and data were log transformed prior to analysis, to address the assumption of normality associated with ANOVA. I conducted basic data management and statistical analyses with Microsoft Excel XP[®]. SPSS v.11.5 for Windows[®] was used for ANOVAs to test the effects of sampling event (1/2), shoreline type (altered/natural), vegetation (presence/absence), and wrack (presence/absence) on each taxon (Zar 1999).

As in the paired-sampling analyses, I also used PC-ORD for Windows v.4.25[®] for multivariate cluster analysis and nonmetric multidimensional scaling (NMDS) (McCune and Grace 2002). NMDS was run on the full log-transformed data set using the Bray-Curtis dissimilarity measure (see *Paired Sampling, Benthic Fauna Cores, Data Analysis*, for complete discussion of the procedure).

Results

As with the paired samples, the synoptic benthic samples were sparsely populated, with few dominant species, and high variance. Oligochaetes were ubiquitous and numerically dominant, but ranged in abundance from 510-400,000 per square meter (1 to 775 per core), with an average of 18,000 per square meter. Nematodes were also

^{†††} The corer used in this synoptic sampling was smaller than that used for the paired benthic core sampling, so raw abundance data is not comparable. All values have been standardized per square meter for comparison, though some sampling bias may exist.

ubiquitous, but found in much lower abundances, only 2,500 per square meter. Adult insects were found infrequently, though immature insects (mostly Diptera) occurred in over 60% of the samples collected, on both sampling dates (Fig. 27). Frequency of occurrence was consistent between sampling events, though some insects (coleopterans and dipterans) and talitrid amphipods occurred more frequently in the second sampling effort. The results were opposite for immature and miscellaneous insects (Fig. 27).

For all taxa, the September samples had higher densities (Fig. 28a); this was especially evident when oligochaetes are removed from the analysis for better resolution of other invertebrates (Fig. 28b). With the exception of immature insects, results of ANOVA analyses indicated that abundances were significantly higher in September, coinciding with greater wrack deposition (Table 9). In addition, talitrids and collembolans were positively correlated with vegetation. Shoreline type (altered/natural) was not significant for any taxon. For the log-transformed data, insects had a marginally non-significant relationship with vegetation; however, when analyzed with raw data, the result was a significant positive correlation with vegetation.

Though few adult insects were collected in the infaunal cores (possibly due to the small core size, but likely because they are highly motile or rare), immature insects (dipertan larvae, predominantly) were collected in moderate abundances. These organisms, though likely to be associated with wrack ($p=0.006$, linear regression) (Fig. 29), are less likely to be directly associated with vegetation ($p=0.197$, linear regression).

Shoreline type and invertebrate assemblages were not correlated (Fig. 30). The best solution for the NMDS analyses based on Bray-Curtis dissimilarity was a three-dimensional model, with a final stress of 10.11 and a final instability of 0.005, achieved after 42 iterations. Wrack abundance (as measured qualitatively in the laboratory) showed a slight signal, with a cluster of samples with moderate wrack debris on the plot (Fig. 31). Vegetation was the most strongly correlated variable, with a slightly associated group of samples (Fig. 32). Taxa were also used as overlays to the NMDS plot. Only talitrid amphipods clustered (Fig. 33), suggesting that, as in the paired sampling regime, talitrids are driving the multivariate model of the synoptic samples.

Discussion

Unlike the benthic fauna at the paired sites, which showed a strong effect of shoreline alteration, the samples from the synoptic sampling regime were not statistically significant in this regard. This may be due to the higher elevations sampled during synoptic sampling. Because the shoreline at modified beach sites was still intact up to MHHW, organisms typical of more natural beaches were probably more prevalent than at the paired sample sites. Marine crustaceans, which were common at the paired sample altered beaches, appeared in just four of the 52 samples collected (average density at altered sites of $6/m^2$) during the synoptic survey, probably due to the higher elevation sampled at altered sites in this regime.

A breakdown of average densities of individual taxa from both the paired and synoptic sampling regimes shows that despite the lack of statistical significance in the latter, patterns are similar between the two sampling regimes (Table 10). The lack of statistically significant results from the synoptic sampling may be in part due to high variances associated with the samples.

Talitrids, which showed a strong response to shoreline armoring in the paired sampling regime, were uniformly distributed between altered and natural shorelines in the synoptic sampling (Table 12). These animals burrow at the high tide line, and because the sites selected for this study all had intact shore to MHHW, beach habitat remained intact at that elevation, even at altered sites. Additionally, wrack could be deposited and accumulate at these higher tidal elevations along both altered and natural shorelines, creating an additional habitat and food source (Bousfield 1981; Colombini et al. 2000; Jedrzejczak 2002a; Koch 1989). Shoreline modifications above MHHW are only likely to impact supratidal fauna during storm events, lessening their degree of impact with daily tidal events.

With the exception of sites P (Glendale, Whidbey Island, natural/vegetated) and H (Dumas Bay, altered/non-vegetated), there was no temporal overlap in the NMDS plots, suggesting that the invertebrate assemblage was different at each site for the two sampling events. This result was anticipated due to the presence of more wrack at the

later sampling date and was confirmed with ANOVA results from individual taxa. Increased sampling frequency and replication may illustrate temporal effects more thoroughly. Additionally, sampling during the winter, when wrack is deposited higher onto the beach by severe storms, may show trends not apparent in this study.

The presence of shoreline vegetation appears to affect the invertebrate assemblage, though no measurement was made of vegetation density or species distribution. Backshore vegetation hosts a variety of insect species (Romanuk and Levings 2003a) and is likely to alter the physical dynamics of a beach stretch through input of organic debris and thermal regulation of the substrate, driven by shading (Jedrzejczak 2002a). Because benthic cores collected few adult insects, a different sampling methodology intended to capture flying insects may elucidate insect community response to site/vegetation differences more clearly.

Table 8. Sites, coordinates, and descriptors showing classification for analysis for synoptic sampling regime. All site information is for both the July and September sampling events.

Site	N	W	Location	Type	Vegetation	Adjacent Land Use	Woody Debris
A	47.32.10.6	122.29.08.1	SE Corner of Blake Is.	Natural	Present	Undeveloped	Extensive
B	47.29.12.1	122.27.34.2	Sylvian Beach, Vashon I.	Natural	Present	Undeveloped	Extensive
C	47.25.53.9	122.26.10.3	Pt. Heyer, Vashon Is.	Altered	Present	Residential	None
D	47.24.45.8	122.26.14.4	Tramp Harbor, Vashon Is.	Altered	Absent	Road	None
E	47.21.56.4	122.28.10.1	Quartermaster Harbor, N. side	Altered	Absent	Residential	None
F	47.21.21.6	122.29.20.4	Quartermaster Harbor, S. side	Natural	Present	Undeveloped	Extensive
G	47.19.17.0	122.24.32.4	N. of Dash Point St. Park	Natural	Present	Undeveloped	Extensive
H	47.19.57.2	122.22.29.4	Lakota, just N. of Dumas Bay	Altered	Absent	Residential	None
I	47.20.34.6	122.20.02.3	Redondo-S. of causeway	Altered	Absent	Residential	Moderate
J	47.23.43.7	122.19.37.4	S. of Des Moines Marina	Natural	Absent	Residential	Extensive
K	47.24.22.5	122.19.58.1	N. of Des Moines Marina	Altered	Present	Residential	Extensive
L	47.24.46.9	122.20.36.4	Marine View Park-N. of boundary	Natural	Present	Undeveloped	Extensive
M	47.28.23.5	122.22.02.5	Seahurst Beach South	Natural	Present	Undeveloped	Extensive
N	47.28.45.9	122.21.44.7	Seahurst Wall	Altered	Absent	Park	Moderate
O	47.31.58.3	122.23.54.7	Lincoln Park, N. of Coleman Pool	Altered	Present	Park	Moderate
P	47.55.42.6	122.22.13.4	Whidbey, S. of Glendale	Natural	Present	Undeveloped	Extensive
Q	47.56.53.3	122.18.27.5	Muk., N. of boat launch	Altered	Absent	Parking lot	None
R	47.56.53.3	122.18.27.5	Muk., S. of boat launch	Altered	Absent	Park	Some
S	47.53.39.3	122.19.46.2	By Shipwreck, N of Picnic Point	Altered	Absent	Residential	Some
T	47.52.54.4	122.20.02.4	Picnic Point, N.	Altered	Absent	Park	Moderate
U	47.51.42.7	122.20.09.0	S. of red pier	Altered	Absent	Railroad	None
V	47.49.44.2	122.22.31.9	N. of Edmonds underwater park	Altered	Absent	Residential	None
W	47.45.41.7	122.22.59.4	RBP, b/t ALT and NAT sites	Altered	Absent	Park	Moderate
X	47.39.39.8	122.26.02.7	West Point, So. Side	Natural	Absent	Commercial	Extensive
Y	47.35.06.7	122.24.07.1	Alki-wall	Altered	Absent	Park	Some
Z	47.41.32.2	122.24.21.1	Golden Gardens, by 2 benches	Natural	Absent	Park	None

Table 9. ANOVA results for selected taxa, $\alpha=0.05$, significant results in bold.

Taxa	Event	Type	Vegetation
Talitridae	0.027	0.696	0.007
Collembola	0.018	0.611	0.022
Insect	0.003	0.005	0.062
Imm. Insect	0.756	0.383	0.210

Table 10. Comparison of benthic invertebrate densities between synoptic and paired sampling regimes. All densities are per square meter.

Sampling Regime	Talitrids	Crustaceans	Oligochaetes	Nematodes	Collembolans	Insects
Synoptic						
<i>Natural</i>	1785	0	9833	3060	2315	337
<i>Altered</i>	1014	6	6515	803	1039	281
Paired						
<i>Natural</i>	1819	47	15086	3274	238	314
<i>Altered</i>	7	91	11236	6608	79	103

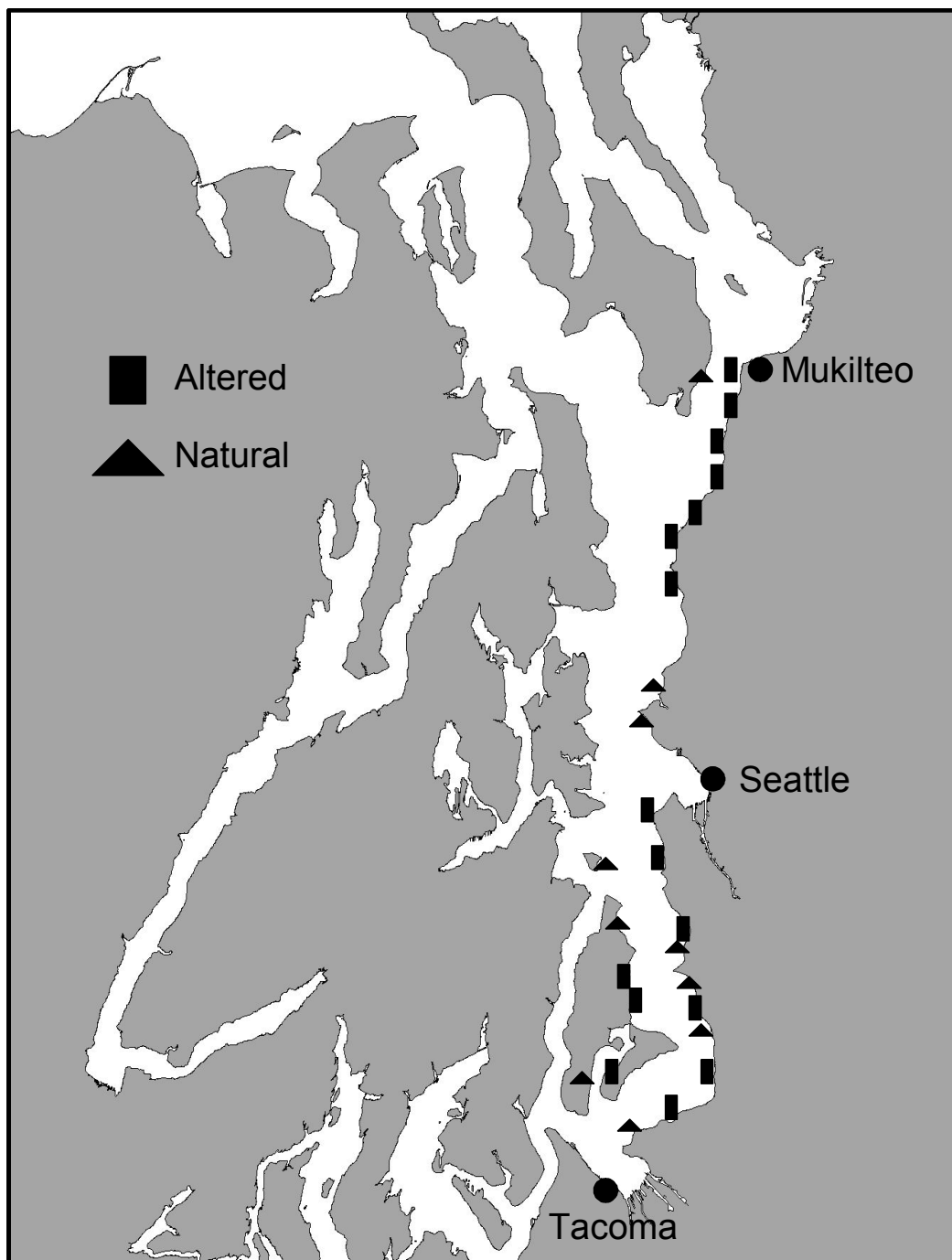


Figure 26. Map of synoptic sampling sites sampled for benthic invertebrates in July and September showing site type designations.

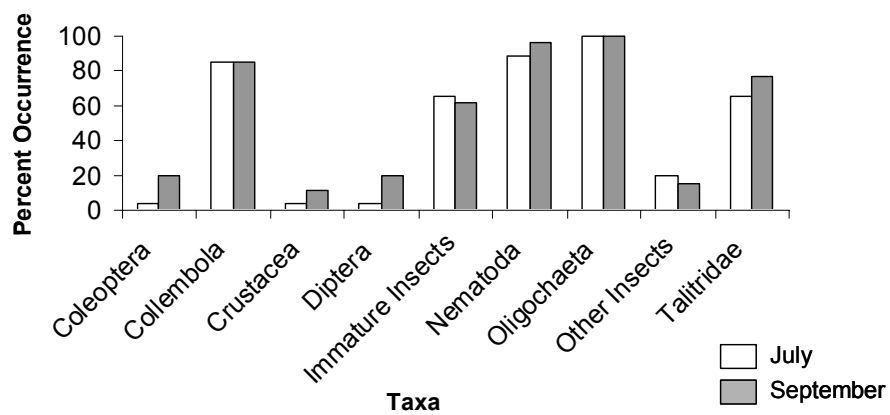


Figure 27. Synoptic sampling taxa and percent frequency of occurrence, for July and September 2001 sampling events.

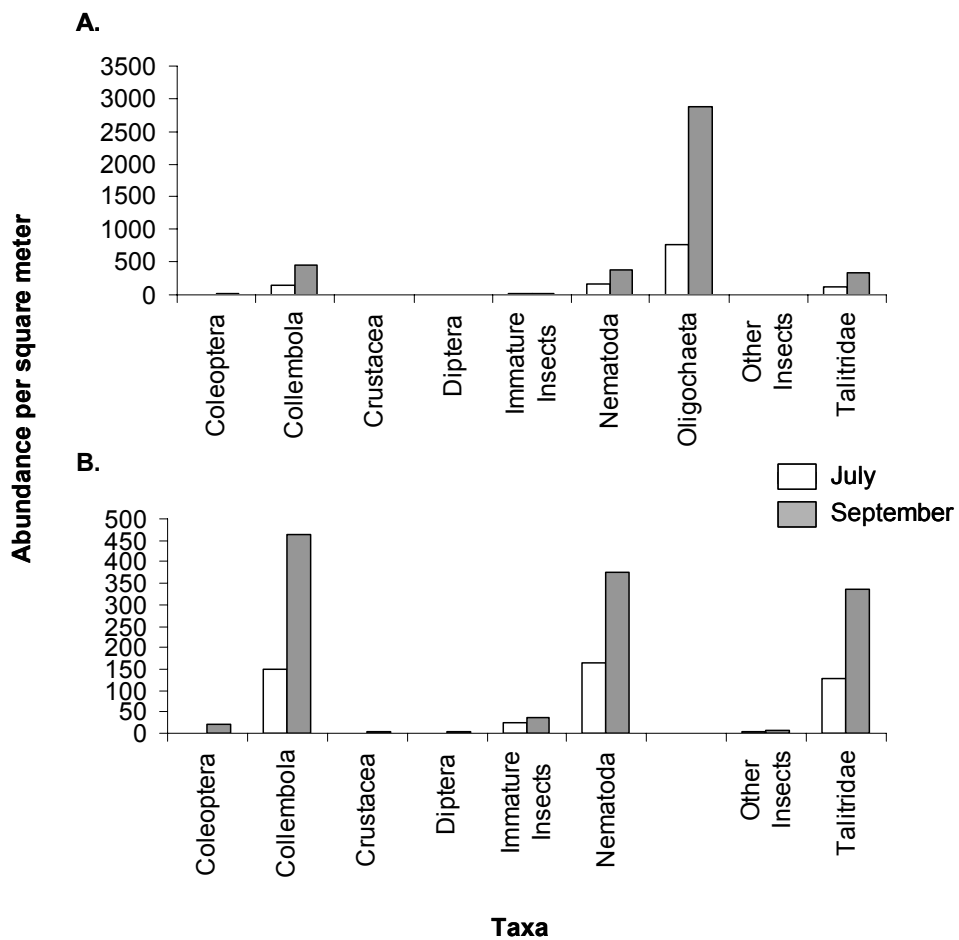


Figure 28. Supratidal taxa densities (abundance per square meter) for both synoptic sampling events, A.) all taxa, and B.) oligochaetes removed.

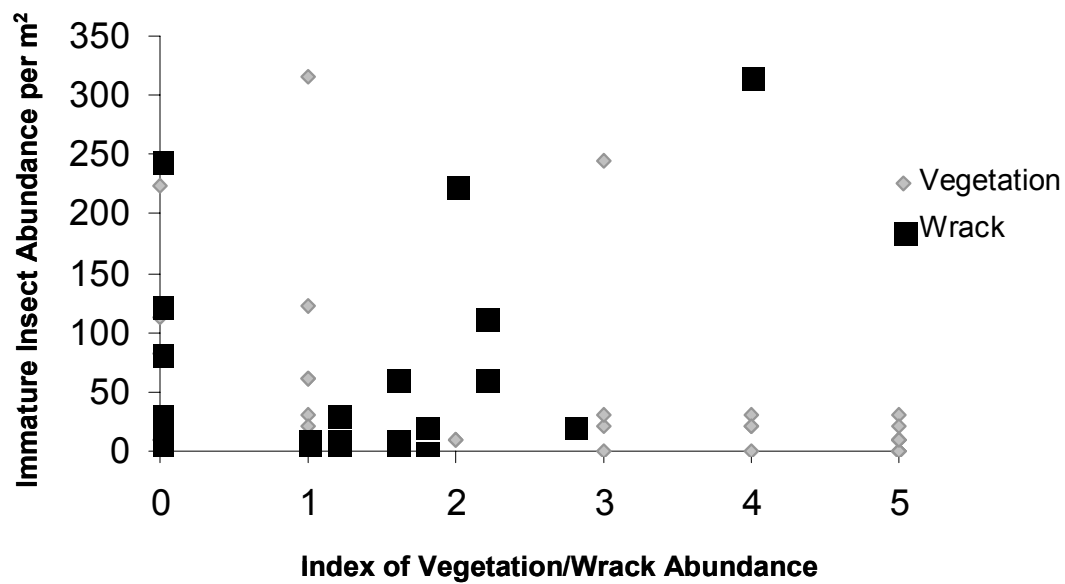


Figure 29. Abundance of immature insects plotted against an index of vegetation and wrack abundance. Immature insects are positively correlated with wrack ($p=0.006$, $r^2=0.140$) but not with vegetation ($p=0.197$, $r^2=0.033$).

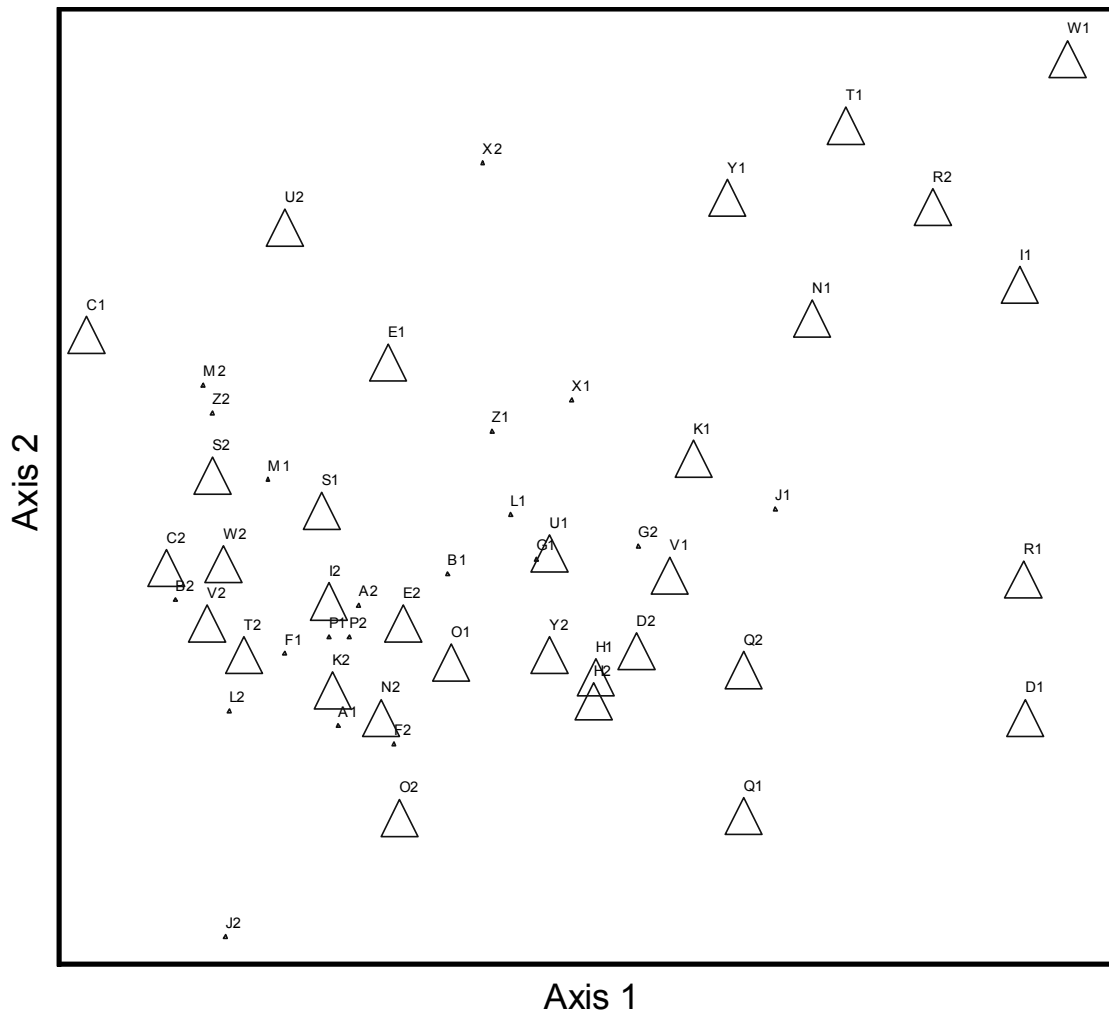


Figure 30. NMDS plot for synoptic sampling, showing array of samples with beach type superimposed. Sites designated X1, were from the July event, and sites designated X2, were collected in September. Large triangles designate sites with shoreline modifications (altered sites) and small triangles show natural sites. There is no correlation between invertebrate assemblage and shoreline type.

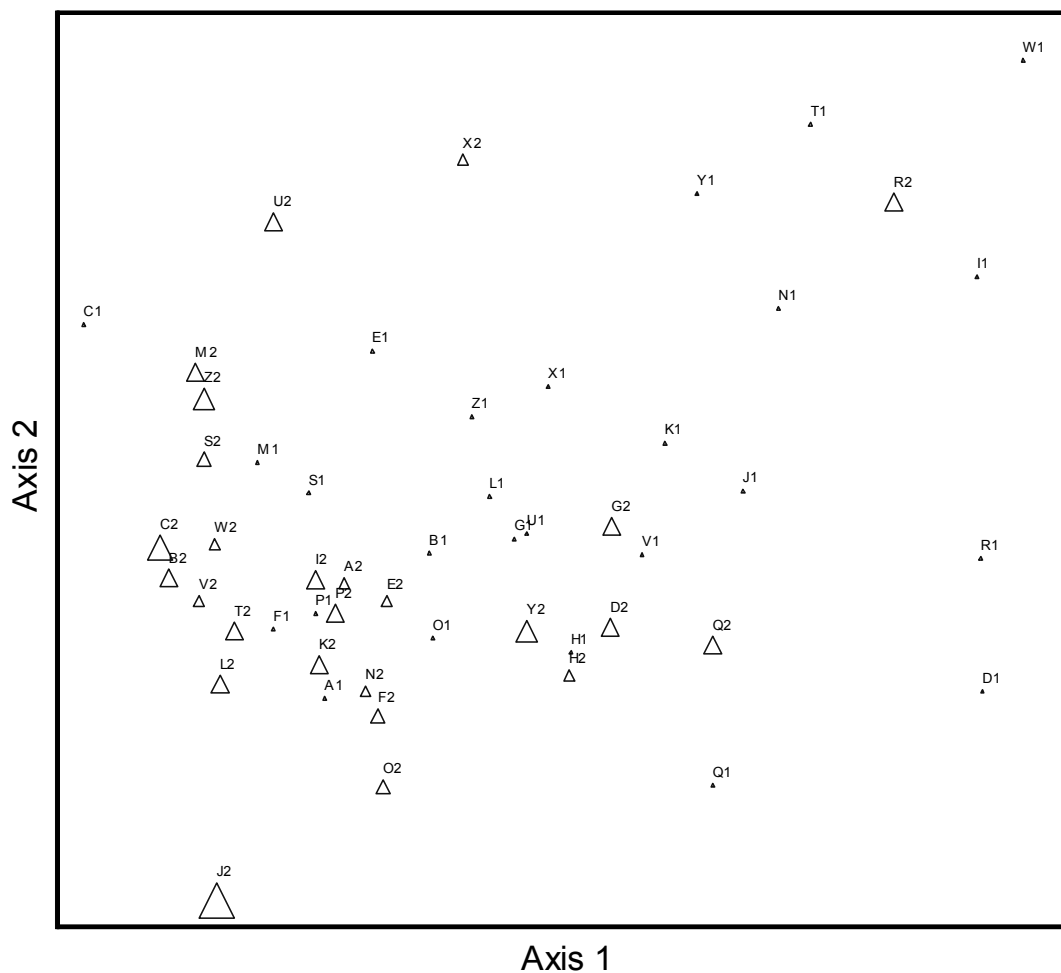


Figure 31. NMDS plot for synoptic sampling, showing array of samples with wrack abundance superimposed. Sites designated X1, were from the July event, and sites designated X2, were collected in September. Large triangles designate sites with extensive wrack and small triangles show sites with little or no wrack. There is a slight correlation between invertebrate assemblage and wrack abundance, as shown by the cluster of larger triangles to the lower left of the plot.

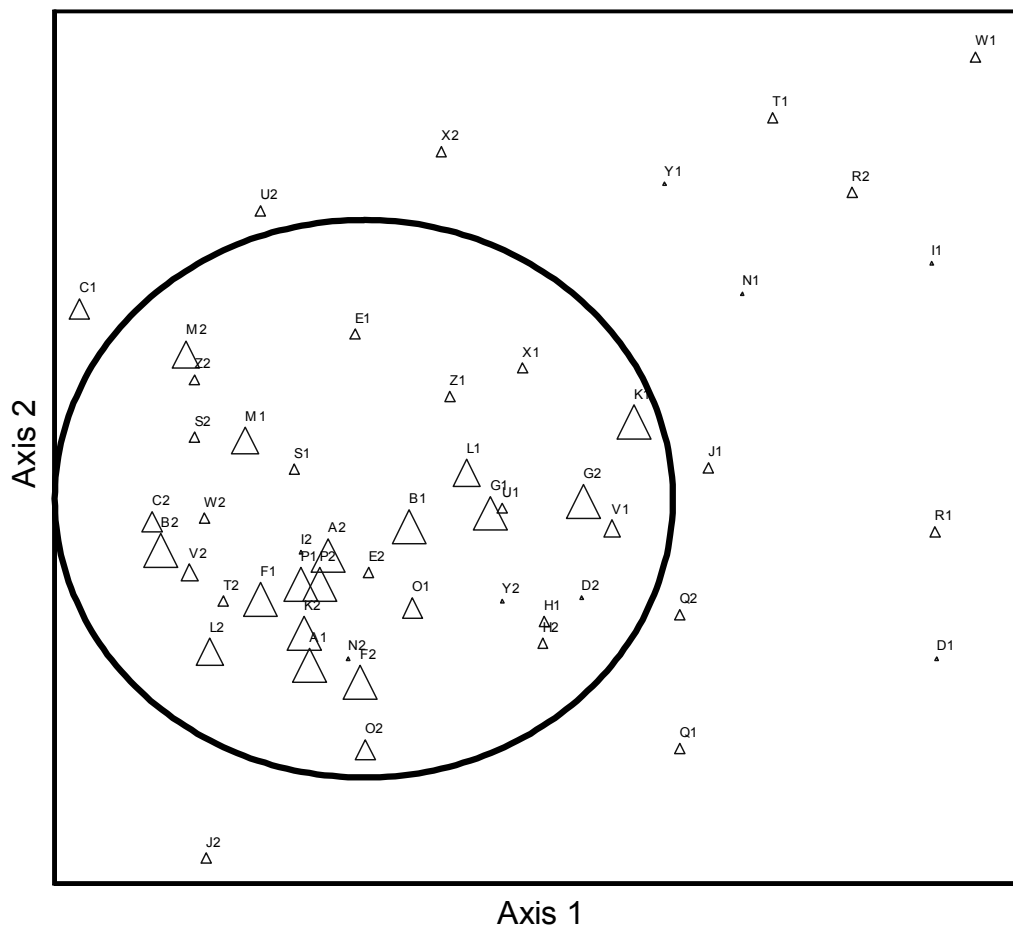


Figure 32. NMDS plot for synoptic sampling, showing array of samples with vegetation abundance superimposed. Sites designated X1, were from the July event, and sites designated X2, were collected in September. Large triangles designate sites with extensive vegetation and small triangles show sites with little or no vegetation. There is a strong correlation between invertebrate assemblage and vegetation abundance, as shown by the cluster of larger triangles encircled, to the lower left of the plot.

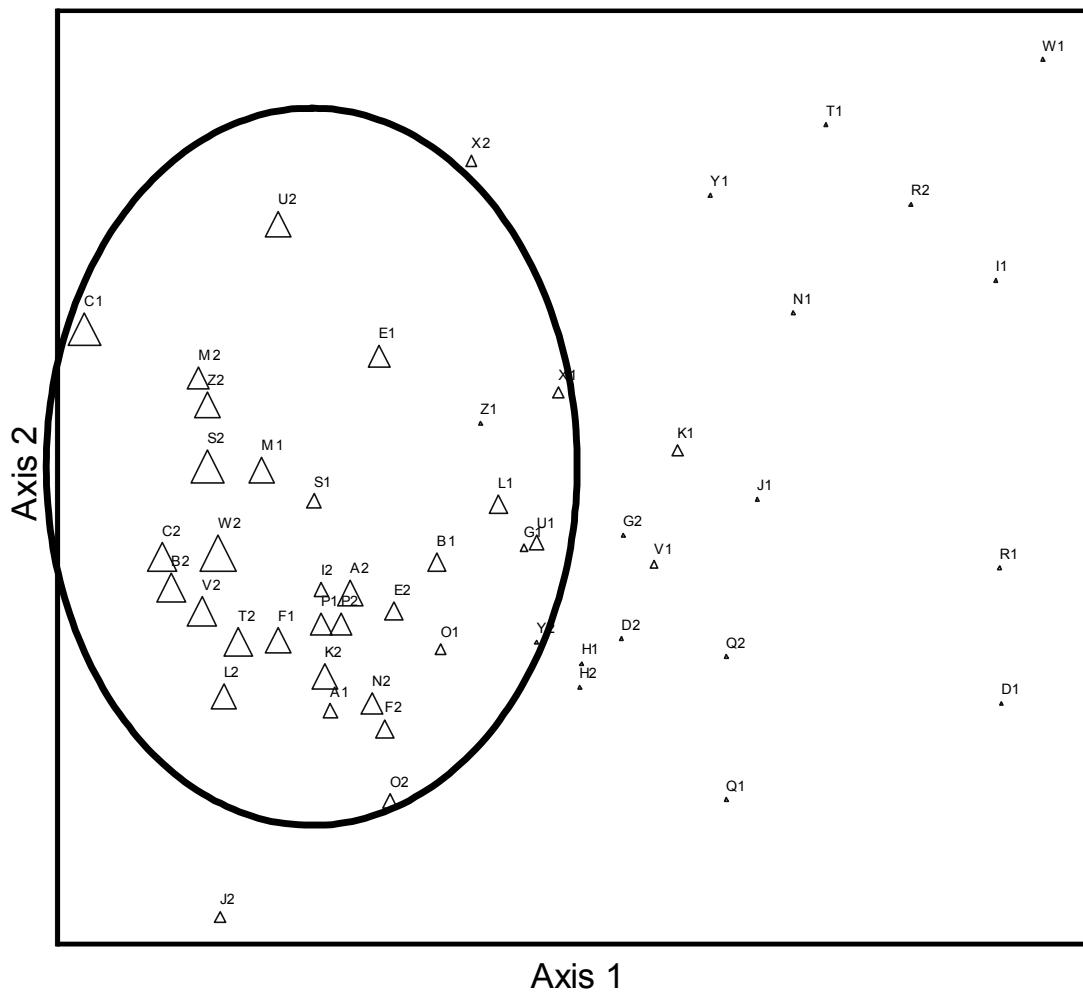


Figure 33. NMDS plot for synoptic sampling, showing array of samples with talitrid abundance superimposed. Sites designated X1, were from the July event, and sites designated X2, were collected in September. Large triangles designate sites where talitrids were abundant and small triangles show sites where talitrids were scarce or absent. There is a strong correlation between sample placement and talitrid abundance, as shown by the cluster of larger triangles encircled, to the left of the plot.

Conclusions

The supratidal zone epitomizes the ecological concept of an ecotone and possesses attributes of an ecological edge between terrestrial and marine ecosystems (Carefoot 1977; Naiman and Decamps 1990; Simenstad et al. 1997). Functions of this zone include: marine wrack deposition; deflection/absorption of wave energy; woody debris and sediment deposition (from drift-cell influenced longshore currents and directly from upland erosion); terrestrial leaf litter deposition; decomposition and recycling of organic debris; and export of organic matter and organisms to the nearshore food web. The ecological impact of large-scale shoreline armoring on these functions is still largely unknown, though this study illustrated some proximal effects of shoreline modifications.

Hypotheses

H₁: There is no difference in benthic invertebrate species composition and abundance between natural, unarmored beaches and beach stretches with shoreline modifications

Paired sampling showed that ecologically important invertebrates, such as talitrids, insects, and collembolans are reduced significantly at sites where shoreline modifications are installed lower than MHHW. Additionally, the invertebrate assemblage changes to include more marine crustaceans when the land/sea interface is lowered by shoreline armoring. The data from synoptic sampling at sites with shoreline modifications installed higher than MHHW, suggests that benthic invertebrates are not as affected by this type of armoring.

H₂: Supratidal insect assemblages are consistent in species composition and abundance between natural, unarmored beaches and beach stretches with shoreline modifications

Insect taxa richness is greater at sites with intact shoreline vegetation than at sites lacking vegetation, as indicated by the paired insect sampling. While individual taxon responses to shoreline armoring varied, fewer insects overall were collected at altered

beach sites. This was also true for amphipods and isopods collected from the paired samples. NMDS analysis of the synoptic samples showed vegetation to be important.

H₃: Sediment grain size is consistent between natural, unarmored beaches and beach stretches with shoreline modifications

Sediment grain size analysis conducted at paired sites, showed armored sites to have coarser sediments (dominated by gravel) than unarmored sites, which were of mixed-medium grain sand.

H₄: Organic debris, such as large wood, wrack, and leaf litter, is found with the same frequency at altered and natural beach sites

Natural beaches had a higher percent occurrence of organic debris, especially wrack, than did altered beaches in the paired sampling regime.

H₅: Differences between supratidal benthic invertebrate communities at natural and altered beach sites are detectable over a broad spatial scale

The synoptic sampling indicated similar benthic invertebrate communities throughout the central Puget Sound basin at armored and natural sites. The Dockton Beach site (paired sampling), located in a low energy embayment, had a slightly different assemblage than did the other sites in that study, suggesting that wave energy, tidal range, or other physical variables may influence invertebrate composition at that site.

Synopsis

Taken together, the results from the synoptic and paired sampling regimes demonstrate the impacts of shoreline armoring on invertebrate assemblages. Presumably, these impacts result from changes in elevation, decrease in the deposition of organic debris, coarsening of sediments, and vegetation removal.

The negative impact of shoreline modifications on the deposition of organic debris is noteworthy because this material, especially wrack, is habitat for much of the supratidal fauna and likely serves as a basis for the nearshore detritus-based food web. Talitrids, in particular, are highly wrack-dependent. As highly motile scavengers that feed on wrack—especially algae—and other detritus (Bousfield 1981; Pank 1997),

talitrids are tightly associated with deposited wrack which provides habitat (moisture and shelter) as well as food (Oakden 1996). Decreased wrack deposition, as a result of shoreline armoring, may have adverse impacts on talitrid populations.

Additionally, talitrids are burrowing animals that prefer sandy substrate and are nocturnal, emerging from their burrows at dusk to forage on wrack. Indicator species analysis from the paired benthic invertebrate sampling showed these animals to be closely associated with natural shorelines and lacking at altered sites, presumably because concrete armoring or coarser substrates have replaced their natural sand beach habitat at altered sites.

Though not common prey of juvenile salmon (Cordell 2000; Simenstad et al. 1979; Stamatiou and Cordell 2003), ostensibly because they are semi-terrestrial, talitrids are considered prey for a number of bird species, staphylinid beetles, and small mammals (Bousfield 1981; Oakden 1996; Pank 1997). The connection between talitrid amphipods and the nearshore food web is still unknown and should be explored further, since these organisms can be densely distributed at natural beaches and are thought to be important in marine nutrient cycling in the supratidal zone (Polis and Hurd 1996).

The results from this research suggest that shoreline modifications, if established above the tidal range, may have fewer impacts on benthic organisms, especially talitrids. However, removal of vegetation, as is prevalent at altered sites, results in benthic invertebrate and insect assemblage change. Maintaining shoreline vegetation and an intact upper-beach is necessary to achieve full function of the supratidal zone.

While this study begins to draw linkages between the terrestrial and marine systems via the supratidal zone, many relationships are still unknown. Describing the point of origin of insects collected in the nearshore zone was not performed in this study, but is necessary to determine connectivity between the upland and marine systems. Quantifying the contribution of organisms from the supratidal zone—from shoreline vegetation, deposited wrack, and the benthos—is an important step in determining large-scale biological impacts of shoreline armoring, especially if impacts are demonstrated over a broad spatial scale.

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