Exxon Valdez Oil Spill
Restoration Project Final Report

Assessment of Bivalve Recovery on Treated Mixed-Soft Beaches In Prince William Sound

Restoration Project 040574
Final Report

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National Oceanic & Atmospheric Administration
National Marine Fisheries Service
Office of Oil Spill Damage & Restoration
11305 Glacier Highway
Juneau, Alaska 99801-8626

August 2007

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Study History: This project began in 2002 as the field portion of the Assessment of Bivalve Recovery on Treated Mixed-Soft Beaches in Prince William Sound (initial project number 02574-BAA). The project number changed to 030574 when funding for the second year of the project (data analysis and report preparation) was approved, and again to 040574 when supplemental funds were approved for further sample analysis. The field study was conducted in July and August 2002. Sample and data analysis were carried out in 2003 and 2004. Report preparation was carried out in 2004 and 2005 and the first draft of the report was submitted in June 2005. After peer review, the report underwent major revisions and several additional analyses were added. A final draft was submitted in April 2007.

Abstract: National Oceanic and Atmospheric Administration treatment effects studies from 1989 through 1997 suggested that bivalve assemblages on beaches in Prince William Sound treated with high-pressure washing were severely injured in terms of abundance, species composition, and function. Restoration Project 040574 assessed the generality and persistence of this apparent injury to this assemblage. We found that the initial conclusions were accurate, indicating that a considerable proportion of mixed-soft beaches in treated areas of the sound remained extremely disturbed and that these beaches are functionally impaired in terms of their ability to support foraging by humans and damaged nearshore vertebrate predators such as sea otters 13 years after the spill. Large, long-lived hard-shell clams remained 66% less abundant at Treated sites than at Reference sites. We also found that standard sediment properties did not appear implicated in lagging recovery. But, based on several lines of evidence, we deduced that a major cause for the delay was the disruption of surface armoring (a stratified organization of mixed-soft shoreline sediments common in southcentral Alaska), an effect of beach washing. Based on the apparent recovery trajectory, we predict that recovery to pre-spill status will take several more decades. We also found that sedimentary components and the biota in the armored mixed-soft sediments in Prince William Sound do not respond according to traditionally described paradigms for homogeneous sediments.

Key Words: armoring, beach washing, bivalves, clams, *Exxon Valdez* oil spill, hard-shell clams, *Hiatella arctica*, high-pressure hot-water wash, injury, Prince William Sound, *Protothaca staminea*, recovery, recruitment, *Saxidomus gigantea*, sediment condition, shoreline treatment.

Project Data: *Description of data* – Extensive field notes were collected to document site conditions in Prince William Sound, Alaska. Sediment and infaunal samples were collected from intertidal field survey at 40 locations in August 2002. Sediment samples were composited from three locations along a transect at each site. The infauna was sampled with core samples to examine its smaller components and with larger excavations to examine its larger components. Elevation of the sampling site was measured relative to water level at each site and corrected to provide an elevation relative to Mean Lower Low Water. Water temperature and salinity data were collected. Considerable data showing site conditions are archived as digital images taken at each site. *Format* – Field notes are located in field notebooks. All infaunal, elevation, and water quality data exist as computer spreadsheet files. Digital photographs are in JPEG image formats. Samples of bivalves and other infaunal organisms from cores and excavation samples are archived in 70% isopropyl alcohol. *Custodian* – Field notes, computer databases, and photo archives are in the custody of Dennis Lees and William Driskell. Bivalve samples from the core and excavation samples are in the custody of Dennis Lees, Littoral Ecological & Environmental Services, 1075 Urania Ave., Leucadia, CA 92924. Phone (760) 635-7998. Fax: (760) 635-7999, dennislees@earthlink.net. William B. Driskell, 6536 20th Avenue NE, Seattle, WA 98115. Phone: (206) 522-5930, bdriskell@comcast.net.

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Executive Summary

Based on findings of 1990 – 1996 National Oceanic & Atmospheric Administration treatment effects study, long-term effects of washing oiled mixed-soft beaches in western Prince William Sound with high-pressure hot-water or warm-water included: 1) dramatic reductions in population densities of long-lived species in surviving infaunal assemblages, especially bivalves; and 2) removal of fines and organics, which substantially changed sediment quality. We hypothesized that these factors could combine to create a negative feedback process that delayed recovery of the infaunal assemblages.

Using methods similar to those used in the National Oceanic & Atmospheric Administration study, we collected bivalves from infaunal cores sieved on a small-mesh screen to provide data comparable to those in the National Oceanic & Atmospheric Administration study to assess younger components of the assemblage. We also collected larger excavation samples that we sieved on a larger mesh screen to focus on the larger, more mature components of the bivalve assemblage. We sampled 23 Treated (oiled-and-washed) and 17 Reference (oiled-but-unwashed) sites. To assess environmental and biological consistency with the earlier National Oceanic & Atmospheric Administration study, the Treated and Reference categories included three oiled-and-washed and one oiled-but-unwashed National Oceanic & Atmospheric Administration sites, respectively.

To examine whether differences still existed between Reference and Treated sites, we compared:

1. sediment conditions (particle grain size, total organic carbon, total Kjeldahl nitrogen, and carbon:nitrogen ratio);
2. environmental variables (*e.g.,* an exposure score and latitude);
3. numbers of individuals (N);
4. species richness (S);
5. species diversity (Shannon-Wiener diversity index [H’]);
6. species composition of the bivalve assemblage;
7. abundance; and
8. size/age structure of dominant bivalves.

To assess the influence of exposure on sediment condition and its potential confounding role in the distribution of bivalves, we devised an exposure index using an integrated analysis of geological and biological factors that reflect exposure at a site. The sites in both treatment categories represented a substantial range of exposures but the exposure regimes did not differ significantly between the categories. Consequently, we concluded that exposure was not a confounding factor.

Abundance of the dominant species and the numerical characteristics for the bivalve assemblage appear to exhibit numerous significant correlations with sediment properties. This appears true for the data set as a whole, implying generality within this bivalve assemblage, and within the respective sample types (core and excavation). The typical responses observed in the dominant species and the numerical characteristics for the bivalve assemblage were decreases in abundance or numbers of species in response to increased median particle grain size and

increases in N or S in response to increased silt/clay, total organic carbon, and total Kjeldahl nitrogen. But the details suggest a more interesting habitat phenomenon and also suggest the probable cause for a delay in the bivalve recovery process.

Sediments at both Reference and Treated sites were classified mainly as gravels and pebbles but overall, sediments were significantly coarser in the Treated category. Because this difference is based on particle sizes that would not be influenced by beach washing, we concluded the effects of beach washing at the Treated category were not the cause of this difference. Although particle size correlated directly with exposure at Treated sites, since the range of exposure extended only slightly higher for Treated sites, we speculate that the higher particle size is a result of historic geologic conditions, *e.g.*, differences in the types, size, or sources of rock at the Treated and Reference sites.

Quantities of silt/clay and concentrations of organic matter (total organic carbon and total Kjeldahl nitrogen) were low in both treatment categories (average silt/clay ≈3.0%; average total organic carbon ≈1.2 – 1.5%) but considerably higher than would be predicted by the traditional sediment paradigms that illustrate the frequently reported inverse relationships between coarse fractions, on one hand, and fine fractions or organic content, on the other. Neither silt/clay (fines) nor organic fractions differed significantly between Treated and Reference sites in Prince William Sound. Since 1996, carbon/nitrogen ratios have decreased at National Oceanic and Atmospheric Administration sites to a point indicating that the major sources of organic matter in these sediments are benthic marine plants from nearby algal or eelgrass beds and terrestrial debris from adjacent shorelines, rather than petroleum hydrocarbons. Although no chemistry samples were taken, based on our experience on other studies, failure to observe sheening in sampling pits at our sampling sites suggests the sediments were clean at our sampling locations. Consequently, although sediment properties appear to exert considerable influence on the bivalves, they do not appear to be an important factor in the lagging recovery of bivalves at Treated sites.

Exposure to wave action and tidal currents appears to play a role in the sediments but primarily at Treated beaches. As the traditional sediment paradigm would predict, median particle grain size exhibited a positive correlation to increasing exposure whereas the silt/clay fraction and the organics all responded negatively. However, the quantities of fines and organics were substantially higher than would be predicted by traditional paradigms. These responses seem to fit well if viewed from the perspective of the recently reported armoring concept for mixed-soft or "gravel" beaches in Prince William Sound. In this process, finer fractions are winnowed away, leaving pebbles and cobbles at the surface of the sediment more concentrated and "organized" (*e.g.*, imbricated or shingled) so that they form an armored surface layer. This layer provides protection to the underlying sediments and allows fines, organics, and long-lived burrowing organisms such as clams to be sequestered in deeper sediment horizons.

This process appears to explain why the relationships traditionally reported between fines, organic matter, or infaunal assemblages and relatively homogeneous mud, sand, or gravel substrata do not pertain to heterogeneous mixtures of cobble, gravel, sand, and fines, *i.e.*, mixed-soft sediments, of southcentral Alaska. Typically, organic matter, infaunal abundance, species richness, and biomass are negatively correlated with grain size, meaning that coarse sediments such as gravel should contain very low or negligible concentrations of fines and organics and an impoverished biota. However, mixed-soft substrata in Prince William Sound are characterized by quantities of organics similar to those observed in stable mud and sand substrata on the continental shelf or in embayments. Like those sediments, the infaunal assemblages are dominated by large, long-lived organisms. Although reports of similar armored sediments and the associated infauna are uncommon, it seems obvious that these armored, mixed-soft sediments function in a distinctively different manner from more commonly studied homogenous intertidal and subtidal sediments (*e.g.*, a sand beach or a mud flat).

Cognizant of the armoring process on mixed-soft beaches, we now posit that disruption of the armor layer by beach washing is at least partially responsible for the positive correlation observed between PGS and exposure and largely responsible for the negative correlation between the fines and organics and exposure observed for Treated sites. More importantly, we believe this disruption is responsible for the lag in recovery of the bivalve assemblage, especially for hard-shell clams. Thus, this report examines the suite of biological and physical factors from the perspective of impacts from disrupted armoring.

For this study, we used two types of samples to examine the bivalve assemblage. Samples excavated from 0.0625-m^2 plots sieved and through a 6.35-mm screen were used to provide insight into the abundance of larger size classes of clams. Samples from 0.009- m^2 cores sieved through 1.0-mm sieves were used to provide insight into the abundance of younger and smaller size classes of clams. Littleneck clams (*Protothaca staminea*), Arctic nestling clams (*Hiatella arctica*), pointed macomas (*Macoma inquinata*), and Washington butter clams (*Saxidomus gigantea*) dominated in both excavation and core samples. The tiny nestling robust mysella (*Rochefortia tumida*) was an added dominant in the core samples. These species will be referred to by their generic names below where only one species of a genus is reported.

As we predicted based on the findings of the National Oceanic and Atmospheric Administration study, both N and S for the excavation samples were significantly higher at Reference than at Treated sites. H’ exhibited a strong trend toward higher values at Reference sites. For core samples, we assumed that the bivalve assemblage at Treated sites was at an early stage of recovery and therefore predicted that S would be lower but, because pioneer species and younger individuals could be more abundant at Treated than at Reference sites, N would be higher. In fact, N and S exhibited strong but not significant trends conforming to the postulated patterns. Species diversity was significantly lower at Treated sites.

In the excavation samples, *Protothaca*, *Hiatella*, *Macoma inquinata*, and *Saxidomus* dominated the bivalve assemblage. The large, long-lived *Protothaca* and *Saxidomus* were significantly less abundant (66%) at Treated than at Reference sites. Contrary to findings in the earlier National Oceanic and Atmospheric Administration study predicting that *Hiatella* would be more abundant at Treated than at Reference sites, it also exhibited a strong trend toward higher abundance at Reference sites in the excavation samples. The biota at the Reference sites, with greater abundance of large, long-lived bivalves, appeared to represent a later stage of succession than the Treated sites. However, the bivalves assemblages observed during this study were not nearly as well developed as the death assemblages observed in uplifted sediments representing pre-1964 earthquake conditions in Prince William Sound.

Differences observed in the dominant bivalves inhabiting core samples from Reference and Treated sites during the earlier National Oceanic and Atmospheric Administration studies still remained in 2002. The bivalve assemblage in the core samples was dominated, in order of abundance, by *Rochefortia*, *Protothaca*, *Hiatella*, juvenile *Modiolus*, *Macoma balthica*, and *Saxidomus*. Hard-shell clams (*Protothaca* and *Saxidomus*) were substantially less abundant at Treated than at Reference sites (44%). *Hiatella* and *Rochefortia* were substantially more abundant at Treated than at Reference sites.

The differences in the bivalve assemblages represent functional or structural differences between Reference and Treated sites. Numerically, large, long-lived clams in core samples were 44% less abundant at Treated than at Reference sites while small, short-lived clams were 98% more abundant. This pattern is more exaggerated in the excavation samples, which provide better insight into the larger sizes of clams. In these samples, hard-shell clams ≥ 20 mm long were 66% less abundant at Treated sites than at Reference sites. Based on size differences among these various clams, we can infer that prey biomass available to sustain nearshore vertebrate predators was considerably higher at Reference sites than at Treated sites.

Subtle differences in the responses to exposure also provide useful insights. In the excavation samples, hard-shell clams at Reference sites increased in abundance with increasing exposure whereas those variables were uncorrelated at Treated sites. In contrast, abundance of the smaller clam component (from core samples) declined significantly at Treated sites with increasing exposure whereas that component was unaffected by increasing exposure at the Reference sites. Since abundance of juvenile clams was similar at Reference and Treated sites, we have inferred that, while exposure did not cause significant injury to populations of smaller clams at Reference sites, it caused substantial mortality for smaller clams at Treated sites. We believe that, in both the excavation and core samples, this was likely a consequence of the disruption of the armor layer. For the smaller clam component, because the disrupted armor layer at Treated sites provided less protection from disturbance, the populations of younger clams suffered higher mortality during storm events and from predators than did those at Reference sites. Consequently, recruitment to adult size classes was slower at Treated sites. In contrast, armoring at the Reference sites resulted in greater recruitment to adult size classes by creating a safer refuge from wave action and predators.

Although abundance for each of the dominant species varied considerably between treatment categories, size structure did not differ appreciably except for one facet. In each species, the relative abundance of part of the size structure was lower at Treated than at Reference sites. For example, 5- to 10-year-old *Protothaca* were 10 and 12% less abundant, respectively, in excavation and core samples from Treated sites. For 6- to 11-year old *Saxidomus*, the difference was 22% for excavation samples; too few were encountered in core samples for comparison. For shorter-lived *Hiatella*, 18 and 23% fewer 2.5- to 3.5-year-old animals, respectively, were observed in excavation and core samples from Treated sites. While these differences are not significant, because of the consistency of the pattern, we suspect the deficits in size structure may indicate real differences in post-recruitment success. In the hard-shell clams, that deficit appeared to operate from about 1991 to 1997.

To examine whether recruitment rates have been affected by site treatment, we compared numbers of juveniles and juvenile/adult ratios between the treatment categories. Correlations between numbers of juveniles and adults for hard-shell clams were highly significant in both treatment categories. The density of *Protothaca* juveniles, a major prerequisite for later stages of succession, was only marginally higher at Reference sites. In contrast, *Hiatella* exhibited a strong trend toward more juveniles at Treated than at Reference sites, suggesting a positive response to disturbance or instability by this opportunistic pioneer species. The fact that juvenile/adult ratios for all three species were higher at Treated sites but, in the case of *Protothaca* and *Saxidomus*, the density of adults remained substantially lower at Treated sites, suggests that post-recruitment phenomena were reducing juvenile survival. Although juveniles were recruiting at similar levels at Treated and Reference sites, they were not surviving to achieve adulthood and consequently the populations at Treated sites were not yet recovering. Reduced organization of the armor layer can probably result in increased predation on juveniles and, very importantly, their resuspension and displacement during storm events. We strongly suspect that the disruption of the armor layer by beach washing is a major factor leading to the apparent increase in post-recruitment mortality.

In bivariate analyses, abundance of the large, long-lived bivalves (*Protothaca* and *Saxidomus*) exhibited significant inverse correlations with distance from the Gulf of Alaska (where latitude was used as a surrogate). However, the response was strikingly similar at Reference and Treated sites in *Protothaca*. *Hiatella*, a pioneer species, did not show this response to latitude. While this phenomenon indicates systematic variability, we do not believe it confounds the results. Multivariate stepwise regressions did not find that latitude was an important factor.

Multivariate regressions show strong correlations with various sets of factors, some of which are quite intriguing. Likewise, cluster analyses, ordinations that also group similar species and stations and with certain data, correlate well with various combinations of physical factors, but sometimes not so well. Overall, the multivariate analyses consistently support the hypothesis that disrupted armoring is the cause of lagging hard-shell clam recovery but do so only obliquely. Ordered patterns observed in plots of residual analysis suggest that a major driving component(s) is missing from the data set. They suggest that some unmeasured factor, possibly armoring, may better correlate with clam abundance.

Conditions observed in the sediments and bivalve assemblage in 2002 are consistent with the patterns observed during the National Oceanic and Atmospheric Administration study. Data from that study generally appear to provide an accurate representation of conditions on Treated or unwashed soft beaches in western Prince William Sound, although conditions at the three treated National Oceanic and Atmospheric Administration sites were more impoverished than was generally the case at our Treated sites. It appears that substantial changes have occurred since 1996. Sediments at Treated sites appear to have gotten coarser. Fines, total organic carbon, and total Kjeldahl nitrogen at both Treated and Reference sites have declined since 1996 with the organics approaching the level observed at unoiled sites in the National Oceanic and Atmospheric Administration study. Reductions in carbon/nitrogen ratios suggest that marine plants and terrestrial vegetation were the predominant sources of organic matter in 2002 and that hydrocarbons (low in nitrogen) present in sediments at the National Oceanic and Atmospheric Administration sites in the earlier study were no longer driving carbon/nitrogen ratios higher.

While the bivalve assemblage at Treated sites was showing signs of recovery, abundance of the most important bivalves, *Protothaca* and *Saxidomus*, remained significantly lower than at Reference sites in this study and at unoiled sites sampled during the National Oceanic and Atmospheric Administration study. In contrast, abundance of the pioneer species *Hiatella*, considerably elevated above levels observed at unoiled National Oceanic and Atmospheric Administration sites at both Reference and Treated sites during the earlier period, had declined in 2002 to levels closer to those observed at unoiled sites in the National Oceanic and Atmospheric Administration study.

In summary, the preponderance of evidence suggests that, on average, Treated sites differed substantially from Reference sites in 2002. The types of differences are consistent with the hypothesis that the Treated sites had been subjected to considerable disturbance by beach washing and they had not yet recovered. Areas of difference included species richness and diversity, overall and species-specific abundance, size structure, and species and functional composition. Paramount among these differences is the fact that after 13 years, hard-shell clams (*Protothaca* and *Saxidomus*) were 66% and 44% less abundant at Treated sites than at Reference sites in excavation and core samples, respectively. Comparison to densities observed during the National Oceanic and Atmospheric Administration study indicates that the trajectory of recovery is relatively flat and, given the apparent recovery trajectory observed since 1996, full functional recovery to the condition existing before the spill will probably not be achieved for several more decades. Generally, other investigators examining effects of disturbance in bivalve assemblages have reported shorter durations for recovery. However, few studies have followed the recovery process for this many years and none, apparently, in this habitat type. Considerable evidence suggests that this substantial delay in recovery in the bivalve assemblage is a result of beach washing, which disrupted the organization of the armor layer that facilitates the development of the long-lived bivalves and the associated infaunal assemblage living in mixed-soft sediments in Prince William Sound.

Introduction

The T/V *Exxon Valdez* ran aground in the northeastern part of Prince William Sound, Alaska, (PWS) on March 24, 1989. Over the next several weeks, a substantial amount of the nearly 41 million liters of spilled Alaska North Slope crude oil was deposited on a large proportion of beaches in the southern and western portions of the sound and on Gulf of Alaska beaches to the southwest. Shoreline cleanup activities were carried out with varying degrees of intensity throughout the summer of 1989 on about 560 km of the 780 km of oiled shoreline in the sound (Harrison 1991). Many of the oiled beaches were "Treated," typically using high-pressure, hot- or warm-water washing (HP-HW) techniques. The objective was to mobilize and dislodge the oil by spraying the intertidal zone with heated seawater (40-60° C) and then skim up the oil as it floated within booms placed just offshore of the beach. Commonly, the hot or warm water was directed at the beach through hand-held hose nozzles or large spray-heads mounted on mechanical arms operated of Maxi- or Omni-barges.

The efficacy of this cleanup method in removing oil varied substantially among habitat types (*e.g.*, Short *et al.* 2002). The process removed a considerable amount of the oil; however, it also flushed out finer sediment fractions and associated organic materials, leaving the sediments substantially altered in terms of particle grain size distribution and organic content, and we surmise that it mixed low concentrations of oil deeper into the sediment. Also, large numbers of infaunal organisms were flushed out of the sediments, displacing, damaging, or killing them (Lees *et al.* 1996), and probably destroying associated burrow systems that helped oxygenate the sediments. The beach cleanup thus left the infaunal assemblage greatly impoverished (Driskell *et al.* 1996). But this scenario only describes the short-term effects.

Later analyses of infaunal data from the National Oceanic and Atmospheric Administration (NOAA) study of treatment effects and recovery (Recovery and Treatment Effects Program) suggested that the HP-HW treated infaunal assemblages remained fundamentally impaired as late as 1996 (summarized from Houghton *et al.* 1997). This impairment was most evident in the bivalve assemblage but was also apparent for most major infaunal taxa. For bivalves, abundance, species richness, and species composition were all negatively affected (Table 1). Based on shell-length:weight relationships, we can also infer that biomass was considerably reduced. Abundance and species richness of infaunal bivalves were significantly lower at Treated (oiled-and-washed) than at Reference (oiled-but-unwashed) sites. Averages for these variables at the Treated sites showed little change over the six years of the program. Based on the large differences between the Treated, on one hand, and the unoiled and Reference sites, this pattern suggests no apparent trends representing recovery. Also, by altering the dominant species from large, long-lived burrowing clams such as *Protothaca* and *Saxidomus* to small nestling, short-lived pioneer species such as *Hiatella*, the process changed the biological functioning of the bivalve assemblage from one that supported human subsistence and predation by sea otters and large sea stars to one with reduced foraging potential.

In addition to bivalves, this pattern was also apparent for polychaetes, echinoderms, snails, and crustaceans as late as 1996 (Houghton *et al.* 1997). Moreover, our studies indicated that a return to the condition observed at unoiled beaches was occurring very slowly, apparently due to lack of recruitment by the larger, longer-lived bivalves. We postulated that restoration might be delayed by the slow rate at which sediments, also seriously disturbed by the effects of HP-HW washing, were recovering to baseline conditions.

Table 1. Abundance and distribution of bivalves by treatment categories at NOAA study sites in western Prince William Sound from 1989 through 1996.

Taxon	**Average Number per Sampling Event** **Unoiled Sites**	**Reference Sites**	**Treated Sites**
Clinocardium ciliatum	0.08		
Compsomyax subdiaphana	0.08	0.09	
Cryptomya californica	0.12		
Diplodonta aleutica		0.54	0.08
Hiatella arctica	3.46	8.51	**18.40**
Macoma spp.	1.15	2.29	0.04
Macoma balthica	6.77	4.23	0.76
Macoma inquinata	11.35	8.54	0.04
Macoma obliqua	0.23	0.03	
Mactridae, unid.		0.06	
Mya arenaria	0.15	0.03	
Mysella tumida	**82.27**	**37.91**	5.16
Protothaca staminea	16.27	14.09	1.36
Saxidomus gigantea	1.27	1.66	0.08
Semele rubropicta		0.06	
Tellina spp.	0.04		
Tellina modesta	0.12	0.03	
Tellinidae, unid.		0.14	
Veneridae, unid.		0.03	
Total Taxa in Category	14	16	8
Ave. No./Sampling Event	123.3	78.2	25.9
Number of Sites Sampled*	3.2; 1 – 4	4.2; 4 – 5	4.0; 3 – 5

* Average and range of sites sampled; number of sites varied by year

The bivalve assemblage observed in unoiled and Reference sites during the NOAA study was dominated by relatively long-lived clams, mainly *Macoma* spp. and *Protothaca staminea*, and a small, short-lived clam *Rochefortia (=Mysella) tumida* (≈5 mm shell length and living to be ≈5 years old [Ockelmann and Muus 1978]; Table 1). Most of the long-lived clams characteristically burrow in stable sediments (*e.g.*, *Macoma* and *Protothaca*; Peterson and Andre 1980; Houghton 1973; McGreer 1983). However, members of the genus *Rochefortia* usually live in a commensal relationship in semi-permanent burrows with large burrowing infaunal organisms such as sea cucumbers, sipunculids, echiurans, or shrimp (Ockelmann and Muus 1978). In contrast, Treated sites were strongly dominated by *Hiatella arctica* (Table 1), a relatively small, opportunistic, widely distributed "weed" species that nestles on the surface of disturbed sediments, on new rocks, or synthetic substrates (Morris *et al.* 1980; Gulliksen *et al.* 1980; MacGinitie 1955) and frequently dominates the biota in those habitats.

The physico-chemical sediment characteristics measured during the NOAA studies (particle grain size [PGS], total organic carbon [TOC], total Kjeldahl nitrogen [TKN], and polycyclic aromatic hydrocarbons [PAH]) can influence development of infaunal assemblages. Generally, sediments at all NOAA sampling sites were relatively coarse; most contained substantial quantities of pebbles. As expected, average median grain size was finest at unoiled sites and coarsest at Treated sites. Concentrations of fines in the sediments averaged four times higher at unoiled sites than at Treated sites. In addition, sediments at unoiled and Reference sites were generally contained significantly higher concentrations of TOC and TKN than Treated sites. Comparison of carbon/nitrogen (C/N) ratios provides further insight into the sediment quality at these sites**.** C/N ratios at unoiled and Reference sites were about 50% lower than at Treated sites, indicating that, per unit of carbon, nitrogen concentrations (contributed largely by benthic diatoms and bacteria on particulates) were lower at Treated sites than elsewhere. This suggests that nutrient quality is poorer for deposit feeders and selected suspension feeders at Treated sites than at unoiled or Reference sites (*e.g.*, Newell 1965).

We decided that, 13 years after the spill, concentrations of PAH in sediments were spatially patchy and insufficiently high to warrant measuring them for this program (James Payne, pers. comm.) PAH concentrations at Reference sites, where they were highest during the NOAA studies (Table 2), were three to four orders of magnitude below concentrations used by Pearson *et al.* (1981) to assess behavioral changes of crab predation on *Protothaca* following exposure to oiled sediments. Furthermore, they were also below concentrations reported by Bernem (1982) as not causing mortality in *M. balthica*. The NOAA ER-L for PAH (4,022 ppb; Long *et al.* 1995) is almost five times that of the highest average observed. Finally, PAH concentrations at both Reference and Treated sites were initially declining at a rate of about 25% per year but the rate has slowed drastically to less than 4% per year as only the few most recalcitrant deposits remain (Short *et al.* 2007).

Table 2. Comparison of physico-chemical characteristics of sediment at 1990 – 1996 NOAA infaunal stations.

Category	**Elevation Above MLLW (feet)**	**Particle Grain Size (mm)**	**Silt/Clay (%)**	**PAH (ng/g)**	**Total Organic Carbon (%)**	**Total Kjeldahl Nitrogen (%)**	**Organic Carbon/ Nitrogen Ratio**
UNOILED							
Mean ± SE	1.0 ± 0.3	1.9 ± 0.4	20.4 ± 1.5	2.7 ± 0.8	1.5 ± 0.2	0.049 ± 0.005	37.0 ± 6.0
REFERENCE							
Mean ± SE	0.6 ± 1.2	>5.8 ± >2.8	15.8 ± 2.1	807 ± 431	3.1 ± 0.6	0.091 ±0.021	49.7 ± 8.0
TREATED							
Mean ± SE	0.1 ± 0.4	3.6 ± 0.3	6.1 ± 1.5	54 ± 17	1.2 ± 0.4	0.024 ± 0.004	63.4 ± 9.6

Objectives

The primary reason for conducting this study was concern about the implications of impoverished conditions and functional component (species) losses that we had observed in the intertidal infauna at Treated sites in western PWS since 1989. We postulated that the differences observed between Reference and Treated sites, initially due to the beach cleanup in 1989 and 1990, were persisting because of differences in sediment properties rather than hydrocarbons in the sediments and compounded by naturally slow and sporadic recruitment patterns.

Generally, the thrust of this study was to see if shoreline treatment had caused greater mortality at Treated sites than at Reference sites. However, given the time elapsed since the spill and the major shoreline cleanup efforts, an implicit issue that needed to be addressed was, "If cleanup caused significant injury to bivalve assemblages, have the effects of that treatment had a significant impact on recruitment of the injured populations?"

Unfortunately, because the geographic scope of our earlier NOAA studies was limited (ten sites divided between three treatment categories) and the sites were not truly randomly selected, those findings cannot be statistically extrapolated to other affected areas in the sound. Hence, this study was designed to expand the geographic scale and evaluate lingering impacts for the entire spill region of the sound. However, to reduce the scope, we focused on just the bivalves. Thus, the two major objectives of the current program were to: 1) assess whether the depressed condition of the bivalve assemblage observed at Treated sites in our earlier work was general to washed sites throughout western PWS; and 2) evaluate the relationship between three sediment properties, particle grain size (PGS), Total Organic Carbon (TOC), and Total Kjeldahl Nitrogen (TKN), and the apparent depression of bivalve assemblages in treated sediments. This report focuses on an evaluation of sediment properties and other environmental variables, the numerical characteristics and species composition of the infaunal bivalve assemblage, and size/age structure of the dominant bivalves.

Hypotheses

Based on the observations during the NOAA studies (see Tables 1 and 2), we addressed specific questions related to physico-chemical sediment properties and the biological assemblages. These included:

> For sediments: Is PGS at Treated sites coarser than at Reference sites? Are silt/clay, TOC, and TKN at Treated sites lower than at Reference sites? Are C/N ratios at Treated sites higher than at Reference sites?
>
> For the biological assemblages: Do numerical characteristics for the bivalve assemblage (number of individuals [N], species richness [S], and species diversity [H']) have higher values at Reference sites than at Treated sites? Does abundance of the dominant bivalves differ between Reference and Treated sites? Specifically, is abundance of *Protothaca*, *Saxidomus*, *Rochefortia*, and *Macoma* spp. greater at Reference sites than at Treated sites? Is abundance of *Hiatella* greater at Treated sites than at Reference sites?

The hypotheses tested for sediment are as follows:

H_o = Sediment properties (percent silt/clay, Total Organic Carbon, Total Kjeldahl Nitrogen, and C:N ratios) are statistically similar at Treated and Reference sites.

H_a = Sediment properties are dissimilar at Treated and Reference sites. Specifically, percent silt/clay, Total Organic Carbon, and Total Kjeldahl Nitrogen are lower at Treated than at Reference sites, and C:N ratios are higher at Treated than at Reference sites.

The hypotheses tested for each sample type for the bivalve assemblage are as follows:

1. H_o = Numerical characteristics of the bivalve assemblage (number of individuals, species richness, and species diversity) are similar at Treated and Reference sites.
   H_a = Numerical characteristics of the bivalve assemblage exhibit lower values at Treated sites than at Reference sites.

2. H_o = Size structure of the dominant bivalves are statistically similar at Rreated and Reference sites.
   H_a = Size structure of the dominant bivalves are dissimilar at Treated and Reference sites, with average shell length of populations at Reference sites being larger than at Treated sites.

The basis for determining whether the alternative hypotheses defined above were 1- or 2-way tests and the direction of the differences in cases where 1-way tests were specified was the patterns that we observed for specific variables during the 1990 – 96 NOAA study.

Study Area

Prince William Sound is a relatively protected fjord system located on the south-central coast of Alaska. The shoreline is heavily dissected and irregular, providing a high diversity of shoreline types and a wide range of exposures. This study was conducted in central, western, and southwestern PWS, areas, which lay in the path of the oil slick as it flowed southwest through the sound (Figure 1). To maximize the potential for finding lingering effects after 13 years, we focused on areas that were moderately to heavily oiled and subsequently exposed to shoreline treatment involving high-pressure hot- or warm-water washing (Treated sites) as well as heavily or moderately oiled sites that were not washed (Reference sites). We further concentrated our efforts on beaches in protected embayments and small coves that are primarily composed of a mixture of cobbles, pebbles, sand, and silt (*i.e.*, mixed-soft habitats). However, we also sampled in relatively more exposed beaches such as Sleepy Bay and Disk Island.

Reference sites were randomly selected and were interspersed throughout the sampling area. Unfortunately, we were unable to include any unoiled sites in our study design.

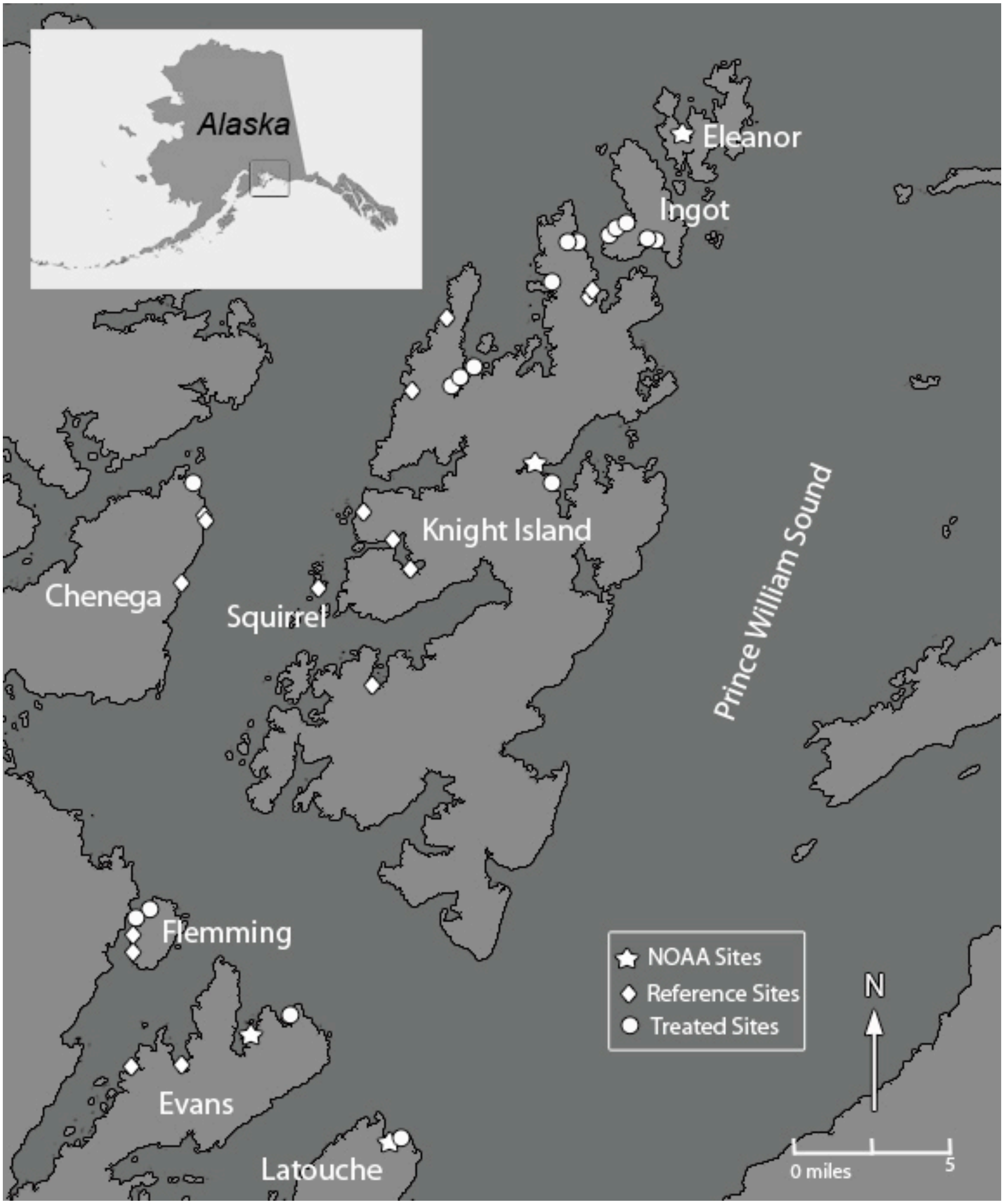

Figure 1. Bivalve sampling sites in western Prince William Sound, Alaska.

In PWS, the semi-diurnal tides have an extreme tidal excursion of about 5.5 m (18.0 feet). Although we focused on sampling selected mixed-soft beaches between Mean Lower Low Water (MLLW = 0 meter) and 0.8 m (+2.6 feet) above MLLW, we actually sampled elevations from

-0.4 m (-1.3 feet) and 0.9 m (+3.0 feet) MLLW. Densities of littleneck and butter clams and other species are common within or above this elevation range at most of the unoiled or Reference sites sampled during our NOAA studies. In contrast, infaunal assemblages were impoverished at sites above +1.3 m (+4.3 feet).

Prior to the oil spill, western PWS was subjected to a substantially more catastrophic event when the 1964 Great Alaska Earthquake uplifted the region. The portion of the sound in which our studies were conducted was uplifted from ~1.2 m (4 feet) in the vicinity of the western mainland and islands to ~3 m (10 feet) on Latouche Island (Hanna 1971). Uplift ranged from ~1.1 to 2.7 m (4 to 8 ft) in areas of heaviest oiling. Therefore, because they were thrust above an elevation at which they can survive, the intertidal clam assemblages in those areas were largely exterminated at that time. Shell remnants of these clam beds, with clam shells still articulated and positioned in the sediments as they were on the day of the quake, can be found at high intertidal to supratidal elevations in many areas in PWS. Thus, it is likely that the intertidal bivalve assemblages existing at the time of the oil spill had been redeveloping for only 25 years. Based on these qualitative observations, it appears the clam assemblages existing at the time of the spill comprised substantially younger and smaller clams than those destroyed by the quake. Moreover, considering the smaller size and lower densities of the more long-living species (littleneck clams [*Protothaca staminea*] and butter clams [*Saxidomus gigantea*]), the post-quake assemblages appeared less developed.

Literature Reviewed

For this project, we reviewed a considerable body of literature relating to various aspects of bivalve ecology with a focus on understanding the manner in which sediment properties can influence recruitment and recovery from disturbances. We also examined the potential for adult abundance to influence recruitment by juveniles. While many of these studies are not directly or wholly applicable to the discussion, they provide a useful background and a context for many of the discussions that follow and are therefore presented here in a separate section. The most relevant studies have been included in the Discussion.

Interactions Between Sediment Conditions and Bivalve Assemblages

With respect to genera similar to the bivalve assemblage discussed herein, MacFarlane and Booth (2001) reported that abundance of *Mysella vitrea*, an analog to *Rochefortia tumida*, varied inversely with concentrations of silt/clay and organics.

Sediments with elevated carbon/nitrogen (C/N) ratios (relatively low amounts of nitrogen or high carbon) tend to support a lower biomass of benthic invertebrates (Grebmeier *et al*. 1988). C/N values of less than 10 typically represent bacteria and rapidly dividing phytoplankton or benthic algae such as diatoms (Tyson 1995; Valiela 1995). These materials are more useful in protein synthesis than materials with high C/N ratios. Detrital materials derived from benthic algae and terrestrial debris have C/N ratios ranging from roughly 15 to 50, respectively, with mixtures and aging of the material producing intermediate values (Tyson (1995). C/N values increase progressively for marine and terrestrial plants and as detrital plant materials degrade or age.

Sediments and Recruitment:

Woodin (1991) emphasized that, “Recruitment is a process of fundamental importance because it is the background upon which all subsequent interactions with the community take place”. Numerous studies have demonstrated that sediment characteristics are used as positive or negative cues of suitability by competent infaunal larvae before recruiting into sediments.

Colonization rates of sediments by infaunal organisms typically vary positively with the quantity and quality of organics (Snelgrove *et al*. 1992). Species-specific factors such as organic or silt content or presence of bacterial films in the sediments often act to stimulate competent larvae to settle out of the water column and are therefore viewed as positive cues. Studies by Wilson (1937, 1948) demonstrated that grain size could be an important factor stimulating settlement and that larvae can delay metamorphosis while searching for the preferred sediments. In later research, Wilson (1955) concluded that a moderate film of living bacteria was more important than grain size in inducing metamorphosis and settlement for the polychaete *Ophelia bicornis* and postulated that sediment specificity may be an important component. Hall *et al*. (1993b) subsequently arrived at the same conclusion based on the distribution of infaunal organisms in subtidal sediment habitats. Snelgrove *et al*. (1998) reported that the surf clam *Spisula solidissima*, a common resident on relatively exposed sandy substrata from Labrador to North Carolina, chose organically poor sand over organically rich mud in flume experiments. Since low organic content is generally a good predictor of high-energy beaches during calm periods, this preference is probably quite useful to *Spisula.* In contrast, Grassle *et al.* (1992) reported that competent larvae of the coot clam *Mulinia lateralis* actively “choose the organically rich sediments characteristic of the adult habitat over abiotic sediments.” Regarding the importance of organic debris, Renaud *et al.* (1999) suggested that recruiting infaunal larvae can respond positively to “detrital and nutrient enhancement on the scale of a meter or less” and noted that “dislodged algae from adjacent hardbottom may be critical in determining infaunal recruitment patterns.”

Several species-specific negative cues have also been identified. Woodin (1985) and Woodin and Marinelli (1991) reported that some polychaete larvae chose not to settle on fecal mounds produced by burrowing arenicolid polychaetes and thalassinid shrimp. Woodin *et al.* (1987) reported on several infaunal organisms that secrete brominated aromatic compounds. She later listed other species (Woodin 1991), and subsequently reported that recruits of a polychaete species rejected sediments containing these biogenically produced compounds (Woodin *et al.* 1993).

Process-specific factors such as the release of ammonium from sediments following disturbance are also considered negative cues because they can cause larvae to reject sediments for a brief period (Woodin *et al.* 1995; Woodin *et al.* 1998). Activities that can cause appropriate disturbance include wave and current-induced erosion, feeding or burrowing activities, defecation by subsurface deposit feeders, and various anthropogenic activities. Oxygen or sulfide contents of sediments are other possible negative cues. All of these types of negative cues were undoubtedly brought into play by shoreline treatment activities. While the process-specific factors may have caused temporary negative influences on infaunal recruitment patterns, it is unlikely that such cues would affect long-term recovery following the cleanup activities.

Influence of Adults on Recruitment

Several investigators have reported that the presence of living clams of the same or different species or their shells are positive cues for recruitment. Ahn *et al.* (1993) reported that settlement rates of the hard clam *Mercenaria mercenaria* were higher in the presence of living specimens of the tiny gem clam *Gemma gemma,* empty *Gemma* shells, or in sediments that *Gemma* previously inhabited. Subsequently, Snelgrove *et al.* (1999) found that settlement rates by competent larvae of *Mya arenaria* showed a significant positive correlation to the abundance of *G. gemma* in the sediments. Also, larval *Mya* exhibited a marked (but not significant) positive trend to the presence of adult *Mya.* Their research also implied that post-settlement processes such as predation and post-settlement transport could have great importance in determining eventual recruitment success in sediments.

Ahn *et al.* (1993) and Thrush *et al.* (1992) have demonstrated that the presence of adult clams can lead to increased recruitment. Thrush *et al.* found that presence of adult *Tellina liliana* in defaunated sediments facilitated recruitment by larval *Tellina* and *Chione stutchburyi*. An implication of these studies is that recruitment rates for clams to the sediments defaunated by HP-HW washing could be depressed because of reduced density of adult clams.

Effects of Disturbance on Bivalve Assemblages

Numerous studies have been published on the effects of sediment disturbance on bivalve survival and subsequent recruitment or recovery. Jewett *et al.* (1999) and Strasser *et al.* (2001) discussed the effects of natural disturbance due to storms and currents. Jewett *et al.* (1999) found that, because of the naturally high degree of disturbance in soft shallow subtidal substrata in Norton Sound, Alaska, that recovery of the benthic assemblage was relatively rapid because that fauna is dominated by small, short-lived species that are well adapted for resuspension by surge and currents. These resuspended organisms subsequently effect rapid recolonization of the disturbed areas. The high abundance and the proportion of juveniles in the Norton Sound infauna in Jewett *et al.*'s (1999) findings imply that recruitment is high in this disturbed environment. Strasser *et al.* (2001) reported that success of bivalve recruitment following harsh winters varied by species, probably mostly due to post-settlement factors. The cockle, *Cerastoderma edule,* and the blue mussel, *Mytilus edulis,* exhibited higher success due to reduced post-settlement predation resulting from predator mortality. In contrast, the Baltic macoma, *Macoma balthica,* and the softshell clam, *Mya arenaria,* demonstrated reduced recruitment success, probably because of increased susceptibility to resuspension by surge and currents. Directly or indirectly, both studies indicate that while disturbance can lead to higher rates of recruitment, post-settlement factors such as predation, competition, and resuspension are important to long-term recovery. It is likely that at least initially the broad-scale mortality associated with HP-HW washing (*e.g.*, Lees *et al.* 1996) resulted in reduced predation and competition within intertidal infaunal assemblages.

Rates of Recovery Following Disturbance

Effects of and recovery from anthropogenic activities such as dredging (*e.g.*, Jewett *et al.* 1999 above) or resource harvest have been documented for several burrowing infaunal organisms, including the bivalves *Cerastoderma* (Kaiser *et al.* 2001; Piersma *et al.* 2001), *Sanguinolaria* and *Cryptomya* (Peterson 1977), the hard clam *Mercenaria mercenaria* and bay scallop *Argopecten irradians* (Peterson *et al.* 1987), and burrowing crustaceans (Wynberg and Branch 1994 and Peterson 1977). The general pattern that seems to emerge is that recovery is relatively rapid for smaller, more ephemeral infauna, especially in sediments that are more exposed (*e.g.*, the razor clam *Ensis* spp, [Tuck *et al.* 2000]) but much slower for the more long-lived target or non-target macrofaunal species (*e.g.*, Newell *et al.* 1998).

Newell *et al.* (1998) demonstrated that the rate of recovery in disturbed sediments can vary inversely with particle size. Thus, recovery can be rapid in fine sediments, which are typically dominated by ephemeral (small, short-lived) species that represent early stages of succession. In contrast, recovery is slow in coarse sediments, especially relatively undisturbed mixed gravel/sand/silt habitats, which are generally dominated by large, long-lived animals representing later stages of succession. These species generally recruit and grow slowly. These authors also pointed out that recruitment might take considerably longer at higher latitudes because successful recruitment episodes are relatively infrequent. Indeed, recovery of the bivalve assemblage at Treated sites seemed to be progressing slowly by 1996 (Driskell *et al.* 1996; Houghton *et al.* 1997).

Similarly, Ferns *et al*. (2000) reported that more complex assemblages found in relatively undisturbed muddy sediments recovered more slowly than less complex assemblages in sandy sediments. In an excellent long-term study of the consequences of clam dredging, Piersma *et al.* (2001) examined the effects of cockle dredging on intertidal bivalve stocks in a relatively protected and undisturbed mud-flat environment that supported a relatively long-lived stable bivalve assemblage. They reported it was eight years before sediment characteristics recovered. Stocks of target and non-target bivalves were far from recovered after 10 years. Recruitment remained considerably depressed in dredged areas after 10 years. They postulated a negative feedback process in which the loss of fines caused by the initial dredging initiated a cascade of consequences that "prevented the accumulation of fine-grained sediments conducive to bivalve settlement." The relationships between sediments and infaunal organisms are reciprocal; any disturbance that affects the infauna will affect the sediment and vice versa. PGS and silt/clay influence the species composition of the assemblage inhabiting sediments and, in turn, the organisms living in the sediment can influence several sediment characteristics, especially abundance of the silt/clay fraction and organics.

Methods

Site Selection

To optimize the potential for detecting treatment effects, sampling was focused on intertidal mixed-soft sediment beaches in central and southwestern PWS where the greatest quantities of oil from the spill were stranded. Using the NOAA Shoreline Segment Summary and Alaska Department of Natural Resources GIS databases and historic spill-survey documents from 1989 and 1990, appropriate shoreline segments were selected based on exposure, sediment type, degree of oiling, and recommended treatment history. A random selection of appropriate shoreline segments was made from this list. Each of the selected segments was then physically viewed during an aerial reconnaissance to determine where suitable sites with an adequate stretch of beach composed of mixed-soft sediments existed at an appropriate tidal elevation. Final selections were made randomly from this final list of confirmed workable sites. Four sites from the previous NOAA program were included to assess the degree of consistency with the NOAA studies. These included one reference site (Bay of Isles) and three treated sites (Northwest Bay West Arm, Shelter Bay, and Sleepy Bay; Figure 1).

Determining the treatment history for any particular stretch of shoreline was a somewhat difficult and complex task. In the manner previously reported by Mearns (1996), we used NOAA's Shoreline Segment Summary database to assign substrate type, relative degree of oiling (no-, light-, moderate-, or heavy oiling), types of treatment (*e.g.*, moderate- to high-pressure or warm- or hot-water), number of types of treatment, and number of treatment days on a segment. Mearns (1996) concluded that, although "… treatment varied greatly among shorelines,…treatment effort was generally proportional to the amount of oil present." According to his data for Eleanor and Ingot Islands, 81% of the heavily oiled sites were exposed to warm or hot water and 71% were exposed to both. In addition, 80% of the moderately oiled sites were exposed to warm or hot water. Only about 10% of the moderately or heavily oiled segments were not treated or did not have accompanying treatment characterization. From these data, one can conclude that most heavily or moderately oiled sites were washed with hot or warm water.

However, we are unaware of any available public records that actually record treatment for the particular beaches within a portion of a shoreline segment. Detailed oiling reports and recommended treatments are recorded in the Shoreline Cleanup Assessment Team (SCAT) reports (available at the Alaska Resource Library and Information Services in Anchorage), which include sketches of the distribution of oil and sediments. The oiling reports and treatment recommendations in these records formed the predominant basis for our decisions on which beaches to survey. However, it should be clear that, except for the NOAA Treated sites, where we were able to observe treatment underway in 1989, the treatment history of both Treated and Reference sites is based only on educated conjecture. It is likely that some of the sites were inadvertently misclassified.

Physico-chemical Sediment Analysis

Bulk sediment samples were collected at all sites for analysis of particle grain size (PGS), total organic carbon (TOC), and total Kjeldahl nitrogen (TKN). These samples were composited from surficial sediments scooped approximately 2 cm deep at points immediately adjacent to three randomly selected sampling locations for the infaunal samples. Thus, the single composite-sample method did not provide a measure of within-site variance. Each sample was preserved by freezing.

PGS distributions were determined using a pipette method (Plumb 1981) modified to correct for dissolved solids (*i.e.*, salinity and the dispersant added to keep silt/clay particles from clumping). Percent weights within each phi category were used to calculate cumulative phi values for 16, 50, and 84 percent of each sample. Two statistics were determined from these values. Median grain size = phi_{50}. Median grain size in mm = $2\exp(-\mathrm{phi}_{50})$. The equation used to calculate the sorting coefficient for each sample = $(\mathrm{phi}_{84} - \mathrm{phi}_{16})/2$.

In the laboratory, the samples used for analysis of organic nutrients in the sediments were purged of inorganic carbon, dried at 70°C, ground, and sieved through a 120-mesh screen. TOC was measured on a Dohrman DC-180 Carbon Analyzer using EPA method 415.1/5310B. TKN was measured by chromate digestion as described in EPA Method 351.4. Quality control (QC) for TOC included analysis of standards, method blanks, and comparison of replicate analyses. All QC analyses for TOC fell within acceptable QC limits. QC for TKN included analyses of spiked blanks and replicate analyses of spiked samples. All spiked TKN blank analyses fell within QC limits. However, none of the RPD or REC for the replicate analyses was within QC limits.

Shoreline Exposure

Because many physical and biological variables can be correlated with the intensity of exposure to wave action, variations in exposure to wave action can be a confounding factor. One commonly used method for estimating exposure is to measure fetch, *i.e.,* the unobstructed distance across open water that wind or waves travel before encountering a beach at a perpendicular angle. Accordingly, we estimated fetch for each site by measuring the distance to the nearest landfall in a directly offshore direction using a navigation chart.

Nevertheless, using fetch as a measure of exposure is a very crude and potentially inaccurate approach. It ignores the importance of the direction from which the dominant wind or waves arrive, the seasonal differences in the potential velocity and frequency of winds from the direction of the fetch, and the mitigating effects of local topography and offshore bathymetry (subtidal reefs, *etc.*), all of which are poorly known in this region. Consequently, we devised another approach that integrates a variety of exposure-related physical and biological factors to provide an index of exposure. Using our site photos and field notes to assess the various criteria, we devised an ordinal evaluation of twelve site conditions that reflect the degree of exposure. The factors included seven physical characteristics of the beach (shape and weathering of individual rocks, degree of imbrication or armoring of the rock “population”, presence of silt on coarser sediments or rocks, and the susceptibility of the site to current or wave action), and five biological characteristics (absence or level of development of epibenthic algae, animals, or an amorphous biological “turf” on the rocks, eelgrass or burrowing organisms in the sediments). Each feature was scored on a scale of 1 to 5. We then averaged factor scores for each site to provide an integrated exposure score for each site. By this method, low exposure scores indicate protected sites whereas high scores indicate exposed sites. Each site was scored without knowledge of its treatment classification in order to avoid biasing the score. The exposure scores were then paired with the appropriate environmental or biological variables for each site to evaluate the importance of exposure in any observed patterns.

Biological Sampling

In the NOAA studies cited above, we used a clam-gun core to sample infauna and the associated bivalves. It became clear when we analyzed these samples that this approach provided good information on smaller clam species and juveniles of larger clam species but did not provide adequate data on abundance and size structure of the naturally less abundant, older, larger size clams. This shortcoming created an important gap in our understanding of the long-term dynamics of clam populations and recovery. Consequently, we chose to use two contrasting methods to gain a fuller understanding of population and recovery dynamics. Smaller bivalves were sampled using core samplers 10.7 cm in diameter (0.009 m^2) by 15 cm deep, replicating the methods used in the NOAA study. Five cores (total of 0.045 m^2 sampled) were collected at randomly selected locations along a 30-m transect laid horizontally at each site at the lowest feasible level for completing the sampling and within the specified elevation range (0 to 0.8 m [+2.6 feet] above MLLW); the actual level varied with differing tide stage. Each sample was field-sieved through a 1.0-mm mesh screen, washed into a double-labeled Ziploc bag, and fixed with buffered 10% formalin-seawater solution. These samples were collected to provide data consistent with and comparable to the NOAA program and to gain an understanding of the status of smaller clam species and younger size classes of the larger, more longevous clams.

For the larger, older, less abundant and typically more dispersed bivalves, sediments were excavated to a depth of 15 cm using a shovel and hands inside a square 0.0625-m^2 quadrat. Three replicate excavations (a total of 0.1875 m^2 sampled) were collected adjacent to first, third, and fifth randomly placed core samples described above. These sediments were sieved on site through 6.35-mm (0.25-inch) mesh hardware cloth, the bivalves removed, placed in labeled bags, and frozen for shipment to the laboratory. This approach provided useful information on abundance and size and age structure of the larger size classes. These samples were collected to gain an understanding of the status of older size classes of the larger, more longevous clams

The two sample types provide complementary data. The core data provide data on a wider spectrum of sizes but, because larger animals are generally rare, these data are better suited for evaluation of the smaller clams and juveniles of the larger species. This component is lost in the sieving process for the excavation samples but, because that approach samples four times the surface area, it provides substantially better information on the larger, less abundant clams. Processing the excavation samples with the finer mesh sieve used for the core samples would require an inordinate amount of time both in the field and in the lab.

Following receipt in the laboratory, the samples were washed on a 1-mm sieve to remove the formalin-seawater solution and then preserved with 70% isopropyl alcohol. After identification and enumeration in the laboratory, shell length was measured with digital calipers to 0.1-mm precision. In addition, age was estimated for four species (*Protothaca*, *Saxidomus*, and *Hiatella*, *Macoma inquinata*) by counting growth checks (annuli). Arbitrary size criteria based on examination of the size-frequency histograms for each species were used to distinguish juveniles from adults for one set of analyses. For *Protothaca*, specimens <10 mm in shell length were classified as juvenile. For *Saxidomus*, *Macoma inquinata*, and *Hiatella*, shell length criteria for juveniles were <12, <15, and <6 mm, respectively.

Statistical Analysis

Summary Statistics

The species-site matrix was summarized numerically in terms of the species richness (S), number of individuals (N), and the Shannon-Wiener information species diversity index (H'). This diversity index accentuates the effects of rare species on the species richness aspects of species diversity (Krebs 1998). The software package, EstimateS, was used to calculate the index (Colwell 2005).

TOC and TKN data were used to calculate C/N ratios for each of the sampling locations. This ratios is useful in assessing the type of organics that predominate at a location, *i.e.*, whether the organics at a site are more by benthic diatoms or bacteria or fresh or weathered detrital material or hydrocarbons. C/N ratios of less than 10 are typical of bacteria and rapidly dividing diatoms (Tyson 1995; Valiela 1995). C/N ratios for fresh benthic algae or seagrass typically range from 12 to 20. Fresh terrestrial plant matter has C/N values between 20 and 30. Finally, petroleum hydrocarbons have very high C/N ratios (James R. Payne, pers. comm.) because they are carbon-rich and nitrogen-poor. As these materials age, their C/N ratios increase, *i.e.*, they have less nitrogen per unit of carbon (Tyson 1995).

Outlier Analysis

C/N ratios calculated from TOC and TKN data were improbably high for several sites, with seven ratios exceeding 100. After conferring with the laboratory on literature values for C/N ratios that can be expected from a variety of biota and detrital materials, *e.g.*, (Tyson 1995), an analytic or handling error seemed likely but uncorrectable. Thus, the only remaining option was to discard TOC and TKN outliers. In a conservative approach, four methods recommended by EPA (1992) were employed. These included a z-score method, a modified z-score method using the median and median of absolute deviation, the boxplot method, and Grubbs (1969) T value. While the results of these analyses varied considerably, all identified the maximum TOC value (6.99%) as an outlier. Consequently, it was omitted from analyses. Two analyses (Grubbs T and boxplot) identified the six lowest TKN values (all below 53.2 mg/Kg and nearly 90% lower than mean TKN) as outliers and these values were also omitted from analyses.

Multivariate Analyses

For multivariate analyses, we used two approaches: 1) stepwise linear regression of single species and sample types using environmental variables as predictors of species abundance; and 2) clustering and ordination using multi-dimensional scaling. To handle the inherent sampling differences of the core and excavation sample types, a single species occurring in both sampling methods was treated as two unique species, which could then appear unique within the same multivariate data set. The same environmental data were used for both sampling methods.

Stepwise regression was performed in Minitab, version 14.20. Predictor variables of high significance were added and retained in the exploratory regression process using the default $\alpha = 0.15$ for both acceptance and rejection values. Standard linear regression was then performed using the stepwise-identified environmental variables to assess the suite of diagnostic statistics, identify outliers, evaluate the residuals, and fine-tune the regression. Abundance data was cube-root transformed. TOC and tidal elevation were Box-Cox transformed.

For another perspective, various combinations of multivariate data were clustered and ordinated, and then the resulting pattern used to regress the environmental data against the results in order to identify correlations between multi-species abundance and the environmental variables. For this process, we used the statistical pattern-analysis software, PATN version 3.11, developed by Lee Belbin and CSIRO and later by Lee Belbin (Blatant Fabrications Pty Ltd) with V1 coding by students at Griffith University (Queensland, Australia). The package greatly simplifies the task of data management, creating similarity matrices, running classification and ordination analyses, and visualizing the results. The utility of the program lies both in the robust nature of its algorithms and in the ease in which queries can be generated, data manipulated, and results evaluated.

In brief, the software follows typical multivariate procedures whereby it computes an association matrix using a selected measure and runs the usual agglomerative hierarchical clustering (or non-hierarchical, if desired) but then computes ordination (based on station similarities from the species abundance data) using a unique semi-strong hybrid multidimensional scaling (SSH) algorithm (Belbin 1991). SSH differs from typical multi-dimensional scaling in two ways. First, from its ability to mix linear (metric) regression with ordinal (non-metric) regression, SSH accommodates for the non-linear bias of association measures. Typically, smaller association values will be linearly related to true distance while larger values are ordinally related to true distance. SSH, in its “hybrid” fashion, uses a cut-off point to switch between linear and ordinal regression to accommodate for this bias. Second, the “semi-strong” label derives from the ability of SSH to break tied values of association. For example, a species abundance table typically comprises sparse data with lots of zeroes that translate into equal values of association (namely, 1.0). Semi-strong ordinal regression allows tied values of association to be broken. SSH also uses an optimization scheme whereby a series of random initial configurations is used to find the best-fitting final configuration as measured by minimum “stress” using Kruskal’s stress formulation.

In practice, various association and linkage measures are available based on the nature of the data set. The classification is hierarchical so the number of groups formed is preset as a variable. After viewing the dendrograms, the user may want to modify the number of groups as each grouping is later used to evaluate the ordination gradient by the Kruskal-Wallis values (a goodness-of-fit value different from the Kruskal stress value). Ordination has options to select 1- to 3-dimensional analysis and to set some pertinent randomization and iteration depth values but they are mostly left to defaults as the routine churns through the data.

Following ordination, environmental variables can be correlated with the ordination (MDS) space using a multiple linear regression method termed "Principal Component Correlation" (PCC) (not related to the variance-based Principal Components Analysis method). The reported r-squared values for each variable reflect the amount of variance accounted for, thus suggesting that species abundances are, in some manner, correlated with the higher r-squared variables. The program expands on this approach by also running a permutation test called "Monte-Carlo Attributes in an Ordination" (MCAO) to test the robustness of the multiple linear regressions. In this test, each environmental variable is randomly swapped between sites and the regression rerun. The swapping/rerun is done multiple times (1000+). The resulting statistic of interest is how many times the swapped r-squared value exceeded the original true value, which reflects how uniquely significant the original value is. Finally, PATN calculates a non-parametric Kruskal-Wallis (KW) measure of fit between the classification-assigned grouping of each species (or station) and the ordination configuration. High KW values suggest good agreement between the gradient of species abundance and the ordination pattern. Box-and-whisker plots are also provided to help visualize the gradient among groupings.

The best and most utilitarian feature is the interactive 3-dimensional ordination plot. While viewing the live-rotating scattergram matrix of stations in their SSH-assigned locations, the reviewer can selectively add correlated environmental variables or obtain relevant sidebar data regarding selected stations or groupings. Pertinent displays are captured as figures for this report.

In summary, results from multivariate data analysis include data histograms, dendrograms and two-way tables, box-and-whisker plots, PCC r-squared values, MCAO permutation results, Kruskal-Wallis degree of fit values, and an interactive, rotatable 3-dimensional ordination plot upon which combinations of data are presented. Specifically for the EVOS clam data, the analyses used the Gower metric for calculating association between stations, agglomerative hierarchical fusion with flexible UPGMA and a beta of -0.10 to classify the sites into 4 or 5 groups, and SSH to ordinate the groups into 3 dimensions. For species data, the Bray-Curtis metric was used to produce 2 or 3 groups.

Inferential Statistics

Comparisons between the Reference and Treated arrays for sediment variables were evaluated using Student's t-test (Sokal and Rohlf 1969) or one-way randomization t-tests run using an Excel add-in, Resampling Stats (Blank *et al.* 2001).

Correlations between variate pairs within the Reference and Treated categories were analyzed using one of two methods to gain an understanding of the manner in which the variables related to one another both within and between treatment categories. In some cases, regression equations describing the relationships and the significance of the relationship were calculated using the Pearson product-moment method (Sokal and Rohlf 1969). In figures describing these relationships, only in cases where a correlation is significant are the details for n, r, and p included. Absence of these details implies that the specific relationship is not significant.

In many cases, the exact significance of the correlations was calculated using Resampling Stats to develop a specific distribution curve for correlation coefficients (r) for each data set. The calculated value of r was then compared against the possible distribution of r from repeated reshuffling of the data for each variate (5000 iterations) to determine the exact probability that the observed value of r could occur.

Inferential Limitations

Three known factors may have affected this study's ability to detect or infer effects. First, 13 years had passed since the spill event; it was possible that some or all of the treated beaches may have recovered, in which case there would have been no effects to detect. Second, intertidal clam assemblages in this region were observed during the NOAA study to have a high degree of variability (Houghton *et al.* 1997), thus suggesting natural disturbance at both Reference and Treated beaches could potentially confound the analyses. And finally, historic beach cleaning records used to classify sites typically described shoreline segments but not necessarily our specific sites. No public records are known to exist that explicitly indicate how any specific part of a shoreline segment was treated. Therefore, assignment of sites to either the Reference or Treated category involved a degree of uncertainty and each category could be "contaminated" with incorrectly classified sites. For these reasons and the desire to minimize false negatives, we adopted $\alpha = 0.1$ as the critical level of significance for all statistical testing. This *a priori* decision seems even more justified in hindsight in view of our hypotheses regarding armoring and the likelihood that sediment disturbance and variable recovery rates could increase the variability observed in the bivalve assemblages at Treated sites (see below).

Results

A broad spectrum of data was collected or developed for this study and a complex array of analyses has been employed to tease the often-buried subtleties from this data set. The following two paragraphs are provided as a road map to the description of results below.

Because of its importance in the consideration of many of the other physical, chemical, and biological variables, the first variable presented is exposure. As described in Methods, the exposure score is a derived variable based on a ranking of twelve factors that represent the response of various features in the physical and biological environment to the intensity of waves and/or currents at each site. Physical and chemical characteristics of the sediments and relationships among these factors, also extremely important in understanding the effects of treatment and the response to and recovery from treatment in the clam assemblage, are described next. An important part of this analysis focuses on the relationships between sediment variables and exposure.

The greatest proportion of the Results section is devoted to a wide range of biological characteristics of the bivalve assemblage and the interactions between this assemblage and these various factors. The initial elements are presentations of the numerical characteristics (N, S, and H') of the excavation and core samples. Relationships between the numerical characteristics and exposure are integrated into these presentations. These are followed by presentations of species distribution and composition patterns for the excavation and core samples. These topics are important in understanding the quantitative and qualitative nature of the two categories. We then compare abundance of juvenile and adult clams and the contrast in patterns between Reference and Treated sites, which are important in understanding differential recovery rates. We also compare size and age structure for the dominant clam species between Reference and Treated sites. We then examine relationships between dominant bivalves and sediment properties and/or exposure in order to gain an appreciation for the role these factors play in clam distribution. Using latitude as a surrogate, we examine the relationship between bivalve abundance and distance from the Gulf of Alaska. Finally, we present an extensive section of multivariate analyses in which we examine the multidimensional relationships among the bivalves and the varied physical, chemical, and other environmental factors quantified during this study.

We recognize that the reader may be challenged by the plethora of data and analyses. As is clear from our stated hypotheses (see above), our initial concept of the major factors responsible for lagging clam recovery involved some combination of physical or environmental factors that would derive from treatment. As analysis progressed, it soon became evident this type of explanation was too simplistic. Only when we began examining the data from the perspectives of a different sediment paradigm (armoring) and the consequences of disrupting that paradigm did the observed patterns begin to make sense. Because our ultimate suggestion regarding the mechanism causing this lag (armoring) involves a novel concept, our field program did not include any direct measurement of that mechanism. Nevertheless, the several data types reported all contribute to the multiple strings of indirect evidence leading to our conclusions regarding the cause of lagging clam recovery.

Exposure

The range of exposure scores indicates that exposure varied considerably and similarly at both Reference (1.9 to 4.1) and Treated (2.0 to 4.6) sites (Table 3). Average exposure scores are also very similar. Consequently, it appears that the two types of sites are not subjected to significantly different exposure regimes.

Table 3. Estimated exposure scores and fetch (km) for Reference and Treated sites in western Prince William Sound in August 2002. Sites are ranked by exposure from least (1) to most (5) exposed.

Treated Sites	**Exposure Score**	**Fetch (km)**	**Reference Sites**	**Exposure Score**	**Fetch (km)**
KN502	2.0	0.1	CH8B	1.9	0.2
KN133	2.3	0.5	KN507	2.1	0.1
CH9	2.3	5.0	KN554A	2.4	1.1
KN131A	2.4	0.5	SL1	2.6	5.5
KN118	2.4	0.5	KN554B	2.7	2.7
IN32	2.7	0.5	CH8A	2.8	0.2
KN131B	2.8	1.8	KN106B	2.8	1.5
KN130	3.2	0.4	KN575	3.2	3.7
DI67B	3.3	21.9	Bay of Isles	3.2	3.8
KN04	3.3	4.9	FL3C	3.2	1.4
KN103A	3.3	3.7	EV8	3.2	8.2
FL4A	3.5	0.5	KN553	3.3	36.6
FL4B	3.7	1.3	KN106A	3.3	1.5
EV16	3.7	11.9	FL3A	3.3	7.3
LA16	3.7	32.9	FL3B	3.4	1.5
DI67A	3.7	21.9	CH1	4.0	6.4
IN31	3.8	0.2	EV70	4.1	6.9
KN103B	3.8	3.7			
NW Bay West	4.0	39.5			
Shelter Bay	4.1	12.8			
DI66	4.1	1.6			
KN104	4.2	40.2			
Sleepy Bay	4.6	64.0			
Mean	3.3	11.8		3.0	5.2
Std. Dev.	0.7	17.2		0.6	8.5

Average fetch, on the other hand, was substantially less for Reference sites (average fetch = 5.2 ± 8.5 km) than for Treated sites (11.8 ± 17.2 km; Table 3; p = 0.16, Student's t test). A comparison of pairs of exposure scores and fetch measurements shows many strong disparities.

In some cases, high exposure scores are paired with short fetches and, in other cases, a low exposure scores are paired with long fetches (Table 3). Because the exposure scores are based on features that reflect the actual exposure at a site, we have concluded they provide a more valid measure of hydrodynamic exposure experienced by a site than do fetch estimates and the differences described above underscore our concern about the weakness of fetch as a useful measure of exposure in such a topographically complex area.

Sediment Conditions

The nature of sediments varied considerably among the sampling sites (Table 4). Median particle grain size (PGS) was generally relatively coarse, even in protected locations. By the Wentworth scale, sediment types on 43% of the beaches were classified as small pebbles and 45% were coarser pebbles; the finest sediment types observed were granules. Sediments on many of the beaches also included a sizable fraction of cobble that is poorly reflected in the grain size analyses. The coarser fractions seem to provide structure and stabilize the sediments, a consideration that will be addressed in the Discussion section below.

Table 4. Sediment properties at Reference and Treated sites in western Prince William Sound in August 2002.

Sampling Location	**Median PGS (mm)**	**Silt/ Clay (%)**	**Sorting Coefficient**	**TOC (%)**	**TKN (mg/Kg)**	**C/N Ratio**
REFERENCE SITES (Oiled-but-Unwashed)						
CH 01	6.38	1.80	2.41	0.42	ND*	2210.5**
CH 08A	8.73	3.60	1.96	1.21	460	26.3
CH 08B	5.01	5.46	1.65	1.71	354	48.3
EV 08	3.48	2.53	2.27	0.47	582	8.1
EV 70	5.81	3.71	3.24	1.00	20.8**	480.8**
FL 03A	5.81	4.72	2.73	1.39	601	23.1
FL 03B	3.53	3.46	3.04	0.99	1110	8.9
FL 03C	3.25	2.71	2.41	0.88	493	17.8
KN 106A	9.87	2.58	1.39	6.99**	305	229.2**
KN 106B	8.39	6.06	2.13	1.02	544	18.8
KN 507	11.42	1.12	1.17	0.54	203	26.6
KN 553	4.99	3.93	1.73	2.90	406	71.4
KN 554A	3.51	3.28	1.98	1.94	800	24.3
KN 554B	9.49	2.18	1.30	0.84	340	24.7
KN 575	10.61	1.34	1.89	1.04	16.2**	642.0**
SL1	6.22	2.34	2.52	1.38	40.7**	339.1**
Bay of Isles†	8.28	2.35	1.98	0.54	117	46.2

Sampling Location	Median PGS (mm)	Silt/ Clay (%)	Sorting Coefficient	TOC (%)	TKN (mg/Kg)	C/N Ratio
TREATED SITES (Oiled-and-Washed)						
CH 09	6.65	6.09	3.38	2.92	450	64.9
DI 066	14.52	0.91	3.38	0.20	99	20.2
DI 067A	16.44	1.34	1.82	0.62	382	16.2
DI 067B	6.29	1.66	1.37	0.45	216	20.8
EV 16	8.21	1.42	1.23	0.76	539	14.1
FL 04A	4.36	4.55	1.99	1.09	438	24.9
FL 04B	2.46	1.74	2.36	0.42	652	6.4
IN 032	16.46	1.16	2.40	1.21	617	19.6
IN 031	19.37	1.62	2.40	1.46	398	36.7
KN 04	5.23	7.05	1.28	1.21	1030	11.7
KN 103A	17.45	2.71	2.18	1.18	399	29.6
KN 103B	5.61	2.00	2.09	0.39	195	20.0
KN 104	8.44	1.22	2.35	0.50	198	25.3
KN 118	5.27	6.22	1.85	3.28	991	33.1
KN 130	3.87	3.15	1.71	0.30	127	23.6
KN 131A	4.47	3.51	2.86	1.65	399	41.4
KN 131B	4.40	4.19	1.37	1.13	53.2**	212.4**
KN 133	4.54	5.07	2.30	3.00	748	40.1
KN 502	7.40	2.57	2.07	1.96	664	29.5
LA 16	32.39	3.03	1.80	2.18	530	41.1
NW Bay†	8.16	1.40	3.16	0.40	143	28.0
Shelter Bay†	13.10	2.62	1.43	0.55	351	15.7
Sleepy Bay†	21.29	2.19	2.58	1.23	32.4**	379.6**

* ND = Not detected; limit of detection was 2.0 mg/Kg.

** Determined to be outliers and omitted from statistical analyses.

† Previous NOAA sites.

Sediments at Treated sites were, on average, considerably coarser than at Reference sites (Table 5). PGS, ranging from 3.25 to 11.42 mm at Reference sites and 2.46 to 32.39 mm at Treated sites, averaged 6.8 ± 0.7 mm and 10.3 ± 1.6 mm, respectively; eight Treated sites had larger average grain size than the coarsest value for the Reference sites (Figure 2). This difference in PGS was significant ($p = 0.028$; 1-way randomization t-test).

The coarseness was accentuated by the paucity of the silt/clay fraction. Ranging from 0.91 to 7.05%, fines averaged 3.1 ± 0.3% at Reference sites and 2.9 ± 0.4% at Treated sites (Tables 4 and 5). Although the quantity of fines was slightly lower at Treated than at Reference sites, the difference was not significant.

Table 5. Averages sediment properties for Reference (Ref) and Treated (Trt) sites in western Prince William Sound in August 2002.

Sediment Properties	Alternative Hypothesis	Site Categories (No. of Sites) (Mean ± SE)		
		Reference* (17)	**Treated* (22)**	**NOAA (4)**
PGS (mm)	Trt > Ref**	6.8 ± 0.7 (17)	10.3 ± 1.5 (23)	12.7± 3.1 (4)
Silt/Clay (%)	Ref > Trt	3.1 ± 0.3 (17)	2.9 ± 0.4 (23)	2.1 ±0.3 (4)
Sorting Coefficient	Trt > Ref	2.11 ± 0.14 (17)	2.10 ± 0.12 (23)	2.07± 0.25 (4)
TOC (%)	Ref > Trt	1.14 ± 0.16 (16)	1.22 ± 0.19 (23)	0.68 ± 0.19 (4)
TKN (mg/Kg)	Ref > Trt	486 ± 72 (13)	456 ± 57 (23)	204±74 (3)
C/N Ratio	Trt > Ref	28.7 ± 5.2 (12)	26.8 ± 2.9 (21)	29.9 ±8.8 (3)

* Reference includes 1 previous NOAA site; Treated includes 3 NOAA sites

** Significant difference ($p = 0.028$) in variables between Treated & Reference sites

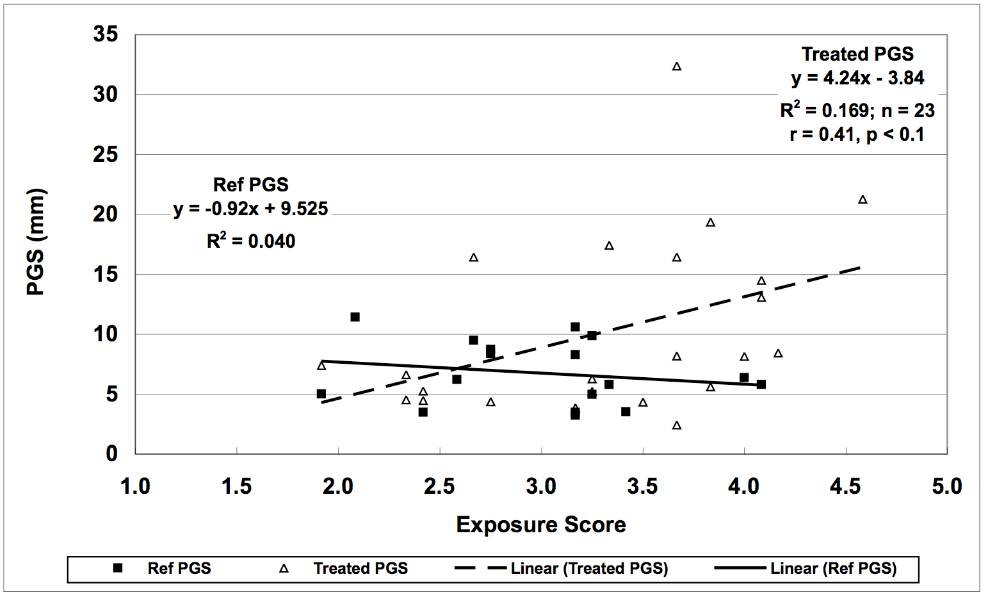

Figure 2. Relationships between median PGS and exposure scores at Treated and Reference sites.

Concentrations of TOC, TKN, and C/N ratios varied considerably, ranging from 0.2% to 3.3%, 99 mg/Kg to 1,110 mg/Kg, and 6.4 to 71.4, respectively, but the averages for all were quite similar (Tables 4 and 5). The range of C/N ratios suggests that the sources of sediment organics varied from primarily benthic diatoms and bacteria to weathered terrestrial detritus (Tyson 1995). The highest TOC value, the lowest TKN values, and the resulting C/N ratios are considered outliers and are not included in statistical analyses (Table 5).

Treatment category averages for these variables (Table 5) indicate that NOAA sites continued to exhibit low levels in silt/clay, TOC, and TKN, as observed from 1990 through 1996 in the NOAA program (Houghton *et al.* 1997). PGS remained quite coarse. Samples from all NOAA sites still were classified as various grades of pebbles or gravel. The averages for silt/clay, TOC, and TKN were considerably lower at the NOAA sites than at the other Reference and Treated sites.

In most cases, the relationships between sediment variables varied in the expected manner (*e.g.*, Tyson 1995, CSIRO 2000), whether or not they were significant. Thus, silt/clay, TOC, and TKN generally correlated inversely with PGS (Table 6). Conversely, TOC and TKN mostly correlated positively with silt/clay. However, concentrations of silt/clay and organics were substantially higher than would be expected considering the coarseness of the sediments (Tyson 1995).

Table 6. Correlation coefficients for relationships between sediment properties in Reference and Treated sites in western Prince William Sound in August 2002.

	Treated Sites					
	Variate	**Median PGS**	**Silt/ Clay**	**TOC**	**TKN**	**C/N**
Reference Sites	**Median PGS**		-0.34**	0.05	-0.12	0.17
	Silt/Clay	-0.36**		0.68†	0.65†	0.42**
	TOC	-0.32**	0.46**		0.65†	0.83†
	TKN	-0.66†	0.29*	0.16		0.01
	C/N	0.05	0.16	0.67**	-0.53**	

* strong trend ($p < 0.2$),
** significant ($p < 0.1$),
† highly significant ($p < 0.01$)

Correlations between variate pairs were examined to assess relationships between the sediment properties and determine if the variates differed between treatment categories. Eleven of twenty potential correlations were significant (Table 6) and two other variable pairs exhibited a strong trend ($0.2 > p > 0.1$). Four variate pairs either correlated significantly or exhibited strong trends in both Reference and Treated categories. These included: 1) PGS and silt/clay (both negatively), 2) silt/clay and TOC (both positively), 3) silt/clay and TKN (both positively), and 4) TOC and C/N ratios (both positively). Thus it appears that sediment properties are generally "behaving" in a similar manner at the Treated and Reference sites. Silt/clay had the most relationships with other variates, demonstrating significant correlations with all other variates within the Treated category, and was significantly correlated or exhibited strong trends with all other variates except C/N within the Reference sites. PGS was the least strongly correlated variate with the other properties. Its only significant correlates were with silt/clay in both Reference and Treated categories and TOC and TKN in the Reference category.

Sorting was not evaluated in the NOAA study and was not considered for evaluation in the design of this study. However, examination of sediment data during this study indicated that sorting was a useful consideration. Averages (± SE) for sorting coefficients did not differ between Reference and Treated sites (2.11 ± 0.14 and 2.10 ± 0.12, respectively; Table 5). However, the strength of correlation between PGS and the sorting coefficients at Reference sites ($r = 0.57$, $p < 0.05$) was not reflected at Treated sites ($r = 0.03$), suggesting that beach washing had disturbed the sorting that existed at beaches before they were washed.

On the whole, relationships between the sediment properties were slightly stronger in the Treated category than in the Reference category (Table 6). Although seven of ten variate pairs for Reference sites and six pairs for Treated sites exhibited at least a strong trend, four correlations in the Treated category were highly significant.

PGS exhibited a strong positive correlation to exposure at Treated sites ($p < 0.01$; Figure 2) but not at Reference sites. This indicates that PGS is not influenced by exposure at Reference sites. Similarly, the other properties were not correlated with exposure at the Reference sites but exhibited significant negative correlations at the Treated sites ($p < 0.01$ for silt/clay and TOC and $p < 0.05$ for TKN and C/N; see Figure 3 for example). These latter relationships suggest the presence of some structural feature that protects fines and organics from increasing exposure at Reference sites but is far less effective at Treated sites.

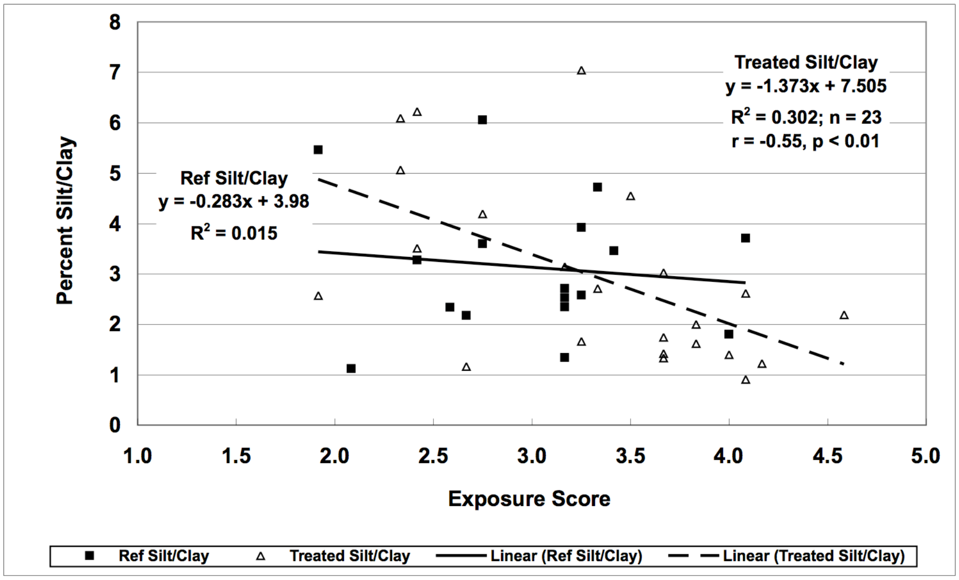

Figure 3. Relationships between silt/clay concentrations and exposure scores at Treated and Reference sites.

Bivalve Assemblage

We collected two types of samples that provide complementary data on the clams. The smaller core sampling approach provides data on a wider spectrum of sizes but, because larger animals are generally rare in these samples, it is better suited for evaluation of the smaller clams and juveniles of the larger species. The larger excavation sampling approach, covering four times more surface area, provides substantially better information on the larger, less abundant clams but is inadequate for the smaller clams because that component is not retained on the large mesh screen used to expedite processing the larger volume of sediment collected by this approach.

Numerical Characteristics

Excavation Samples

The bivalve assemblage from excavation samples represents the less abundant, larger, older size fractions for the various clam species. Samples collected from 17 Reference and 22 Treated sites were dominated by *Protothaca staminea* (littleneck clam; 51.6% of total numbers; Table 7) in terms of both abundance and, based on qualitative observations, biomass. *Hiatella arctica* (Arctic nestling clams; 24.8%), *Macoma inquinata* (pointed macomas; 10.8%), and *Saxidomus gigantea* (butter clams; 8.3%) were also common. Only three of the eleven species encountered, *Protothaca*[1], *Hiatella*, and *Saxidomus*, occurred at half or more of the sites. Six species occurred at three or fewer sites.

Number of individuals (N) and species richness (S) per site varied substantially among the site (Table 7). N, ranging from 0 to 263, averaged 41.3 ± 55.8 clams per site. S, with a maximum of seven species per site, averaged 2.9 ± 1.5. Consequently, Shannon-Wiener species diversity indices (H') were generally low, averaging 0.58 ± 0.38.

Both N and S had significantly higher values at Reference sites than at Treated sites (Table 8). N for Reference sites averaged more than twice as high as for Treated sites (1-way randomization t-test; $p = 0.012$). Even though species richness was low, S also was significantly higher at Reference sites ($p = 0.075$). Trends for H' agreed with the alternative hypotheses but the difference was not significant (Table 8).

Comparisons of the relationships between numerical characteristics of the excavation samples and exposure scores provide useful insights into the differing ways the bivalve assemblages were responding to conditions at Reference and Treated sites. Overall bivalve abundance (N) for Reference sites showed a significant positive response (Figure 4; $p = 0.08$) but a strong negative trend at Treated sites ($p = 0.13$). Species richness (S) was not significantly influenced by exposure at Reference sites but exhibited a significant decline with increased exposure at Treated sites (Figure 5; $p = 0.08$). Patterns for species diversity (H') were similar with a significant decline in H' at Treated sites in response to increased exposure (Figure 6; $p = 0.06$). For all three

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[1] The commonly discussed species in this report (*e.g.*, *Hiatella arctica*, *Protothaca staminea*, *Rochefortia tumida*, and *Saxidomus gigantea*) that are not subject to confusion with congeners will be referred to by genus in the remainder of this report after first mention in the text except in tables.

Table 7. Pooled numbers of bivalve species, numbers of individuals (N) and species (S), and Shannon-Wiener species diversity (H') for triplicate excavation samples from Reference and Treated sites in western Prince William Sound, August 2002.

Treatment *Category/* Site	***Protothaca staminea***	***Hiatella arctica***	***Macoma inquinata***	***Saxidomus gigantea***	***Diplodonta impolita***	***Macoma balthica***	***Macoma golikovi***	***Modiolus modiolus***	***Clinocardium nuttallii***	***Macoma* sp. 1**	***Cryptomya californica***	**Lasaeidae, unid.**	**N**	**S**	**H'**
REFERENCE SITES															
CH1	132	0	0	20	1	0	0	0	0	0	0	0	153	3	0.43
CH8A	18	0	2	0	0	0	0	0	0	0	0	0	20	2	0.33
CH8B	32	0	2	2	13	2	0	5	0	0	0	0	56	6	1.23
EV8	61	8	0	0	0	2	0	0	0	0	0	0	71	3	0.48
EV70	45	13	0	5	0	0	0	0	0	0	0	0	63	3	0.77
FL3A	133	1	28	30	0	0	1	0	1	0	1	0	195	7	0.94
FL3B	29	60	2	10	0	1	0	0	0	0	0	0	102	5	1.02
FL3C	55	3	5	10	0	0	0	0	0	0	0	0	73	4	0.80
KN106A	23	234	1	3	0	1	0	0	1	0	0	0	263	6	0.43
KN106B	10	3	0	0	0	0	0	0	0	0	0	0	13	2	0.54
KN507	11	1	0	0	0	0	0	0	0	0	0	0	12	2	0.29
KN553	0	0	14	1	0	0	0	0	0	0	0	0	15	2	0.24
KN554A	15	1	5	2	0	0	0	0	0	0	0	0	23	4	0.96
KN554B	10	3	9	0	0	1	3	0	0	0	0	0	26	5	1.36
KN575	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0.00
SL1	8	0	0	1	0	0	0	0	0	0	0	0	9	2	0.35
Bay of Isles*	1	0	0	0	0	1	0	0	0	0	0	0	2	2	0.69
Variable Total	585	327	68	84	14	8	4	5	2	0	1	0	1098	10	1.21
Averages/Site	34.3	19.2	4.0	4.9	0.8	0.5	0.2	0.3	0.1	0.0	0.1	0.0	64.6	3.5	0.64
Std. Dev.	41.1	57.2	7.3	8.4	3.1	0.7	0.8	1.2	0.3	0.0	0.2	0.0	74.9	1.8	0.37
% of Sites Occupied	94	59	53	59	12	35	12	6	12	0	6	0			
% of Total N	53.3	29.8	6.2	7.7	1.3	0.7	0.4	0.5	0.2	0.0	0.1	0.0			
TREATED SITES															
CH9	18	0	23	0	0	1	0	0	0	0	0	0	42	3	0.78
DI66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
DI67	13	0	1	9	0	0	0	0	0	0	0	2	25	4	1.04

Treatment ***Category/*** **Site**	***Protothaca staminea***	***Hiatella arctica***	***Macoma inquinata***	***Saxidomus gigantea***	***Diplodonta impolita***	***Macoma balthica***	***Macoma golikovi***	***Modiolus modiolus***	***Clinocardium nuttallii***	***Macoma* sp. 1**	***Cryptomya californica***	**Lasaeidae, unid.**	**N**	**S**	**H'**
DI67B	4	0	8	0	0	5	0	0	0	0	0	0	17	3	1.06
EV16	9	1	0	0	0	0	0	0	0	0	0	0	10	2	0.33
FL4A	66	2	17	14	0	4	0	0	0	0	0	0	103	5	1.06
FL4B	28	4	0	3	0	0	0	0	0	0	0	0	35	3	0.64
IN31	2	0	0	0	0	0	0	0	0	3	0	0	5	2	0.67
IN32	17	0	0	4	0	0	0	0	0	0	0	0	21	2	0.49
KN4	21	1	0	4	0	0	5	0	0	0	0	0	31	4	0.93
KN103A	4	0	0	0	0	0	0	0	0	0	0	0	4	1	0.00
KN103B	3	0	0	0	0	0	0	0	0	0	0	0	3	1	0.00
KN104	1	0	0	5	0	0	0	0	0	0	0	0	6	2	0.45
KN118	0	0	0	0	8	1	0	0	0	0	0	0	9	2	0.35
KN130	14	3	0	2	0	0	0	0	0	0	0	0	19	3	0.75
KN131A	4	4	40	4	0	0	0	0	1	0	0	0	53	5	0.87
KN131B	4	0	23	4	0	0	1	0	0	0	0	0	32	4	0.87
KN133	4	21	0	0	0	0	0	0	0	0	0	0	25	2	0.44
LA16	23	28	0	1	0	0	0	0	0	0	1	0	53	4	0.85
NW Bay West Arm**	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0.00
Shelter Bay**	10	1	0		0	0	0	0	0	0	0	0	11	2	0.30
Sleepy Bay**		7	0		0	0	0	0	0	0	0	0	7	1	0.00
Totals	245	73	112	50	8	11	6	0	1	3	1	2	512	11	2.61
Averages/Site	11.1	3.3	5.1	2.3	0.4	0.5	0.3	0.0	0.0	0.1	0.0	0.1	23.3	2.5	0.54
Std. Dev.	14.9	7.2	10.8	3.6	1.7	1.3	1.1	0.0	0.2	0.6	0.2	0.4	24.0	1.4	0.38
% of Sites Occupied	82	50	27	45	5	18	9	0	5	5	5	5			
% of Total N	47.9	14.3	21.9	9.8	1.6	2.1	1.2	0.0	0.2	0.6	0.2	0.4			

* Untreated NOAA site, ** Treated NOAA sites

Table 8. Mean numbers of bivalve individuals (N) and species (S), and Shannon-Wiener species diversity index (H') in excavation and core samples from Reference (Ref) and Treated (Trt) sites in western Prince William Sound, August 2002.

Sample Type/ Assemblage Variables	Alternative Hypothesis	Reference $\bar{X}$ ± sd	Treated $\bar{X}$ ± sd	Exact p*
EXCAVATION				
N (Site Average)	Ref > Trt	64.6 ±74.9	23.3 ± 24.0	0.012**
S (Site Average)	Ref > Trt	3.4 ± 1.6	2.5 ± 1.3	0.075**
H' (Site Average)	Ref > Trt	0.64 ± 0.37	0.54 ± 0.38	0.20
H' (Pooled by Treatment)	Ref > Trt	1.21	1.36	–
CORE				
N (Site Average)	Trt > Ref	51.1 ± 60.3	77.8 ± 94.4	0.17
S (Site Average)	Ref > Trt	4.9 ± 2.3	4.2 ± 2.4	0.21
H' (Site Average)	Ref > Trt	1.06 ± 0.4	0.64 ± 0.47	0.003**
H' (Pooled by Treatment)	Ref > Trt	1.50	1.08	–

* Calculated with a randomization t-test using 5000 iterations
** Significant differences

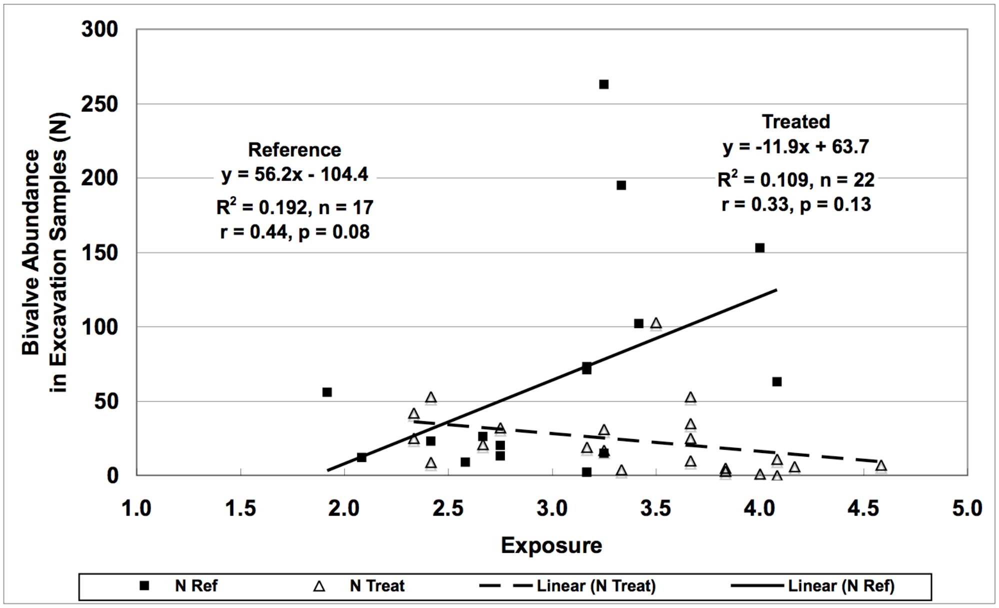


Figure 4. Comparison of relationships between bivalve abundance (N) and exposure scores in excavation samples at Treated and Reference sites.

variables, the response to increasing exposure was significantly negative at Treated sites but significantly positive or showed no effect at Reference sites. As with the sediments, these patterns suggest the presence of some structural feature that protects the clams from increasing exposure at Reference sites but is far less effective at Treated sites.

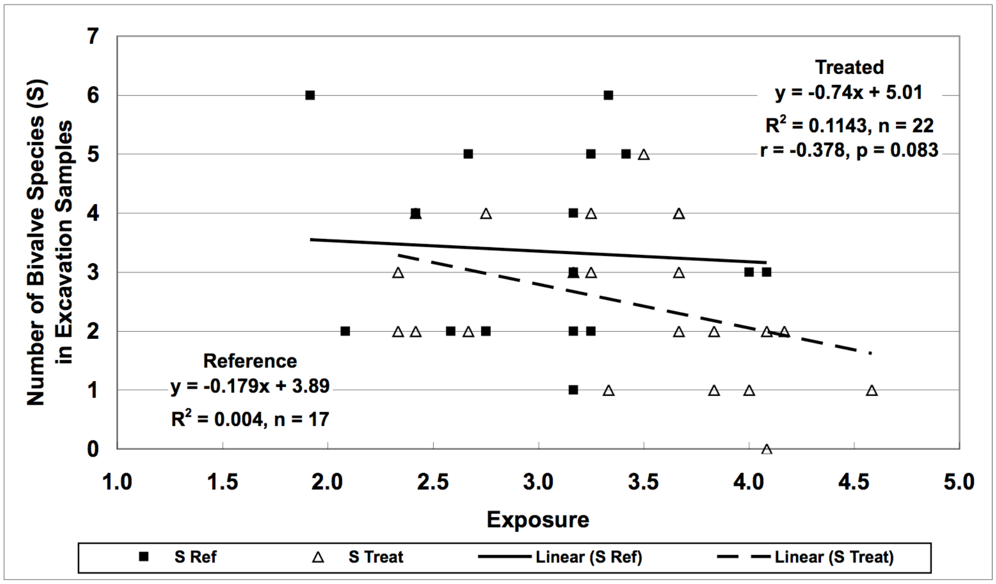


Figure 5. Comparison of relationships between bivalve species richness (S) and exposure scores in excavation samples at Treated and Reference sites.

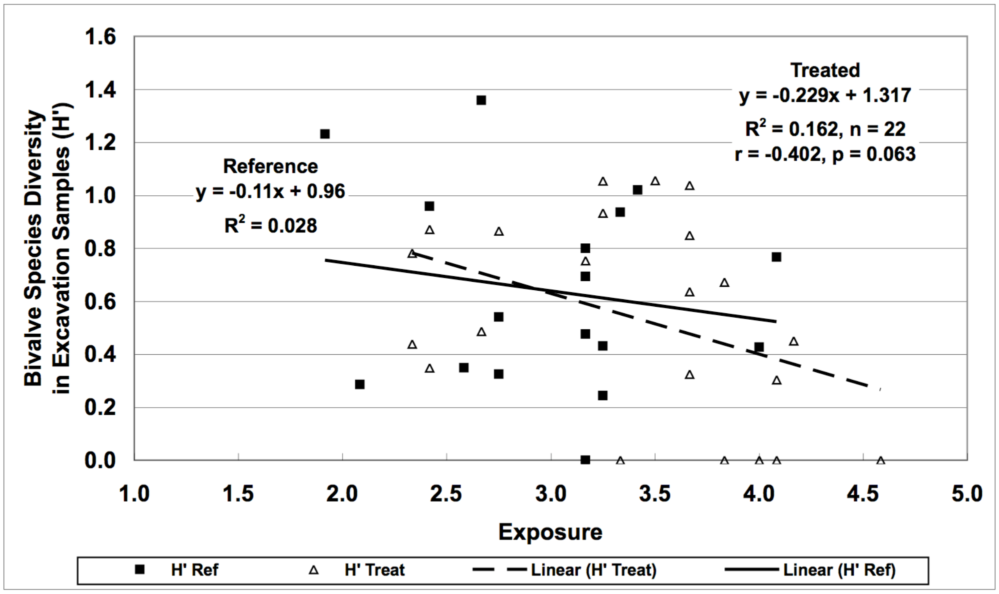


Figure 6. Comparison of relationships between bivalve Shannon-Wiener species diversity (H') and exposure scores in excavation samples at Treated and Reference sites.

Core Samples

Bivalves in the core samples represent the younger, smaller fraction of the larger clams as well as smaller species that are not retained on the sieve used to screen the excavation samples. Consequently, more species were encountered in the core samples. Samples were collected from 17 Reference sites and 20 Treated sites. A tiny nestling clam, *Rochefortia tumida*, dominated numerically (robust mysella; 59% of the total) but *Protothaca* (17% of the total numbers) were the biomass dominant (Table 9; pers. obs.). Other common species included *Hiatella*; 17%), juvenile *Modiolus modiolus* (horsemussels; 3.3%), and *Saxidomus*; 3.0%). Six of the 14 species encountered occurred in at least half the sites while seven species occurred at three or fewer sites.

As in the excavation samples, number of individuals (N) and species richness (S) varied substantially among the stations (Table 9). N, ranging from 0 to 285, averaged 65.5 ± 80.6 clams per site. S, with a maximum of nine species per site, averaged 4.5 ± 2.4. Consequently, while higher than in the excavation samples, Shannon-Wiener species diversity (H') was generally low, averaging 0.83 ± 0.48.

Patterns for numerical characteristics in the core samples differed from those observed in the excavation samples (Table 8). N exhibited a strong trend toward higher values at Treated sites than at Reference sites ($p = 0.17$), agreeing with the alternative hypothesis for core samples. Species richness values were similar in the treatment categories. Shannon-Wiener diversity agreed with the alternative hypothesis; H' was significantly higher at Reference sites (1-way randomization t-test; $p = 0.003$; Table 8).

Although all numerical characteristics conformed to the patterns proposed by the alternative hypotheses, only the difference in H' was significant (Table 8; $p = 0.003$). In looking at number of individuals (N), we anticipated a normal recolonization response with high numbers of recruits. We expected to observe an abundance of younger, smaller animals characteristic of core samples at Treated sites, *i.e.*, the alternative hypothesis states that $N_{\text{Treated}} > N_{\text{Reference}}$. While N exhibited only a strong trend, the diversity index (H', which emphasizes the importance of rare species) demonstrated a significant difference agreeing with the alternative hypothesis.

Again, the response of the numerical characteristics for core samples to exposure provides important insights. Both N and S exhibited significant negative responses to increased exposure at Treated sites but the responses were not significant at Reference sites (Figures 7 and 8). The species diversity pattern did not appear significantly influenced by exposure at either Reference or Treated sites. As with sediments and the excavation samples, these patterns suggest that some structural feature protects smaller clams from increasing exposure and is more effective at Reference sites than at Treated sites, with the result that conditions at Treated sites are somehow less suitable for intertidal bivalve assemblages that at Reference sites.

Table 9. Pooled numbers of bivalve species, numbers of individuals (N) and species (S), and Shannon-Wiener species diversity (H’) for core samples from Reference and Treated sites in western Prince William Sound, August 2002. Each number represents the number of individuals from five core samples.

Treatment Category/ Site	***Rochefortia tumida***	***Hiatella arctica***	***Protothaca staminea***	***Modiolus modiolus***	***Macoma balthica***	***Saxidomus gigantea***	***Macoma inquinata***	***Neaeromya compressa***	***Nutricola tantilla***	**Bivalve, unid.**	***Diplodonta impolita***	***Macoma golikovi***	***Nutricola lordi***	***Mya pseudoarenaria***	***Axinopsida serricata***	**N**	**S**	**H’**
REFERENCE SITES																		
CH1	5	1	34	1	0	2	0	0	0	0	0	0	0	0	0	43	5	0.75
CH8A	1	1	5	1	0	2	0	0	0	0	0	0	0	0	0	10	5	1.36
CH8B	21	0	14	14	8	3	0	0	0	0	0	0	0	0	0	60	5	1.47
EV8	14	8	15	1	0	2	0	0	0	0	0	0	0	0	0	40	5	1.30
EV70	5	5	11	1	1	0	0	0	0	0	0	0	0	0	0	23	8	1.29
FL3A	83	31	56	3	4	3	6	0	1	0	0	0	0	0	0	187	8	1.37
FL3B	38	53	7	0	6	6	0	0	0	1	0	0	0	0	0	111	6	1.25
FL3C	15	6	16	0	5	3	0	0	0	0	0	0	0	1	0	46	6	1.50
KN106A	5	26	16	1	0	2	0	0	0	0	0	0	0	0	0	50	5	1.14
KN106B	10	4	1	0	0	1	0	2	0	0	0	0	0	0	0	18	5	1.23
KN507	24	7	11	19	1	1	0	0	0	0	0	0	0	0	0	63	6	1.41
KN553	0	0	1	0	3	0	0	0	0	0	0	0	0	0	0	4	2	0.56
KN554A	164	10	10	3	1	2	0	1	4	1	0	0	0	0	0	196	9	0.72
KN554B	2	2	0	0	5	0	0	0	0	0	0	0	0	0	0	9	3	1.00
KN575	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0.69
SL1	0	0	3	1	0	2	0	0	0	0	0	0	0	0	0	6	3	1.01
Bay of Isles*	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Variable Totals	388	155	200	45	34	29	6	3	5	2	0	0	0	1	0	868	11	1.50
Averages/Site	22.8	9.1	11.8	2.6	2.0	1.7	0.4	0.2	0.3	0.1	0.0	0.0	0.0	0.1	0.0	51.1	4.9	1.06
Std Dev	41.8	14.4	14.4	5.4	2.6	1.6	1.5	0.5	1.0	0.3	0.0	0.0	0.0	0.2	0.0	60.3	2.3	0.40
% of Sites Occupied	82	76	82	59	53	71	6	12	12	12	0	0	0	6	0			
% of Total N	45	18	23	5.2	3.9	3.3	0.7	0.3	0.6	0.2	0.0	0.0	0.0	0.1	0.0			
CH9	117	3	3	3	4	0	0	0	0	0	0	0	0	0	0	130	5	0.46

Treatment Category/ Site	***Rochefortia tumida***	***Hiatella arctica***	***Protothaca staminea***	***Modiolus modiolus***	***Macoma balthica***	***Saxidomus gigantea***	***Macoma inquinata***	***Neaeromya compressa***	***Nutricola tantilla***	**Bivalve, unid.**	***Diplodonta impolita***	***Macoma golikovi***	***Nutricola lordi***	***Mya pseudoarenaria***	***Axinopsida serricata***	**N**	**S**	**H'**
TREATED SITES																		
DI66	3	19	0	1	0	0	0	0	0	0	0	0	0	0	0	23	3	0.56
EV16	1	0	1	7	0	0	0	0	0	0	0	0	0	0	0	9	3	0.68
FL4A	129	14	53	1	12	1	1	1	0	0	0	0	2	0	0	214	9	1.13
FL4B	4	5	9	0	0	2	0	0	0	0	0	0	0	0	0	20	4	1.26
IN31	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.00
IN32	35	121	10	0	1	3	0	3	0	0	0	0	0	0	1	174	7	0.94
KN103A	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.00
KN103B	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0.00
KN104	4	1	0	0	0	1	0	0	0	0	0	0	0	0	0	6	3	0.87
KN118	124	0	1	9	0	0	2	0	0	0	1	0	0	0	0	137	5	0.40
KN130	2	23	10	0	0	1	0	0	0	0	0	0	0	0	0	36	4	0.90
KN131A	265	5	2	1	5	1	6	0	0	0	0	0	0	0	0	285	7	0.37
KN131B	253	7	2	0	12	0	0	0	0	0	1	0	0	0	0	275	5	0.36
KN133	36	22	5	9	0	1	0	0	2	0	0	0	0	0	0	75	6	1.30
KN4	73	4	25	4	3	1	0	0	0	1	0	1	0	0	0	112	8	1.08
KN502	6	0	13	0	2	1	0	0	0	0	0	0	0	0	0	22	4	1.02
NW Bay West Arm**	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0.00
Shelter Bay**	1	0	1	0	0	0	0	2	0	0	0	1	0	0	0	5	4	1.33
Sleepy Bay**	0	27	1	0	0	0	0	0	0	0	0	0	0	0	0	28	2	0.15
Variable Totals	1,053	253	139	35	39	12	9	6	2	1	2	2	2	0	1	1556	14	1.08
Averages/Site	52.7	12.7	7.0	1.8	2.0	0.6	0.5	0.3	0.1	0.1	0.1	0.1	0.1	0.0	0.1	77.8	4.2	0.64
Std Dev	83.5	27.0	12.5	3.1	3.7	0.8	1.4	0.8	0.4	0.2	0.3	0.3	0.4	0.0	0.2	94.4	2.4	0.47
% of Sites Occupied	75	65	85	40	35	45	15	15	5	5	10	10	5	0	5			
% of Total N	68	16	8.9	2.2	2.5	0.8	0.6	0.4	0.1	0.1	0.1	0.1	0.1	0.0	0.1			

* Untreated NOAA site; ** Treated NOAA site

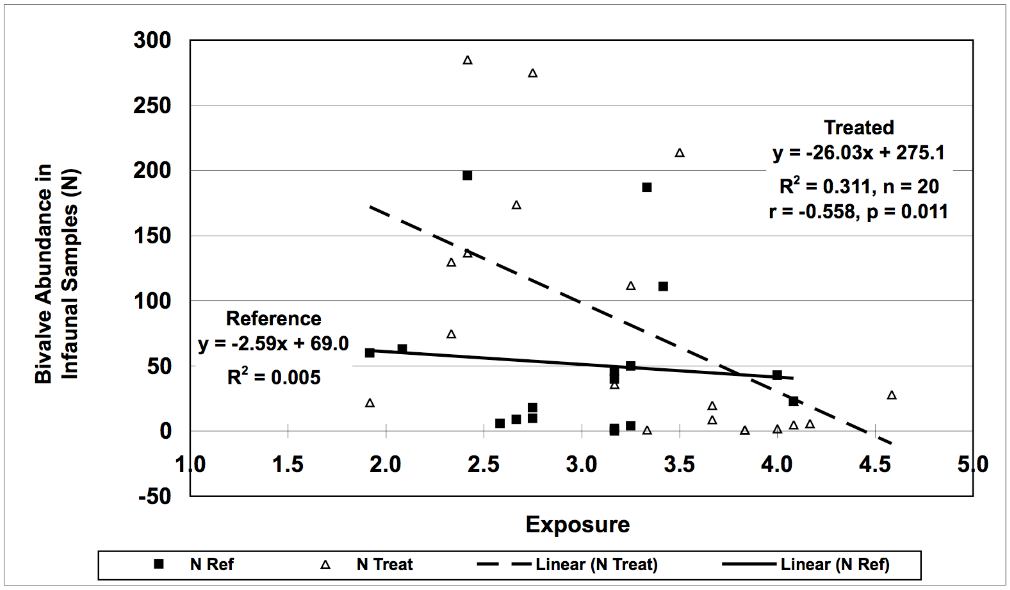


Figure 7. Comparison of relationships between bivalve abundance (N) and exposure scores in core samples at Treated and Reference sites.

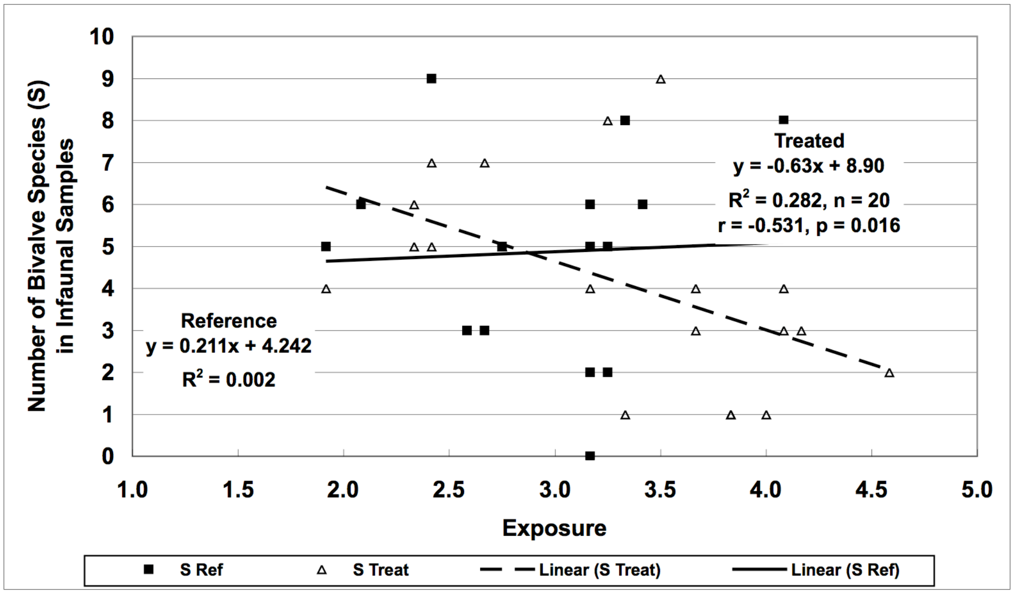


Figure 8. Comparison of relationships between bivalve species richness (S) and exposure scores in core samples at Treated and Reference sites.

Species Distribution

Excavation Samples

The four most abundant bivalves in the excavation samples were *Protothaca*, *Hiatella*, *Saxidomus*, and *Macoma inquinata* (Table 7). Our expectation was that large individuals of long-lived species such as *Protothaca*, *Saxidomus*, and *M. inquinata* would be less abundant at Treated sites because of a the initial mortality during treatment and a lag in recovery due to disturbances associated with HP-HW treatment. In contrast, we postulated that *Hiatella*, a pioneer species (inferred from Gulliksen *et al.* 1980 and Morris *et al*. 1980), would be more abundant at Treated sites, as we observed during our NOAA study (Houghton *et al.* 1997). We observed that *Protothaca* and *Saxidomus* were significantly more abundant at Reference sites (Table 10; p = 0.007 and 0.099, respectively). In contrast to findings in the earlier NOAA studies which we used in establishing the alternative hypothesis, *Hiatella*$_{\text{Trt}}$ > *Hiatella*$_{\text{Ref}}$, the small, short-lived nestling *Hiatella* also exhibited a strong trend toward higher abundance at Reference sites in the excavation samples. It seems clear that the alternative hypothesis adopted for *Hiatella* in the excavation samples, based on observations in core samples during the NOAA study, is incorrect, possibly because different size-classes are represented in the two types of samples. Of the five species represented by more than 20 individuals overall, only *M. inquinata* was less abundant at Reference sites.

Table 10. Comparison of mean abundance (± sd) for bivalve species in excavation and core samples from Reference and Treated sites in western Prince William Sound, August 2002. Bolded p-values indicate significant differences and underlining indicates a strong trend.

Sample Type/ Bivalve Species	**Alternative Hypothesis**	**Reference** $\bar{X}$ **± sd**	**Treated** $\bar{X}$ **± sd**	**Exact p***
EXCAVATION				
Protothaca staminea	Reference > Treated	34.4 ± 41.1	11.1 ± 14.9	**0.007**
Hiatella arctica	Treated > Reference	19.2 ± 57.2	3.3 ± 7.2	0.83
Saxidomus gigantea	Reference > Treated	4.94 ± 8.40	2.27 ± 3.56	**0.099**
Macoma inquinata	Reference > Treated	4.00 ± 7.30	5.09 ± 10.8	0.63
CORE				
Rochefortia tumida	Reference > Treated	22.8 ± 41.8	52.7 ± 83.5	0.91
Protothaca staminea	Reference > Treated	11.8 ± 14.4	7.0 ± 12.5	0.143
Hiatella arctica	Treated > Reference	9.1 ± 14.4	12.7 ± 27.0	0.35
Modiolus modiolus	Reference > Treated	2.7 ± 5.4	1.8 ± 3.1	0.26
Macoma balthica	Reference > Treated	2.0 ± 2.6	2.0± 3.7	0.47
Saxidomus gigantea	Reference > Treated	1.7 ± 1.6	0.6 ± 0.8	**0.006**

* Calculated with a randomization t-test using 5000 iterations

As in the case of numerical characteristics, the response of dominant clams to exposure provides useful insight into the influence of exposure on intertidal bivalve assemblages. For hard-shell clams (*i.e., Protothaca* and *Saxidomus*), the larger, older size fraction in excavation samples became significantly more abundant with increasing exposure at the Reference sites (Figure 9; p = 0.04). In contrast, that size fraction showed no response to exposure at the Treated sites. None of the other clam species in the excavation samples exhibited significant correlations with exposure.

Core Samples

The six most abundant bivalves in the core samples were *Rochefortia*, *Protothaca*, *Hiatella*, *Modiolus*, *Macoma balthica*, and *Saxidomus* (Table 9). Again we expected that *Rochefortia*, *Protothaca*, *Saxidomus*, and *Macoma balthica* would be less abundant at Treated sites, but that *Hiatella* would be more abundant at Treated sites. Indeed, *Saxidomus* was significantly more abundant at Reference sites (Table 10; p = 0.006) and *Protothaca* demonstrated a strong trend (p = 0.143). In contrast to the pattern observed in the NOAA studies and adopted as its specific alternative hypothesis, *Rochefortia* was substantially more abundant at Treated sites than at Reference sites. *Hiatella* demonstrated a weak trend agreeing with its specific alternative hypothesis, *i.e*., it was more abundant at Treated sites.

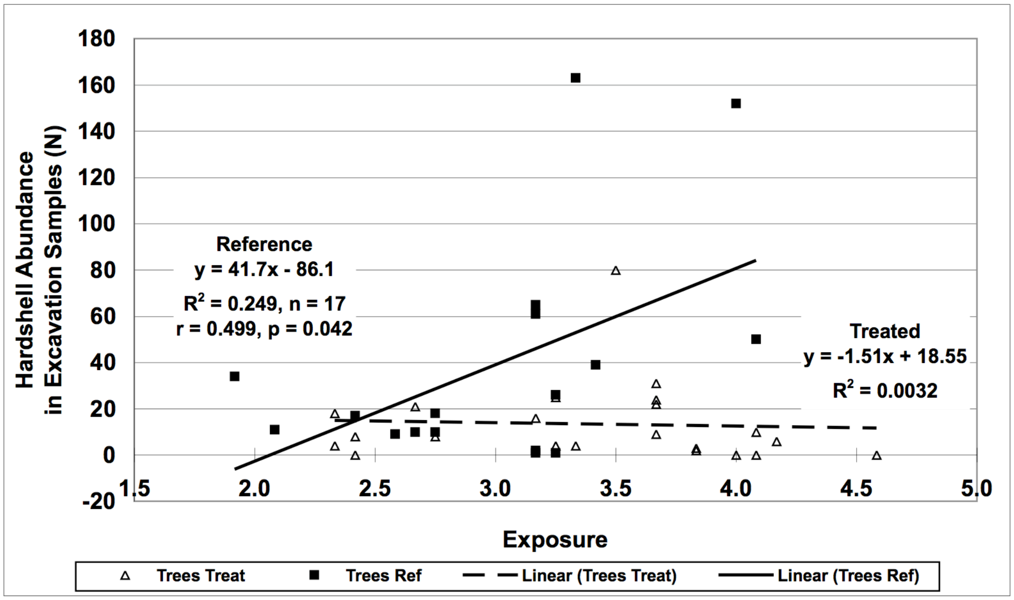
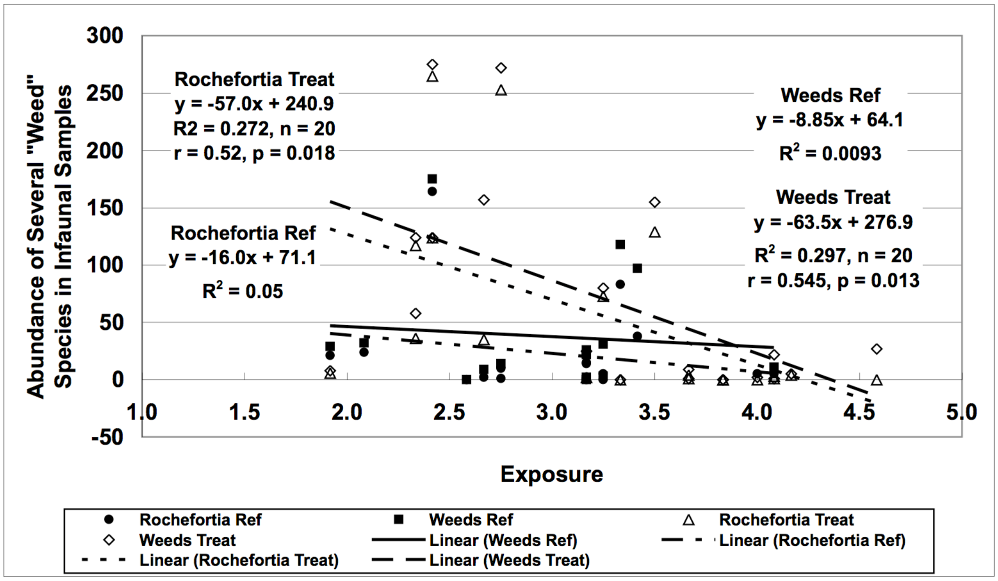


Figure 9. Comparison of relationships between abundance of hard-shell clams and exposure scores in excavation samples at Treated and Reference sites.

In the core samples, the smaller, shorter lived, "weed" species such as *Rochefortia*, *Hiatella*, and *Macoma balthica* and hard-shelled clams both exhibited significant responses to increasing exposure at Treated sites (Figures 10a and b). The "weed" species were considerably more abundant at Treated than at Reference sites. These patterns contrast to those exhibited by hard-shell clams in the excavation samples, in which hard-shell clam abundance increased with increasing exposure at Reference sites but demonstrated no response at Treated sites (Figure 9).

a. “Weed” species (*Rochefortia, Hiatella,* and *Macoma balthica*)



b. *Protothaca*, representing hard-shell clams

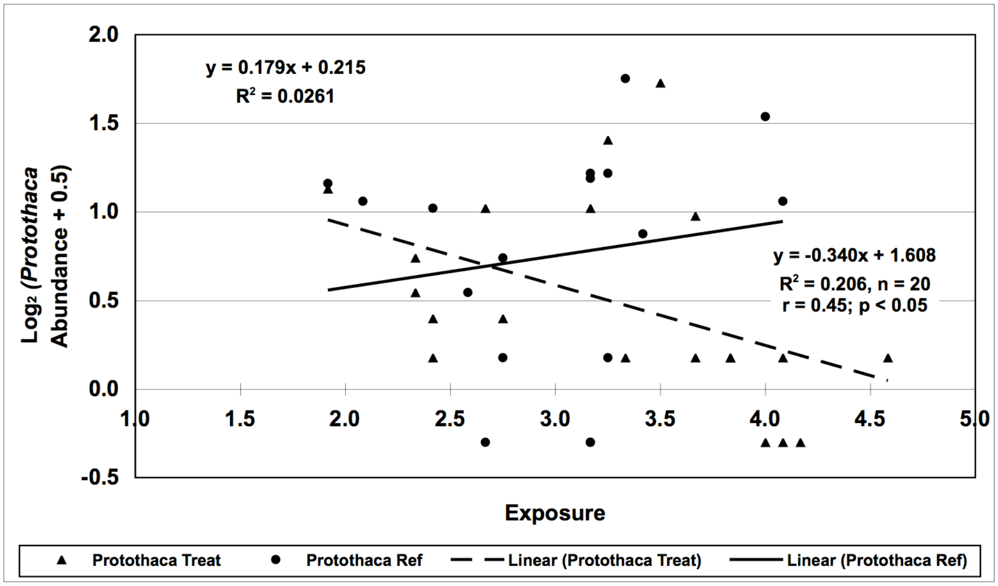


Figure 10. Comparisons of relationships between smaller clams in core samples, *i.e.*, (a) three “weed” species and (b) *Protothaca*, and exposure scores at Treated and Reference sites.

Comparative Abundance of Juvenile and Adult Bivalves

The effect of altered sediment conditions and reduced abundance of adults on larval recruitment to washed sediments are important issues to address with regard to the effect of HP-HW washing. To examine whether abundance of juveniles and adults were related, *i.e.*, whether adults are important in attracting juveniles, size data for *Protothaca*, *Saxidomus*, *Hiatella*, and

Macoma inquinata were sorted into juvenile and adult categories based on their respective size structure and shell annuli data. Because core samples provided the most unbiased contrast of juvenile and adult abundance, they were the primary focus for this analysis in cases where abundance was adequate.

First, we compared average numbers of juveniles per site for *Protothaca*, a large, long-lived species, and *Hiatella*, a small, short-lived species. Because sediments were relatively undisturbed and adult abundance was higher at Reference sites, we postulated they would support greater numbers of juvenile *Protothaca*. Although the average number of juvenile *Protothaca* per site was higher for Reference sites (6.4 vs. 4.9), the difference was not significant ($p = 0.32$, 1-way randomization t-test). The juvenile/adult ratio for *Protothaca* was lower for Reference than for Treated sites (1.39 vs. 1.93 juveniles per adult, respectively). Because *Hiatella* is a pioneer species, we postulated that juveniles would be more abundant at Treated sites and, in fact, numbers of juveniles were higher at Treated than at Reference sites (means = 15.5 vs. 4.8 juveniles per site, respectively; $p = 0.15$). Although large *Hiatella* were substantially less abundant in core samples from Treated than from Reference sites, the juvenile/adult ratio for *Hiatella* was higher for Treated than for Reference sites (3.44 vs. 1.70). This is not a surprising pattern for a pioneer species. The patterns for both species seem to indicate that Treated sites have more juveniles per adult than Reference sites even though adults are less numerous than at Reference sites.

The relationships between juvenile and adult abundance also varied among these species. Abundance of juvenile and adult *Protothaca* in core samples exhibited positive highly significant correlations at both Reference and Treated sites ($p \ll 0.01$ for both; Figure 11). These data suggest that recruiting *Protothaca* larvae may be positively attracted to sediments inhabited by adults. This figure also demonstrates that while juveniles occurred in similar numbers at Treated and Reference sites, numbers of adults were far lower at Treated sites.

Abundance of juveniles and adults of *M. inquinata*, with sufficient abundance only in the excavation samples, was positively correlated ($p < 0.1$). Juvenile and adult abundances were not correlated ($p > 0.1$) for *Hiatella* or *Saxidomus* from excavation samples.

Size and Age Structure of Dominant Bivalves

Differences in size and age structure provide helpful insights into the effects of shoreline treatment. Among the larger clams, adequate data for age estimation (based on annuli on the shells) were available for *Protothaca*, *Saxidomus*, *Macoma inquinata*, and *Hiatella*. Size and annuli data from individual sites were pooled by treatment types to provide adequate numbers of individuals for comparison of treatments. For comparison of size structure, data for excavation and core samples are presented separately because the differences in numbers of individuals sampled by the different techniques and the inclusion of younger animals in the core samples would skew the size-frequency histograms. However, since these factors were not considered important in comparing shell length with numbers of annuli, size and annuli data from excavation and core samples were combined before examining the relationship between shell length and number of annuli for each species.

Generally, comparisons of size structures between the treatment categories were not statistically different (see below). However, we believe it is important to point out a pattern of differences across species and sample types that, because of its consistency, suggests shoreline treatment has effected size structure.

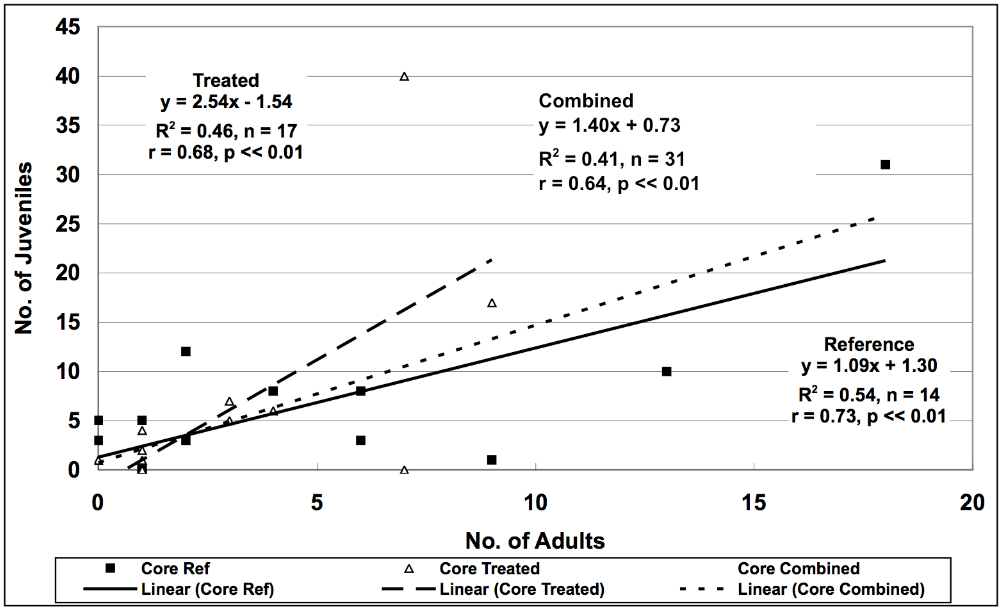


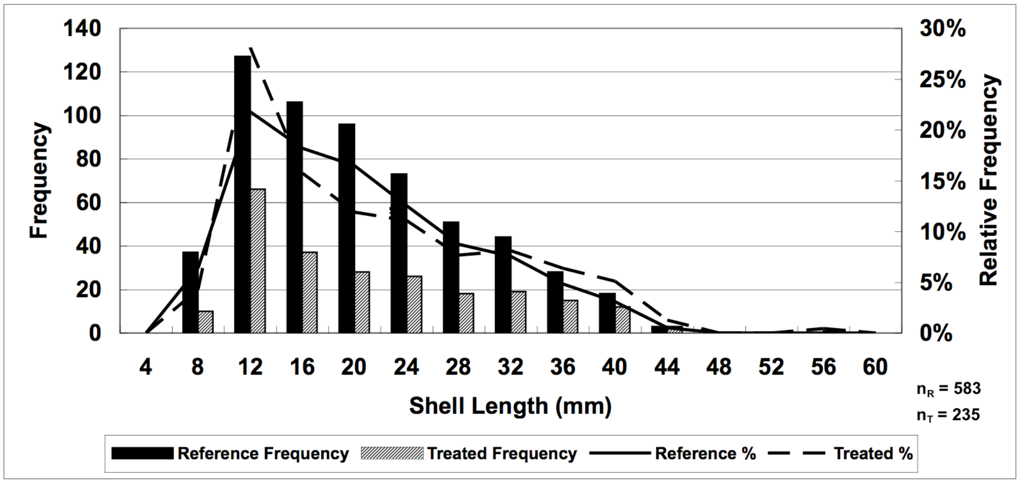
Figure 11. Correlations between juvenile and adult specimens of *Protothaca staminea* in core samples from Reference and Treated sites in western Prince William Sound, August 2002.

Although the number of individuals of *Protothaca* in excavation samples was substantially lower at Treated than at Reference sites, a comparison of relative abundance in the various size classes indicates that size structure was generally similar (Figure 12a). Shell length averaged 18.8 ± 9.3 mm and 18.4 ± 8.4 mm at Reference and Treated sites, respectively. Neither the means nor relative abundance of the size classes in the frequency histograms (relative abundance data for size structure compared using the Kolmogorov-Smirnov two-sample test) differed significantly. However, relative abundance of the year-classes between about 5.4 and 8.3 years was about 10 percent lower at Treated than at Reference sites (Figure 12b). Based on the relationship between shell length and age, the average age of these populations was about 6 years (Figure 13; Table 11).

As a consequence of the difference in mesh sizes used in screening excavation and core samples (6.35 mm vs. 1 mm, respectively), average size and size structure in core samples were driven by juvenile and younger specimens of *Protothaca* (Figure 12b). The two smaller year classes (4- and 8-mm) included 50-60 percent of the specimens in the core samples (Figure 12b) whereas they comprised only about 5 percent in the excavation samples (Figure 12a). Shell length averaged 11.6 ± 9.0 mm and 10.4 ± 8.6 mm at Reference and Treated sites, respectively. Neither the mean length nor size structure differed significantly. However, relative abundance of the year-classes between about 5.3 and 7.4 years was about 12 percent lower at Treated than at

Reference sites. Based on the relationship between shell length and age, the average age of these populations was about 3-4 years (Figure 13; Table 11).

a. Excavation samples



b. Core samples

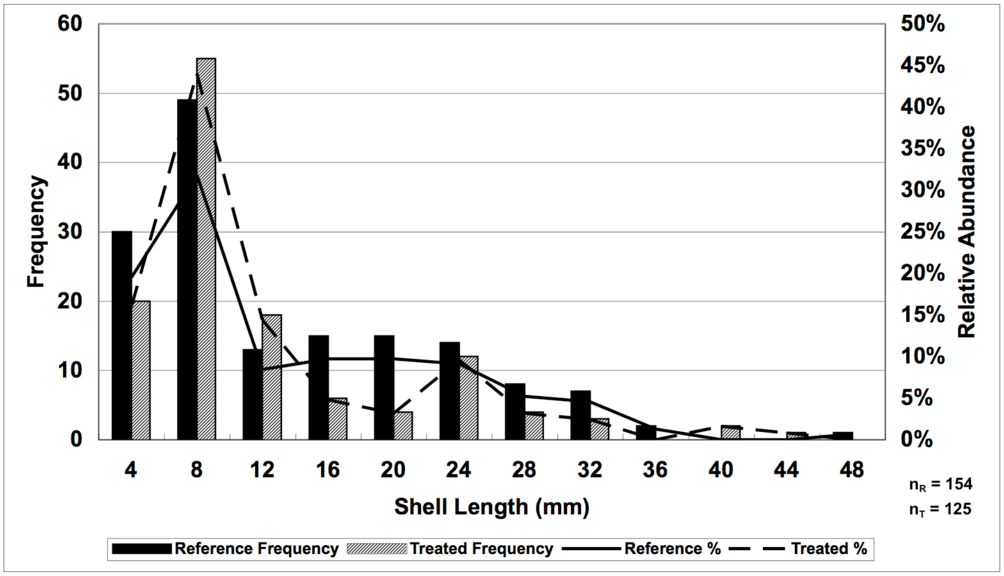


Figure 12. Comparison of shell length frequency for *Protothaca staminea* in (a) excavation and (b) core samples from Treated and Reference sites.

The relationship between shell length and numbers of annuli (growth checks) for *Protothaca*, although exhibiting substantial variability, was nevertheless strongly correlated ($p << 0.001$; Figure 13). Reasons for variability in the relationship are several, including inaccuracies in counting annuli resulting from shell erosion, especially the oldest portions of the shell near the umbones, and poor definition of annuli, differences in growth rates due to variation in food availability, *etc*. The strong overlap of the respective lines representing correlation equations for clams from Reference and Treated sites indicates that growth rates did not differ between the treatment categories. Specimens of *Protothaca* with shell lengths of 45 mm and up to 18 annuli were observed. The maximum size observed in this study was substantially smaller than the shell length predicted for age 18 (74.9 mm; Table 11) by the regression equation describing the data (Figure 13). Based on the annuli, approximately 5 percent of both the Reference and Treated populations were more than 12 years old, *i.e.*, were recruited in or before 1990.

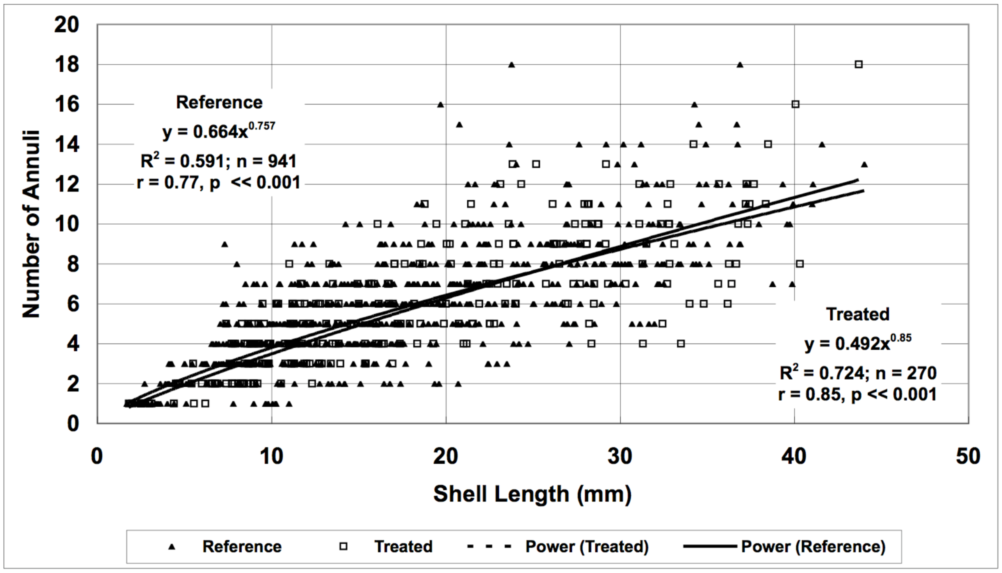


Figure 13. Relationships between shell length and number of annuli for *Protothaca staminea* in excavation and core samples from Treated and Reference sites. Estimated shell lengths estimated using the regression equations for the combined specimens in length/annuli figures ($y = 0.607x^{0.786}$).

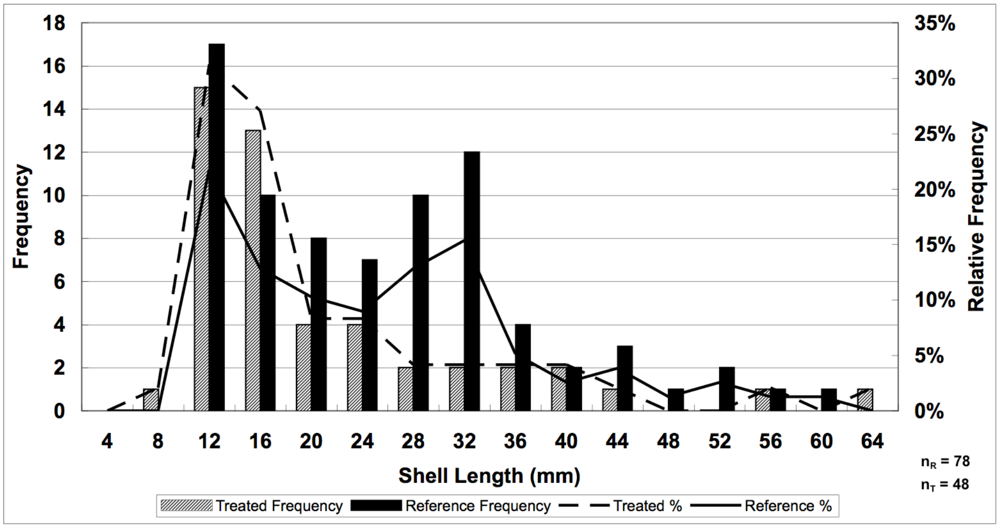
Table 11. Estimated shell length at specific estimated ages, based on shell lengths and number of annuli observed in specimens of *Protothaca staminea*, *Saxidomus gigantea*, *Macoma inquinata*, and *Hiatella arctica*. Shell lengths are estimated using regression equations shown in figures demonstrating relationships between length and number of annuli for the various species.

Number of Annuli	**Estimated Shell Length (mm)**			
	Protothaca staminea	***Saxidomus gigantea***	***Macoma inquinata***	***Hiatella arctica***
1	1.9	1.5	1.2	2.7
2	4.6	2.8	4	8.1
3	7.7	6.5	6.8	15.4
4	11	10.2	9.7	24.1
5	14.7	13.9	12.5	34.3
6	18.5	17.6	15.3	45
7	22.5	21.3	18.1	58.3
8	26.7	25	20.9	

Number of Annuli	Estimated Shell Length (mm) *Protothaca staminea*	 *Saxidomus gigantea*	 *Macoma inquinata*	 *Hiatella arctica*
9	31	28.7	23.7	
10	35.4	32.4	26.5	
11	40	36.1	29.3	
12	44.7	39.7	32.2	
13	46.5	41.4	35	
14	54.4	47.1	37.8	
15	59.4	50.8	40.6	
16	64.5	54.5	43.4	
17	69.6	58.2	46.2	
18	74.9	61.9	49	
19		65.6		
20		69.3		
21		73		
22		76.6		

As was the case for *Protothaca*, numbers of *Saxidomus* were lower at Treated than at Reference sites in the excavation samples (Figure 14a). Average shell length was smaller at Treated sites (18.9 ± 12.1 mm) than at Reference sites (23.5 ± 11.6 mm) but not significantly. Neither the means nor size structure differed significantly. However, relative abundance of the year-classes between about 6.5 and 11 years old was about 22 percent lower at Treated than at Reference sites (Figure 14a) but younger year-classes (between 3.5 and 7 years) were relatively more abundant at the Treated sites. Based on the relationship between shell length and age, the average age of these populations was about 7.5 years at Reference sites and 6.5 years at Treated sites (Figure 15; Table 11).

a. Excavation samples



b. Core samples

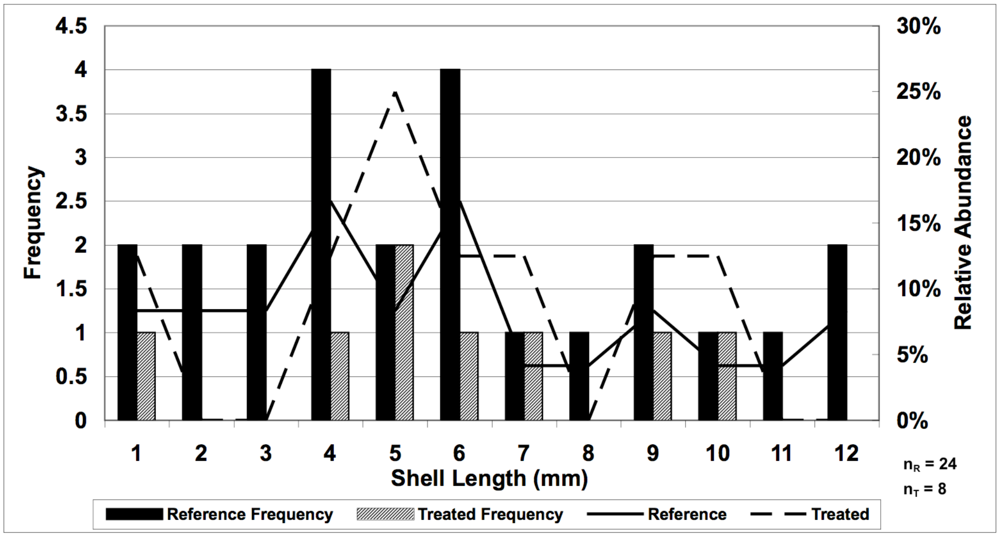


Figure 14. Comparison of shell length frequency for *Saxidomus gigantea* in excavation and core samples from Treated and Reference sites.

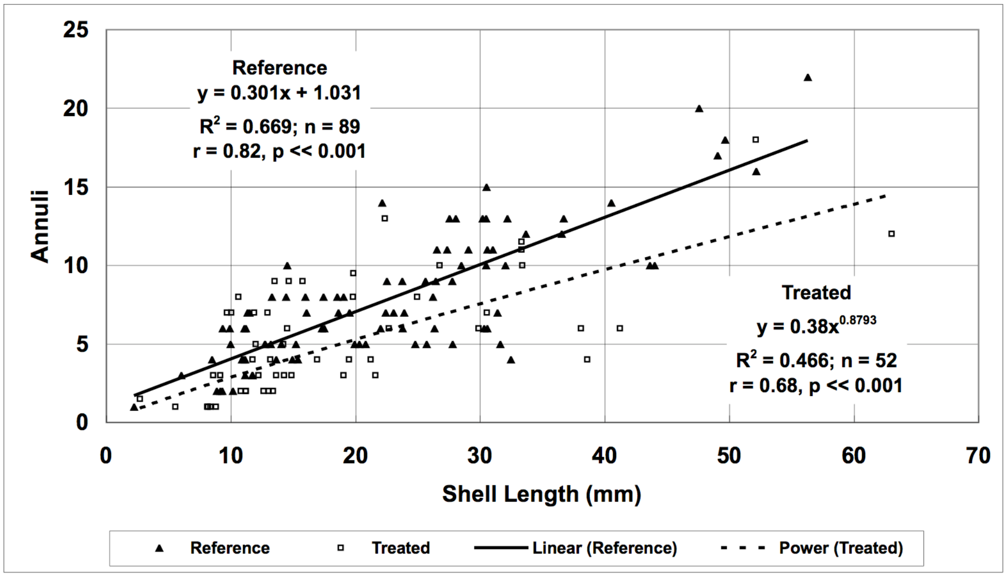


Figure 15. Relationships between shell length and number of annuli for *Saxidomus gigantea* in excavation and core samples from Treated and Reference sites.

Specimens of *Saxidomus* were sparse in the core samples. Shell length, averaging 21.5 ± 13.0 mm and 21.6 ± 10.8 mm at Reference and Treated sites, respectively, was virtually identical at Reference and Treated sites (Figure 14b). Based on the relationship between shell length and age, the average age of these populations was about 7 years (Table 11; Figure 15).

As with *Protothaca*, the relationship between shell length and annuli for *Saxidomus* was highly variable (for the same reasons) but strongly correlated ($p << 0.001$; Figure 15). *Saxidomus* appeared to grow slightly faster at the Treated sites. Specimens up to 63 mm in shell length and with 22 annuli were observed. Based on annuli, the fraction of the population more than 12 years old (recruited in or before 1990) was 18 percent at the Reference sites but less than 6 percent at the Treated sites (Figure 15).

Numbers of *Macoma inquinata* in the excavation samples were substantially greater in Treated than in Reference samples (Figure 16). Nevertheless, neither the means nor size structure differed significantly. In this case, relative abundance of the year-classes between about 5 and 8 years old was greater at Treated than at Reference sites (Figure 16) but younger year-classes were relatively less abundant at Treated sites. Shell length, averaging 18.2 ± 6.8 mm at Reference sites and 18.1 ± 6.8 mm at Treated sites, was virtually identical. Based on the relationship between shell length and age, the average age of these populations was about 7 years (Figure 17; Table 11).

The relationship between shell length and annuli exhibited considerable variability by was highly correlated ($p << 0.001$; Figure 17). Growth rates appeared to be similar in both types of sites. Specimens as large as 38 mm and with up to 18 annuli were observed. Based on annuli, the fraction of the population more than 12 years old (recruited in or before 1990) was only 4 percent at the Reference sites but about 12 percent at the Treated sites (Figure 17). *Macoma inquinata* was not sufficiently abundant in the core samples to warrant analysis of size or age structure.

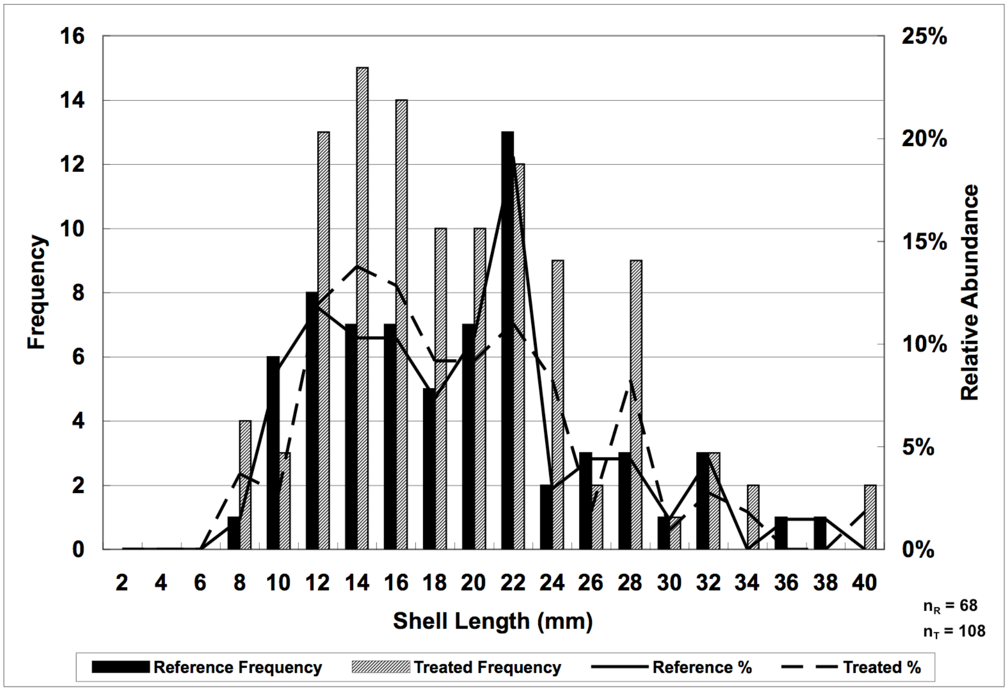


Figure 16. Comparison of shell length frequency for *Macoma inquinata* in excavation samples from Treated and Reference sites.

Hiatella was considerably less abundant at Treated than at Reference sites in the excavation samples (Figure 18a). Nevertheless, shell lengths, averaging 15.1 ± 3.8 mm and 14.6 ± 5.0 mm at Reference and Treated sites, respectively, were quite similar and neither the means nor size structure differed significantly. Nevertheless, relative abundance of the year-classes between about 2.5 and 3.5 years was about 18 percent lower at Treated than at Reference sites (Figure 18a). Based on the relationship between shell length and age, the average age of these populations was about 3 years (Figure 19) and growth appeared to be quite rapid compared to the other species (Figures 13, 15, and 17). However, based on the maximum number of annuli counted (7), *Hiatella* appears short-lived compared to the other three species discussed.

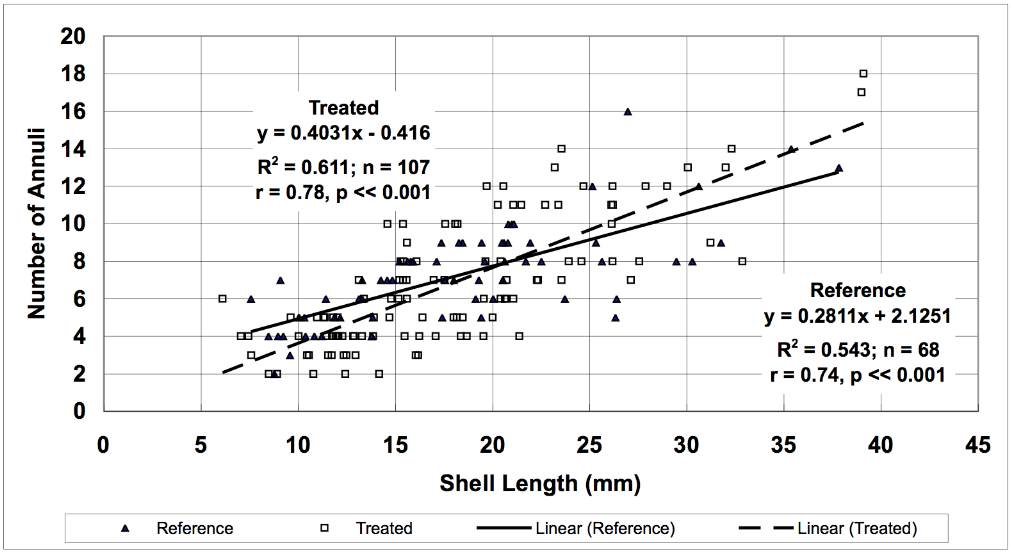


Figure 17. Relationships between shell length and number of annuli for *Macoma inquinata* in excavation and core samples from Treated and Reference sites.

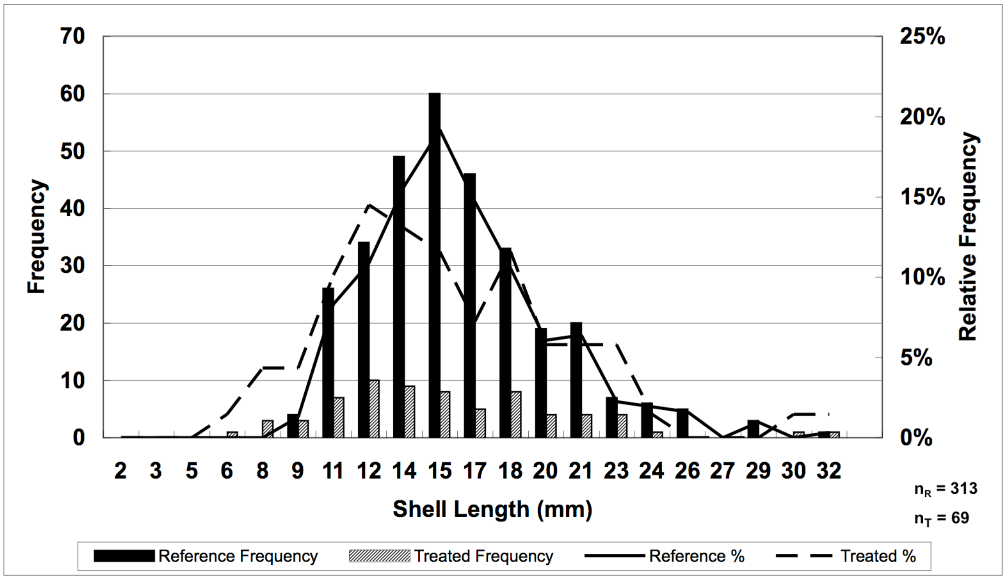
In the core samples, *Hiatella*, especially the younger animals, were considerably more abundant at Treated sites. Average shell length differed somewhat between Reference (6.4 ± 4.5 mm) and Treated (4.4 ± 3.3 mm) sites, but neither the means nor size structure differed significantly. However, relative abundance of the year-classes between about 2.5 and 3.5 years was about 23 percent lower at Treated than at Reference sites (Figure 18b). Based on the relationship between shell length and age, the average age of these populations was about 1-1.5 years (Figure 19).

Again, the relationship between shell length and annuli was quite variable but strongly correlated ($p << 0.001$; Figure 19). Growth rates were similar in both treatment categories. Specimens with shell lengths up to 32 mm were observed but the maximum number of annuli noted was 7, indicating that *Hiatella* lives a considerably shorter time than the other species considered in this section. Only 6 percent of the population was more than 4 years old; 76 percent of these were from Reference sites even though specimens at Reference sites only accounted for 58 percent of the total number of *Hiatella* measured.

Relationships Between Sediment Properties and Bivalves

To gain an appreciation of the importance of sediments on the distribution of the bivalve species and assess whether sediments played a role in the differences we have observed in abundance of bivalve species between Reference and Treated sites, we examined the relationships between sediment properties and abundance of dominant bivalves in Reference and Treated samples.

a. Excavation samples



b. Core samples

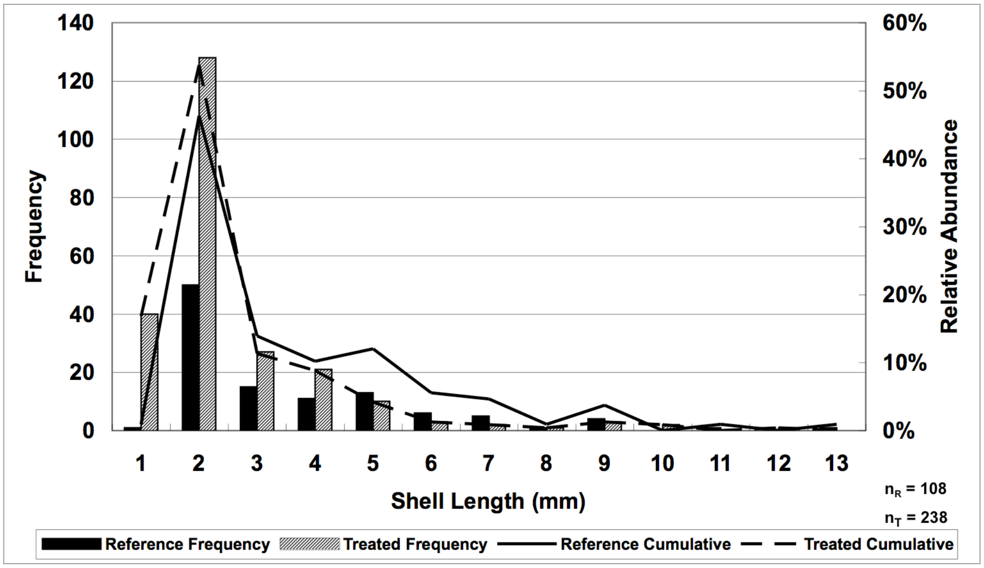


Figure 18. Comparison of shell length frequency for *Hiatella arctica* in excavation samples from Treated and Reference sites.

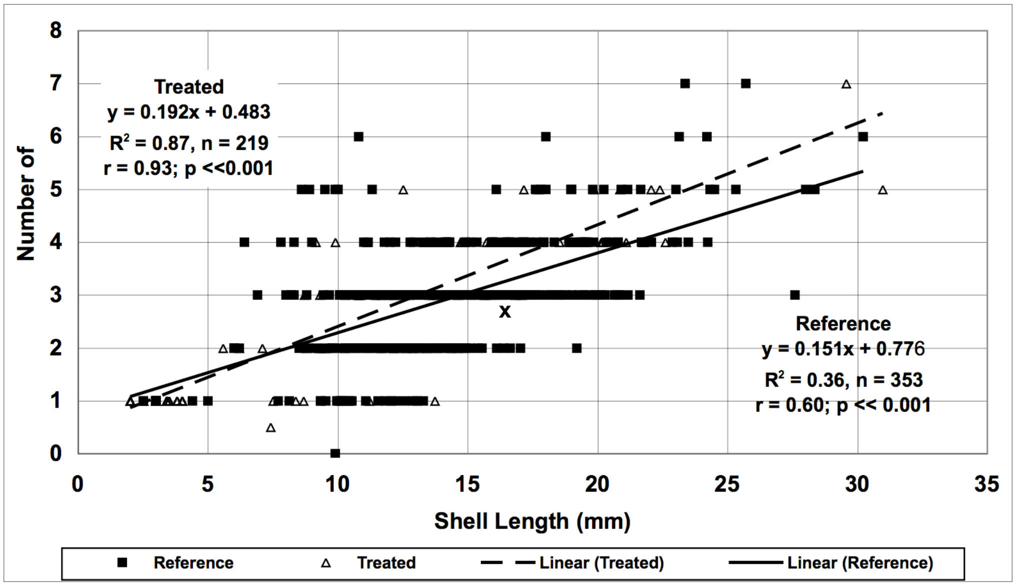


Figure 19. Relationships between shell length and number of annuli for *Hiatella arctica* in excavation and core samples from Treated and Reference sites.

Approximately one-third of the relationships between sediment properties and bivalve species abundance or numerical characteristics for the bivalve assemblage were statistically significant (Table 12). If strong trends are included ($0.2 > p > 0.1$), over 40% of the relationships are relevant. PGS appeared to have the greatest influence; half of these comparisons were significant. All species except *Modiolus* and the numerical characteristics of the bivalve assemblage responded to PGS with at least a strong trend in one of the sample types. Significant correlations with PGS were nearly twice as frequent in core samples as in excavation samples. This suggests that younger bivalves respond to PGS more than the more mature component.

Likewise, TKN, a useful indicator of the abundance of bacteria, significantly correlated in one-quarter of the comparisons overall, appeared particularly influential in core samples, in which it was significantly correlated with N and S in both treatment categories. Since TKN exhibited less influence in the excavation samples than in core samples, it appears that organic nitrogen in the sediments may exert a greater influence over the distribution of the younger than older bivalves. Relationships between the remaining sediment and biological characteristics were relatively weaker (Table 12). Among the numerical characteristics, S was most highly correlated with the range of sediment properties. This trend was strongest in the core samples (Table 12a). N and S for core samples from Treated sites correlated significantly with all sediment properties except C/N. N and S responded negatively to coarser PGS whereas they responded positively to increases in fines, TOC, and TKN. These responses appeared to be more intense at Treated sites, where PGS was coarser and fines were reduced, than at Reference sites. Although the patterns are weaker in the excavation samples, the response patterns are basically the same.

In the core data, *Rochefortia* from Treated sites was the only species for which abundance correlated significantly with more than two sediment properties. Its abundance correlated negatively with PGS and positively with silt/clay, TOC, and C/N (Table 12a). None of the species in the core samples from Reference sites showed correlations with more than two sediment properties.

Table 12. Correlations between dominant bivalve species or assemblage characteristics and sediment properties in core and excavation samples from western Prince William Sound, August 2002.

a. Core data.

	Sediment Variables Correlation Coefficient (r)				
Abundance	PGS	Silt/Clay	TOC	TKN	C/N Ratio
Reference					
Hiatella arctica	-0.33	0.30	0.21	**0.64**	**-0.49**
Rochefortia tumida	**-0.44**	0.18	0.40	0.49	0.02
Protothaca staminea	-0.41	-0.31	-0.24	0.06	-0.19
Saxidomus gigantea	*-0.58*	0.29	0.28	**0.72**	-0.37
Modiolus modiolus	0.38	-0.26	0.20	**-0.61**	0.67
Macoma spp.	-0.26	**0.60**	0.16	0.24	0.50
Total Individuals	**-0.40**	0.21	0.18	**0.55**	-0.26
Number of Species	**-0.37**	0.30	-0.27	**0.46**	**-0.50**
Treated					
Hiatella arctica	**0.54**	-0.35	0.02	0.15	-0.18
Rochefortia tumida	**-0.40**	**0.48**	**0.60**	0.18	**0.59**
Protothaca staminea	**-0.30**	0.29	-0.12	0.25	-0.23
Saxidomus gigantea	0.69	**-0.54**	-0.19	0.26	-0.44
Modiolus modiolus	-0.28	0.36	**0.59**	**0.69**	-0.05
Macoma spp.	*-0.65*	0.14	-0.24	-0.38	-0.18
Total Individuals	**-0.36**	**0.51**	**0.34**	**0.34**	0.34
Number of Species	**-0.46**	*0.61*	**0.34**	**0.53**	-0.07

b. Excavation data.

Reference					
Hiatella arctica	0.29	-0.15	-0.31	-0.2	**-0.65**
Protothaca staminea	**-0.39**	0.33	-0.21	0.26	-0.28
Saxidomus gigantea	0.27	-0.14	**-0.48**	0.41	-0.47
Macoma inquinata	-0.21	0.32	0.29	0.06	0.28
Macoma spp.	-0.15	0.39	**0.33**	0.05	0.2
Total Individuals	-0.09	0.28	-0.18	0.15	**-0.36**
Number of Species	**-0.37**	**0.35**	0.18	0.31	-0.27

Abundance	Sediment Variables Correlation Coefficient (r)				
	PGS	Silt/Clay	TOC	TKN	C/N Ratio
Treated					
Hiatella arctica	**0.61**	0.23	**0.81**	0.29	**0.67**
Protothaca staminea	-0.19	0.34	0.09	0.26	-0.27
Saxidomus gigantea	-0.32	0.08	-0.18	0.23	-0.28
Macoma inquinata	**-0.75**	**0.66**	**0.63**	0.45	**0.7**
Macoma spp.	**-0.57**	0.27	0.13	-0.41	0.54
Total Individuals	-0.27	**0.4**	0.21	0.18	0.19
Number of Species	-0.3	**0.38**	0.17	0.21	-0.06

- Underlining indicates strong trend ($p < 0.15$), bold and italic types indicate significant ($p = 0.1$) and highly significant ($p < 0.01$) differences, respectively.

In excavation samples, *Hiatella* and *Macoma inquinata* from Treated sites were significantly correlated with at least three sediment properties (especially PGS, TOC, and C/N) but were poorly correlated among the Reference sites (Table 12b). *Protothaca*, *Saxidomus*, N, and S exhibited weak relationships with sediment properties among both Reference and Treated sites.

Generally, the response pattern (positive or inverse) of the various biological characteristics to specific sediment properties was consistent (Table 12), *i.e.*, the vast majority of the biological characteristics in both the core and excavation data responded similarly. The biological characteristics typically showed a strong inverse correlation to PGS (24 inverse vs. 4 positive correlations); exceptions included mainly *Hiatella*, for which abundance was positively correlated with PGS. Otherwise, the correlations to silt/clay, TOC, and TKN were generally overwhelmingly positive (14 vs. 1, 12 vs. 3, and 22 vs. 1, respectively). Hall *et al.* (1993a) concluded that the positive infaunal response to organics (available food) was more relevant than the positive response to increased silt/clay. The response to C/N ratios was mixed (10 negative vs. 8 positive correlations).

Relationships Between Latitude and Bivalves

To assess the potential effect of distance from the Gulf of Alaska, we examined the relationship between latitude and the bivalve assemblage. Sites lacking values (*i.e.*, 0 values) were excluded from the calculations based on an assumption that strong factors other than potential latitudinal effects (*e.g.*, exposure) could be operating to make a habitat untenable for bivalves.

Correlations for all variables examined were inverse, *i.e.*, values decreased with increasing distance away from the Gulf of Alaska (latitude). Over half of the relationships exhibited either strong trends or significance (Table 13). N exhibited the weakest relationships, with the only significant correlation among Treated sites in the excavation samples. S exhibited a significant negative correlation among Reference sites or a strong trend among Treated sites with latitude in core samples.

Both *Protothaca* and *Saxidomus* demonstrated declining trends or significant negative correlations with increasing latitude in both types of samples (Table 13). The patterns observed for *Protothaca* among Reference and Treated sites in the excavation samples appear quite similar except that no Treated sites with high abundance were sampled closer to the gulf (Figure 20). Patterns were stronger for *Protothaca* than for *Saxidomus* and were stronger among Reference sites, where they have had more time to be expressed than among Treated sites. *Hiatella*, a pioneer species, and S did not display any consistent patterns and were poorly correlated with latitude. These relationships suggest that the species richness of bivalve assemblages and the density of both *Protothaca* and *Saxidomus* naturally decline in suitable sediments with increasing distance away from the Gulf of Alaska.

Table 13. Relationship between selected biological characteristics and latitude within Prince William Sound

Biological Characteristic	r	Exact p	Biological Characteristic	r	Exact p
N			**S**		
Core			Core		
Reference	-0.21	>0.2	Reference	-0.35	**0.085***
Treated	-0.05	>0.2	Treated	-0.17	0.106
Excavation			Excavation		
Reference	-0.13	>0.2	Reference	-0.26	>0.2
Treated	-0.38	**0.055**	Treated	-0.19	>0.2
Protothaca staminea			***Saxidomus gigantea***		
Core			Core		
Reference	-0.33	0.124	Reference	-0.64	*0.008*
Treated	-0.21	0.176	Treated	0.02	>0.2
Excavation			Excavation		
Reference	-0.35	**<0.1**	Reference	-0.47	**<0.1**
Treated	-0.61	**<0.01**	Treated	-0.04	>0.2

* Underlined, bold, and italicized numbers indicate strong trends, significant, and highly significant results.

Multivariate Analyses

Stepwise linear regressions were run in two phases, once with the Reference and Treated station data combined and using treatment as a dummy variable and then again as separate data sets to find the best set of environmental predictors for abundance of each species. From subsequent linear regressions using the variables identified by the stepwise selections, results varied with final multivariate correlations (r^2) ranging from 2% to 92% (Table 14). Normally, at this stage of the procedure, one would look at the list of selected variables for each species and the strength of the correlations and attempt to elucidate some cogent scenario of cause and effect. There were indeed some insights suggested from the list of species-specific predictors (albeit maybe not with water temperature) but after inspecting the standardized residual plots, there appeared to be a universal problem with the analyses. If a model (regression equation) describes the data well, the unexplained, leftover variance is considered to be "residual error" and is expected to appear in random patterns if the variances of the data are normally distributed. Systematic patterns imply systematic (and non-normal) issues in the data as a fit to the model. From our bivalve data, visibly non-random patterns of linear stripes suggested that either some interaction or an unmeasured variable was not accounted for (Figure 21). Since we evaluated a number of interaction terms and only had a single variable that was significant, we assume the residual structures are not from a combination of existing data but instead result from a missing variable. In discussions below, we postulate that most of these predictor variables are secondary indicators of beach armoring, which likely is the missing variable.

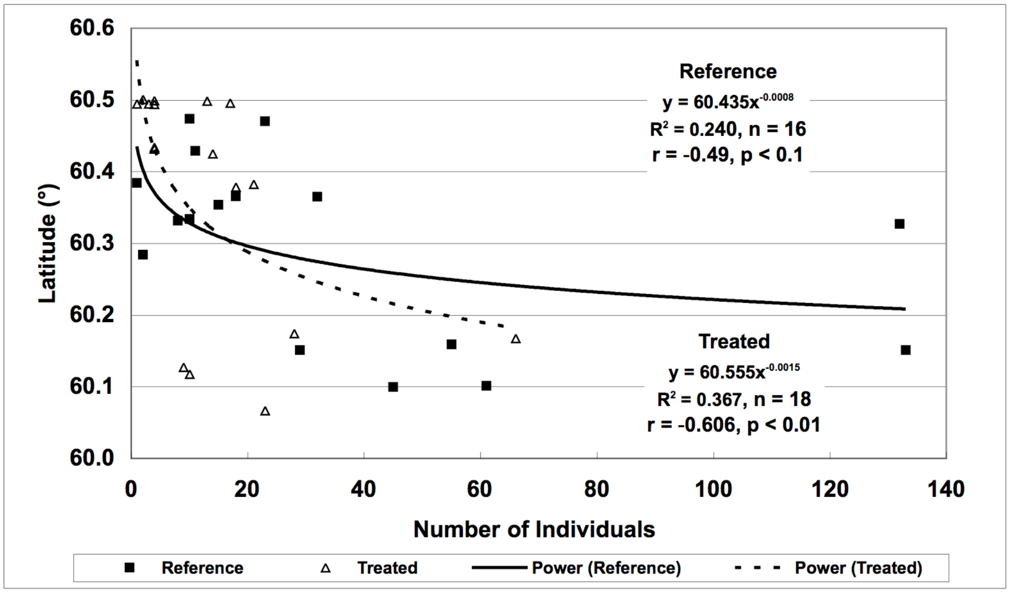


Figure 20. Relationships between abundance of *Protothaca staminea* in excavation samples from Reference and Treated sites and latitude within Prince William Sound.

For multivariate ordination, the core and excavation species were combined into one data set (cube-root transformed) with the different sampling methods coded by adding the prefixes "i" or "e" to species names found in core or excavation samples, respectively. The same environmental variables were used for both methods but species richness (S) and abundance (N) were calculated and coded for each method. Rare or anomalous species from either method were effectively discarded by designating them as non-functional extrinsic environmental variables. Likewise, stations missing either core or excavation results were also discarded from their respective analyses.

From initial runs, it was apparent that two assemblages were appearing; these comprised silt-affiliated species and sand-affiliated species. Since silt-affiliated species, primarily *M. balthica, M. inquinata*, and *Rochefortia*, were rare or sampled only in core samples, and co-appeared in ordinations quite separate from the other dominants, this line of analysis was deferred as less pertinent to this project. The subsequent analyses were instead focused on three dominant species, *Protothaca*, *Saxidomus,* and *Hiatella.*

Table 14. Regression components and adjusted r^2 for independent variables selected by standard stepwise regressions. The i and e species prefixes indicate core or excavation sample variables.

	Selected Variables	Adjusted r^2 (%)	Selected Variables	Adjusted r^2 (%)
	Combined Reference and Treated Sites			
e*Protothaca*	-Pebble, -Elevation, +tTOC[1]	36.3		
i*Protothaca*	-Pebble, -Elevation, +tTOC	55.7		
e*Saxidomus*	-Pebble, -tElevation	30.2		
i*Saxidomus*	-Pebble, +Ref x Silt, -Elevation	46.1		
e*Hiatella*	-Latitude	43.4		
i*Hiatella*	-tElevation	23.4		
	Reference Sites only		**Treated Sites only**	
e*Protothaca*	-Elevation, -Water Temp	91.2	+Sand	20.6
i*Protothaca*	-Water Temp, -Elevation	40.2	-Pebble	41.7
e*Saxidomus*	-Median Grain, -Elevation, +Exposure	55.5	-Pebble	2.2
i*Saxidomus*	+Silt	13.2	-Pebble	8.3
e*Hiatella*	-Latitude	30.7	-Latitude	53.8
i*Hiatella*	-Latitude	25.0	-tElevation	17.1

[1] tTOC = transformed TOC; tElevation = transformed tidal elevation; Ref x Silt = interaction term.

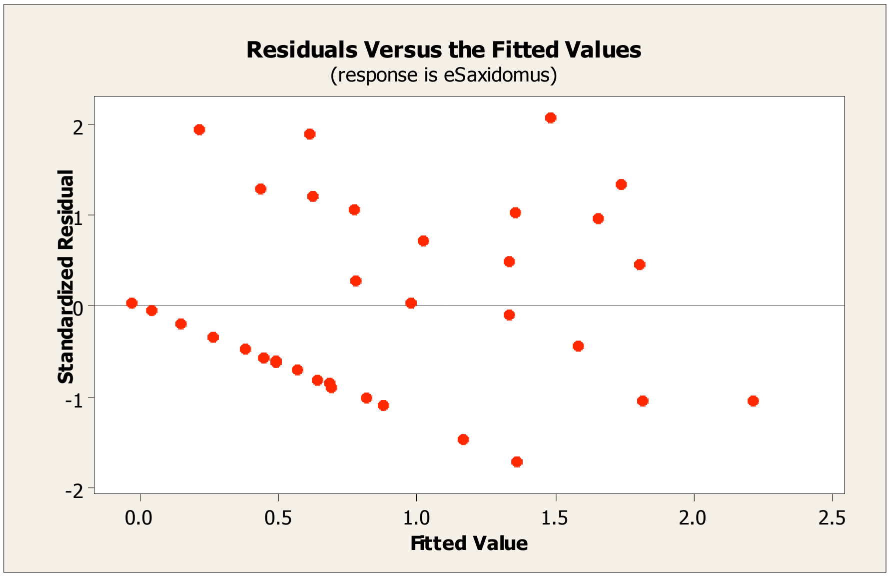


Figure 21. Example standardized residual plot from linear regression of excavation *Saxidomus* showing nonrandom patterns from missing variable.

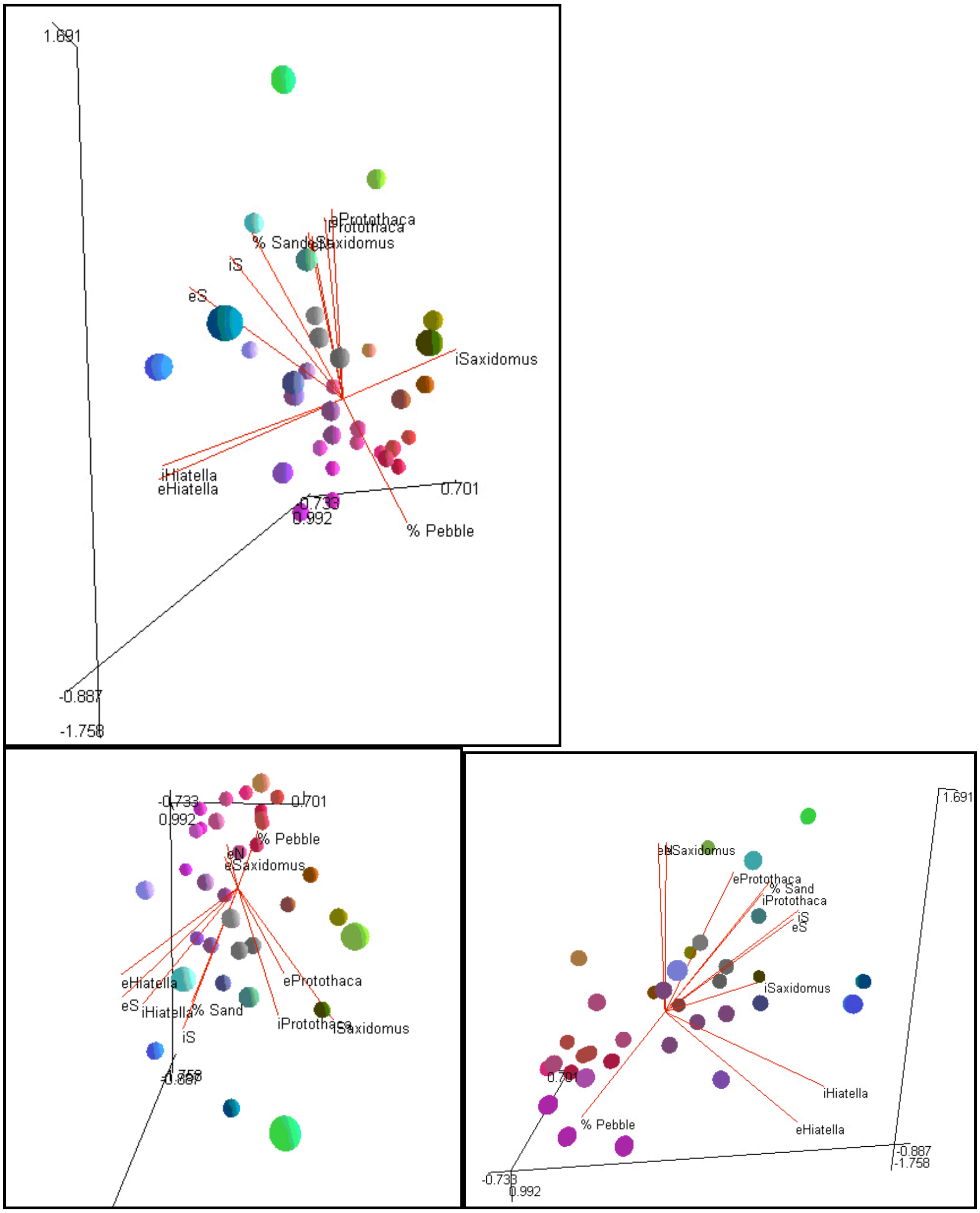


Figure 22. Three views of an ordination plot of stations (spheres) with selected species and environmental variables. Stress = 0.0839.

From results for the combined data (three species x two sampling methods), several features are apparent. The ordination (Figure 22) shows three views of a mostly linear cloud of stations represented by spheres ordered within perspective-distorted xyz axes, using a spectrum of color to aid in site identification in the three views, and varying size to imply depth of field. The placement of the stations (their configuration in ordination space) is based on the species' abundance and shows a rough axially aligned, multivariable gradient of the six species (versus differentiating separate clusters of sites). Judging from the low Kruskal stress value (0.0839), this station configuration is an excellent fit in the ordination space and well below 0.15, the cutoff value for acceptable fit suggested by Belbin (1991). Line symbols plotted amidst the stations represent the correlations of the species and selected environmental variables. Remember that variables showing a high correlation in ordination space are either responsible for the patterns or potentially causative, as in the case of the environmental variables. The species and variables form a scatter-line pattern resembling a daisy flower and stem (clearest in bottom right, Figure 22). From the placement of the plotted lines, the species fall spatially into four groups, the core and excavation *Protothaca* that are roughly proximal, both *Hiatella* placements that are close to each other but entirely separate from *Protothaca*, and the two separate *Saxidomus* points that are oriented orthogonally and separate from all others. The low KW value for *iHiatella* suggests the groupings were not a good description for its distribution (they don't fall into a single gradient pattern; there are more than one set of highs and lows) but the abundance gradient did correlate well with the ordination, producing a respectable $r^2 = 0.68$.

Among the environmental factors, the community descriptors, S and N (excepting iN), had the highest correlation to the ordination gradient (Figure 22). This finding is typical in ordinations of benthic communities. The richest, most prolific and species-diverse habitats are usually the most similar. The depauperate, least developed or poorly functioning communities are also similar but appear at the opposite end of the gradient.

Note that S and N fall between the four dominant bivalve groupings as they attempt to represent the richest sites for all species and sampling methods (Figure 22; eN is barely visible next to *eSaxidomus*). Striving for the best fit among the disparate species groups explains their mediocre r^2 and KW values (typically much higher for single treatment data subsets). The poor r^2 and KW values and "off-to-one-side" placement of iN (not plotted) is due to dominance of *Protothaca* and *Saxidomus* over *Hiatella* in the excavation data; iN best describes their abundance rather than paralleling the abundance of *eHiatella*.

More interestingly, the particle grain size variables, % sand and % pebble (Table 15), were mediocre in both their KW values and r^2 values (0.24-0.25) meaning that the ordination was somewhat correlated with the sediment grain size but the amount of variance explained by the multiple linear regressions was not impressive. Reassuringly, sand and pebbles plotted in opposite directions and intercepted the middle of the species groupings. The species appear to have higher affinity for % sand and a negative relationship with % pebble. The remaining environmental variables correlated poorly with the ordination components.

The species dendrogram (Figure 23) represents the result of the species clustering process, which has created three affiliated species groups. Here, it has nicely paired up the same species from each sampling method except that it linked the *eSaxidomus* into the *Protothaca* group prior to linking to *iSaxidomus*. This unexpected pairing suggests a subtle difference in their distributions. The station dendrogram (Figure 24) shows five major groupings. It was anticipated that these results would show, to some degree, a dichotomy between Reference and Treated sites. The results provide only weak support for the multi-species-based dichotomy concept (Table 16) but, if that concept is valid, either some stations were misclassified (discussed in Methods above) or response during intervening years to differing environmental gradients has blurred the distinctions.

The two-way coincidence table (Figure 25) overlays the species and station groups after they have been arranged in the order observed in their respective dendrograms. The species abundance data have been standardized (0.0 – 1.0) and color-coded such that the darkest squares indicate the highest abundances of the given species. For example, sites in station group 1 were rich with high abundances of *Protothaca* and *Saxidomus*. Station groups 2 and 3 were actually quite similar with moderate numbers of all species. They were also the first to link together. Station group 4, which included rich sites that had fewer *Protothaca* and a good crop of small *Saxidomus* but also more *Hiatella*, appeared to represent a rather mixed state of succession. Station group 5, comprising mostly Treated sites, was mostly impoverished sites totally lacking *Saxidomus*.

Table 15. Ordination coordinates and diagnostic statistics for evaluating species and environmental variables. Prefixed "i" and "e" refer to infaunal core or excavation variables. PPC = Principal component correlation; MCAO = Monte Carlo Attributes in an Ordination.

Variable	**X**	**Y**	**Z**	**Kruskal-Wallis**	**PCC r^2**	**MCAO (%)**
Species						
iProtothaca	-0.355	0.621	-0.699	22.87	0.80	0
eProtothaca	-0.497	0.72	-0.484	19.84	0.78	0
iSaxidomus	-0.921	0.237	-0.308	22.90	0.84	0
eSaxidomus	0.325	0.736	-0.594	19.24	0.87	0
eHiatella	0.001	-0.666	-0.746	13.75	0.77	0
iHiatella	0.006	-0.749	-0.662	5.57	0.68	0
Environmental						
eS	-0.569	0.604	0.558	14.01	0.60	0
eN	-0.165	0.981	-0.107	19.28	0.80	0
iS	-0.709	0.651	0.273	21.21	0.61	0
iN	-0.674	0.576	0.462	13.66	0.37	0.10
% Silt	-0.682	0.729	-0.058	3.63	0.06	59.2
% Sand	-0.417	0.575	-0.704	8.24	0.24	3.1
% Pebble	0.455	-0.606	0.653	9.10	0.25	2.7
Exposure	0.942	0.064	-0.33	6.01	0.18	7.9
Elevation (ft)	0.857	0.318	-0.406	8.08	0.08	42.5
Salinity	0.506	-0.752	-0.422	3.19	0.02	89.1
Water Temp	0.391	-0.279	-0.877	3.08	0.05	62.9
Latitude	0.482	-0.33	0.812	3.32	0.13	19.1
TOC	-0.13	-0.841	-0.526	1.19	0.09	40.6
Status (Ref/Trt)	-0.845	0.533	0.048	2.46	0.16	12.8

Finally, the cluster-group-sequenced box-and-whisker plots are another way to summarize and view the grouped variables (Figure 26). The box-and-whisker plot is a traditional exploratory data method whose symbology in this graphic represents the range, quartiles, mean and median of each variable horizontally and the respective groups assigned by the station clustering analysis

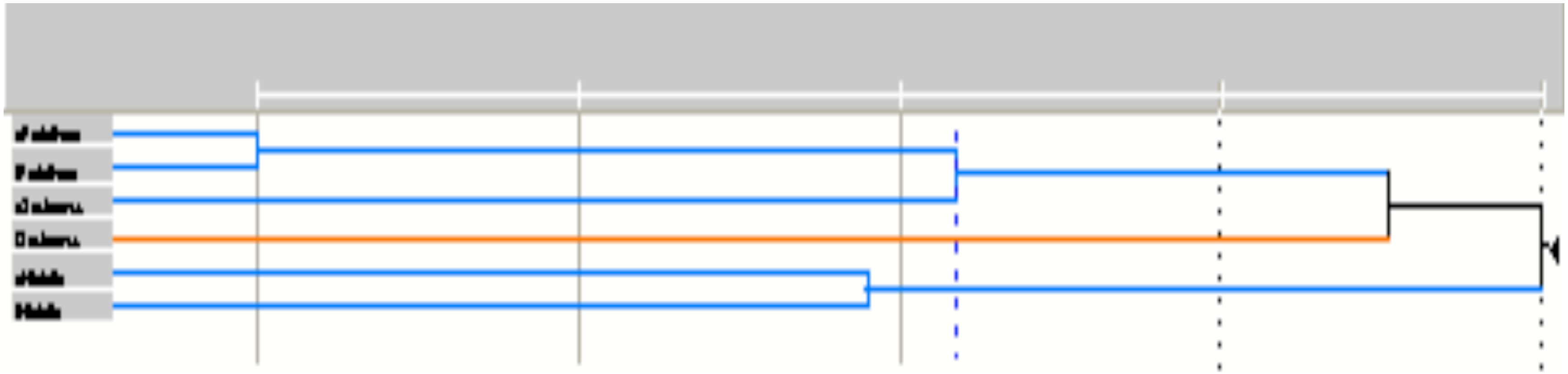


Figure 23. Dendrogram of species abundance showing three major groupings as defined by dashed vertical blue line.

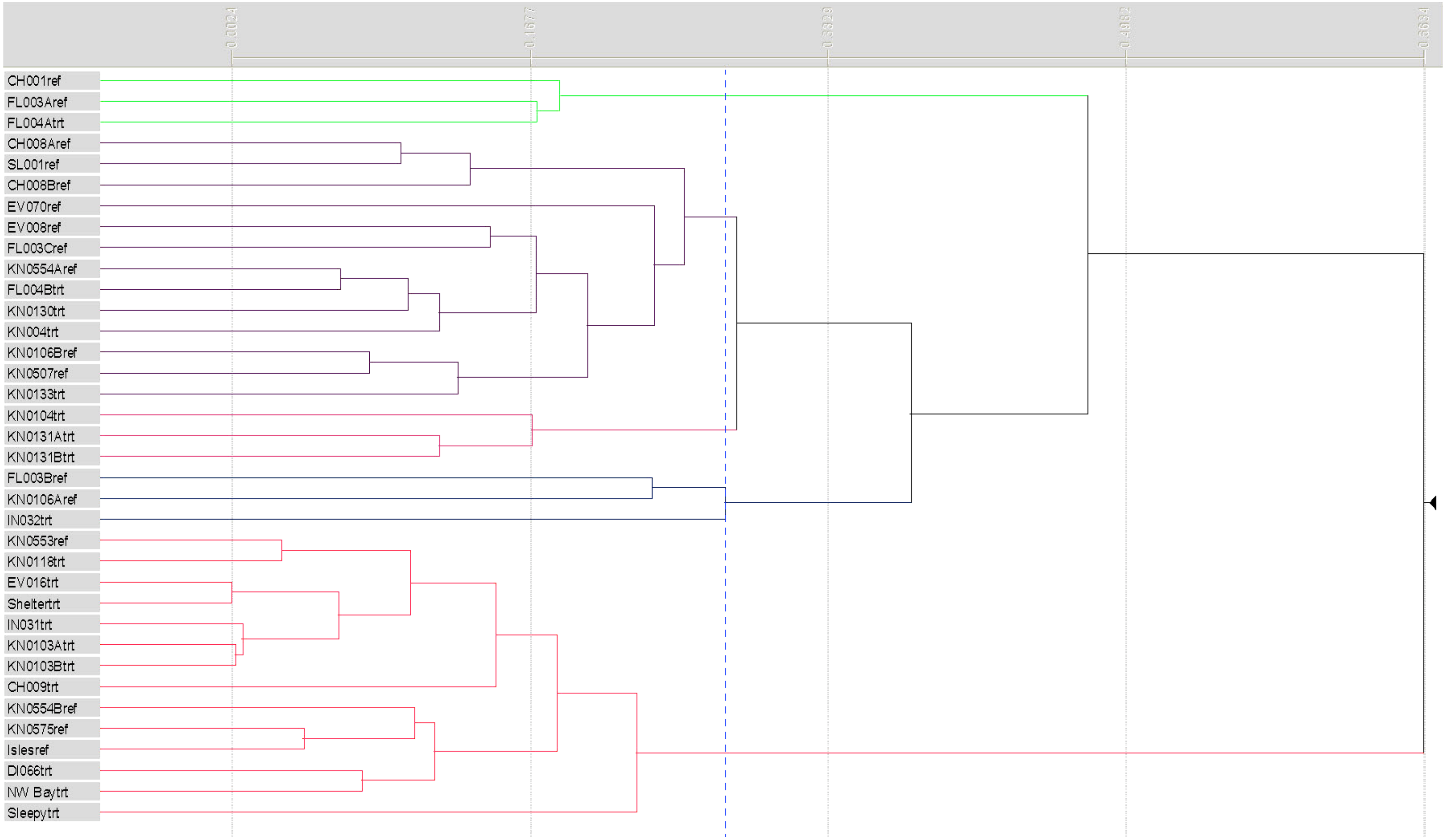


Figure 24. Dendrogram of stations showing five major groupings as delineated by the dashed vertical blue line.

Table 16. Composition of multi-species-based site-dendrogram groups showing the lack of clean dichotomy between Reference and Treated sites.

Dendrogram Group Number	Reference Sites	Treated Sites
1	2	1
2	9	4
3	0	3
4	2	1
5	4	10

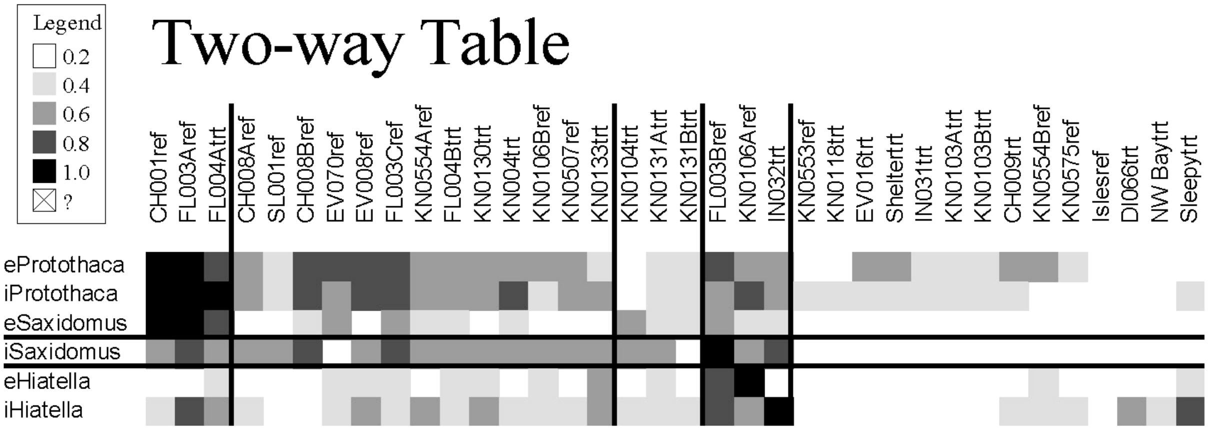


Figure 25. Two-way table showing standardized abundance data for the three-species and five-site cluster groups.

vertically. Here, each plot represents a station-cluster group's distribution of values for the chosen variable (only the top six variables are presented). If the cluster-group assignments mirrored perfectly the distribution of values for the environmental variable, the resulting pattern would have the five groups' ranges (box and whiskers) form a non-overlapping staircase-like pattern across the plot (the variable's total range). The posted KW value for each variable provides an index value for the graphic gradient by representing the uniqueness of the data groups (*i.e.*, their ability to create a gradient); a higher KW value means greater distribution differences among groups, which may imply a better fit to the ordination gradient. A KW value can also be evaluated for statistical significance as chi-squared values with df = 1.

While working with the full data set, we noted that the species pairs in the excavation and core data tended to separate spatially in the ordinations, thus suggesting differences in the distribution gradients of the methods were real. To further assess this dichotomy, we separated the excavation and core data and ran combinations of Reference and Treated sites for each (Tables 17 and 18). Ideally, for each sampling method, each site combination would have strong and yet unique correlations that could be interpreted in some cogent manner. For this exercise, the hope was that the KW and r^2 values for each variable would suggest its importance in conforming to or potentially driving the ordination pattern of stations based on species abundance.

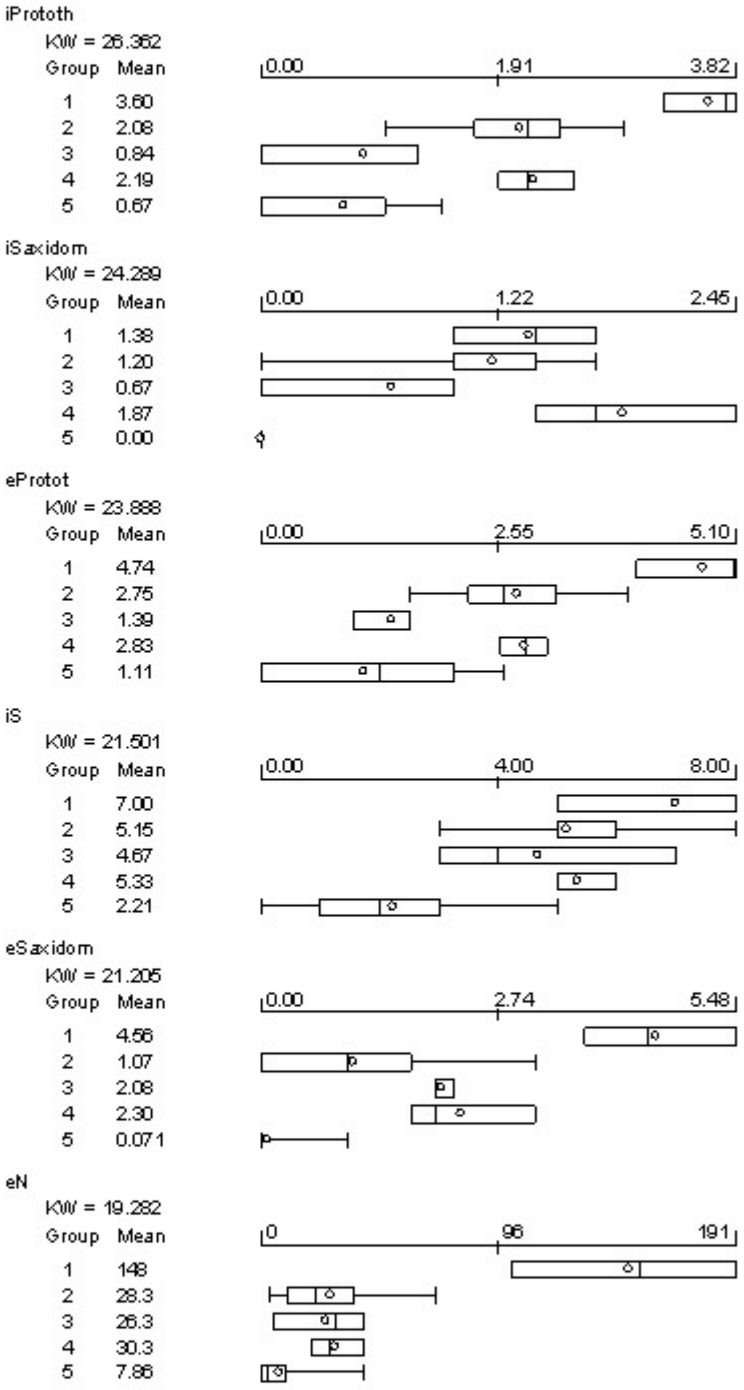


Figure 26. Box-and-whisker plots showing distribution of groups correlated with ordination. Kruskal-Wallis (KW) values represent non-parametric uniqueness of groupings along ordination axes, *i.e.*, fit of a variable's group gradient.

From the excavation samples, the ordinations did present a credible scenario (Table 17). The combined Reference and Treated sites were an excellent fit to the ordination pattern (stress =

0.075), had superb group fidelity for all three species to the ordination gradient (KW values were greater than critical 95% chi^2 value, 9.488, with df = 4), and four environmental variables as well as the usual well-correlated N and S community descriptors have suggestive r^2 values between 0.27 and 0.30. After splitting the data to look at just the Reference sites, all of these characteristics became even stronger. These results imply that an environmental structure was being expressed in the data; clam abundances varied directly with TOC, latitude, elevation, and, to a much lesser extent, with grain size, temperature, salinity and exposure. The bivariate results presented above mirror some of these correlations. With such strong correlations, it would be easy to label some range or combination of these characteristics as indicators of a successionally mature mixed-soft beach in PWS.

At Treated sites, the scenario faltered slightly. The KW values for treated *Protothaca*, *Saxidomus* and *Hiatella* were significant at p values of approximately 0.1, 0.005, and 0.15, respectively, saying that two of the species groups did not differentiate themselves across the gradient as well as at the Reference sites. Nevertheless, all still showed very tight correlations with the ordination. In general, the Treated sites complemented the developing scenario and, as a group, differentiated themselves by losing correlations with exposure, salinity, and water temperature while becoming modestly stronger with latitude, elevation, and grain size. These results parallel the bivariate analyses, suggesting that disrupted beach armoring at Treated sites would show increased correlation with PGS while Reference sites would not. Furthermore, these variables could well support the concept that treated beaches in the spill area are evolving towards the combined “mature characteristics” of the gradient of reference beaches.

The core data were not so impressive. For the combined data set (Table 18), the species data again fitted the ordination space very well (stress = 0.079) and with highly significant KW and r^2 values but, other than S, only grain size and latitude showed modest correlation (r^2, 0.26-0.28). Surprisingly, dendrograms groupings for the combined N data formed a well-defined gradient across their range but N was a weak fit to the ordination (r^2 = 0.24). Perhaps with N driven by the total number of mostly juvenile individuals, regressing the summed species variability for each of these non-linear, juvenile-dominated samples just didn’t create a smooth gradient relative to the multi-species distributions. Perusing just the Reference sites’ r^2 and KW values for something distinctive, species abundance and elevation appeared moderately correlated (0.52 and 0.39) but the KW value for *Hiatella* fell and the “mature beach characteristics” so apparent in the aforementioned multi-correlated, excavation Reference data disappeared. For the Treated sites, the KW values for two of the three species became highly significant while sand and gravel became more strongly correlated (r^2 = 0.45 and 0.50) and salinity was modestly correlated (0.31). The core ordinations suggest that species data were well described by the ordination but environmental variables’ correlations were mediocre to poor.

In summary, the classification and ordination analyses do not provide a striking revelation that distinguishes between Treated and Reference sites. The sites, at this point in time, tend to form a gradient rather than separate into differentiated clusters. The dendrogram has some degree of grouping of Treated versus Reference sites but the dichotomy is not clean. Again, the suggested-but-indistinct classification results may result from a combination of varying rates in recovery as time erases differences or of misclassified treatments. The three dominant species segregate by species and sizes (sampling type) as might be expected, with *Hiatella* unique from the other two

Table 17. Classification and ordination diagnostic statistics from three combinations of excavation sites using dominant species.

	Reference & Treated Sites			**Reference Sites**			**Treated Sites**		
Stress (MDS fit)	0.0750			0.0477			0.0857		
Species Variable	Kruskal-Wallis	PCC r^2	MCAO (%)*	Kruskal-Wallis	PCC r^2	MCAO (%)	Kruskal-Wallis	PCC r^2	MCAO (%)
eProtothaca	23.48	0.93	0	11.55	0.90	0	7.70	0.93	0
eSaxidomus	28.05	0.98	0	8.82	0.97	0	15.93	0.92	0
eHiatella	12.73	0.96	0	9.58	0.94	0	6.47	0.97	0
Environmental Variables									
eS	17.43	0.66	0	5.31	0.66	0.4	10.16	0.75	0
eN	24.71	0.77	0	12.16	0.92	0	9.83	0.70	0
Latitude	10.25	0.30	1.1	11.27	0.46	4.5	2.30	0.49	2.2
% Silt	1.41	0.04	69.8	0.23	0.02	97.3	2.57	0.10	57.6
% Sand	10.24	0.26	0.9	9.95	0.26	26.6	5.75	0.37	2.4
% Pebble	10.20	0.27	0.9	9.61	0.27	26.1	5.51	0.38	2.2
Exposure	3.21	0.07	47.1	9.16	0.24	29.9	2.44	0.04	86.3
TOC	0.62	0.27	2.7	4.80	0.61	1.3	3.82	0.09	63.4
Water Temp	5.67	0.10	30.1	2.79	0.33	14.1	0.89	0.01	99.3
Salinity	1.51	0.24	3.1	3.91	0.30	23.1	3.59	0.39	2.4
Elevation (ft)	8.90	md**		5.61	0.44	5.4	4.03	md	
Status	4.20	0.17	7.9						

* % Permutions > Actual r^2

**md = missing data

Table 18. Classification and ordination diagnostic statistics for dominant infaunal species.

Stress (MDS fit)	**Reference & Treated Sites**			**Reference Sites**			**Treated Sites**		
	0.0792			0.0619			0.0602		
Species Variable	Kruskal-Wallis	PCC r^2	MCAO (%)*	Kruskal-Wallis	PCC r^2	MCAO (%)	Kruskal-Wallis	PCC r^2	MCAO (%)
iProtothaca	17.97	0.93	0	8.57	0.91	0	12.47	0.83	0
iSaxidomus	26.48	0.91	0	8.68	0.94	0	13.65	0.90	0
iHiatella	11.69	0.95	0	6.32	0.97	0	6.89	0.94	0
Environmental Variables									
iS	19.30	0.63	0	8.01	0.67	0.3	10.34	0.63	0.1
iN	10.67	0.24	2.7	8.40	0.52	3.1	5.14	0.20	32.4
Latitude	2.27	0.26	1.5	2.59	0.15	58.4	3.16	0.11	55.3
% Silt	3.90	0.10	36.1	2.06	0.23	38.3	6.26	0.26	20.1
% Sand	4.39	0.26	2.5	3.30	0.14	59.5	6.52	0.45	2.8
% Pebble	4.82	0.28	1.5	4.93	0.17	51	8.46	0.50	1.3
Exposure	5.06	0.12	21.4	2.63	0.22	36.6	5.30	0.20	33.8
TOC	0.57	0.02	89.3	0.96	0.03	92.1	0.74	0.06	80.8
Water Temp	4.17	0.12	28.3	3.42	0.21	41.4	1.91	0.11	61.1
Salinity	2.29	0.15	17.4	5.26	0.04	83.7	4.21	0.31	11.1
Elevation (ft)	5.43	md**		2.98	0.39	10.3	4.88	md	
Status	2.92	0.18	10.7						

* % Permutations > Actual r^2

**md = missing data

species. For both core and excavation data, sand and pebble (PGS) distributions correlated well with the three species at Treated but not at the Reference sites. These results support the disrupted-armored-beach theory. Bivalves at the Treated sites are still subject to the same disruptive turbulence that influences the finer particles. At Reference sites, bivalves sheltered beneath the armor are more protected from the turbulence.

Discussion

In this report, we have demonstrated a considerable lag in the recovery of intertidal hard-shell clam populations on treated mixed-soft sediments in western PWS and we are describing a paradigm shift in our understanding of sediment dynamics on mixed-soft southcentral Alaskan beaches and a heightened awareness of the complex phenomena underlying the infaunal assemblage. We have studied these beaches for many years but only during the analyses for this study did we come to recognize armoring and gain an appreciation for the implications of this structural phenomenon.

In PWS, where the beaches and the infauna were severely disturbed by the cleanup, a broad-scale ecological manipulation has occurred over many kilometers of beaches. In studying the patterns of delayed recovery in the clam assemblage on these beaches, we discovered that neither the sediments nor the biota conform to traditional concepts of the relationships among sediment grain sizes and organics, or even between sediments and organisms. Based on sediment data, it seems obvious the Treated beaches are still in the process of re-armoring, even though armoring was not measured directly. When viewed from this perspective, most of the biological and sedimentary data then make sense as piece after piece shows some unusual twist that describes either effects from disrupted armoring (Treated sites) or enhancements due to undisturbed armoring (Reference sites).

We begin with a discussion of why the PWS species assemblage and sediments differ from expectations derived from those described in most reports. The first section discusses the nature of this specific infaunal assemblage, which appears to differ somewhat from the type of assemblage that has been traditionally predicted on the basis of: 1) the exposure regime of many of the beaches; 2) the coarseness of the sediments; and 3) the latitude of PWS. We then address sediment conditions, which also differ considerably from what is expected on the basis of traditional sediment paradigms. We propose that increased organization of the coarser sediment fractions (armoring) is a major factor in the departure of infaunal and the sediment conditions on these beaches from traditional paradigms. We follow this discussion with a section describing some ways that sediment paradigms in armored sediments differ from those in traditional described sediments. The goal of these discussions is to illustrate the atypical nature of 1) the infaunal assemblage and 2) the sediments in which these animals live relative to expectations from traditional paradigms and to demonstrate the complexity of the physical and biological processes involved in creating this complicated habitat.

We then return to our study data, evaluating the relationships between sediment properties and exposure and then between dominant bivalves and exposure, sediment properties, and some other environmental variables. We have evaluated these interactions from both bivariate and multivariate viewpoints because the two approaches reveal different nuances.

In view of the high level of variability observed in several of the data types, we discuss several factors that potentially are responsible for the variations in findings.

We then address in considerable depth the response of sediments to washing, the response of the infauna to the cleanup and chemical effects associated with the spill, and the potential effects of shoreline treatment on recruitment.

We also reflect on rates of recovery, pointing out two catastrophic events that constitute important benchmarks setting different starting points for Reference and Treated sediments. As part of this discussion, we note that, because of these two events, these treatment categories represent two differing levels of recovery. We then evaluate the potential role played by the armoring process in the respective recovery processes.

For the NOAA sites, we compare conditions in 1990-96 and 2002 to assess whether sediment and infaunal conditions at these sites are generally representative of the spill area. Finally, we evaluate the effectiveness of HP-HW or –WW washing and describe a conceptual model illustrating the consequences of beach washing and the armor recovery process.

Nature of the Infaunal Assemblage

Early theory postulated that the organization of infaunal assemblages in boreal and temperate environments is influenced largely by their response to the harsh environment, *i.e.*, they were driven by physical factors (Sanders 1968). Many of the beaches examined during this survey could be considered physically accommodated because they are frequently exposed to strong winter storms. Typically, short-lived pioneer species characterize physically accommodated assemblages (Alongi and Christoffersen 1992; Jewett *et al.* 1999; Valiela 1995). However, it is clear from this and previous studies on mixed-soft beaches in western PWS (Houghton *et al.* 1997; Driskell *et al.* 1996) that relatively long-lived, slow-growing, obligate or facultative suspension feeders (*Protothaca*, *Saxidomus*, and *Macoma* spp.) strongly dominate the intertidal infaunal assemblage. Moreover, other large, relatively long-lived burrowing organisms such as burrowing holothurians, echiurans, and thalassinid shrimp are common in these sediments. Dominance by such large, long-lived species implies that the habitat in which this assemblage lives is quite stable.

In this regard, we have observed well-developed death assemblages with similar bivalve species composition in uplifted sediments above the present beaches at several locations in PWS (*e.g.*, Zaikof Bay and Crab Bay; Figure 27). A comparison of these death assemblages and the extant bivalve assemblages suggests considerable continuity following a major perturbation. The enormous magnitude of the injury caused by the 1964 Great Alaska Earthquake to clam assemblages was well documented by Baxter (1971). In many of the uplifted deposits, shells of individual clams are still articulated and oriented in the sediment as they were before the earthquake elevated their beaches to a level too high for survival. The geologic evidence provided by these deposits echoes Baxter's report and clearly suggests that many beaches in the sound supported dense populations of large, old *Saxidomus* and *Protothaca* before the 1964 earthquake. Based on the size of these "fossil" shells and the regression equations generated for the clam species (Figures 13 and 15), these assemblages appear to have been dominated by *Saxidomus* up to 25 years old and *Protothaca* up to at least 16 years old. Furthermore, the occurrence of dense populations of large, old animals implies that the assemblages were not frequently subjected to excessive disturbance or predation. It is crucial to mention, however, that these assemblages existed prior to the return of sea otters to the sound. As long as sea otter predation remains intense, it is unlikely that the currently recovering bivalve assemblage will return to the pre-quake level of maturity.

Figure 27. Example of an intact death assemblage of large bivalves (*Saxidomus* and *Protothaca*) in Crab Bay showing about 15 articulated pairs of shells. The 1964 Great Alaska Earthquake uplifted this sheltered, mixed-soft, moderately armored beach into the mid-intertidal zone and wave action has subsequently eroded fines and exposed the shells during the armoring process. *Fucus* plants in upper corners provide a comparative size scale.

The mature successional state of the death assemblage suggests that, although the upper few centimeters of sediment may be subject to considerable disturbance, especially during winter storms, once animals are large enough to burrow below that upper region of instability, they are reasonably well protected from wave-induced sediment disturbance caused by normal storm activity as well as temperature and salinity extremes and predation. They are therefore able to achieve stages of succession in which large, long-lived species dominate the biota. Consequently, if a disturbance or contaminant penetrates into deeper sediment horizons in the mixed-soft sediments in PWS, it is likely that the effects will have far greater impact and duration than has commonly been reported in many disturbance studies on bivalve assemblages on disturbed sandy beaches, which typically support less complex infaunal assemblages.

Hall (1994) noted that many studies "indicate how… disturbance results in slower growing, longer-lived species (particularly molluscs) being replaced by shorter-lived polychaete species". A crucial issue in assessing recovery from disturbance is basing the evaluation on functional recovery rather than numerical (N or S) recovery. Moreover, size or age structure is an important aspect of recovery. Replacing large, long-lived, hard-shell clams (*e.g.*, *Protothaca* and *Saxidomus*) with an equal or greater number of small, short-lived bivalves (*e.g.*, *Rochefortia* and *Hiatella*), as is seen in the core data (Table 9), does not constitute functional recovery, especially "in the eyes" of the major predators depending on those clams for nutrition. These short-lived species have longevities of between 5 and 10 years (*e.g.*, *Hiatella* [Table 11] and *Rochefortia* [Ockelmann and Muus 1978]) compared to the hard-shell clams that live at least 15 to 20 years (*e.g.*, *Protothaca*, Table 11; [Chew and Ma 1987]) and contribute far more biomass to high-level vertebrate predators. In the core samples, which reflected comparative abundance of both adults and juveniles better than excavation samples, large long-lived clam species were 44% less abundant, on average, at Treated sites (7.6 vs. 13.5 large, long-lived clams/sample, respectively) than at Reference sites whereas small, short-lived clams were 98% more abundant (67.3 vs. 33.3 small, short-lived clams/sample, respectively). More importantly, average abundance of the larger hard-shell clams sampled in the excavation samples (more reflective of resources available to large predators) was 66% lower at Treated than at Reference sites (14.8 vs 39.4 hard-shell clams/sample, respectively). Moreover, the small short-lived species were 79% less abundant at Treated sites than at Reference sites (4.2 vs 19.7 small, short-lived clams/sample, respectively). As a result, treated beaches provide far less nutritional resources than oiled-but-unwashed beaches to clam predators such as sea otters.

Sediment Conditions

Sediments on many of the beaches in western PWS are relatively atypical in comparison with beach structure and relationships typically described for beaches elsewhere. Differing characteristics include particle grain size, the "organized" manner in which the rocks are imbricated or "shingled", and relationships between grain size and concentrations of organics contained within the sediment matrix.

Two general patterns regarding mixed-soft beaches in western PWS are important to this discussion. Although many of the beaches sampled in this study are relatively protected from wave action or currents, their sediments are relatively coarse (Table 4). Typically, protected beaches are characterized by fine sediment (*e.g.,* Gray 1981). However, the beaches in PWS are quite young in geologic terms, having been recently thrust up into the intertidal zone by the Great Alaska Earthquake. Prior to the quake, these sediments were submerged and probably were characterized by greater proportions of sand or silt/clay, as is typical of subtidal sediments in most embayments in western PWS (pers. obs., Lees). Upon emergence into the intertidal zone, however, they became exposed to greater wave action and immediately started losing fines. For example, in the case shown in Figure 27, based on the exposure of those clamshells, that beach had probably lost at least 20 cm of sediment since it was uplifted in 1964. Most of these beaches also are remote from substantial sources of fine materials (*e.g.*, glaciers, large rivers, or coastal plains). Consequently, replacement rates of lost fines have apparently been slower than the loss rate. As a result, the beaches have probably become coarser than they were when they were elevated.

When finer sediments are transported out of the bed and off a beach, the upper bed layers of sediment become stratified with the coarser fractions at the surface (Petrov 1989). This process is referred to as armoring. This surface stratification is one of the defining characteristics of an armored beach. Also, in cases where wave action was driving the process, Petrov showed that coarse bed material (pebbles and cobbles) became more "organized", *i.e.*, the coefficient of rock flatness increased as an "armor" was formed. While organizing, the rocks may also become somewhat imbricated or shingled. Armoring is complete when coarse bed materials (*e.g.*, cobbles, pebbles, and sand) cover the entire bed and protect finer sediments below them. Because armored beaches sequester fine sediments below the armor layer, we infer that they are more stable than unarmored beaches when subjected to physical disturbance from wave action or strong currents. We have observed anecdotally that concentrations of fine sediments generally tend to be considerably higher a few centimeters below the sediment surface on many of these mixed-soft beaches (pers. obs., Lees and Driskell). Consequently, it probably would have been more appropriate to examine that fraction several centimeters below the surface, below the normally disturbed surface horizon, to obtain a more accurate notion about possible effects of shoreline washing, which undoubtedly injected seawater many centimeters into and flushed fines from the sediments on most treated beaches.

While armoring has been well studied on gravel bars in rivers (*e.g.*, White and Day 1982), it was first recognized and described on marine gravel or mixed-soft beaches in PWS during the spill by Hayes and Michel (1999, 2001) as they showed that beach washing disrupted the armor layer. Unfortunately, we do not have quantitative data on armoring at our sites.

It is likely that armoring is a widespread feature of coarse sediments exposed to wave action or strong currents, just as it is in streams and rivers. Since becoming aware of the phenomenon, we have observed armoring on several beaches on the west side of Cook Inlet and subtidally in Kachemak Bay (pers. obs., DCL and WBD) as well as in southern California. In addition, in a review of disturbance and recovery of the biota in the sea bed following dredging, Newell *et al.* (1998) discuss numerous studies in the North Sea on coarse sediments (*e.g.*, gravel) and, in passing, mention the term "armouring" and comment that such a process "...allows the establishment of communities…reflecting the complex relationships between the physical deposits and biological activities of the animals themselves." Further in the discussion, although they cannot cite examples, they suggest that the processes of consolidation and stabilization are probably considerably more important "in controlling the time course of recovery of an equilibrium community…" than solely granulometric properties. Our findings appear to provide strong support for their suggestion and, for coarse sediments, indicate a likely mechanism for control.

Armoring probably provides considerable benefits to deep-burrowing infaunal organisms such as hard-shell clams. It is also likely that armored beaches are "friendlier" to recruiting larvae than unarmored beaches. Unless wave action is intense, the interstices among the rocks in the armor layer remain filled with finer sediments into which larval infaunal animals can settle. If the recruits survive until they are large enough to burrow into the fines below the armored layer, they will be somewhat protected from normal physical disturbance of the sediment because the armoring provides a stable shield from the wave action. On the other hand, if armoring is disrupted, that level of protection is lost for a period that probably varies with the degree of exposure to wave action and currents.

The armor layer is also important in the discussion of fines and organics, variables of unknown direct relevance to bivalves in this assemblage but certainly indicative of the sediment structure, stability, and food resources available for the deposit-feeding assemblage. Typically, concentrations of fines and organics are positively correlated in sediments (Newell 1965; Tyson 1995). While the nature of these relationships is applicable in this suite of predominantly gravelly sediments, the concentrations of organics (TOC and TKN) are more comparable to those observed in fine sands and silts on protected beaches and continental shelves and are substantially higher than would be predicted on the basis of the traditional relationships between grain size and organics reported for deep water sediments in Alaska (*e.g.*, Grebmeier *et al.* 1988; Lees *et al.* 2002) or elsewhere (*e.g.*, see Tyson 1995). However, based on scant literature available for organics in predominantly gravel sediments, concentrations of TOC in these sediments (mean = 1.33%) appear quite comparable to those observed by Thrush (1986) in subtidal gravel sediments in Lough Hyne, Ireland. Thrush's subtidal sediments, with ~50% gravel, 35% sand, and 8% silt/clay, were finer than those encountered in this study (76, 20, and 3%, gravel, sand, and silt/clay, respectively). They contained, on average, 2.14% organic matter. Using a factor of 0.55 for converting total organic matter to TOC (Ramrath *et al.* 1999), we estimated that TOC concentration in Thrush's sediments (~1.2%) was very comparable to ours.

C/N ratios for organics in these sediments, ranging from 6.4 to 71.4 (Table 4), were, on average, in a range suggestive of primarily terrestrial or marine plants. But, as pointed out by Valiela (1995), analytical issues may be at play in the magnitude of the C/N values. Few sites were in the range considered to provide adequate nutrition to consumers (<17, Russell-Hunter 1970). However, it is likely that the animals ingesting and recycling detrital materials and fine particulates are selectively digesting the microbial flora that colonizes the surface of the particles within days of being eliminated as fecal pellets (*e.g.*, Newell 1965; Johannes and Satomi 1966).

Although relationships between physical (PGS and silt/clay) and chemical (TOC, TKN, and C/N) sediment variables in this study were moderate to strong (Table 6), the statistical significance of the relationships was weaker than has frequently been reported, especially in subtidal fine sediments (*e.g.*, Tyson 1995; MacFarlane and Booth 2001; Burone *et al.* 2003). The strongest correlations in this study were in the range of r = -0.6 to -0.75, whereas many other studies report -0.95 on relatively homogenous sediments.

These relative weaknesses in observed correlations could be due to the extreme degree of environmental variation and exposure that occurs in intertidal habitats in western PWS and the wide range in sediment grain size in the beaches examined. It is also likely that variability among the beaches in their degree of recovery and re-establishment of armoring following the quake and the cleanup accounts for much of the variability. Moreover, Gross (1967) and Romankevich (1984) have shown that the range of TOC values is wider in shelf than in deep-ocean sediments, implying looser correlations at shallower depths. This pattern may be even greater in intertidal or nearshore sediments. For example, Cammen (1982) reported that TOC, organic nitrogen, and C/N ratios exhibited no predictable relationship to PGS in samples from intertidal or very shallow subtidal sites. He found that concentrations of organic carbon and nitrogen varied widely among the particle size fractions within a bulk sample and when compared among the same size fractions in bulk samples from different sites. Since grain size classifications for samples in our study range across five Wentworth scale size classes (from gravel [$\phi = -1.3$] to very large pebble [$\phi = -5.0$]), his caution is quite relevant. As noted above, TOC concentrations in the samples for the present study are in the range generally reported for much finer sediments in subtidal sediments. Given the coarseness of these sediments and armoring, the surface-area relationships that generally drive concentration of organics in finer or more homogeneous sediment may be less important to the quantity of organics than the proximity of these beaches to large sources of terrestrial and marine plant material and the availability of interstitial pores where detrital and fine inorganic particles can accumulate.

Again, the relevance of concentrations of sediment organics to our dominant suspension-feeding bivalves is unknown but one could postulate linkages between sediment organics and veliger settlement cues or the availability of food resources for juveniles whose siphons may not extend beyond the boundary layer of the sediment-water interface.

Conformity of Armored Sediments with Traditional Sediment Paradigms

Traditional sediment paradigms are based on examination of sediments from homogeneous sediments from mud flats, estuaries, beaches, and continental shelves. The expected relationships among sediment grain size fractions and between these fractions and concentrations of organics contained in the sediments are generally relatively predictable. Generally, coarser sediments contain lower concentrations of fines and, in homogeneous sediments, the concentration of fines approaches 0 when ϕ approaches

When we started examining sediment characteristics of the sediments on the clam beaches in PWS in 1989 and 1990, we noticed the concentrations of fines and organics in these sediments seemed paradoxical relative to the traditional paradigms. Concentrations of fines and organics were much higher than would be predicted by traditional relationships. Departures of some of these properties from the traditional relationships are demonstrated in Figures 28 – 32. For this analysis, sediment characteristics from our Reference and Treated sites are compared with similar data from a major survey of soft sediments on the relatively exposed continental shelf in southern California (Anonymous 1965) and a reconnaissance survey of beaches in middle and upper Cook Inlet (Lees *et al.* 2002). Unfortunately, the only measure of organic content analyzed in the continental shelf program was TKN. Depth of the continental shelf sediments ranged from 4.3 m (14 ft) to 55.5 m (182 ft). Sampling locations were selected from this large database in an unbiased manner. Median PGS is represented by phi ($\Phi = -\log_2$ (median PGS in mm) in this analysis because the log scale helps clarify the distinct contrasts between these sediments. Φ relates inversely to PGS, *i.e.*, large positive values of Φ represent very fine sediments whereas large negative values represent very coarse sediments.

Sediments on the continental shelf and the beaches in Cook Inlet, with PGS ranging from +7.158 to +0.454 Φ (0.007 to 0.73 mm), were considerably finer than those on the clam beaches in western PWS (Figure 28). PGS in sediments from the beaches sampled during this study are distinctively coarser, ranging from -1.3 to -5.02 Φ (2.46 - 32.39 mm).

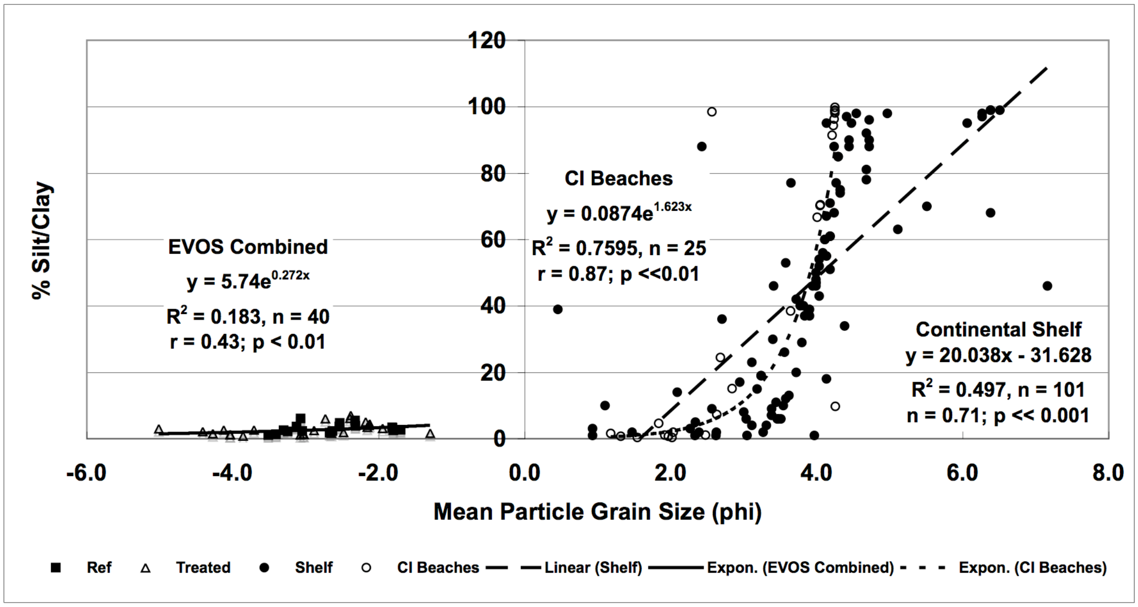


Figure 28. Comparisons for relationships between mean particle size and silt/clay in sediments from clam beaches in western Prince William Sound and the continental shelf in southern California.

In PWS and shelf sediments, the quantity of silt/clay showed a significant positive correlation with Φ (or negative correlation with PGS). The range for silt/clay in the shelf sediments was large, ranging from 1 to 99% and far higher than in the beach sediments from PWS, where quantities of silt/clay were small (0.91 – 7.05%). However, the quantities of fines in the sediments from PWS clam beaches were much higher than would be expected based on the highly significant regression equation for the shelf sediments (Figure 28), which predicted disappearance of silt/clay at a PGS approximating 1.58 Φ (0.33 mm). In the PWS sediments, quantities of silt/clay at Reference and Treated sites were very similar and correlated significantly with PGS and were therefore pooled for this comparison.

As with silt/clay above, concentrations of TKN were similar in both types of sediments (Figure 29). They also occurred in the same range in beach sediments from middle and upper Cook Inlet (Lees *et al*. 2002). TKN ranged from 0.01 to 0.11% in PWS sediments, 0.0001 to 0.231% in shelf sediments, and from 0.003 to 0.081% in sediments on Cook Inlet beaches. The similarity in the relationship between TKN and PGS in sediments from beaches in Cook Inlet and the continental shelf in southern California clearly demonstrates the generality of that traditional model. Similarly to silt/clay, TKN correlated negatively with PGS. The correlations were significant in sediments from EVOS Reference sites, the continental shelf in southern California, and beaches in middle and upper Cook Inlet, but not in the EVOS Treated sediments.

Also similarly, the concentrations of TKN were much higher in PWS sediments than would be predicted on the basis of the relationship observed in beach sediments in Cook Inlet or shelf sediments in southern California. In this case, the regression models for Cook Inlet beaches and continental shelf sediments predict that TKN would be absent in sediments coarser than approximately 1.1 Φ (0.45 mm). Obviously, this prediction is inappropriate for the armored sediments on beaches in western PWS.

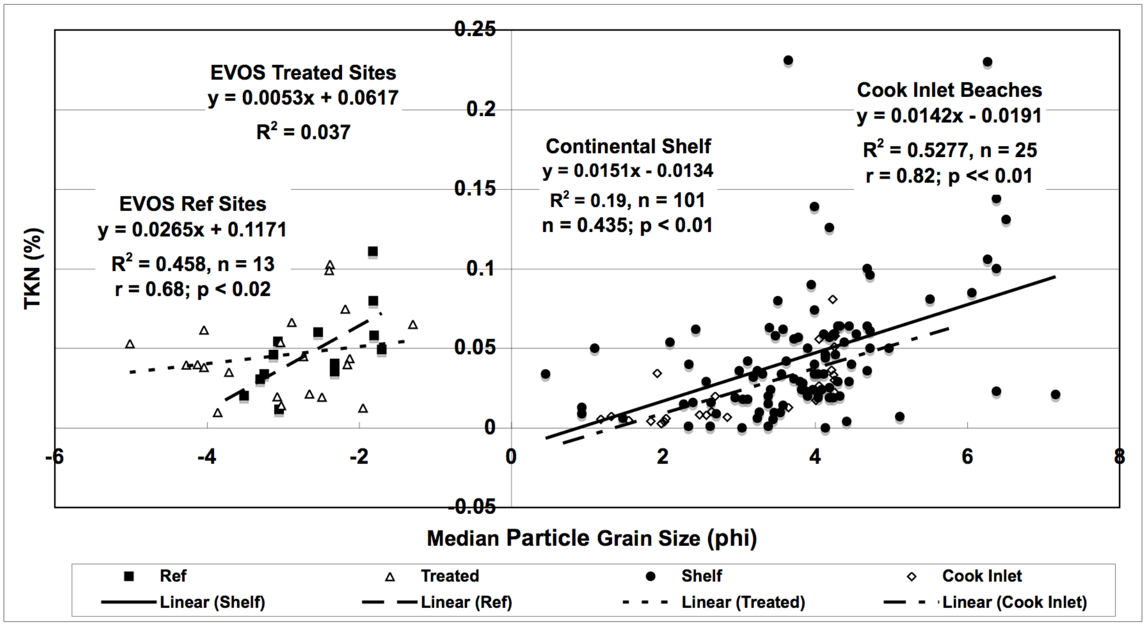


Figure 29. Comparisons for relationships between mean particle size and Total Kjeldahl Nitrogen in sediments from clam beaches in western Prince William Sound, beaches in middle and upper Cook Inlet, and the continental shelf in southern California.

Sorting exhibited a similar relationship in sediments from EVOS Reference sites and the continental shelf (Figure 30). Sorting was best (lowest sorting coefficient) in coarser sediments in both sediment types. However, sediments were only poorly or very poorly sorted in both cases. Again, with regard to the spectrum of grain sizes, the two types of sediments do not appear to be responding to the same paradigm. It is interesting to note that the significant relationship observed between PGS and sorting in Reference sediments does not occur in Treated sediments.

Based on TKN, it appears that the relationships between organics and both sand and silt/clay also differed between EVOS clam beach and shelf sediments (Figures 31 and 32). For sand, the traditionally recognized pattern, represented by the shelf sediments, is for TKN to decline significantly with increasing quantities of sand ($p < 0.01$; Figure 31). In contrast, TKN increased significantly with increasing sand in sediments at Reference sites in this study ($p < 0.01$). However, the variables were uncorrelated at the Treated sites. For silt, the traditionally recognized pattern is for TKN to increase with increasing quantities of fines ($p < 0.01$; Figure 32). The nature of this pattern was the same in both Reference and Treated sediments in PWS ($p < 0.01$ for the combined data from Reference and Treated sites) but the rate of increase was far steeper in these sediments. In the case of silt/clay, the relationships for the treatment categories were virtually indistinguishable. Thus, TKN attained similar levels of TKN (≈0.065 percent) at about 6 percent silt/clay in EVOS sediments and about 80 percent silt/clay in shelf sediments.

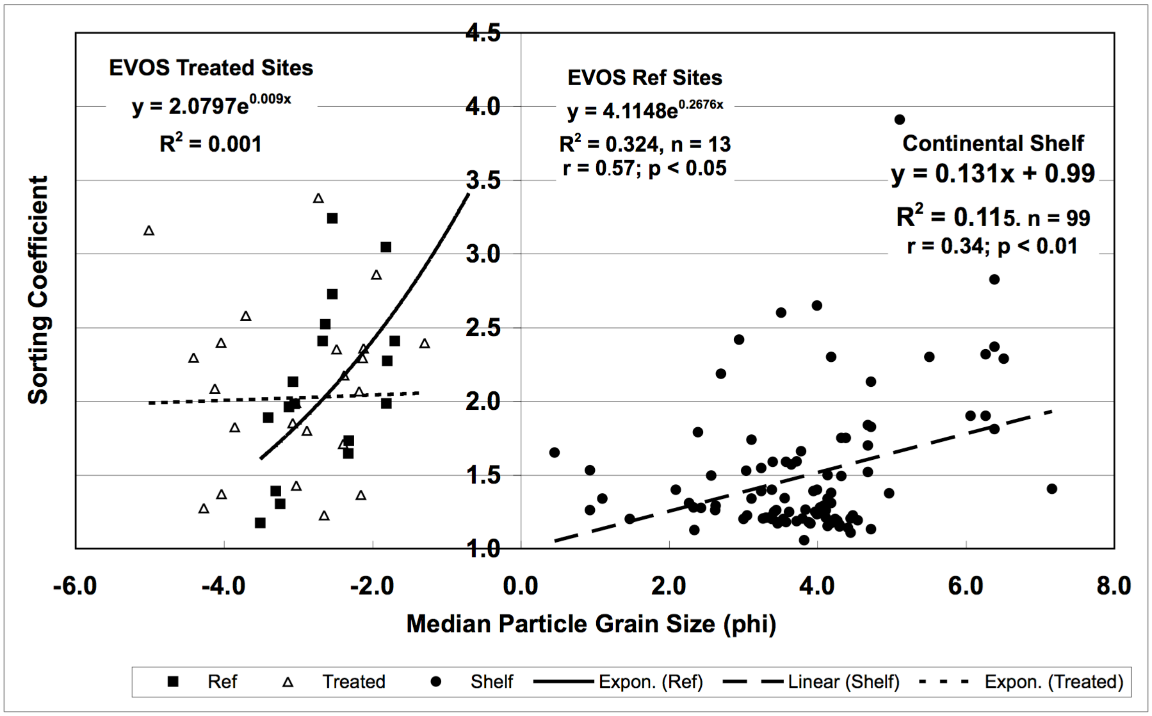


Figure 30. Comparisons for relationships between mean particle size and the sorting coefficient in sediments from clam beaches in western Prince William Sound and the continental shelf in southern California.

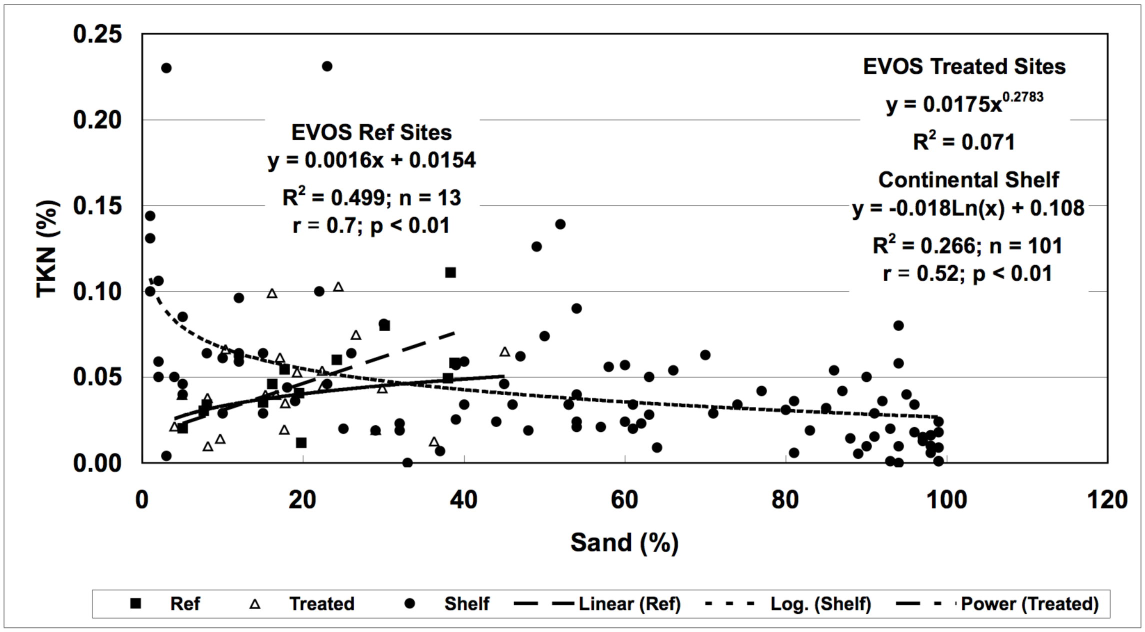


Figure 31. Comparisons for relationships between sand and Total Kjeldahl Nitrogen in sediments from clam beaches in western Prince William Sound and the continental shelf in southern California.

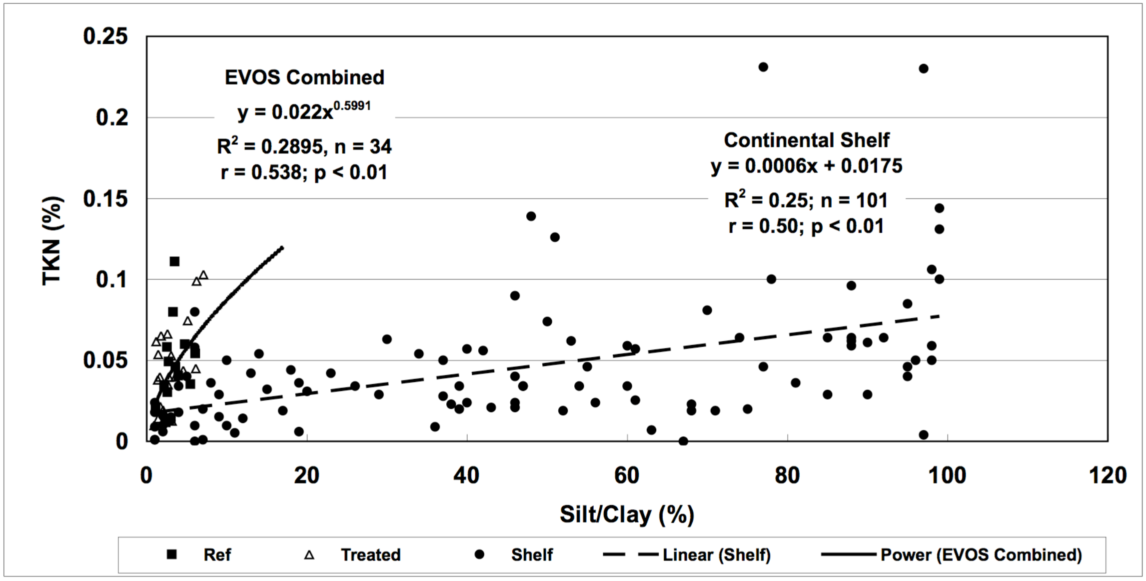


Figure 32. Comparisons for relationships between silt/clay and Total Kjeldahl Nitrogen in sediments from clam beaches in western Prince William Sound and the continental shelf in southern California.

An interesting facet of these analyses is that in several cases, it was clear that the beach washing process had interfered with the specific relationship. Thus, it appears that washing disrupted the relationships between PGS and TKN, sorting, and sand (Figures 29 - 31). However, it did not appear to affect the relationships with silt/clay (Figures 28 and 32).

The patterns described above provide convincing support for an argument that the armored sediments observed in western PWS do not conform to the traditional paradigms that apply in the more homogeneous sediment types observed on beaches and the continental shelf. Median grain size is substantially coarser than typical beach or shelf sediments and the range of size fractions is substantially greater as well (roughly -5 to +7 Φ vs -1 to +8 Φ, respectively; Figure 28 - 30). Quantities of silt/clay and organics are considerable greater than would be expected on the basis of the models that describe beach or shelf sediments (Figures 28 and 29). The relationship between PGS and sorting coefficients is quite different than would be predicted by the traditional sorting model. Sorting ranged from poor to very poor in both types of sediments but the coarse sediments at the EVOS sites were just as well sorted as shelf sediments (Figure 30). The relationship observed between TKN and sand in PWS sediments was opposite that observed in shelf sediments (Figure 31). TKN and silt/clay exhibited similar (positive) relationships in both PWS and shelf sediments but PWS sediments accumulated organics much more rapidly than shelf sediments (Figure 32). The consistency and statistical significance of these differences are compelling indications that armored sediments conform to models for sediment relationships that differ dramatically from the traditionally described paradigms.

Relationships between Sediment Properties and Exposure

Due to a wide range of exposures experienced by the study sites (Table 3), it is necessary to consider how exposure influences the sediment properties. Exposure appears correlated positively with PGS at Treated sites but poorly with exposure at Reference sites (Figure 2). We speculate this difference may be partially a consequence of geologic factors (*e.g.*, type of rock) affecting the size of the pebbles, cobbles, and boulders on individual beaches as well as a response to exposure. Certainly exposure acts to reduce concentrations of fines at a site. However, it also acts to induce armoring, which, by ameliorating turbulence along the sediment-water interface, can sequester the quantities of fines within deeper layers of the rocky matrix. Thus, the effects of exposure might become disconnected with PGS.

In contrast to PGS, silt/clay content showed a significant negative correlation with exposure at Treated sites (Figure 3) but no correlation was observed at Reference sites. TOC, TKN, and C/N ratios also exhibited significant negative correlations to exposure similar to silt/clay at Treated sites but not at Reference sites. In view of the armoring discussion above, it seems likely that disruption of the armored layer during the washing process at Treated sites might have resulted in a continuing loss of fines. According to Petrov's hypothesis (1989), loss of fines will continue during storm events until armoring is restored. In fact, PGS increased while fines and TOC declined between 1996 and 2002 at the revisited Treated NOAA sites (Table 19), suggesting that the armoring process may still be progressing at these sites.

The failure to detect correlations between the sediment properties and exposure at the Reference sites suggests that, under undisturbed conditions, exposure is not an important factor at unwashed sites. In contrast, following beach washing and the disruption of the armor layer, we suggest that exposure became an important factor, influencing changes in silt/clay, TOC, and TKN concentrations at Treated sites following the disruption of armoring. In the multivariate analyses, both sand and pebble contents correlated strongly for both the hard-shell clams in excavation and core samples at Treated sites but not at Reference sites. In contrast, exposure and % silt never correlated strongly with the clams while TOC was only important for excavation samples at Reference sites (discussed above).

Table 19. Comparison of sediment characteristics at NOAA sites between 1992 – 1996 and 2002. C/N ratios are calculated from actual site data for TOC and TKN rather than the averages in this table.

Category/Site	Period	Mean ± SE PGS (mm)	 Fines (%)	 TOC (%)	 TKN (%)	 C/N Ratio
NOAA Unoiled Sites	1990 – 96 4 sites	1.9 ± 0.4	20.4 ± 1.5	1.5 ± 0.2	0.049 ± 0.005	37.0 ± 6.0
Reference	1990 – 96 4 sites	>5.8 ± >2.8	15.8 ± 2.1	3.1 ± 0.6	0.091 ± 0.021	49.7 ± 8.0
	2002 17 sites	6.8 ± 0.7	3.1 ± 0.3	1.1 ± 0.2	0.049 ± 0.007	28.7 ± 5.2
Bay of Isles	2002	8.3	2.4	0.5	0.012	46.2
Treated	1990 – 96 3 sites	3.6 ±0.3	6.1 ± 1.5	1.2 ± 0.2	0.024 ± 0.004	63.4 ± 9.6
	2002 23 sites	10.3 ± 1.5	2.9 ± 0.4	1.2 ± 0.2	0.046 ± 0.006	26.8 ± 2.9
Northwest Bay West Arm	1990 - 1996	3.9	3.6 ± 0.4	1.0 ± 0.1	0.013 ± 0.003	85.9 ± 21.4
	2002	8.2	1.4	0.4	0.014	28.0
Shelter Bay	1990 - 1996	3.1	9.8 ± 4.4	1.0 ± 0.2	0.028 ± 0.012	44.5 ± 9.2
	2002	13.1	2.6	0.6	0.035	15.7
Sleepy Bay	1990 - 1996	3.9	4.8 ± 1.4	1.6 ± 0.4	0.030 ± 0.004	59.7 ± 17.3
	2002	21.3	2.2	1.2	-	-

Relationships Between Dominant Bivalves and Exposure

The response of biological characteristics to exposure varied consistently by treatment category and sample type. These patterns provide crucial evidence for explaining the differences between the bivalve assemblages and sediments at Treated and Reference sites. Numerical characteristics for the bivalve assemblage responded uniformly. In excavation samples, N exhibited a significant positive correlation at Reference sites but a significant negative response at Treated sits. On the other hand, both S and H’ showed no correlation to increased exposure at Reference sites but significant negative correlations at Treated sites (Figures 4 through 6). In contrast, both N and S in core samples exhibited a significant negative correlation at Treated sites but a significant negative response at Reference sites (Figures 4 through 6); H' showed not response in either treatment category.

Hard-shell clams from Reference sites exhibited a significant positive correlation with exposure in excavation samples, which focus on larger clams, but no relationship at Treated sites (Figure 9). In core samples, which focus on smaller clams, both *Rochefortia*, a commensal species probably associated mostly with large burrowers, and *Protothaca* exhibited significant negative correlations with exposure at Treated sites but no response at Reference sites (Figure 10a and 10b). Thus, for adult hard-shell clams, increased exposure was a benefit at Reference sites but elicited no response at Treated sites. In contrast, for smaller clams, increased exposure was accompanied by significant reductions at Treated sites but no effect was observed at Reference sites. Consequently, young clams did not appear to be recruiting to the adult size classes at Treated sites but were recruiting at Reference sites. These patterns suggest some type of structural difference between the two treatment categories and seem to support the hypothesis that beach washing disrupted the organization of the armored sediments, resulting in poorer protection for small or younger clams at Treated sites.

Relationships Between Bivalves and Sediment Properties

Although numerous investigators have shown that various aspects of sediment grain size and organics exert considerable influence over bivalve species and the general nature of infaunal assemblages, relationships between the bivalves and sediment properties were relatively weak in this study. Various investigators have shown that the quantity of fine particulates in the sediment can have a strong influence on species composition. For example, Gray (1981) reported that deposit feeders such as *Macoma* typically need concentrations above 30% for greatest development but that abundance of suspension feeder like *Protothaca* typically decline at silt/clay concentrations above 10%. Silt/clay concentrations on the beaches in this study averaged below 3% (Table 5). Predictably then, these beaches are more favorable for populations of suspension feeders such as *Protothaca*, *Rochefortia*, *Hiatella*, and *Saxidomus*, than for deposit feeders such as *Macoma* spp. The only taxa that demonstrated significant positive correlations with silt/clay were *Macoma* spp. and *Rochefortia* (Table 12). Only younger *Saxidomus* in the core samples expressed a significant negative correlation to silt/clay (Table 12).

All species except *Hiatella* expressed only significant negative relationships with PGS (Table 12). This suggests that most of these species respond differently to silt/clay than to the coarser sediment fractions. That is, they were not attracted by increased concentrations of silt/clay, even at the low concentrations typical of these sediments, but they also responded negatively to increases in coarser fractions, which, on unarmored beaches, typically reflect increased exposure. *Hiatella*, in contrast, had significant positive correlations with PGS at Treated sites in both core and excavation samples. This could be viewed as reflecting a response to disturbance by this pioneer species. Similar results were seen in the multivariate regressions (Table 14).

Relationships between the bivalve species and organics were somewhat weaker, especially in the excavation samples. In all but two cases, the significant correlations were positive. Generally, relationships were stronger among the Treated sites and for the core samples (Table 12) but no species exhibited either strong or consistent patterns.

When considered together, we conclude that sediment properties exerted mixed influences on the bivalve assemblage in the mixed-soft sediments. The low concentrations of silt/clay typical of these sediments appear to exert a strong influence on species composition of this assemblage, resulting in domination by suspension feeders and a subdominant role for deposit feeders. Grain size variables, especially the concentration of silt/clay, do not appear play an especially important role in the actual distribution (as contrasted with species composition) of the bivalve species among the sites. Moreover, we conclude that organics do not play a particularly important role in the distribution of these bivalves although they may relate secondarily to settlement cues or food resources. The modest correlations observed in the ordinations support this interpretation. Our conclusions regarding grain size variables appear to agree nicely with the findings of Newell *et al.* (1998) that granulometric properties are less important to the long-lived bivalves than stability of the sediments.

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With regard to the numerical characteristics, N and S typically exhibited negative correlations to PGS and positive correlations to silt/clay (Table 12; more than 60% significant). The correlations to silt/clay, TOC, and TKN were generally overwhelmingly positive. N and S appeared positively correlated to the organic properties (TOC and TKN) but these relationships were only significant in the core samples, especially at Treated sites. N and S for core samples were significantly positively correlated with TKN in both Treated and Reference data sets. These findings suggest that the community structure of the bivalve assemblage sampled during this study was moderately influenced by sediment properties, especially PGS and TKN, *i.e.*, the number of species and individuals found at the sampling sites was most strongly correlated with PGS, silt/clay content, and TKN, and more markedly at Treated than at Reference sites.

Multivariate Relationships Among Bivalves and Environmental Variables

The cluster and ordination results show that we can differentiate among sites on the basis of species and substrate groups (*e.g.*, *Protothaca*-dominated or silt versus non-silt affiliated species). The correlated placements of species in the ordination plots also show that excavation samples reflect a distribution pattern different from the core samples for the same species. This suggests the collection methods did sample different populations of individuals, a desired goal of the sampling design, *i.e.*, more adults in excavation samples. Furthermore, in the excavation samples, there are differences between the Reference and Treated sites. Several of the environmental variables show significant correlations with species distribution as represented by the placement of stations in ordination space, *i.e.*, the multi-species gradient of abundance (Tables 15, 17, and 18). The results from excavation samples at Treated sites support a scenario of ongoing beach recovery, *e.g.,* stronger correlations with sand and pebble content. The core data from Treated sites also show strong correlations with sand and pebble content.

The multivariate ordination for the dominant bivalves in the excavation samples showed a very strong correlation with TOC ($r^2 = 0.61$) for Reference sites and almost none ($r^2 = 0.09$) with Treated sites (Table 17). These values support the disrupted-armoring hypothesis, *i.e.*, the Reference site bivalves with established armor are responding to conditions that accumulate TOC while bivalves at Treated sites correlate best with grain size factors while armoring progresses. TOC levels at Treated sites, although similar to Reference site values (Table 5), have not yet accumulated in a gradient correlating with species abundance. Unfortunately, this scenario falters slightly with the core data as neither Reference nor Treated sites ordinations correlate with TOC (Table 18); however, the Treated sites do correlate well with grain size as they did in the excavation data.

Stepwise regression results (Table 14) show a variety of intriguing associations with various variables, some appropriate and some seemingly coincidental, that support an ongoing armor-recovery scenario. It is not surprising to see factors such as tidal elevation and pebble content being negatively correlated with various species abundances at the combined sites but the negative influence of latitude on *Hiatella* was unexpected, especially since they did not correlate in the bivariate analyses. But latitude correlations do address a concern that the skewed distribution of Reference and Treated sites relative to distance from the Gulf of Alaska may bias the comparisons. From the stepwise regressions *of Protothaca* or *Saxidomus*, latitude was not one of the selected variables, thus suggesting that while it may have an effect, it was less important than other factors in correlating with their distributions. The bivariate analyses may show latitudinal correlations but, when evaluated with the other variables, it was not one of the better-correlated factors. The fact that northern and southern sites were relatively evenly segregated among the groups in the cluster analysis (Figure 24) seems to support the view that asymmetrical distribution of the treatment categories is not an important concern. Also curious was TOC, which positively correlated with N and S in the bivariate analyses for core samples but did not appear among the more significant stepwise components.

A result that did lend strong support to the re-armoring concept was the linkage of the hard-shell clams at Treated sites to some form of coarse grain size. Without protection from the armor, clams would be subjected to the same turbulence that removes finer grained sediments; abundance would be lower where turbulent forces and coarser grains prevail. Still, it is difficult to interpret the overall results knowing the analyses are, to some degree, incomplete. However, telltale patterns in the regression residuals indicate an important factor, probably armoring, is not yet accounted for.

Factors Potentially Causing Variation in Findings

The strength of the disturbance signal from beach washing could be affected by several factors, including misclassification of sites based on vague historic information on treatment, variation in site exposure, varying rates of recovery among sites, natural fluctuations at recovering sites, and the effects of proximity or remoteness to the Gulf of Alaska within PWS (*i.e*., latitudinal effects). While lingering oil is a concern in the spill area, continuing exposure to hydrocarbons seeping out of sediments is not considered an important cause of variability at our sites.

As discussed above, documentation of the treatment history for all but the NOAA sites is sketchy, based primarily on the recommended treatments within a shoreline segment as provided by the shoreline cleanup assessment teams (SCATs). First, it is not clear that the recommended treatment was implemented in all cases. Moreover, many of these segments are hundreds of meters long and it is unclear whether recommended treatment would have been carried out on the entire segment or just in certain areas. Consequently, placing sites in Reference or Treated categories involves appreciable potential for error. Such an error would tend to favor accepting rather than rejecting the null hypothesis, however. Any untreated (or recovered) Treated sites would be noise increasing the variation or reducing the impact signal.

Exposure varied considerably (Table 3) at the sites and potentially could exert substantial influence over the rate at which bivalve assemblages recover at Treated sites and the degree to which they develop at all sites. For example, Ganning *et al.* (1984) has shown that the state of recovery at disturbed sites can fluctuate dramatically during the recovery process but within the snapshot of a single sampling event such as this study, this would appear as intersite variability. Our study is a mixture of snapshots; some of the environmental data are highly transient (*e.g.*, temperature and salinity) while population structure and grain size data will fluctuate on longer time scales. Data from the two treatment categories, of course, represent snapshots from two different time-series and represent recovery from different disturbance dates. All sites in this study were uplifted varying amounts to their present elevation on 24 March 1964, the date of the Great Alaska Earthquake. For Reference sites, that date is the most important "start" date. For Treated sites, recovery would have restarted following treatment in 1989 and 1990. Combined with differences of exposure and the accompanying differences in rates of re-armoring, these differences in duration of recovery could account for a considerable amount of the variability observed among the Treated and Reference sites and within the Treated sites. Basically, Reference sites should have a 25-year head start in the recovery and re-armoring processes over Treated sites.

Based on Short *et al.* (2002; 2007), it is obvious that subsurface sediments on numerous beaches in PWS retained considerable quantities of oil as late as 2002. Hydrocarbons seeping from the sediments at these sites could act as a negative cue for settling bivalve larvae and therefore delay recovery. Two of Short *et al.*'s sites that retained relatively unweathered oil were located within 100 m of two of our Treated sites (LA 16 and Shelter Bay). Such proximity to a chronic source of relatively unweathered hydrocarbons could cause local adverse effects (reduced abundance of juveniles as a consequence of negative settlement cues) that increase the variability within the Treated sites. However, at such exposed sites, it is likely that low concentrations of hydrocarbons seeping from the sediments would be diluted to extremely low levels before reaching our sites. Since we encountered no sheening to indicate lingering oil in any of our sampling excavations, we do not consider exposure to lingering oil an important cause of variability in our study.

Finally, we have demonstrated above that numerical characteristics for the bivalve assemblage (Table 13) and abundance of *Protothaca* and *Saxidomus* exhibit inverse correlations or trends to proximity to the Gulf of Alaska. The strength of the relationships was mixed for N and S but stronger for *Protothaca* (Table 13, Figure 20) and *Saxidomus* (Table 13). The patterns observed for *Protothaca* among Reference and Treated sites in the excavation samples appear quite similar except that none of the Treated sites near the gulf had abundances nearly as high as two of the Reference sites closest to the gulf (Figure 20). The six sites with more than 40 specimens of *Protothaca* occurred in the southern half of the study area; only one was a Treated site. *Hiatella*, a pioneer species, did not display any consistent patterns and was poorly correlated with latitude in bivariate analyses. Multivariate ordinations for these three species showed significant correlations with latitude for Reference, Treated, and combined sites with the excavation data (Table 15; $r^2 = 0.30$, 0.46, and 0.49) but no significance with the core data. Thus, it appears that species richness of the bivalve assemblages and the density of both *Protothaca* and *Saxidomus* in suitable sediments declined as a natural response to increasing distance away from the Gulf of Alaska. Such systematic natural variation could mask real differences but, since this appears to be operating similarly at Reference and Treated sites (Figure 20), it is not considered an important confounding factor.

Response of Sediments to Washing

HP-HW and HP-WW washing were widely used in heavily or moderately oiled areas. The primary physical effects of this treatment probably included sediment disturbance (homogenization and disruption of the armor layer) and removal of quantities of fine sediments and organic matter from the sediments. Although PGS, driven by the coarser fractions at several sites with a wide range of exposure (Figure 2), was certainly significantly coarser at Treated sites (Tables 4 and 5), we speculate that this difference is related more to the geologic setting and the nature of the rock type than to beach washing.

Quantities of silt/clay were generally low at all sites. Although it is clear from the large silt plumes documented in numerous photographs of the cleanup that fines were being washed from treated beaches, quantities of silt/clay and organics were not significantly different at Treated and Reference sites (Tables 4 and 5). Thus, the sediment patterns observed in this study generally did not appear to support the alternative hypotheses that HP-HW or -WW treatment caused long-term changes in 1) the sediments, by washing away the fine fractions, or 2) the organics. Those hypotheses were based on patterns observed during the earlier NOAA studies. Although conditions at the resampled NOAA Treated sites remained similar to those observed from 1990 through 1996, conditions at the Reference and Treated sites selected for this study were considerably different (Tables 5 and 19). An analysis of these conditions (see below in section on Comparison of 1990-96 and 2002 Conditions at NOAA Sites) suggests that sediment conditions at the 1990-96 NOAA sites probably represented conditions at treated and oiled-but-untreated beaches in the spill area reasonably well at that time.

Regarding the coarser grain size at Treated sites, we believe it is unlikely that beach washing caused any appreciable increase in the coarse fractions that are driving PGS at treated beaches. We cannot envision a mechanism associated with beach washing that would cause such an increase, especially in the particle size classes that are characteristic of many of the more exposed Treated sites (median particle size of >10 mm). Berm-relocation operations were employed on some exposed cobble/boulder beaches but not at the types of beaches or elevations that we were sampling. It seems more likely that environmental (esp. physical and geological) factors are implicated.

Responses to Chemical Effects of the EVOS and the Cleanup

The spill was accompanied by a variety of chemical insults to the various biological assemblages and the environment. Foremost were the acute and chronic effects of exposure to crude oil when it stranded on the beaches. But in addition, the cleanup, including the beach-washing program, also exacerbated some of these effects or exposed the biological assemblages to several other chemical insults.

A purported beneficial chemical effect of beach washing was removal of appreciable quantities of hydrocarbons from the sediments, especially its surface. However, Mearns (1996) concluded that, while substantial quantities of organic debris were flushed from the sediments, significant quantities of hydrocarbons were also mixed into the sediments. Moreover, several chemical formulations were applied to or injected into sediments, either on a small scale or, in the case of the "bioremediation" agents, Inipol and Customblen, over large areas (Mearns 1996). The objective of these applications was to "fertilize" the sediments with inorganic nutrients (particularly nitrogen and phosphorus) and thus promote microbial degradation of the hydrocarbons. Application of nutrients such as Customblen was probably generally innocuous. However, the application of Inipol, in which the nutrients are dissolved in 2-butoxyethanol, may have caused long-term effects. Unfortunately, no studies were conducted to determine effects on epibiota or infauna either before or after application, despite evidence prior to application that Inipol: 1) caused negative impacts to mussel larvae (Lees 1992); and 2) poses known toxicological hazards (see NIOSH 1990) that required crews applying the substance to wear full-face respirators and full-coverage personal protection equipment (Ott 2005) and place repellant devices on the beaches to discourage visits by humans or vertebrate predators. Ironically, Mearns (1996) estimated that the combined treatments during the spill removed only about 10% of the stranded oil from the beaches.

Peterson (2001) summarized several studies demonstrating a variety of effects associated with exposure of intertidal and subtidal biota to hydrocarbons and shoreline treatment from the spill. One of those studies (Houghton *et al.* 1997), summarized in the introduction above, observed significant negative impacts to growth rates for *Protothaca* in response to exposure to hydrocarbons. In other specifically relevant studies, Fukuyama *et al.* (2000) and Trowbridge *et al.* (2001) demonstrated that individuals of *Protothaca* suffered higher mortality and grew more slowly in oiled sediments than at unoiled reference sites. Several studies have also demonstrated that effective treatment mixes variously weathered crude oil into the sediments (*e.g.*, Broman *et al.* 1983). Moreover, ineffective treatment left pockets of unweathered crude oil in the sediments (Short *et al.* 2002).

Although Short *et al.* (2002) and Heintz *et al.* (1999) found it is likely that hydrocarbons remain on some beaches and could have an influence on the acceptability of sediments to competent larvae in some areas, we do not think this concern applies to our study. First, residual (lingering) oil appears to be spatially patchy and occurs only on particular beaches. Our study covered a broad region of random sites with no intent to occupy known currently oiled beaches. But more importantly, we observed no sheening in our field excavations, which suggests we were likely never close to residual oil deposits. In view of the high rates of dilution resulting from tidal and other currents, it seems unlikely that lingering hydrocarbons have exposed clams living at our sampling sites to chronic effects in recent years. It is far more likely they were exposed to potentially acute effects during the spill and cleanup but that any continuing effects are due to secondary effects of the cleanup (*e.g.*, disruption of the armor layer).

Effects of Shoreline Treatment on Recruitment

One implicit question addressed in this study was whether altered sediment properties have affected recolonization for infaunal assemblages, especially bivalves. Although this study was not designed to measure recruitment rates of bivalve larvae to treated beaches, this is an important aspect of recovery because, as Woodin (1991) stated, "Recruitment is a process of fundamental importance because it is the background upon which all subsequent interactions with the community take place." Numerous studies have demonstrated that sediment properties are used as positive or negative cues of suitability by competent infaunal larvae before recruiting in sediments. The question assumes, of course, that treatment did, in fact, alter the sediments in the manner observed during the spill cleanup (Mearns 1996) and documented with *a posteriori* data in the NOAA study (Driskell *et al.* 1996; Houghton *et al.* 1997).

While some studies indicate that disturbance can lead to higher rates of recruitment (*e.g.,* Jewett *et al.* [1999] discussing recolonization of subtidal sediments following storm activity), Strasser *et al.* (2001) reported that post-settlement factors such as predation, competition, and resuspension may be more important to long-term recovery, even when recruitment is elevated. They postulated that one potentially important cause of reduced recruitment success following storm disturbance of the sediments was increased susceptibility to resuspension of the recruits by surge and currents. This fits nicely with our suspicions regarding the effect of disruption of the armor layer.

Wilson (1955) reported that bacterial films were an important positive cue in recruitment of a polychaete. He found that reduced concentrations of TKN, which reflect lower microbial biomass, were accompanied by reduced recruitment. While our three dominant species exhibited significant correlations with TKN (Table 12), the patterns were mixed and certainly do not provide convincing evidence that TKN influenced recruitment of these bivalves.

Although several investigators have reported that presence of living clams of the same or different species, or sometimes just their shells, act as positive cues to recruits (Ahn *et al.* 1993; Snelgrove *et al.* 1999), it does not appear that the substantially reduced abundance of hard-shell clams at Treated sites has led to reduced recruitment of *Protothaca* (Figure 11). Although comparisons of abundance for juveniles and adults of *Protothaca* and *Macoma inquinata* in this study suggest that abundance of juveniles and adults is positively correlated, it is not clear that the relationship is affecting recruitment success for either species. Total *Protothaca* abundance was significantly higher at Reference sites (Figure 12) but the slope of the regression line relating juvenile and adult abundance was steeper for Treated sites (Figure 11), suggesting that juveniles were recruiting to the population faster at Treated sites. In fact, it appears that juvenile densities were attaining comparable levels at Treated sites as at Reference sites despite substantially lower numbers of adults. However, in view of the reduced abundance of adults at Treated sites after 13 years, post-recruitment success may still be an issue. Disrupted armoring, or more specifically, greater sediment instability and the lack of refuge, could lead to higher post-recruitment mortality from increased vulnerability to turbulence from significant storm events or currents or from reduced protection from predators.

Not unexpectedly, juvenile and adult abundances are not correlated for *Hiatella.* Recognized as a weedy, pioneer species, juveniles often settle in large numbers on new or disturbed substrata (*e.g*., Gulliksen *et al.* 1980). Because of its low density in the core samples, the situation is not clear for *Saxidomus.*

Woodin *et al.* (1995, 1998) reported that process-specific factors such as release of ammonium or sulfides from underlying sediments (chronical releases from unsuitable anaerobic sediments) could have temporary negative influences on infaunal recruitment patterns in sediments that would otherwise be acceptable to recruiting larvae. All of these types of negative cues were undoubtedly set in motion by shoreline treatment activities. However, it is unlikely that such cues would affect long-term recovery phenomena.

In addition to significant differences or strong trends in abundance and species richness between Treated and Reference sites, some consistent differences in size structure may also reflect the effects of differential post-recruitment success. For *Protothaca*, the size classes representing animals between ≈5 and 8 years old were about 10% and 12% less abundant in excavation and core samples from Treated sites, respectively (Figure 12). For *Saxidomus*, size classes representing animals from 6 to 11 years old were about 22% less abundant in excavation samples from Treated sites (Figure 14a). For *Hiatella*, size classes representing animals from 2.5 to 3.5 years old were about 18% and 23% less abundant at Treated than at Reference sites, respectively (Figure 18). The consistency of this deficit in the middle age classes at Treated sites for three of the four dominant species, despite relatively comparable numbers in the younger year classes, suggests that post-recruitment survival is poorer at Treated sites than at Reference sites. This pattern also seems to fit well with the hypothesis that some difference in a structural feature, presumably armoring, exists between Reference and Treated sites.

Neither *Protothaca* nor *Hiatella* appeared to exhibit differences in growth rates between treatment categories (as assessed by the relationship between shell length and age [annuli]; Figures 13, 15, and 19). Growth rates for *Saxidomus* may have been slightly higher at Reference than at Treated sites. However, it appears that environmental conditions affecting growth rates do not differ enough between treatment categories exert an important growth effect.

Biological Effects of the Cleanup

Beach washing involved two components causing mortality of the infaunal assemblages on mixed-soft beaches. First, thermal stress from the high water temperatures associated with HP-HW (and probably warm-water) washing caused substantial mortality. Moreover, the high-pressure water jets directed into the sediments caused considerable physical injury to bivalves and other infaunal organisms buried in the sediments (Lees *et al.* 1996; Mearns 1996).

Biologically, the physical component of the beach-washing program was similar to other anthropogenic activities such as dredging or resource harvest in soft sediments. In the sound, we observed broad-scale mortality associated with beach washing (*e.g.*, Lees *et al.* 1996). At least initially, this reduction in density probably resulted in reduced predation and competition within intertidal infaunal assemblages but could have resulted in higher recruitment and post-recruitment success. However, as pointed out above, because of the likely effects of the disrupted armor layer, it may have resulted in a widespread increase in resuspension (and probably mortality) of recruits during storm events.

Rate of Recovery

Effects of anthropogenic activities such as dredging (*e.g.*, Jewett *et al.* 1999 above) or resource harvest have been documented for several infaunal organisms, particularly bivalves and burrowing crustaceans. The general pattern that seems to emerge from these studies (*e.g.*, Kaiser *et al.* 2001; Peterson 1977; Peterson *et al.* 1987; Piersma *et al.* 2001; and Wynberg and Branch 1994) is that recovery is relatively rapid for smaller, more ephemeral infauna, especially in sediments that are more exposed (*e.g.*, the razor clam *Ensis* spp.; Tuck *et al.* 2000) but much slower for the more long-lived target or non-target macrofaunal species (*e.g.*, Newell *et al.* 1998). The bivalve assemblages at the Treated sites in this study appear to exhibit a response similar to the latter case.

Newell *et al.* (1998) also demonstrated that the rate of recovery in disturbed sediments can vary inversely with particle size. Thus, recovery can be rapid in fine sediments, which are typically dominated by ephemeral (small, short-lived) species that represent early stages of succession. In contrast, they reported that recovery was slow in coarse sediments, especially relatively undisturbed mixed gravel/sand/silt habitats, which are generally dominated by large, long-lived animals representing later stages of succession. These species generally recruit and grow slowly. These authors also pointed out that recruitment might take considerably longer at higher latitudes because successful recruitment episodes are relatively infrequent. Indeed, recovery of the bivalve assemblage at Treated sites seems to be progressing slowly.

Similarly, Ferns *et al.* (2000) and Piersma *et al.* (2001) reported that more complex assemblages found in relatively undisturbed sediments recovered more slowly than less complex assemblages. Piersma *et al.* (2001), in an excellent long-term study of the consequences of clam dredging, reported it was eight years before sediment properties recovered and that stocks of target and non-target bivalves were far from recovered after 10 years. Recruitment remained considerably depressed in dredged areas after 10 years.

Thus, it appears that solid evidence exists elsewhere showing that recovery of injured clam assemblages can take over a decade. In this case, it is unclear how long may be required. Thirteen years after the spill, densities of larger hard-shell clam (≥20 mm shell length) on Treated beaches are still ≈ 66% lower than on Reference beaches. Considering that the maximum estimate of mortality is about 71%, it is unclear how much progress has been achieved to date. Certainly, recovery of the complex infaunal assemblage characterizing armored mixed-soft sediments will require not only re-establishment of the long-lived bivalve populations but also the return of the other large, long-lived species (*e.g.*, echiurans, sea cucumbers, and burrowing shrimp) that dominate these assemblages. Given the apparent relatively flat recovery trajectory since 1989 (Lees *et al.* 1996) and 1996 (Houghton *et al.* 1997), it seems reasonable to suggest that full functional recovery of the treated beaches to the condition existing before 24 March 1989 will probably not be achieved for several more decades.

Comparison of 1990-96 and 2002 Conditions at NOAA Sites

Generally, conditions in sediment and bivalve assemblages at the NOAA sites were somewhat similar to those observed during the first six years of the survey (Houghton *et al.* 1997). To provide a baseline perspective, the comparison of sediments for the 1990 – 96 period and 2002

(Table 19) includes data from the unoiled sites surveyed during the NOAA surveys. During the earlier study, sediments at unoiled sites had finer PGS and more silt than either Reference or Treated sites (Table 19). The pattern for fines reflected expected effects of beach washing, *i.e.*, the tendency of washing to flush fines from the sediments. Elevated concentrations of TOC and TKN at Reference sites and depressed concentrations at Treated sites appeared to demonstrate that the washing process had been effective in reducing concentrations of hydrocarbons in treated sediments and that the microbial flora was enhanced by the presence of hydrocarbons. Overall, between the 1990 – 1996 period and 2002, it appears that PGS became coarser at the NOAA Treated sites and was somewhat (190%) coarser at Treated sites for this study than at the NOAA sites during the 1990 – 1996 study. In contrast, silt/clay concentrations in 2002 were substantially lower at NOAA Treated sites than during the earlier study (290%) and at Treated sites for this study (52%). Highest TOC and TKN concentrations were observed at the NOAA Reference sites during the early period, probably because the higher concentrations of hydrocarbons present in the sediments at that time supported a larger microbial flora. TOC values were substantially lower (65%) at NOAA Reference sites during this survey than in earlier study and converged on the levels observed initially at the NOAA Treated sites. They declined 41% at the NOAA Treated sites. Likewise, TKN values at Reference sites were markedly lower (46%) during this survey than at the NOAA Reference sites. However, they didn’t change markedly at the Treated sites from the early study until 2002. In the early period, C/N ratios were lowest at unoiled sites and highest at Treated sites. The lower C/N values at the unoiled sites suggest that organics largely comprise terrestrial and marine macroalgal organic matter. In contrast, the high values at the Reference and Treated sites suggest a strong influence of hydrocarbons, which have high C/N ratios. C/N ratios in both treatment categories had decreased appreciably by 2002, exhibiting values slightly lower than those observed at the unoiled sites from 1990 – 1996. This suggests that the influence of hydrocarbons in the sediments has declined considerably.

Disruption of armoring is a possible cause for the apparent continued loss of fines at Treated sites, especially the NOAA Treated sites. This view is strengthened by the similarity in loss of fines at the Reference (80%) and the Treated sites (62%) between in the earlier study and 2002. The increase in PGS at Treated sites (186%) also falls within the 290% average increase observed at the resampled NOAA Treated sites.

This comparison of sediment conditions between the 1990 – 1996 period and 2002 provides some useful insights into changes that have occurred at the NOAA sites and into the similarity of sediments sampled during the NOAA and 2002 sites. First, it appears that sediment organics have become more normal (as defined by the values at the NOAA unoiled reference sites) at both NOAA Reference and Treated sites (Table 19). The 2002 values for TOC, TKN, and C/N at these sites are more in line with what was observed at the unoiled reference sites, suggesting appreciable recovery. Next, grain size characteristics have consistently become appreciably coarser, especially at the Treated sites; PGS increased and quantities of silt/clay have decreased at both NOAA Treated and Reference sites. The changes suggest that these sites are still undergoing the armoring process, another indication of recovery, and that sediment conditions at the early NOAA sites were probably reasonably representative of sediment conditions in mixed-soft beaches in western PWS. Although sediment conditions were substantially different in 2002 than during the earlier study, reasonably similar changes were observed at specific resampled sites.

The trends observed in average numbers of bivalve taxa and individuals during the NOAA study and in 2002 suggest that little change has occurred at the NOAA sites since 1997 (Figure 33). Values for both variables are still lower at Treated sites (oiled & washed in this table) than at Reference sites (oiled & unwashed in this table) and are basically unchanged in both categories since 1997. It appears that the substantial decline in numbers of taxa observed at the Reference sites between 1991 and 1997 did not continue until 2002.

Even though little change was observed in the biological characteristics at the NOAA sites from 1997 to 2002, several important changes were observed in species abundance patterns (Table 20). During the early period, the most abundant species at both unoiled and Reference sites was *Rochefortia* but *Hiatella* was most abundant at Treated sites. All dominant species except *Hiatella* were most abundant at unoiled sites and least abundant at Treated sites. In contrast, abundance of *Hiatella* was higher at both Reference and Treated sites in the early period than at the unoiled sites and higher at Treated sites than at Reference sites in 2002. These patterns seem to support the notion that HP-HW washing caused major injury to *M. balthica, M. inquinata*, *Rochefortia*, *Protothaca*, and *Saxidomus* whereas *Hiatella*, a pioneer species, benefited from the disturbed conditions at the Treated sites.

Among the Treated sites, relative abundance of *Hiatella* and *M. balthica* declined 84 and 81%, respectively between the earlier period and 2002, while *Rochefortia* increased 90%. In relative terms, the importance of *Protothaca* became greater at only at Reference sites in 2002. Relative abundance of *Saxidomus* remained unchanged at both Reference and Treated sites.

Thus, it appears that the numerical characteristics of the bivalve assemblage in the core samples at Treated and Reference sites changed little between 1997 and 2002 but species composition and relative abundance patterns changed substantially. N and S continued to be lower at Treated than at Reference sites and were still not markedly changed from the levels observed in 1997 (Figure 33). In terms of species composition, however, several important changes occurred. Abundance of *Hiatella*, which had been the dominant species at Treated sites in the earlier period, declined somewhat and *Rochefortia* replaced *Hiatella* as the dominant by 2002 (Table 20). The latter had been dominant at Reference sites in the earlier study and retained that position in 2002. Important changes were observed in the hard-shell clams. Actual abundance increased substantially in both *Protothaca* and *Saxidomus* at Treated sites in 2002 (400 and 650%, respectively). Nevertheless, their abundance at Treated sites remained substantially below that observed at Reference sites (41 and 65%, respectively, in the core samples).

Effectiveness of HP-HW or -WW Washing

Several investigators have commented on either the ineffectiveness of high-pressure hot- or warm-water washing of beaches or the injury caused by this process. Mearns (1996) estimated that, while the process was visually effective, it removed only about 10% (from 4 – 19%) of the stranded oil. Short *et al.* (2002 and in review) have demonstrated that a substantial amount of oil still remains in the sediments of cleaned beaches in western PWS. Moreover, several

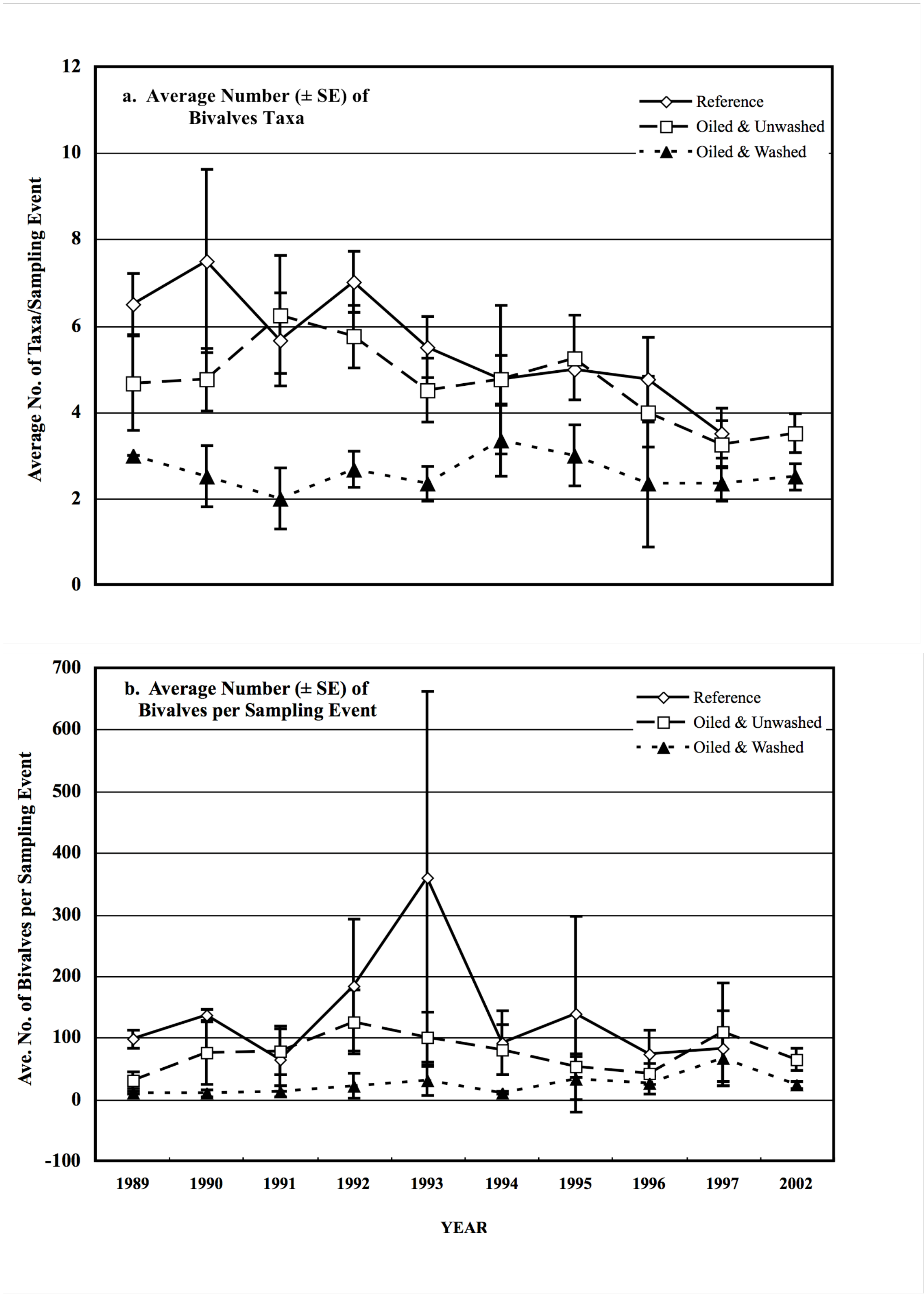


Figure 33. Combined data for average numbers of bivalve taxa and individuals by treatment category from NOAA (1989 – 1997) and current (2002) studies.

Table 20. Average and relative abundance (dominance) of dominant bivalves in core samples at unoiled, Reference, and Treated sites in 1990 – 96 (NOAA sites) and 2002 (this study).

Taxon	Category	Average Abundance		Relative Abundance	
		1990 - 97	2002	1990 - 97	2002
		Mean ± SE (No.)	Mean ± SE (No.)	Mean ± SE (%)	Mean ± SE (%)
Hiatella arctica	Unoiled	3.5 ± 0.9	–	3.3± 0.8	–
	Reference	7.6 ± 3.4	9.1 ± 3.5	12.8± 5.2	21.2 ± 8.4
	Treated	19.2 ± 7.6	12.7 ± 6.0	62.3 ± 10.6	9.7 ± 4.8
Macoma balthica	Unoiled	7.0 ± 2.2	–	7.8 ± 2.2	–
	Reference	4.5 ± 2.3	2.0 ± 0.6	4.7 ± 2.2	4.7 ± 1.5
	Treated	0.9 ± 0.7	2.0 ± 0.8	7.8 ± 5.5	1.5 ± 0.7
Macoma inquinata	Unoiled	10.4 ± 1.9	–	11.4 ± 2.2	–
	Reference	9.1 ± 2.3	0.4 ± 0.4	13.0 ± 1.7	0.8 ± 0.8
	Treated	0.04 ±0.04	0.5 ± 0.3	0.3 ± 0.3	0.3 ± 0.2
Rochefortia tumida	Unoiled	94.1 ± 31.2	–	61.0 ± 4.1	–
	Reference	40.4 ± 9.1	22.8 ± 10.1	42.4 ± 3.9	53.1 ± 24.3
	Treated	4.9 ± 3.6	52.7 ± 18.7	21.3 ± 9.4	40.5 ± 14.7
Protothaca staminea	Unoiled	16.9 ± 4.7	–	13.2 ± 1.5	–
	Reference	15.0 ± 2.2	11.8 ± 3.5	19.8 ± 1.9	27.4 ± 8.3
	Treated	1.4 ± 0.2	7.0 ± 2.8	7.3 ± 1.5	5.3 ± 2.2
Saxidomus gigantea	Unoiled	1.1 ± 0.4	–	1.4 ± 0.5	–
	Reference	1.8 ± 0.4	1.7 ± 0.4	1.7 ± 0.3	4.0 ± 0.9
	Treated	0.08 ± 0.06	0.6 ± 0.2	0.4 ± 0.3	0.5 ± 0.1

investigators have demonstrated that the process causes long-term injury to the epibiota (Broman *et al.* 1983; Houghton *et al.* 1996, 1997) and the infauna (Driskell *et al.* 1996; Lees *et al.* 1996). In the sediments, HP-HW washing causes direct loss of bivalves and other important long-lived invertebrates. Although the loss of fines and organics could create a negative feedback loop by reducing recruitment, our data do not provide support for this hypothesis. Instead, the findings of this study strongly suggest that washing had two effects. The direct effect was to cause considerable mortality of the bivalve populations living in the sediments at the time of the cleanup. The secondary effect was a long-term indirect consequence that probably has been considerably more important than the initial acute injury because it has impeded recovery for over 13 years. In areas where armored sediments were disrupted, the loss of organization in the armor layer has probably resulted in reduced survival of recruits for hard-shell and probably other species that are dominant members of the climax assemblage. Nevertheless, whatever the mechanisms, the fact remains that in 2002, densities of hard-shell clams in excavation samples from Treated sites remained over 65% lower than at Reference sites and over 40% lower in core samples. Such an injury must be considered a serious impact.

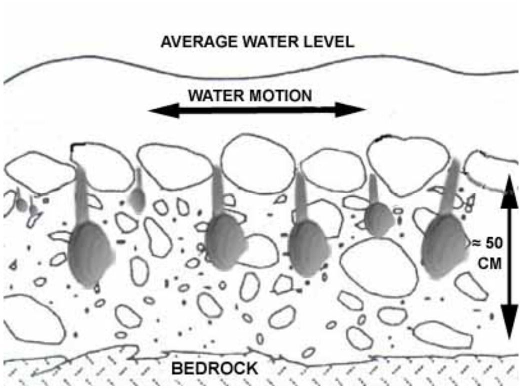
Based on these findings, it is logical to conclude that HP-HW or any other type of vigorous washing are poor ways to deal with mixed-soft beaches that support long-lived complex infaunal assemblages. It was not especially effective at actually removing oil from the environment (Mearns 1996) and was responsible for major mortality in bivalve and other infaunal assemblages (Driskell *et al.* 1996; Lees *et al.* 1996). However, Fukuyama *et al.* (2000) and Trowbridge *et al.* (2001) have also shown that continued exposure to oiled sediments resulted in increased mortality and slower growth in *Protothaca*. Moreover, considerable evidence has accrued that higher trophic levels were damaged by residual oil in the environment even after the beaches were cleaned (Peterson 2001; Integral Consulting 2006). Thus, it appears that once oil is on the beach, neither major alternative (cleaning or not cleaning) provides a wholly satisfactory solution. The only satisfactory solution is to keep oil off the beaches.

Conceptual Model of Consequences of Beach Washing and Armor Recovery Process

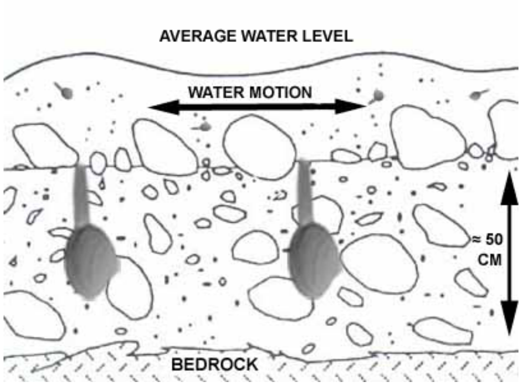
The hypothetical sequence in sediment organization and the hard-shell clam assemblage that we contend followed beach washing in PWS is illustrated in the pictorial time-series shown below (Figure 34). The sediment was armored and organized prior to beach washing, clam density was moderate and the size structure of the clam population was diverse (Figure 34a). Following beach washing, the organization of the armored sediments on Treated beaches was substantially disrupted, density of clams was reduced substantially (*e.g.*, Lees *et al.* 1990), and the remaining clams were mostly large individuals that lived deeply enough in the sediments to avoid being flushed out or thermally stressed by the washing (Figure 34b). The organization of the cobbles and pebbles was disrupted and considerably more fine sediments were exposed at the surface. Fine sediments and newly recruited clams, no longer protected by the armored layer and therefore more susceptible to resuspension, were washed away by any appreciable wave action or strong tidal currents and mostly swept out of the area. Following washing, the system commenced recovery. Coarser fractions of the sediment responded to water motion by reorganizing, especially as the exposed finer sediments were eroded (Figures 34c – e). This reorganization consisted of three major actions. First, the export of fine sediments probably resulted in a some reduction in sediment thickness. In combination with the water motion, this caused the coarser fractions to concentrate at the surface of the sediment (Petrov 1989; Hayes and Michel 1999, 2001) and reoriented the rocks to create a more streamlined (flattened) surface, as described by Petrov (1989). As the rocks reoriented, they began to imbricate or shingle, and increasingly protect the open patches of finer sediments. Also, with increasing organization providing greater protection, the clam assemblage commenced recovery, with density increasing and the size structure becoming more diverse as juveniles recruited to the sediments and post-recruitment survival improved. The recovery rate probably varied widely among areas in accordance with differences in exposure; the more exposed an area (within limits), the more rapidly re-organization occurred and the sooner population density and diverse size structure of clam assemblages could become re-established. It is likely the resulting variation led to and accounts for considerable variability in the degree of recovery observed at the sites where we sampled 13 years after the spill.

A bedrock layer was included in these figures solely to demonstrate the concept of loss in sediment thickness through dispersion and erosion of the finer fractions. In fact, we did not encounter a bedrock foundation at any of our sampling sites, where we excavated sediments to a

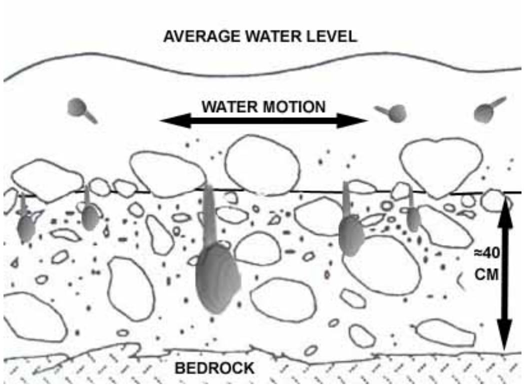
a. Armored substratum and clam assemblage prior to beach cleaning.



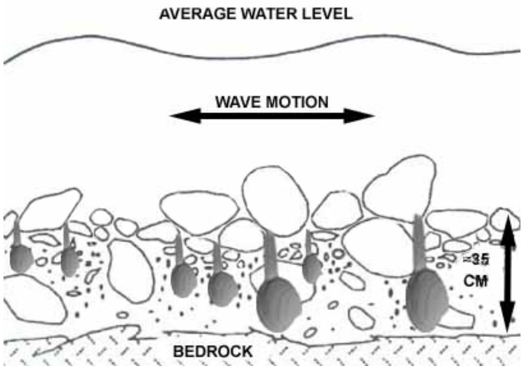
b. Disorganized substratum and damaged clam assemblage immediately following beach cleaning.



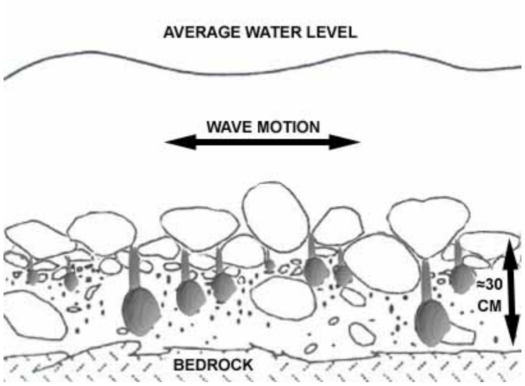
c. Substratum and clam assemblage early in the recovery process following beach cleaning.



d. Substratum and clam assemblage later in the recovery process following beach cleaning.



e. Substratum and clam assemblage near the end of the recovery process following beach cleaning.



Key to figures:

This symbol represents various sizes of clams residing in the sediment or resuspended in the water column.

· · · · Represents fine particles in sediment or water column.

Figure 34. Time-series diagrams showing hypothesized sequence of sediment organization and clam assemblage starting before beach treatment and progressing through the restoration process for sediments (armoring) and clams. (Figures adapted from Hayes and Michel 1999.)

depth of 15 cm. That such erosion occurs can be observed at numerous locations in PWS where the shells of living buried clams that were uplifted by the 1964 earthquake are now substantially exposed above the present surface of the sediment. Many of the large specimens of *Saxidomus* in Figure 27 were living buried at least 15 cm deep in the sediment in northern Crab Bay, Evans Island, at the time of the earthquake. Their intact, still-articulated shells graphically attest to the amount of sediment loss that has occurred due to dispersion and erosion in this location during the armoring process.

Summary

Earlier NOAA studies reported long-term effects of cleaning oiled mixed-soft beaches in western Prince William Sound with HP-HW or –WW washing including: 1) very large reductions in population densities of long-lived species in existing infaunal assemblages, especially bivalves; and 2) removal of fines and organics, which substantially changed sediment quality (Lees 1992; Driskell *et al.* 1996; Lees *et al.* 1996; Houghton *et al.* 1997). We hypothesized these factors could delay recovery of the infaunal assemblages. Based on samples collected in 2002, we found a striking number of differences between the treatment populations and their correlated responses to population characteristics and single environmental variables. Using multivariate regressions, several of the environmental factors appear to correlate significantly with species abundance but the suite of factors appears to be missing a variable. Ordinations suggest similar pattern; aspects of the abundance data distinguish Treated and Reference populations and show significant but not "causally convincing" correlations with the environmental factors. However, most results are consistent with the hypothesis that these patterns are related to disruption in the organization of sediment armoring at Treated sites.

Sediments

Sediments at both Reference and Treated sites were classified mainly as gravels and pebbles but overall, sediments were significantly coarser in the Treated category. Because this difference involves particle sizes that should not be influenced by beach washing (>3 cm), we concluded that beach washing was not the cause of this difference. Although particle size correlated directly with exposure at Treated sites, since the range of exposure extended only slightly higher for Treated sites (see, for example, Figures 2 and 3), we speculate that the higher particle size is simply variability in geologic conditions, *e.g.*, differences in the types of rock at the sites. Quantities of silt/clay were low in both treatment categories (average ≈3.0%) but considerably higher than would be predicted by inverse relationships traditionally reported between coarse and fine fractions. Neither the silt/clay nor the organic fractions differed significantly between Treated and Reference sites. C/N ratios have decreased since 1996 and now indicate that the major sources of organic matter in these sediments are benthic marine plants from nearby intertidal and subtidal substrata and terrestrial plant debris from adjacent shorelines. This decrease also suggests that petroleum hydrocarbons are no longer a significant component in the sediments on the sampled beaches. Although no chemistry samples were taken in the field, lack of observable sheening in sampling pits suggests the sediments were essentially clean (J. R. Payne, pers comm.) Consequently, although sediment properties appear to exert moderate influence on the bivalves, they do not appear to be an important factor in the lagging recovery of bivalves at Treated sites.

Exposure appears to play a role in the sediments but primarily at Treated beaches, where median grain size exhibited a positive correlation to exposure (Figure 2) but the silt/clay fraction and the organics all responded negatively (Figure 3). These responses are strong evidence for the beach armoring concept reported by Hayes and Michel (1999, 2001) for mixed-soft or "gravel" beaches in Prince William Sound. Under this concept, finer sediment fractions at the surface of the sediment are winnowed away while the surficial pebbles and cobbles become more concentrated at the surface of the sediment so that they form an armor layer. This surficial layer then provides some protection to the underlying sediments and sequesters fines and organics while also improving recruitment success and survival of long-lived burrowing organisms such as clams. As the armor layer becomes more "organized" (imbricated) due to exposure to wave action and strong currents, the degree of protection increases. This process appears to explain why the expected relationships observed between fines, organic matter, or infaunal assemblages and relatively homogeneous mud, sand, or gravel substrata do not pertain in the heterogeneous mixtures of cobble, gravel, sand, and fines, *i.e.*, mixed-soft sediments, observed in southcentral Alaska. Typically, organic matter and infaunal abundance, species richness, and biomass are negatively correlated with grain size, meaning that coarse sediments such as gravel should contain very low concentrations of fine sediments and organics and an impoverished biota. However, mixed-soft substrata in PWS are characterized by quantities of organics similar to those observed in stable mud and sand substrata on the shallow to mid-depth continental shelf or in embayments and, like those sediments, the infaunal assemblages are dominated by large, long-lived organisms. In fact, standing stocks of infaunal organisms are generally substantially higher in the armored sediments than in intertidal or offshore homogeneous sediments. Reports of similar habitats and the infauna are starting to emerge from the North Sea and the United Kingdom but discussions of a fauna associated with armored sediments are uncommon.

Based on this understanding of armored beaches, we posit that disruption of the organization of the armor layer by beach washing at Treated sites is at least partially responsible for the positive correlation observed between PGS and exposure and largely responsible for the negative correlation between the fines and organics and exposure. More importantly, we also believe this disruption is responsible for the lag in recovery observed in the bivalve assemblage, especially for hard-shell clams (see below).

Bivalve Assemblage

We used two types of samples to examine the bivalve assemblage. Samples from 0.0625 m^2 plots sieved through a 6.35-mm screen were used to provide insight into the abundance of larger size classes of clams. Samples from 0.009 m^2 cores sieved through 1.0-mm sieves were used to provide insight into the abundance of younger and smaller size classes of clams. *Protothaca*, *Hiatella*, *Macoma inquinata*, and *Saxidomus* dominated in both excavation and core samples. A tiny nestling clam, *Rochefortia*, was an additional dominant in the core samples.

As we predicted from the findings of the NOAA study, both N and S for the excavation samples were significantly higher at Reference than at Treated sites. H' exhibited a strong trend toward higher values at Reference sites. For core samples, we assumed that the bivalve assemblage at Treated sites would be at an early stage of recovery and therefore predicted that S would be lower but, because pioneer species and younger individuals would be more abundant at Treated than at Reference sites, N would be higher. In fact, N and S exhibited strong but non-significant trends conforming to the postulated patterns. Species diversity indices were either significantly lower at Treated sites or exhibited a strong trend in that direction.

Differences observed in the dominant bivalves inhabiting core samples from Reference and Treated sites during the earlier NOAA studies still remained in 2002. In order of abundance, *Protothaca*, *Hiatella*, *Macoma inquinata*, and *Saxidomus* dominated the bivalve assemblage sampled with the excavation samples. The large, long-lived *Protothaca* and *Saxidomus* were significantly less abundant (66%) at Treated than at Reference sites.

As was observed in the earlier NOAA study, the pioneering *Hiatella* was more abundant at Treated than at Reference sites in the core samples but the difference was no longer significant. It seems clear, however, that the alternative hypothesis based on core samples during the NOAA study was incorrect for *Hiatella* in the excavation samples. In fact, the species exhibited a strong trend toward higher abundance at Reference sites in the excavation samples (p = 0.17). Closer examination of size data indicated that the *Hiatella* specimens in the core samples were predominantly juveniles that would not be retained in excavation samples whereas mainly adult *Hiatella* were retained in the our excavation samples. Thus, while juvenile *Hiatella* in the core samples exhibited a weak trend toward higher abundance at Treated sites, the excavation samples showed a strong trend toward fewer adults at Treated sites.

The bivalve assemblage in core samples was dominated, in order of abundance, by *Rochefortia*, *Protothaca*, *Hiatella*, juvenile *Modiolus*, *Macoma balthica*, and *Saxidomus*. *Saxidomus* was significantly more abundant at Reference than at Treated sites and *Protothaca* exhibited a strong similar trend. *Hiatella* and *Rochefortia* were substantially more abundant at Treated than at Reference sites. The Reference sites, with greater abundance of large, long-lived bivalves, appeared to represent a later stage of succession than the Treated sites. However, none of the bivalves assemblages observed during this study were nearly as well developed as the death assemblages observed in uplifted sediments representing pre-1964 earthquake conditions in PWS.

A comparison of responses to exposure provides insights into armoring effects. In the excavation samples, hard-shell clams at Reference sites exhibited a significant positive correlation with exposure (suggesting that increased exposure enhances abundance) whereas they were uncorrelated at Treated sites (Figure 9). In contrast, abundance of the smaller clam component (from the core samples) declined significantly at Treated sites in response to increased exposure whereas that component was unaffected by exposure at the Reference sites (Figure 10). Considering that the abundance of juvenile clams is generally similar at Reference and Treated sites (Figure 11), this suggests that, while exposure was causing little injury to populations of smaller clams at Reference sites, it was causing considerable mortality for that size class of clams at Treated sites. We believe that, in both the excavation and core samples, we are seeing a consequence of disrupted organization of the armor layer. For the smaller clam component at Treated sites, because they are less sheltered from disturbance during storm events and less protected from predation, they are suffering higher mortality than are those at Reference sites. Consequently, recruitment to adult size classes is slower at Treated sites. In contrast, at the better armored Reference sites, increased protection results in greater recruitment to adult size classes due to both a safer refuge and an enhanced food supply since increased wave action or currents lead to better access to plankton and more frequent resuspension of organics into the water column.

Although abundance for each of the dominant species varied considerably between treatment categories, size structure did not differ appreciably, with one exception. In each species, the relative abundance of part of the size structure was lower at Treated than at Reference sites. For the size classes representing 5- to 8-year-old *Protothaca*, these differences were 10 and 12% for excavation and core samples, respectively. For 6- to 11-year-old *Saxidomus*, this difference was 22% for excavation samples. For the shorter-lived *Hiatella*, the difference for 2.5- to 3.5-year-old animals was 18 and 23%, respectively, for excavation and core samples. We suspect these consistent deficits in the size structure may indicate differences in post-recruitment success and the subsequent loss of recruitment to adult size classes. In the hard-shell clams, that deficit appeared to develop during a "window" about 5 to 11 years before 2002, or from about 1991 to 1997.

Abundance of the major large, long-lived bivalves (*Protothaca* and *Saxidomus*) exhibited inverse correlations with distance from the Gulf of Alaska. This phenomenon introduces systematic variability and could possibly mask some effects. However, *Protothaca* exhibited a strikingly similar response at Reference and Treated sites. Moreover, multivariate analysis did not indicate that distance from the gulf was an important factor. Total number of individuals per site (N) also exhibited a negative correlation in excavation samples but not in core samples. In both *Protothaca* and N, abundance was low at the northern sites but higher at the southern sites. Also, *Protothaca* and N were substantially lower at similarly located Treated and Reference sites. *Hiatella*, the pioneer species, did not show this response to distance from the gulf.

The differences in the bivalve assemblages between Reference and Treated sites represent functional or structural differences. Numerically, large, long-lived clams in core samples were 40% less abundant at Treated than at Reference sites while small, short-lived clams were 98% more abundant. This pattern is more striking in the excavation samples, which provide better insight into the larger sizes of clams. In these samples, the hard-shell clams at Treated sites were 66% less abundant that at Reference sites. Based on the size of the various clams, we can infer from these differences that bivalve biomass available as prey for nearshore vertebrate and invertebrate predators remained considerably lower at Treated sites than at Reference sites in 2002.

To examine whether recruitment rates have been affected by site treatment, we compared numbers of juveniles and juvenile/adult ratios between the treatment categories. Successful recruitment (recovery) depends upon sources of larvae, appropriate cues for settlement, and proper conditions for survival and growth. Cues for settlement can depend upon several species-specific factors including presence of adults, microbial preconditioning, or other specific physico-chemical stimuli. The density of *Protothaca* juveniles was only marginally greater at Reference sites. However, the ratio of juveniles to adults was higher at Treated sites (Figure 11). This evidence suggests that although the supply of recruits is similar, higher post-recruitment mortality results in significantly lower abundance of adults at Treated sites. Conditions promoting post-recruitment survival and growth include empty physical space in an acceptable sediment matrix, appropriate food sources in adequate quantities, and protection from predation and disturbance. We strongly suspect that disruption of the armor layer by beach washing has been a major factor leading to the apparent increase in post-recruitment mortality at Treated sites. Reduced organization of the armor layer can lead to increased predation on juveniles and, very importantly, their resuspension during storm events.

Correlations between numbers of juveniles and adults for hard-shell clams were highly significant in both treatment categories. In contrast, numbers of juvenile and adult *Hiatella* were not correlated, reflecting a requisite characteristic for a pioneer species that must colonize areas where adults are absent. In fact, *Hiatella* exhibited a strong trend toward more juveniles per site at Treated than at Reference sites, suggesting a positive response to disturbance by this opportunistic pioneer species. Numbers of juvenile and adult *Macoma inquinata* in the excavation samples were significantly correlated and juvenile/adult ratios were also higher for Treated than for Reference sites. The fact that juvenile/adult ratios for all three species were higher at Treated sites but, in the case of *Protothaca* and *Saxidomus*, the density of adults remained substantially lower at Treated sites, suggests that post-recruitment phenomena were reducing juvenile survival.

Abundance of the dominant species and the numerical characteristics for the bivalve assemblage appear to exhibit numerous significant correlations with sediment properties. This appears true for the data set as a whole, implying generality within this bivalve assemblage, and within the core and excavation sample types. The typical responses observed in the dominant species and the numerical characteristics for the bivalve assemblage were decreases in abundance or number of species in response to increased PGS and increases in N or S in response to increased silt/clay, TOC, and TKN.

From the bivariate comparisons, within both the excavation and core sample types, the Treated sites appear to exhibit stronger patterns than the Reference sites. Furthermore, the patterns were more pronounced in the core data. Since the core samples were collected to examine the effects on young and newly recruiting clams, seeing more and stronger correlations at the Treated sites implies that the postulated effects were more intense on recruitment and the juveniles. Based on the general lack of differences in sediment properties measured between Reference and Treated sites, it does not appear that the standard sediment factors exert an important influence on the lagging recovery at the Treated sites. The multivariate results suggest that some process related to grain size affects species abundance at Treated sites but the correlating factor is not well expressed in the available environmental data.

Conditions observed in the sediments and bivalve assemblage in 2002 are consistent with the patterns observed during the NOAA study. The NOAA data provided a generally accurate representation of conditions on Treated or oiled-but-unwashed soft beaches in western PWS, although conditions at the three treated NOAA sites were more impoverished than were Treated sites overall. It appears that changes have occurred since 1996. Sediments at Treated sites appear to have gotten coarser (Table 19) and fines, TOC, and TKN at both Treated and Reference sites have declined with the organics approaching the level observed at the unoiled NOAA sites. Reductions in C/N ratios suggest that marine plants and terrestrial vegetation were now the predominant sources of organic matter and that EVOS hydrocarbons (high in carbon but low in nitrogen) were no longer elevating C/N ratios. While the bivalve assemblage at Treated sites showed signs of recovery, abundance of the most important bivalves, *Protothaca* and *Saxidomus*, remained significantly below that observed at Reference sites and at unoiled NOAA sites (Table 20). In contrast, abundance of the pioneer species *Hiatella*, considerably elevated above unoiled sites at both Reference and Treated sites, is declining to levels closer to that observed at unoiled NOAA sites.

Conclusions

Treated sites had not recovered from the effects of HP-HW or HP-WW beach washing by 2002. The bivalve assemblages continued to differ considerably in numerous respects between the Treated and Reference sites. The preponderance of evidence suggests that, on average, the bivalve assemblages at Treated sites differed substantially from those at Reference sites in 2002 and the types of differences are consistent with the hypothesis that the Treated sites had been subjected to considerable disturbance from which they had not yet recovered. Paramount among these differences is that, after 13 years, hard-shell clams (*Protothaca* and *Saxidomus*) in excavation and core samples were 66% and 44% less abundant, respectively, at Treated sites than at Reference sites. Other areas of difference included species richness and diversity, overall and species-specific abundance, size structure, and species and functional composition. Most evidence is consistent with a hypothesis that recovery has been prolonged because of effects resulting from disrupted organization of an armored layer at the surface of the mixed-soft sediments.

Unfortunately, we did not directly measure armoring. We instead have a pattern of evidence that supports, to various degrees, the disrupted-armor hypothesis. In view of the differences in exposure among the sites and the appreciable uncertainty associated with assigning treatment categories to sites, we would expect to see considerable variability among the sites within each treatment group and in the state of recovery among treated sites. We do see considerable variability but many differences are still significant or exhibit strong trends. Furthermore, in view of the generally shorter durations of recovery reported by other investigators examining disturbance effects in bivalve assemblages, we would not expect to see such large differences between treated and untreated areas after 13 years.

Comparison to densities observed during the NOAA study indicates that the trajectory of recovery is relatively flat. Given the apparent recovery since 1996, full functional recovery to the condition existing on 24 March 1989 will probably not be achieved for several more decades.

Another important conclusion is that the sediment type that characterizes the unconsolidated beaches in western PWS differs distinctively from traditionally described beaches in the manner in which inorganic and organic fractions and the biota interact. The models describing these armored mixed-soft sediments differ sharply from those describing homogeneous sediments on sand and mud beaches and shallow to mid-depths on the continental shelf. Relative to the findings of this study and lagging clam recovery, the most significant factor is likely the manner in which the coarse fraction comprising the armor layer that protects the underlying sediments, organics, and biota from physical disturbance becomes organized to provide a safer haven to the biota from disturbance by wave action and strong currents, and from predation. Although this coastal geomorphological process is apparently described for marine beaches only in Alaska, based on personal observations and reviewed literature, it probably is widespread globally in intertidal and subtidal habitats.

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