

FRI-UW-9205

June 1992

Fisheries Research Institute
School of Fisheries WH-10
University of Washington
Seattle, WA 98195

**MITIGATION OF DUNGENESS CRAB, *CANCER*
MAGISTER, LOSSES DUE TO DREDGING
IN GRAYS HARBOR BY DEVELOPMENT
OF INTERTIDAL SHELL HABITAT:
PILOT STUDIES DURING 1991**

David A. Armstrong, Oscar Iribarne, Paul A. Dinnel, Kay A. McGraw, J. Anne
Shaffer, Raul Palacios, Miriam Fernandez, Kristine Feldman, and
Greg Williams

FINAL REPORT

For

Seattle District
U. S. Army Corps of Engineers
Seattle, Washington 98124

Contract No. DACW67-85-C-0033

Approved

Submitted

6-15-92

R. P. Fromm

Director

TABLE OF CONTENTS

	Page
LIST OF FIGURES	iv
LIST OF TABLES	vi
EXECUTIVE SUMMARY	viii
INTRODUCTION	1
MATERIALS AND METHODS	2
Shell Placement and Evaluation.....	2
Shell Habitat Evaluation	6
Shell Elevation Survey	6
Crab Density Assessment	7
Sampling Procedure.....	7
Subtidal Crab Recruitment Experiment	7
Eelgrass	8
Sampling for Other Fauna.....	8
RESULTS.....	9
Shell Habitat Integrity.....	9
Percent Cover	9
Shell Sinkage and Sediment Accumulation.....	11
Burrowing Shrimp Density	11
Crab Density	13
Gear Efficiency	16
Subtidal Crab Recruitment Experiment	16
Eelgrass Densities.....	16
Other Infaunal and Epifaunal Invertebrates	19
DISCUSSION.....	24
Shell Habitat Integrity.....	28
Crab Density.....	29
Subtidal Crab Recruitment	29
Eelgrass Densities.....	29
Epibenthic Community.....	30
REFERENCES.....	34

LIST OF FIGURES

Figure	Page
1. Map of Grays Harbor, Washington showing the general locations of the shell mitigation test sites in 1990 and 1991.....	3
2. Locations of the shell mitigation experimental plots in North Bay during 1991.....	4
3. Locations of the shell mitigation experimental plots along South Channel during 1991	5
4. Estimates of average percent shell cover for all study sites in Grays Harbor.....	10
5. Top two graphs: Mean elevation of the top of the shell layer with respect to the surrounding undisturbed mudflat. “Surface” is the reference elevation of the surrounding mudflat. Bottom two graphs: Mean depth of accumulated sediment on top of the shell layers two and five months after shell placement.....	12
6. Comparison of mean shell surface elevation vs. time after placement for three sites constructed in June 1991.....	13
7. Contour maps of shell surface elevation above or below the original intertidal surface	14
8. Top: Mean shrimp burrow counts per square meter by species. Bottom: Relationship between burrow counts and percent shell cover estimated in September 1991.....	15
9. Juvenile Dungeness crab per square meter estimated by the “excavation” method	17
10. Results of two experiments to compare the efficiency between the “Quadrat-Rake-Count” and the “excavation” methods of sampling juvenile crab in shell with side-by-side samples	18
11. Size-frequency distribution of juvenile Dungeness crab captured by the QRC method compared with crab captured with the “excavation” method	19
12. Frequency distribution of eelgrass turion counts/0.25 m ² in a control plot next to Site 11 in March 1991.....	20
13. Eelgrass density estimated from control plots next to each of the shell sites	20

Figure	Page
14. Average densities and 95% confidence intervals for selected harpacticoid and non-harpacticoid taxa from pump samples collected over shell and mud.....	31
15. Average densities and 95% confidence intervals for selected harpacticoid and non-harpacticoid taxa from “excavation” samples collected from shell and mud.....	32

LIST OF TABLES

Table	Page
1. Mean number and standard deviations of epibenthic organisms/m ² estimated from pump and excavation samples collected in 1991 from two areas of Grays Harbor, Washington.....	21
2. Diversity indices and taxa richness for excavation and pump samples taken from shell and mud habitats at Campbell Slough and South Channel, Grays Harbor, Washington.....	21
3. Average density, standard deviation, and % numerical occurrence of epibenthic organisms collected by pump sampling at South Channel, Grays Harbor, during 1991.....	22
4. Average density, standard deviation and % numerical occurrence of epibenthic organisms collected by pump sampling at Campbell Slough, Grays Harbor during 1991.....	23
5. Average density, standard deviation and % numerical occurrence of epibenthic organisms collected by excavation sampling at South Channel, Grays Harbor during 1991.....	25
6. Average density, standard deviation and % numerical occurrence of epibenthic organisms collected by excavation sampling at Campbell Slough, Grays Harbor during 1991.....	26
7. Summary of two-way ANOVA analysis for eight selected epibenthic species.....	28

ACKNOWLEDGEMENTS

Funding for this study was provided by a contract (DACW67-85-C-0033) from the Seattle District, U.S. Army Corps of Engineers. The authors thank B. Brun, L. Scudder, J. Waller, and K. Northup, Seattle District Corps of Engineers for their support and coordination efforts. Field and laboratory assistance was provided by J. Cordell, T. Wainwright, H. Andersen, G. Jensen, J. Armstrong, T. McDonald, P. Wardrup, C. Adkins, V. Souze, J. Larsson, J. Fuerstenberg, R. McConnaughey, D. Herren, and Y. Shi. Research vessel support was provided by R. Lusk. Helicopter support and dock facilities were provided by the U. S. Coast Guard, Westport. Assistance and dedication of numerous state and federal agency representatives is appreciated; these especially included: G. Ging, C. Iten, P. LaRievère, R. McMillan, and D. Guy, who persisted through wind, rain, fog, and numerous meetings.

KEY WORDS

Dungeness crab, dredging, mitigation, recruitment, shell habitat, mortality, eelgrass, burrowing shrimp, Grays Harbor

EXECUTIVE SUMMARY

In 1990, the Port of Grays Harbor and the U.S. Army Corps of Engineers dredged the main navigation channel in Grays Harbor to widen and deepen the channel to accommodate increased shipping efficiency of timber products. During removal of approximately 8.5 million cubic yards of sediment, an estimated 161,561 Dungeness crab (*Cancer magister*), normalized to age 2+, were entrained and killed by the dredges even though attempts were made to minimize crab loss. Previous pilot studies in Grays Harbor had shown the feasibility of replacing lost crab by constructing intertidal oyster shell beds on essentially barren sand flats. Larval crab settle in the new shell, which provides refuge habitat for several hundred crab/m² for the youngest juveniles, and in excess of 20 crab/m² 3-4 months after settlement, and at a size that can survive most predation pressures.

Although original plans called for full-scale mitigation shell plots (approximately 14 ha) to be deployed concurrent with dredging, uncertainties regarding shell retention, eelgrass (*Zostera marina*) impacts, pollution and possible introduction of exotic species (e.g., cordgrass, *Spartina*) seeds required additional shell plot pilot studies in 1991. Those studies, reported herein, involved the placement of 11 new shell plots (of varying sizes, some triplicate, stratified by tide height) throughout intertidal areas of Grays Harbor and the monitoring of shell retention, crab densities, impacts to eelgrass, and the habitat value of shell plots for other invertebrate fauna.

Results of the 1991 studies showed that shell retention at all but two areas in Grays Harbor was very poor, but where shell was successfully retained, densities of late stage juvenile crab were as high as 50+ crab/m². Concurrent monitoring of burrowing ghost and mud shrimp (*Callinassa californiensis* and *Upogebia pugettensis*) around the shell plots showed a high inverse correlation between shrimp densities and degree of shell sinkage, burial, or both. Brief investigation of subtidal recruitment of crab into shell showed that crab would settle into subtidal experimental shell trays, but that the trays rapidly accumulated silt. Generally, eelgrass densities were positively correlated with shell retention, both apparently requiring firm ground and low burrowing shrimp densities. However, eelgrass was judged sparse enough at the two favored sites (15-20 turions/m² at one site and <5/m² at the other) to allow for full mitigation shell deployment in 1992. Review of eelgrass plots transplanted into shell beds the previous year showed good growth and survival and strongly suggests that mitigation shell beds and eelgrass might co-exist successfully.

Pump and excavation sampling for infaunal and epifaunal invertebrates showed that excavation was superior to pump sampling and that samples from shell plots had higher diversity and taxa richness as compared with open sand/mud flats. Significant increases in densities of harpacticoid copepods, amphipods, and cumaceans were observed in the shell plots. We hypothesize that higher productivity of infauna and epifauna observed in the shell plots may provide better foraging territory for juvenile salmonids and marine fish. During full mitigation shell placement, the chance to monitor basic ecological changes in relation to eelgrass, burrowing shrimp, and the relative habitat values of both eelgrass and shell (and combinations thereof) should not be lost.

INTRODUCTION

Since the late 1800s, Grays Harbor has been a major West Coast port for exporting wood products to foreign nations. An integral part of that trade has been the maintenance dredging and occasional improvement of the navigation channel by the U.S. Army Corps of Engineers (COE). The most recent construction project began in April 1990 and involved widening and deepening (W&D) the channel from the Grays Harbor Bar up to Aberdeen by removing ~8.5 million cubic yards (cy) of sediment to accommodate the passage of large, fully loaded log ships, thereby increasing shipping efficiency and reducing costs.

Planning and coordination for the present W&D project began about 20 years ago. From the beginning of the planning process, one species of concern to agencies and fishermen has been the Dungeness crab (*Cancer magister*), which is entrained during dredging operations. The COE funded several studies in response to questions raised about potential adverse impacts on crab; among those were entrainment studies (Tegelberg and Arthur 1977; Stevens 1981; Armstrong et al. 1982; Dinnel et al. 1986a, 1986b; Dumbauld et al. 1988; McGraw et al. 1988; and Wainwright et al. 1990); population and ecological studies (Armstrong et al. 1989; Armstrong et al. 1985; Armstrong et al. 1986; and Dumbauld et al. 1987); an impact model (Armstrong et al. 1987, Wainwright et al. 1992); pilot shell mitigation study (Dumbauld and Armstrong 1987); and contaminant and sediment disposal studies (Pearson 1987; Pearson and Woodruff 1987; Pearson et al. 1987).

The approach to crab mitigation was developed over several years through coordination with resource agencies, biologists, and crab fishermen, and is also based on the results of the field studies listed above, conducted by the University of Washington, COE, and Battelle Northwest Marine Laboratory. Mitigation proposed in the 1982 Environmental Impact Statement (EIS) (U.S. Army Corps of Engineers 1982) for loss of Dungeness crab caused by the present project focused on avoiding entrainment by modifying of dredging equipment. Because this method was unsuccessful in field tests, a combination of other approaches was considered based on a Dredge Impact Model (DIM; Armstrong et al. 1987) used to calculate theoretical crab loss under different scenarios of seasonal and spatial abundance and COE dredging programs. Those estimates were used to adjust project plans to minimize adverse impacts to crab by: (1) scheduling dredging, to the extent practicable, to avoid times and areas of high crab densities; (2) locating offshore disposal sites to avoid high concentrations of crab and interference with the crab fishery; and (3) using clamshell dredges instead of hopper dredges to reduce crab entrainment wherever it was cost effective.

Although these actions were implemented in the project schedule, some unavoidable crab losses occurred during construction dredging, and will continue to occur during maintenance dredging after widening and deepening of the channel is completed. In order to assess real-time impacts from construction dredging, Dinnel et al. (1991) monitored actual crab densities in the navigation channel during the period of construction dredging—from April through December 1990. Estimated crab losses (by size, sex, month, and location) due to construction dredging, together with dredging data (amounts dredged, gear type, location, and time) were integrated into the existing DIM to calculate total project crab losses, which were 161,561 crab, normalized to age 2+.

Because the creation of intertidal oyster shell habitat for 0+ crab has been shown to be effective and feasible for increasing the abundance of this age group (Dumbauld and Armstrong 1987, Armstrong et al. 1991), it was chosen as the primary method to mitigate for loss of crab in the dredged channels. A mitigation plan was devised based on estimated crab losses and data from the pilot shell habitat study (U.S. Army Corps of Engineers 1989) to be implemented with the initiation of construction dredging in 1990. A total of 14 ha (35 acres) of shell habitat was to be constructed during the first year after construction dredging. However, because of time constraints, uncertainty about shell retention and deployment techniques, and some controversy regarding site selection, shell placement for 1990 was reduced to only four experimental sites of 0.4 ha each. Results of the 1990 shell plot studies (Armstrong et al. 1991) emphasized the need to find intertidal locations in Grays Harbor with substrate qualities that promoted shell retention, since shell at three of the four experimental sites essentially disappeared because of sinkage, burial by sediments, or both. Additionally, placement of mitigation plots has been severely constrained by private ownership of tide lands, alleged pollution of the inner harbor by pulp mill effluents, agency concerns about impacts to eelgrass (*Zostera marina*), and the possibility that imported oyster shell may contain seeds of cord grass (*Spartina* spp.). As a consequence, instead of full mitigation shell placement in 1991, additional small-scale test plots were constructed in 1991 in areas generally removed from pulp mill pollution sources and with little or no eelgrass.

This report details the study plan, methods, results and conclusions of monitoring 11 new test plots deployed throughout intertidal areas of Grays Harbor in 1991. Additional work included surveys of eelgrass densities at selected sites and the deployment of experimental subtidal shell trays to explore the possibility of using some of the mitigation shell in subtidal channels. The results of the 1991 studies should lead to the successful placement of full mitigation amounts of shell in spring 1992 to replace the estimated 161,561 (2+) crab lost to construction dredging.

MATERIALS AND METHODS

SHELL PLACEMENT AND EVALUATION

Early in spring 1991, new oyster shell mitigation test plots were constructed at eight new sites (Fig. 1) in North Bay of Grays Harbor. All plots were 30 m x 30 m in size. Oyster shell was deployed at low tide from a barge by a crane and scoop bucket. This method of placement provided for uniform shell coverage of the plots to a depth of about 15 cm and eliminated disruption of the site (ridges and gullies from prop wash) as had happened the previous year when shell was deployed at high tide from moving barges. Single, 30-m x 30-m plots were established in North Bay at Sites 2, 3, 6, 7 and 11, and triple plots (varying by tide height, Low, Medium & High = ~0.5, 1.0 & 1.5 m above MLLW, respectively) were constructed at Sites 1, 5, and 8 (Fig. 2).

Because shell at many of these new plots disappeared rapidly (due to sinkage, burial by sediment, or both), three additional smaller plots (15 m x 15 m; Sites 13, 14 and 15; Figs. 2 and 3) were constructed during mid-Summer. In addition, we continued to monitor one large plot (0.4 ha) of shell that was constructed during test studies in 1990 and which still had shell coverage of about 60% during spring of 1991 (Fig. 2).

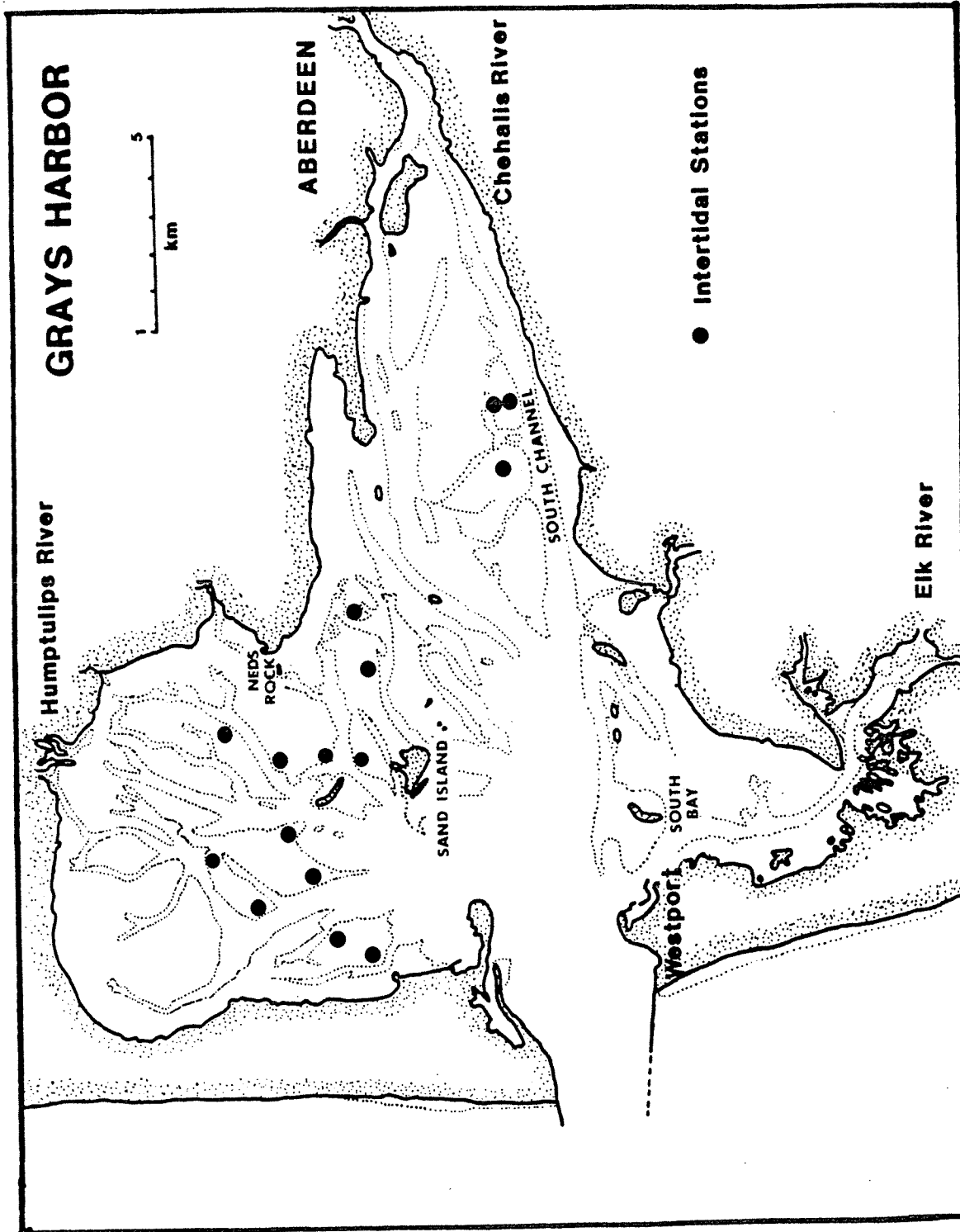


Figure 1. Map of Grays Harbor, Washington showing the general locations of the shell mitigation test sites in 1990 and 1991.

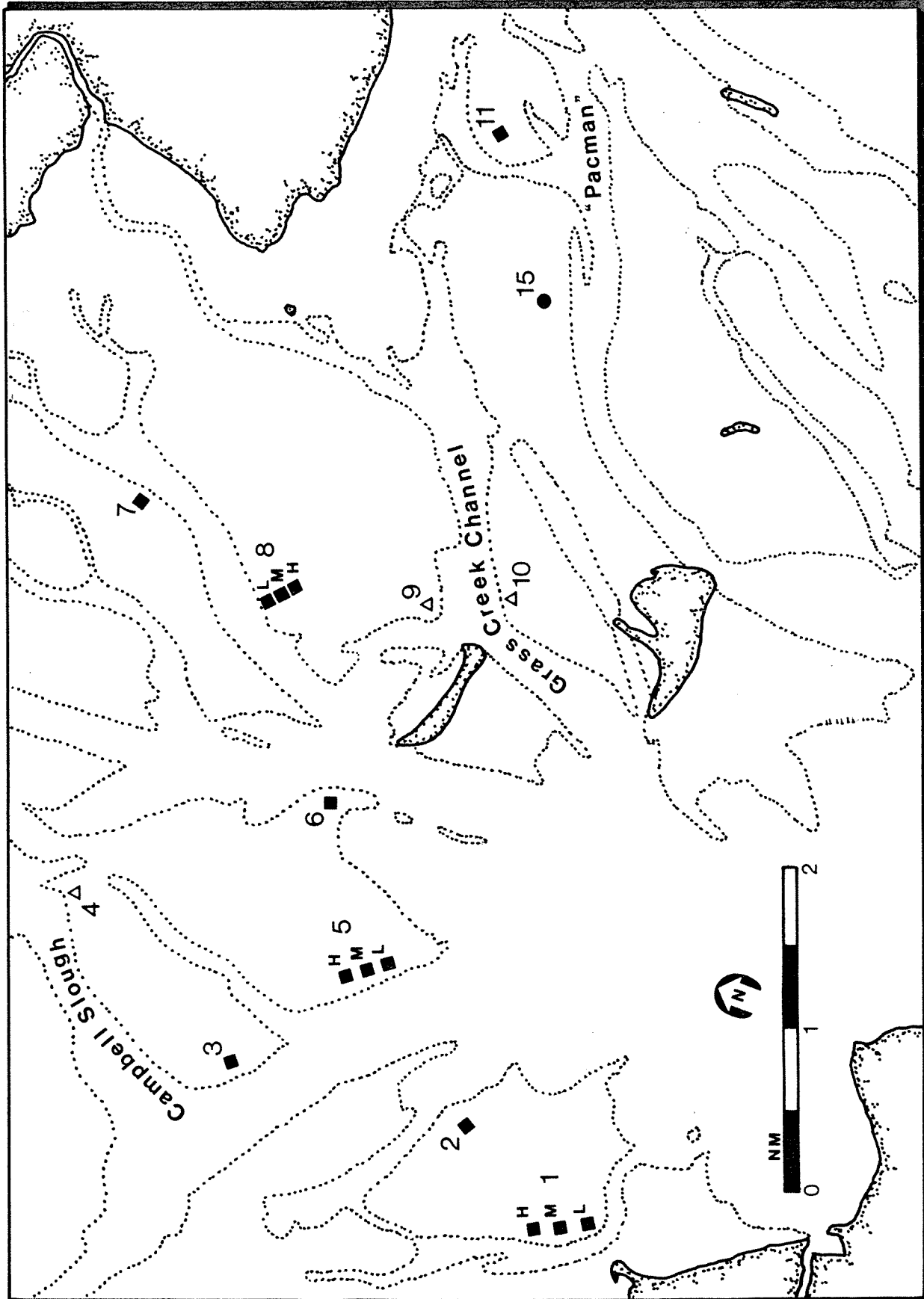


Figure 2. Locations of the shell mitigation experimental plots in North Bay during 1991. ■ = 30 x 30 m plots; ● = 10 x 10 m plots deployed mid-summer; Δ = 0.4 ha plots established and monitored in 1990 (not monitored in 1991). For the triplicate sites (1, 5, 8), L = low elevation (~+0.5 m), M = mid elevation (~+1 m), and H = high elevation (~+1.5 m). The shell plot sizes are not drawn to scale. See Figure 3 for the South Channel sites.

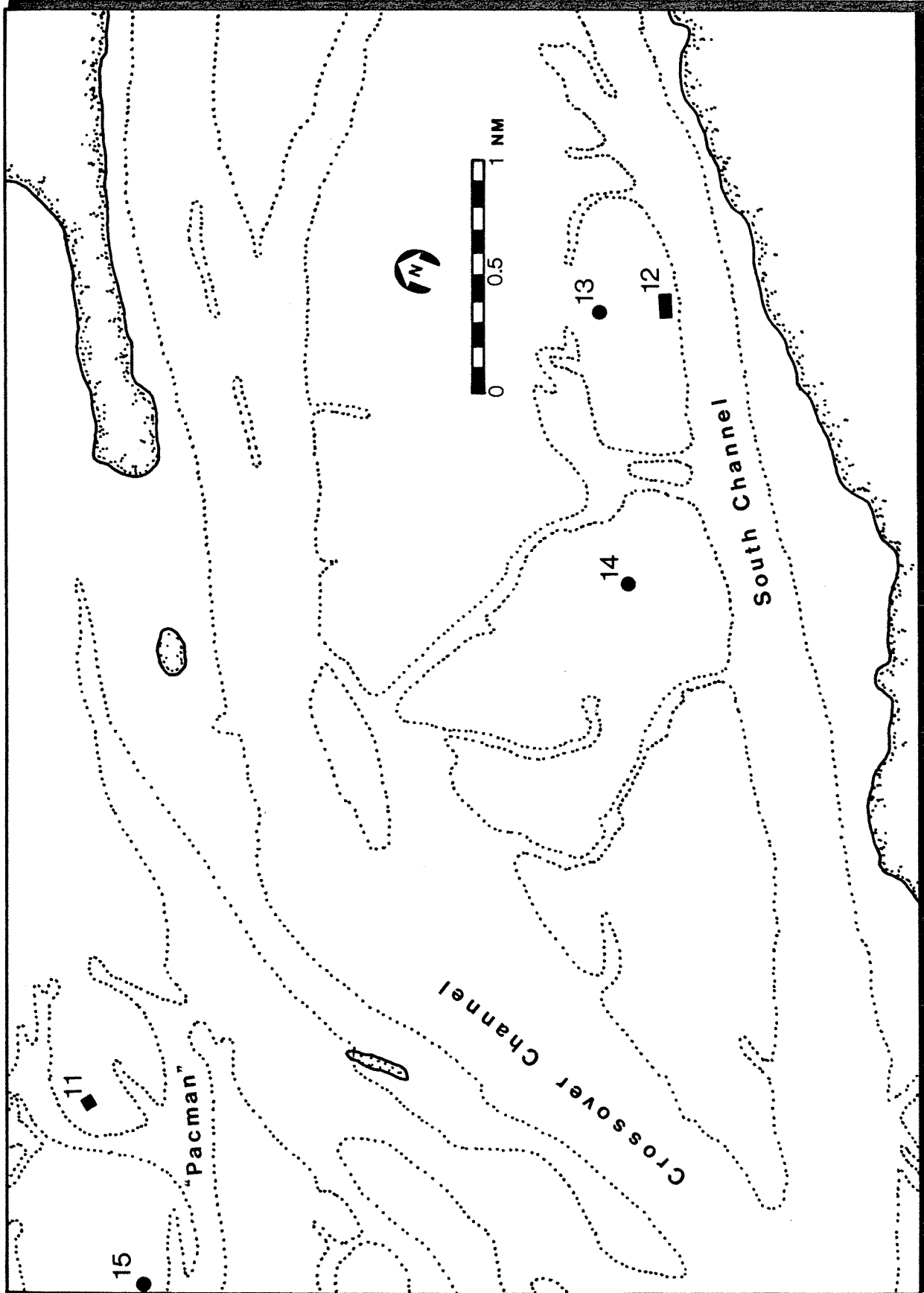


Figure 3. Locations of the shell mitigation experimental plots along South Channel during 1991. ■ = 30 x 30 m plots; ● = 10 x 10 m plots deployed mid-summer; ■ = 0.4 ha plot established in 1990 and also monitored in 1991. The shell plot sizes are not drawn to scale. See Figure 2 for the North Bay sites.

SHELL HABITAT EVALUATION

Soon after construction in March 1991, most of the shell test plots in North Bay began to disappear because of a combination of sedimentation and apparent sinkage (subsidence) into the substrate. Accordingly, two sets of measurements were taken to describe and follow this pattern.

Shell Elevation Survey

As soon as possible after initial construction of the shell test plots, the relative height of the top of the shell layer was measured at each site with a Ni2 Zeiss autolevel. As noted previously, plots 30 m on a side were divided into 5-m x 5-m squares, and elevation measurements were taken at the center of each square. The first shell elevation survey was done in June 1991, two months after shell habitat construction. Smaller plots constructed in June of that year were subdivided into 2.5 m x 2.5 m grids, and measurements were taken at the intersection of the corners of each square. Essentially, change in elevation within the shell plots was based on comparison to the ambient grade of the extensive surrounding mudflat. When sediment covered the shell layer, the total height of shell plus sediment was first measured, and then sediment was excavated by hand until the top of the shell layer was reached, whereupon a second measurement was taken of the shell elevation alone. Additional elevation measurements were taken outside the plots along the axis of the squares. To account for possibility of any slight slope from one end to the other of the 30-m plot axes, we used the height of the undisturbed intertidal flat as an elevation benchmark and estimated it as the mean of two sets of values from linear regression of tideflat heights at the ends of the experimental plots. Shell height contour curves were calculated with SYSTAT programs (Wilkinson 1988), using negative exponentially weighted smoothing (McClain 1974).

Burrowing Shrimp Density

We hypothesized that subsidence of shell was probably associated with presence of ghost and mud shrimp (*Callinassa californiensis*, and *Upogebia pugettensis*). Burrow density, as a relative measure of shrimp density, was estimated in May and June 1991. Ten systematic sample units of 0.25 m² were counted for burrows in a control area around the perimeter of each shell plot.

Shell Evaluation

Successful use of oyster shell reefs for crab mitigation is dependent on long-term integrity of the shell, which must remain in place and not be covered with sediment or sink into the substrate. During 1991, we periodically measured shell coverage at each site via multiple visual estimates of subdivisions within each plot. Each 30-m x 30-m plot was subdivided into thirty-six 5-m x 5-m sections and numbered. Ten of these sections for each plot were then selected via random numbers; shell coverage on each of these sections was visually estimated by three or four different people, and the 10 sections estimated were averaged for percent cover over the entire plot. A similar approach was used for the large plot at Site 12 and for the three smaller plots (Sites 13, 14 and 15; Figs. 2 and 3). In the case of the small plots, these were each subdivided into nine 5-m x 5-m sections, and estimates of shell coverage made in all nine sections (e.g., estimates were made for 100% of the area of small plots).

When it became evident that shell was being lost from sinkage or burial at many of the North Bay sites, two additional measurements were made in an attempt to define the mechanics and cause(s) for the shell disappearances. First, we determined whether shell was sinking or being buried by sedimentation by measuring shell height (relative to the surrounding intertidal flat) at all plots using a surveyor's level and transit. Second, we hypothesized that shell burial was associated with the presence of ghost and mud shrimp. Accordingly, burrow counts were made around the periphery of each plot using a 0.25 m² grid at randomly selected points or along transects in a side-by-side control plot equal in size to the shell plots.

CRAB DENSITY ASSESSMENT

Sampling Procedure

Two different sampling methods were used during 1991: one was based on a Quadrat-Rake-Count (QRC) procedure designed to provide many samples in a short period of time; the second was an "excavation" method based on careful removal of shell down to the sediment layer (see Armstrong et al. 1991). The QRC method had been used routinely in past years (e.g., Dumbauld and Armstrong 1987) but was considered less efficient than the excavation method. Our intention was to obtain paired samples of crab density determined by each method, then derive an efficiency conversion factor to go from past data based on QRC to comparable data obtained by the excavation method. At a given test site, 10 randomly selected plots were used to obtain paired samples of crab density by both the QRC (0.25 m²) and Excavation (0.1 m²) method. Gear efficiency was then expressed as (QRC/Excavation) x 100. All crab and megalopae in samples were measured to 0.1 mm forward of the tenth anteriolateral spine and sexed if the carapace width (CW) was larger than 20 mm. Although data for megalopae were recorded, they were not used to estimate density (CPUE); only older stage young-of-the-year crab were used from August data to estimate densities.

SUBTIDAL CRAB RECRUITMENT EXPERIMENT

In 1991, we briefly explored the plan to construct subtidal shell habitat as a portion of the required mitigation. In a limited study, we deployed trays of shell in subtidal channels to learn if crab would recruit to this type of habitat. The primary objectives of this work were twofold: (1) determine the durability and integrity of subtidal shell (i.e., would it remain unburied?), and (2) assess the density of 0+ crab in subtidal shell as compared to intertidal shell.

For the subtidal shell recruitment experiment, we used 20 molded plastic oyster grow-out trays (55 cm², 8.5 cm deep, with side and bottom perforations of 0.8 cm in diameter). The trays were lined with 1- to 2-mm mesh window screen and filled to the top with oyster shell. Buoys were attached to the trays with 5 m lengths of line for relocating and retrieving the trays.

Test trials with a few trays in Campbell's Slough and Grass Creek Slough (Figs. 2 and 3) showed that trays filled with sediment within 1 week in these locations. Trays in the small channel west of Site 1 fared better, and we chose this channel for the experimental location since it was also sheltered from most ocean swells and storm influences. A total of 20 trays were deployed on 12

June 1991 in the channel at intervals of about 50 m and at a depth of about 3.5 m. One month later, we retrieved the trays, counted and measured 0+ crab, and noted other organisms in the trays.

EELGRASS

Because Washington and federal resource agencies were concerned about possible impact of shell habitat on eelgrass (*Zostera marina*) beds, most test plot sites (and, potentially, full mitigation sites) chosen in 1991 were specifically selected to avoid dense eelgrass beds. However, Sites 11, 12, 13 and 14 (Figs. 2 and 3) contained noticeable amounts of eelgrass, and particular attention was given to these sites because of their good potential (based on early shell-retention data) for full-scale mitigation.

Shell for the test plots was deployed by an independent contractor in late March 1991, except at Sites 13, 14, and 15, which received shell in late May. Surveys of eelgrass density were conducted at Site 11 in March 1991 prior to shell deployment (pre-shell assessment was required by the resource agencies to facilitate a decision to approve/disapprove the site), and in April in a control plot (no shell) adjacent to the shell plot. Pre-shell eelgrass density estimates were also made at Sites 13, 14 and 15 in April. Eelgrass was assessed next to the shell plots at all remaining 1991 sites (Sites 1, 2, 3, 5, 6, 7, and 8; Fig. 2) in April following shell deployment in March. One additional 1990 shell site (Site 4, Campbell's Slough) was assessed for survival of eelgrass transplanted into pools in 1990. Eelgrass was not surveyed at 1990 Sites 9, 10 or 12.

Surveys of eelgrass density were generally conducted by counting the number of turions (shoots) inside a 0.25 m² quadrat frame placed at designated distances along transects either within a plot or across an entire area. At many of the sites in North Bay, eelgrass densities were essentially zero and judged as such visually without quadrat counts. For assessing transplanted eelgrass survival at Campbell's Slough (Site 4), all eelgrass turions within the small transplant ponds were counted.

SAMPLING FOR OTHER FAUNA

The estuarine epibenthic community, which consists of organisms living in and above the top 0.5 cm of substrate, is home to critical prey species for juvenile salmonids and English sole (*Parophrys vetulus*), as well as other marine fish (Simenstad et al. 1991). The epibenthic community of southern Grays Harbor mudflats has been documented in past COE studies (Simenstad and Eggers 1981; Cordell and Simenstad 1981), but no information is currently available on the epibenthic community of North Bay or on the shellhash placed on north and south Grays Harbor mudflats in spring 1990. In April 1991, shell and adjacent control mudflat epibenthos from one test plot each in North Bay and South Bay were sampled to define the epibenthic community on the two substrate types at each location.

Two COE mitigation test sites, Campbell Slough (Site 4) and South Channel (Site 12), were sampled for epibenthic organisms on 15 April 1991 (Figs. 2 and 3). Both sites had (1) 30-m x 30-m test areas where Pacific oyster, *Crassostrea gigas*, shell had been placed in spring of 1990, and (2) adjacent untreated control plots of equal size. Test plots were adjacent to main water channels

and were 0.6-0.9 m and 0.4-0.6 m above MLLW for South Channel and Campbell Slough, respectively. Average cover of shell in April 1991 was 10% and 40% for Campbell Slough and South Channel (1 year after construction). The shell habitat consisted of a 0-0.5 m deep layer of shell, often with a surface layer of fine sediment, diatoms, and macroalgae. Control plots consisted of bare mudflat with medium-fine mud. The x and y axes of all plots were staked at 5-m intervals, which served as coordinates for random sampling.

Two methods, epibenthic pumping and excavation of the substrate, were used to sample the epibenthos. To sample the epibenthic zooplankton over shell and bare mudflat during the flood tide, we used a battery-powered epibenthic pump with an 18-cm diameter opening and an 8 cm high neoprene collar around the mouth. Samples were taken during flood tide when the site was covered with approximately 0.5 m of water. Sampling consisted of locating a pre-marked sample location, placing the pump firmly over the substrate, and pumping for 30 sec through a 130- μ m mesh screen. Excavation sampling was used to document the benthic infauna and epifauna of the shell habitat during aerial exposure. Shell habitat was excavated by placing a 0.10-m² quadrat on the shell habitat and removing 5 oyster shells within the quadrat. Shell dimensions were recorded, and each rinsed thoroughly over a 130- μ m mesh sieve. Excavation control samples were taken from adjacent bare mudflat by coring to 5 cm with a 2.2 cm diameter corer. Ten samples each were randomly collected by both pump and excavation from each of the shell and control plots. All samples were fixed in 10% buffered formalin and stained with rose bengal. In the lab, samples were sorted and fauna identified and counted. Large samples were subsampled by splitting. In these cases, the sample was transferred into a petri dish that was partitioned into quarters and swirled until evenly distributed between the four sections. One quarter of the dish was then randomly selected and sorted.

Data were analyzed for total taxa, numerical dominance, diversity, and richness using SUPERPLANKTON for DOS computers (Simenstad and Swanson, unpublished). The numerically dominant harpacticoid species and a few other selected crustacean species that have been documented as important juvenile salmonid prey taxa (as defined by Simenstad et al. 1991) were compared by two-way analysis of variance (ANOVA) to identify differences in densities between the two habitat types (shell vs. mud) and sampling sites.

RESULTS

SHELL HABITAT INTEGRITY

Percent Cover

Shell habitat was constructed in April 1991 at Sites 1 through 8 and 11, and in early June at Sites 13, 14, and 15 (Figs. 2 and 3). By late April (about 9-10 days after construction), large portions of shell test plots at most sites in North Bay had been lost as visible (and viable) habitat for juvenile crab (Fig. 4). Assuming 100% coverage at the time of construction, most of the shell plots from Sites 1 through 6 (including those done as triplicates to test effects of tidal elevation on crab density) had less than 30% shell cover remaining (see upper panel, Fig. 4). In contrast, Sites

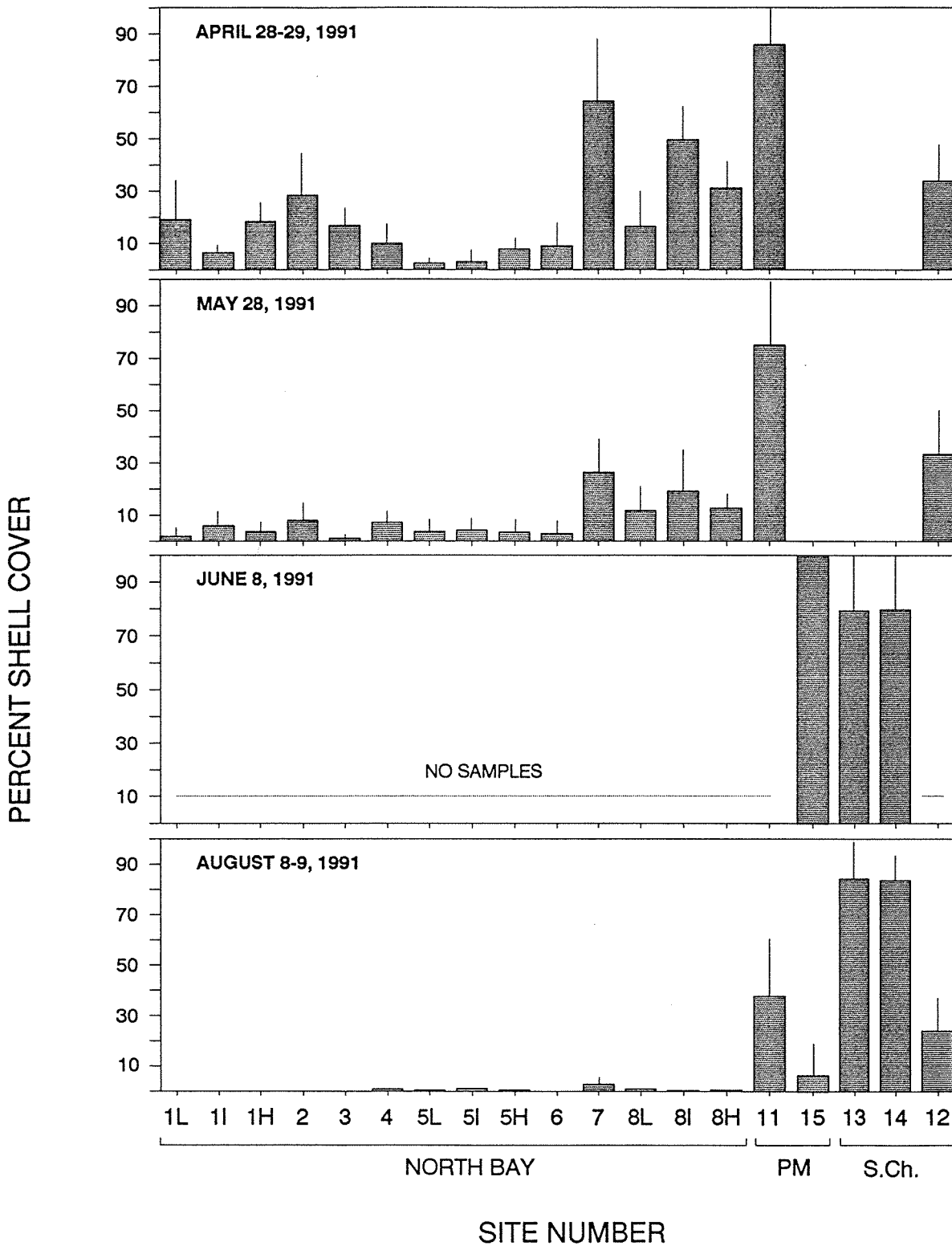


Figure 4. Estimates of average percent shell cover (± 1 standard deviation) for all study sites in Grays Harbor. Columns represent the average percent shell cover and lines are $+1$ standard deviation. PM = Pacman (Site 11), S. Ch. = South Channel; tidal elevation: L = low, I = intermediate, H = high; see Figures 2 and 3.

7, 8 and 11 were in reasonably good condition, with exposed shell exceeding 50% of original construction. By early August virtually all shell had disappeared at most of the test sites of North Bay, and the only viable habitat remaining was at Site 11 (“Pacman,” about 40%) and Sites 13 and 14 at South Channel (Fig. 4). The only test area still in existence from 1990 experiments was Site 12, also at South Channel, which had an average percent cover of about 30% during the summer of 1991.

Shell Sinkage and Sediment Accumulation

Shortly after the shell habitat was constructed at many test sites, two processes occurred that reduced its utility as crab habitat. The most pronounced process was sinkage of the shell into the substrate, which seemed to be correlated with burrowing shrimp density (see next section). Shell habitat was also lost because of heavy sedimentation on-site, again somewhat correlated with relative shrimp density and their burrowing activity. At the time of construction, shell habitat was about 10-20 cm thick on top of the surrounding tideflat at each site. By June, at most sites the top of the shell layer was about 5 cm above the surrounding grade of tideflats and in many instances the shell was actually below ambient grade (Fig. 5, top panel). In addition to sinkage, there were areas of shell still above grade but nonetheless covered by sediment that had accumulated on top. For instance, at Site 7 the top of the shell layer in June was still approximately 5 cm above surrounding grade, but there was also approximately 5 cm of sediment overlying much of that particular site (Fig. 5). Five months after construction in April 1991, all but one of the initial 11 experimental sites had sunk below or level with the top of the surrounding tideflats in each location (Fig. 5). Only at Site 11 (Pacman) was a substantial proportion of shell still above grade. The three smaller plots (Sites 13, 14, 15) constructed in June had also subsided by August. The worst was Site 15, to the west of “Pacman,” which had sunk below grade in the two month interval (Fig. 6). Exemplary contour maps of shell elevation (or subsidence) are shown in Figure 7. A good contrast is Site 6 in North Bay, where most of the shell was 10-20 cm below grade by early September 1991 compared to Site 11 (Pacman), where shell over much of the area was still above the surrounding tideflats grade (note that the values shown in these contours are the elevation of the top of the shell layer relative to the surrounding tideflat elevation, without reference to presence or absence of overlying sediment; i.e., the depth to which the shell had sunk).

Burrowing Shrimp Density

High densities of ghost shrimp burrows (primarily *Callinassa*) were measured at Sites 1 through 10 (Fig. 8). Burrow counts in excess of 200/m² were common, and at several sites density exceeded 500/m². Lowest densities (<50/m²) were recorded at “Pacman” (Site 11) and South Channel (Sites 12-14). There seems to be a relationship between the amount of shell cover still visible (and functional as crab habitat) over time after construction and relative density of infaunal shrimp (Fig. 8). Only 1-2 months after construction, percent shell cover ranged from 0% to 10% on test sites where burrow counts exceeded approximately 150/m², but percent cover was relatively high (>50%) where burrow counts were low (Fig. 8; significant negative correlation, $r = -0.68$, $p < 0.05$). Sediment accumulation did not seem related to burrow density ($r = -0.17$, $p > 0.05$) but seemed to be higher at experimental sites in North Bay compared to South Channel.

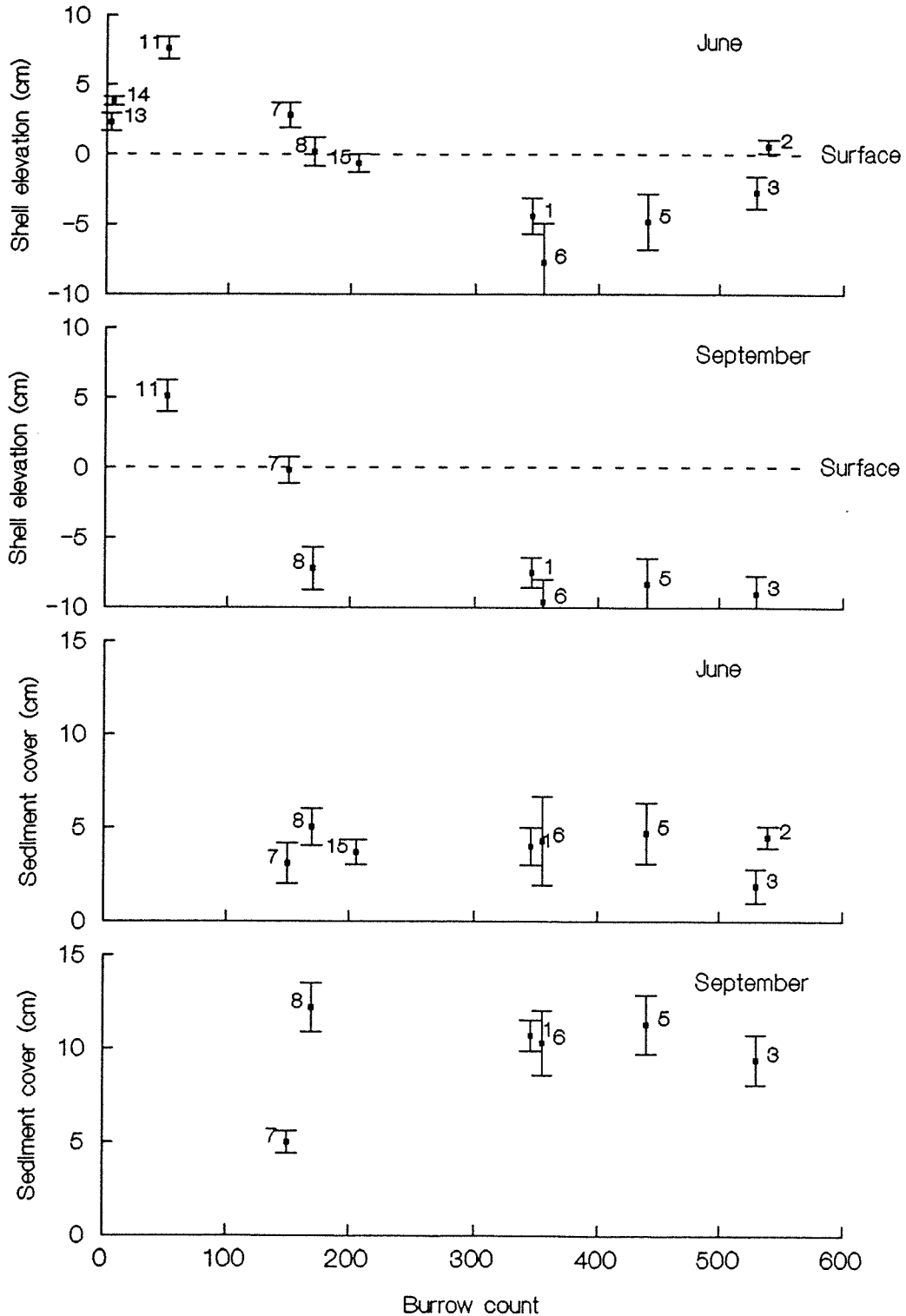


Figure 5. Top two graphs: Mean elevation of the top of the shell layer with respect to the surrounding undisturbed mudflat. "Surface" is the reference elevation of the surrounding mudflat. Bottom two graphs: Mean depth of accumulated sediment on top of the shell layers two (June) and five (September) months after shell placement. Numbers indicate the sites and vertical lines are ± 1 standard deviation of the means.

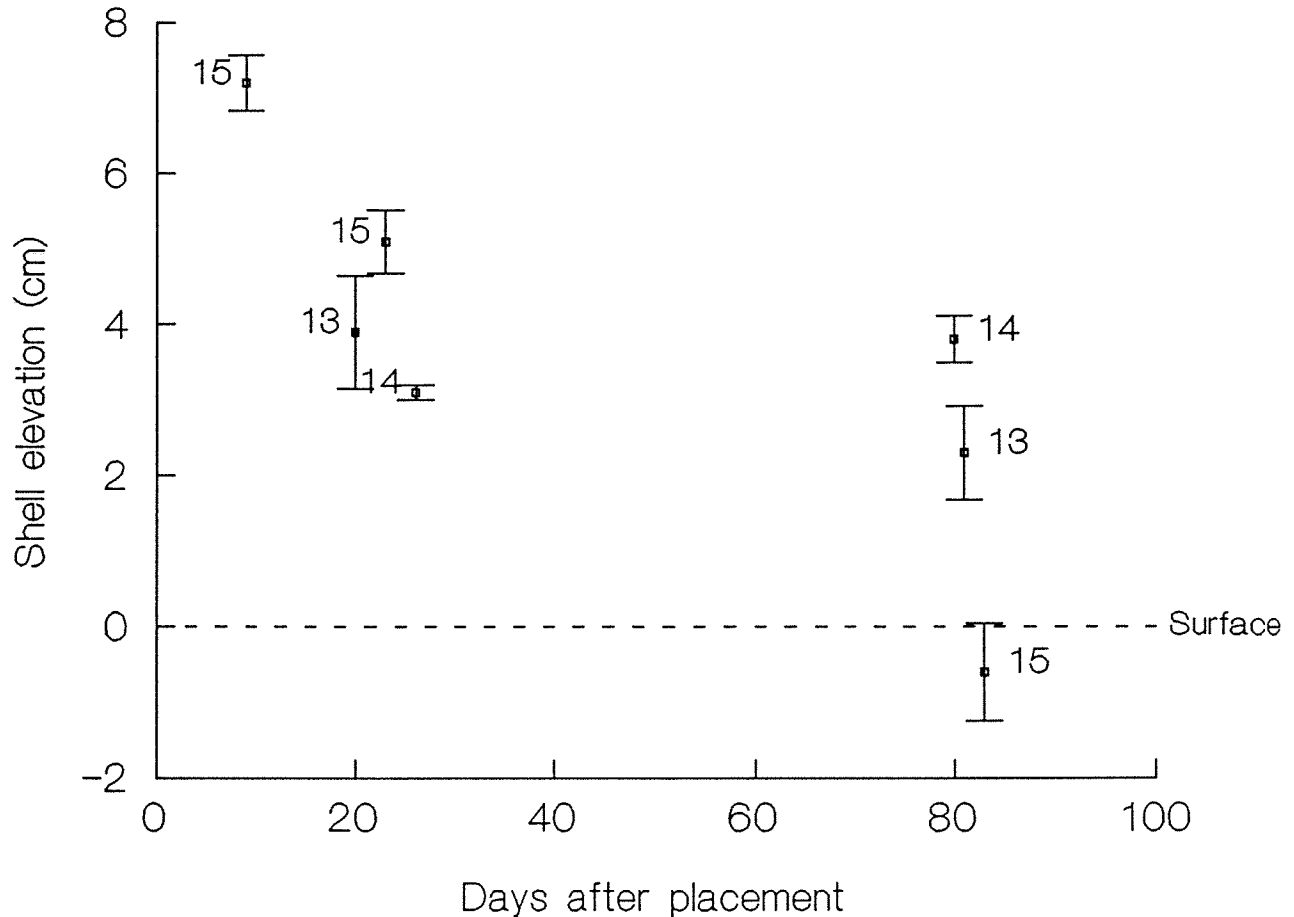


Figure 6. Comparison of mean shell surface elevation (± 1 standard deviation) vs. time after placement for three sites constructed in June 1991. Note that the shell surface at Site 15 eventually sank below the ambient surface elevation (and was covered by sand).

CRAB DENSITY

During 1991, two cohorts of megalopae entered the Grays Harbor estuary, the first between May 15 to May 25 and the second a month later in mid-June. There is evidence that the first cohort may have cannibalized and reduced density of the second cohort as the latter arrived and settled from the plankton. A fortuitous test of this possibility was contained in the second set of smaller test plots constructed at both "Pacman" and South Channel (Sites 13, 14, 15), which were devoid of the larger, earlier crab of the first cohort as the second settled. For instance, the mean densities of first instar juvenile crab (J1) in June were 298 and 168/m² at Sites 13 and 15, respectively (see Fig. 1 for locations), which were areas constructed after settlement of the first cohort in May. However, J1 densities at Sites 11 and 12 were only 9 and 37/m², respectively, indicating cannibalistic predation by the earlier, larger 0+ crab on the incoming second cohort.

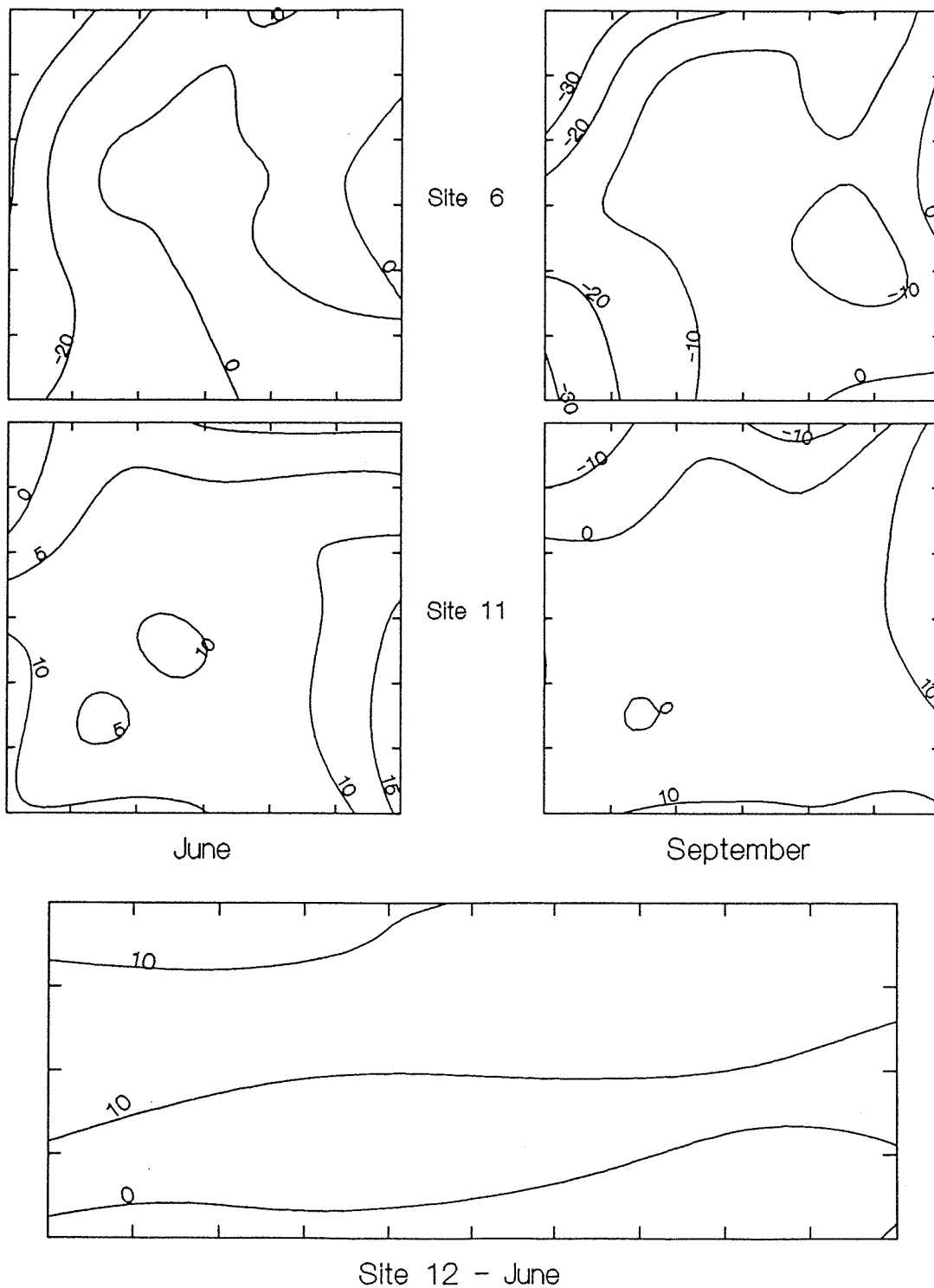


Figure 7. Contour maps (isopleths) of shell surface elevation (in cm) above or below the original intertidal surface. Sites 6 and 11 are two (June) and five (September) months after shell placement. Example: “-10” means that the surface of the shell sunk 10 cm *below* the original substrate surface. Site 12 was constructed in March 1990.

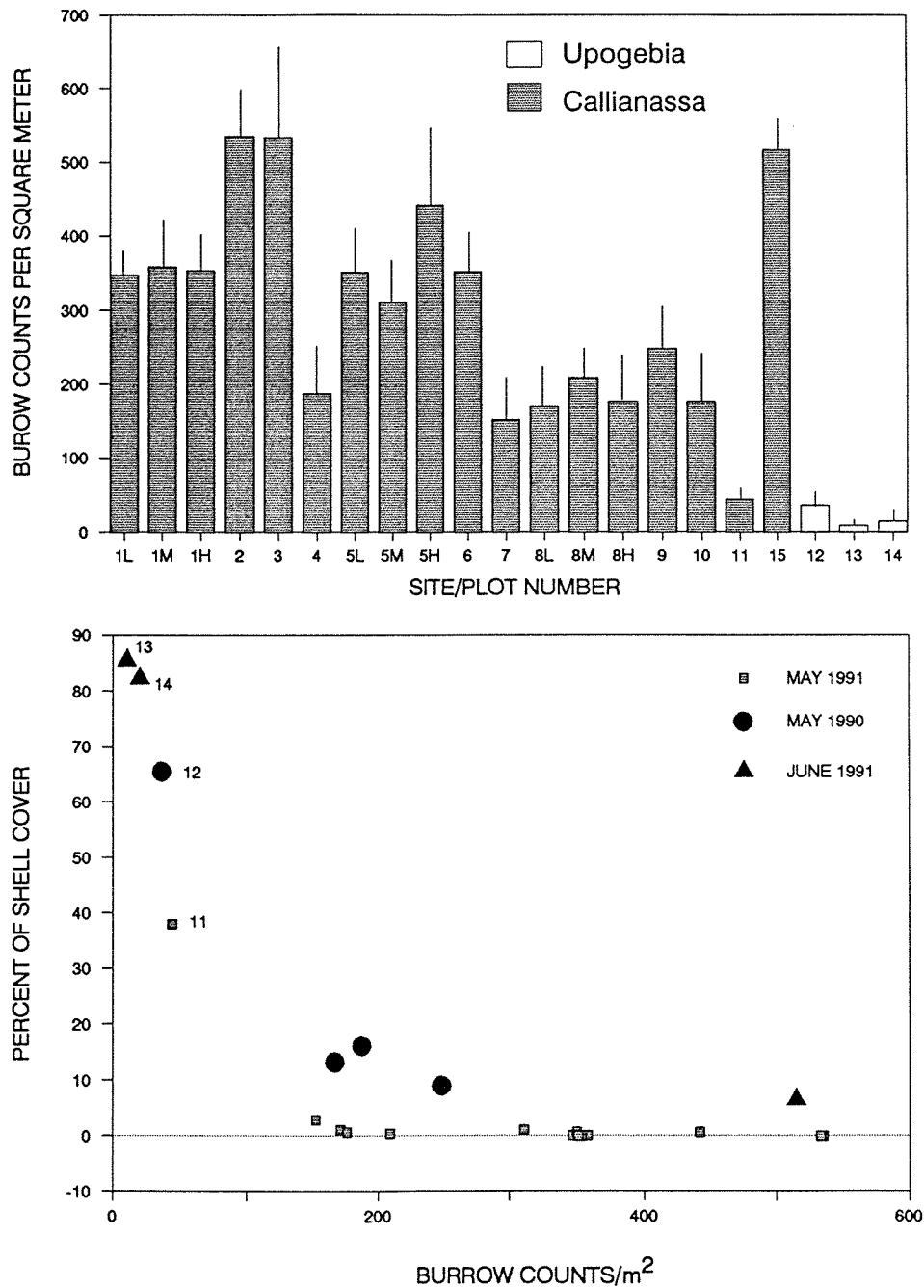


Figure 8. Top: Mean shrimp burrow counts (± 1 standard deviation) per square meter by species. Bottom: Relationship between burrow counts and percent shell cover estimated in September 1991. Burrow counts were obtained only in 1991 and assumed to be similar to counts the previous summer in the case of plots constructed in 1990. The shell deployment dates are given in the upper right corner and numbers identify sites where shell cover remained reasonably high.

Generally, crab densities were relatively high, often in excess of 100/m² in May through July (Fig. 9). As mentioned, less than half of the original test sites retained enough shell to warrant sampling of crab density, and by late summer data were only obtained from Sites 11 and 12 where densities declined from about 80 to 50 crab/m² (Fig. 9). Settlement at the second set of sites constructed in June was similarly high, between 180 and 300 crab/m², and declined to approximately 50/m² by September (Sites 13 through 15, Fig. 9).

Gear Efficiency

QRC efficiency was approximately half of the excavation method and ranged from a mean of 41% (SD=15%, N=14) in May to 64% (SD=49%, N=12) in August (Fig. 10). The estimated efficiency value for August is biased by one sample in which the QRC efficiency is approximately 180% that of the excavation; this bias had the effect of increasing the mean and the variance. If this value is excluded from the August data set, then the QRC efficiency was 48% (SD=20%, N=11) of the excavation method. Although the results indicate substantial difference in efficiency and resultant estimated densities, there was no size-selective difference in instar composition between the two methods (Fig. 11), which suggests that the efficiency comparison was not biased by size (e.g., the QRC method might underestimate J1 crab).

SUBTIDAL CRAB RECRUITMENT EXPERIMENT

Of the 20 subtidal trays deployed, only 12 were found a month later. Most of the trays contained a fair amount of sediment (predominantly sand) and were covered with algae (*Ulva* sp. and *Enteromorpha* sp.). Numbers of 0+ Dungeness crab in the trays ranged from 0 to 23, with a mean for the 12 trays of 4.2 (S.D. = 6.2) crab per tray, or 13.8 crab/m². Sizes of 0+ crab in the trays ranged from 11 to 21 mm CW, and the mean size of all crab was 14.1 (S.D. = 3.4) mm. Other animals found in the trays included polychaetes, cockles (*Clinocardium nuttallii*), mud shrimp (*Upogebia* sp.), clams (*Mya arenaria* and *Macoma* spp.), mussels (*Mytilus* sp.), red rock crab (*Cancer productus*), shore crab (*Hemigrapsus* sp.), juvenile staghorn sculpin (*Leptocottus armatus*), and saddleback gunnels (*Pholis ornata*).

EELGRASS DENSITIES

Eelgrass densities at North Bay Sites 1, 3, 5, 6, 7, and 8 were visually judged to be essentially zero (<0.1 turion/m²). Eelgrass turion counts taken in March at Site 11 (Pacman) averaged 17.6 (S.D. = 30.1, N = 20), 21.0 (S.D. = 32.7, N = 20) and 13.2 (S.D. = 10.2, N = 20) turions/m² on three cross-site transects for an overall site average of 17.3 turions/m² (S.D. = 26.0, N = 60); transect means were not significantly different from one another (ANOVA, F = 0.438, p>0.65). Individual eelgrass shoots in March were ~60-70 mm in length by 2 mm width. Distribution of eelgrass at Site 11 was patchy, with individual quadrat counts ranging from 0 to 35 turions/0.25 m²; however, 90% of the counts fell within a range of 0 to 14 turions/0.25 m² (Fig. 12). Mean eelgrass density in April in a control plot next to Site 11 was similar to that found in March (mean = 14.0 turions/m², S.D. = 15.2, N = 49). Mean eelgrass density in April at Site 2 (Fig. 2) was <1 turion/m², and at the remaining sites was <5 turions/m² (Sites 13, 14, and 15; Fig. 13).

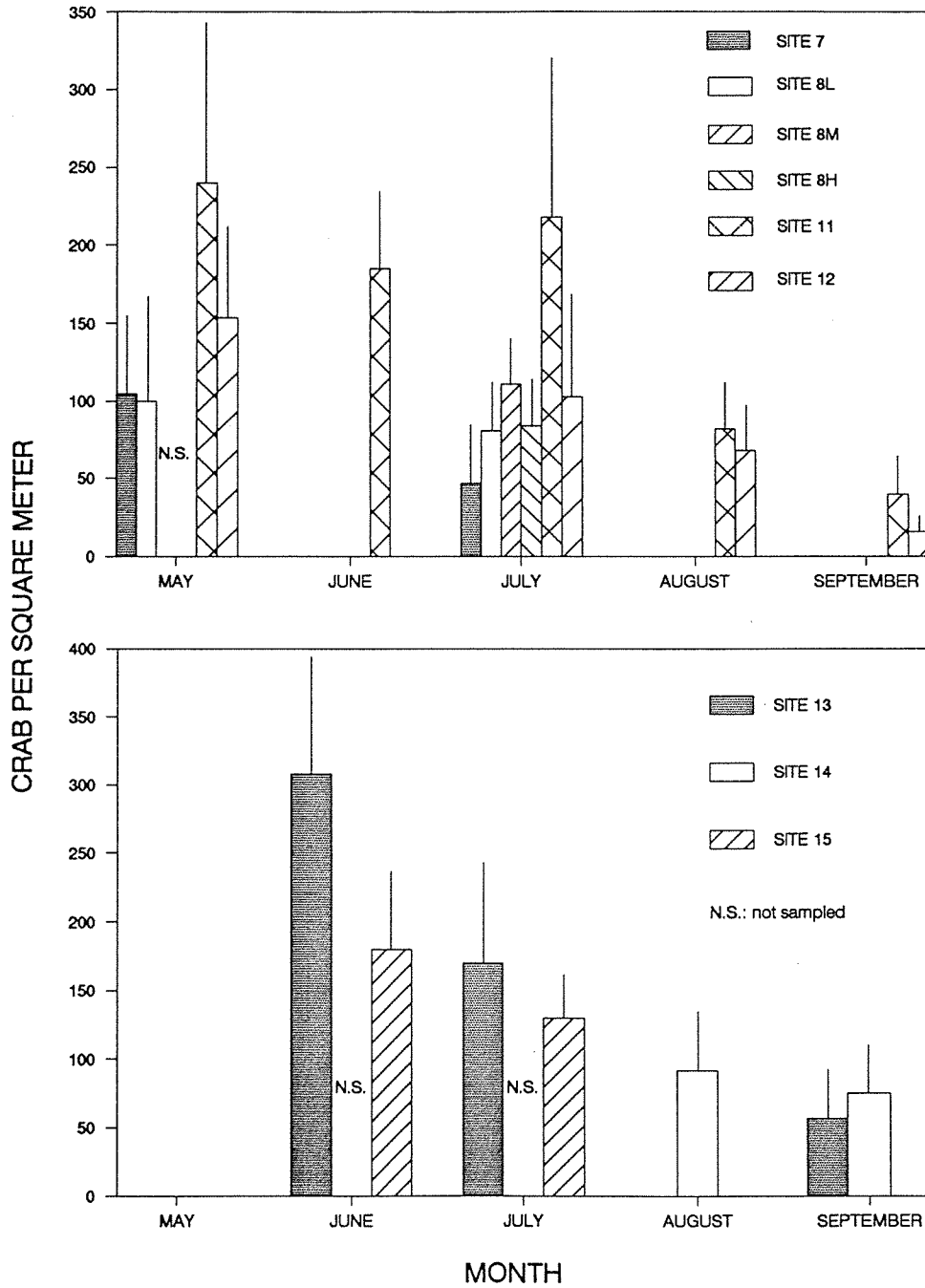


Figure 9. Juvenile Dungeness crab per square meter (means ± 1 standard deviation) estimated by the "excavation" method. For Sites 7 to 11, shell was deployed in May 1991, and for Site 12, shell was deployed April 1990. In June 1991, shell was placed at Sites 13, 14, and 15.

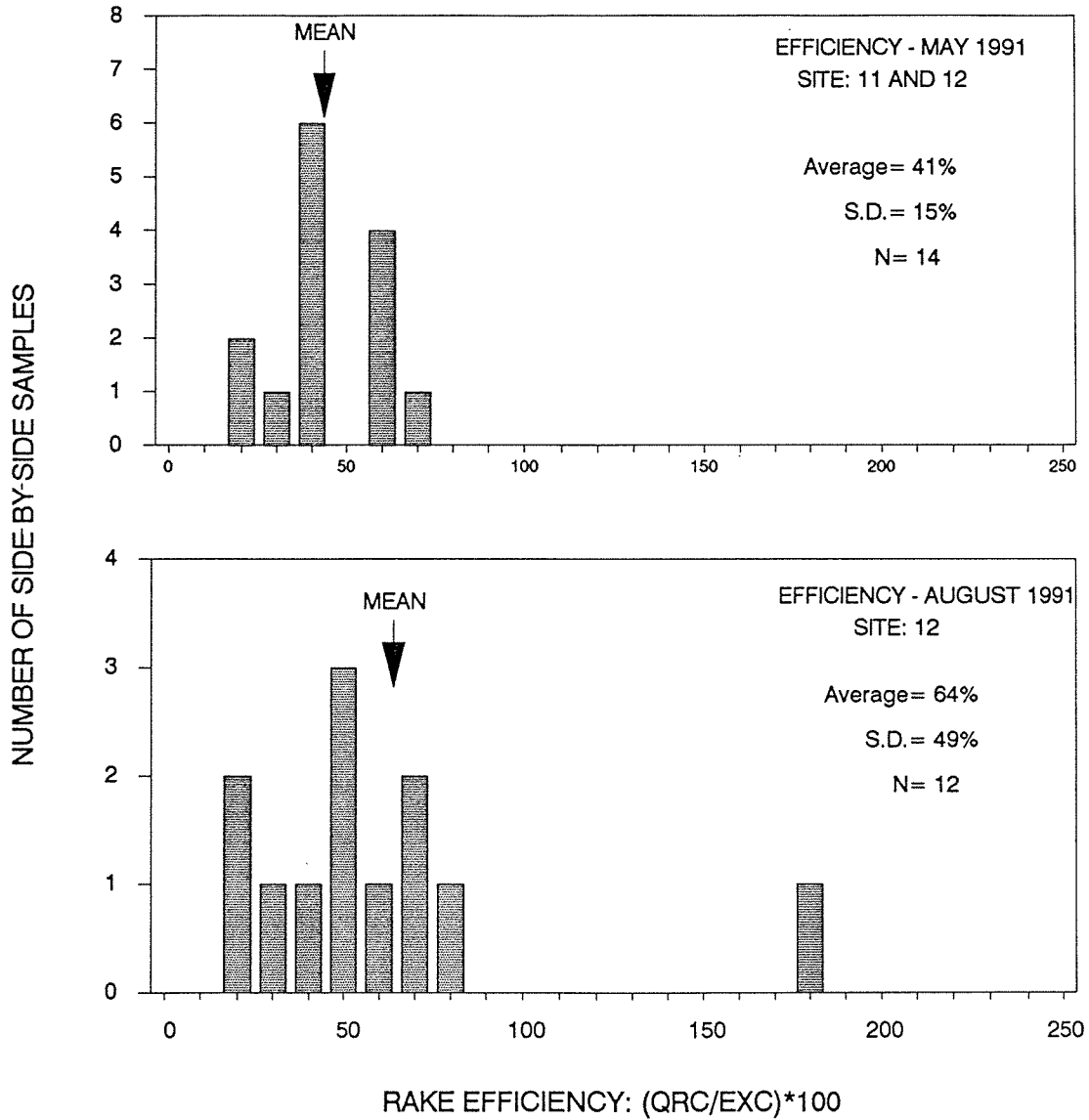


Figure 10. Results of two experiments to compare the efficiency between the "Quadrat-Rake-Count" (QRC) and the "excavation" methods of sampling juvenile crab in shell with side-by-side samples. The results indicate (deleting the one abnormally high value in August) that the QRC method recovers only about 50% of the juvenile crabs actually present in the sample.

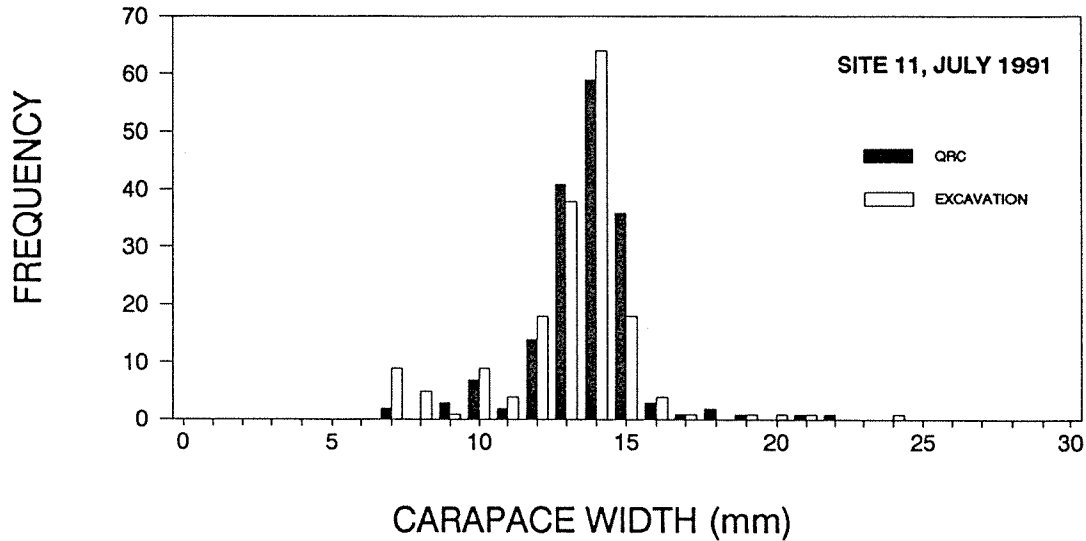


Figure 11. Size-frequency distribution of juvenile Dungeness crab captured by the QRC method compared with crab captured with the "excavation" method.

Counts of eelgrass turions transplanted to two small ponds within the Campbell's Slough 1990 test plot showed that the number of turions had increased at least fourfold in each of the experimental ponds (from 50 to 248 in pond "A" and from 50 to 206 in pond "B," or increases of 396% and 312%, respectively).

OTHER INFAUNAL AND EPIFAUNAL INVERTEBRATES

Comparison of data collected by pump and excavation sampling methods showed the latter always resulted in higher average densities and (with one exception) higher diversity of species from samples at the same site and habitat (Tables 1 and 2). Pump samples, on the other hand, generally had higher taxa richness than did excavation samples (e.g., South Channel shell excavation samples contained a total of 50 taxa categories, while pump shell samples had 54 categories; Table 2). In both excavation and pump samples, higher diversity and taxa richness were measured in shell than in mud. For example, South Channel excavation shell samples had a total of 50 plankton categories and a diversity of 2.72, while the excavation mud samples had a total of 24 categories and a diversity of 2.33 (Table 2).

Comparison of sites for each sample type indicated that Campbell Slough excavation and pump samples had higher diversity than samples from South Channel (Table 2). Campbell Slough pump samples also had a significantly higher mean total epibenthic organism count than South Channel (Table 1; $p < 0.0025$), and there was a significant site and substrate interaction within the pump samples ($p < 0.001$). No other significant differences in site and substrate within each sampling type were found for mean total number of epibenthos.

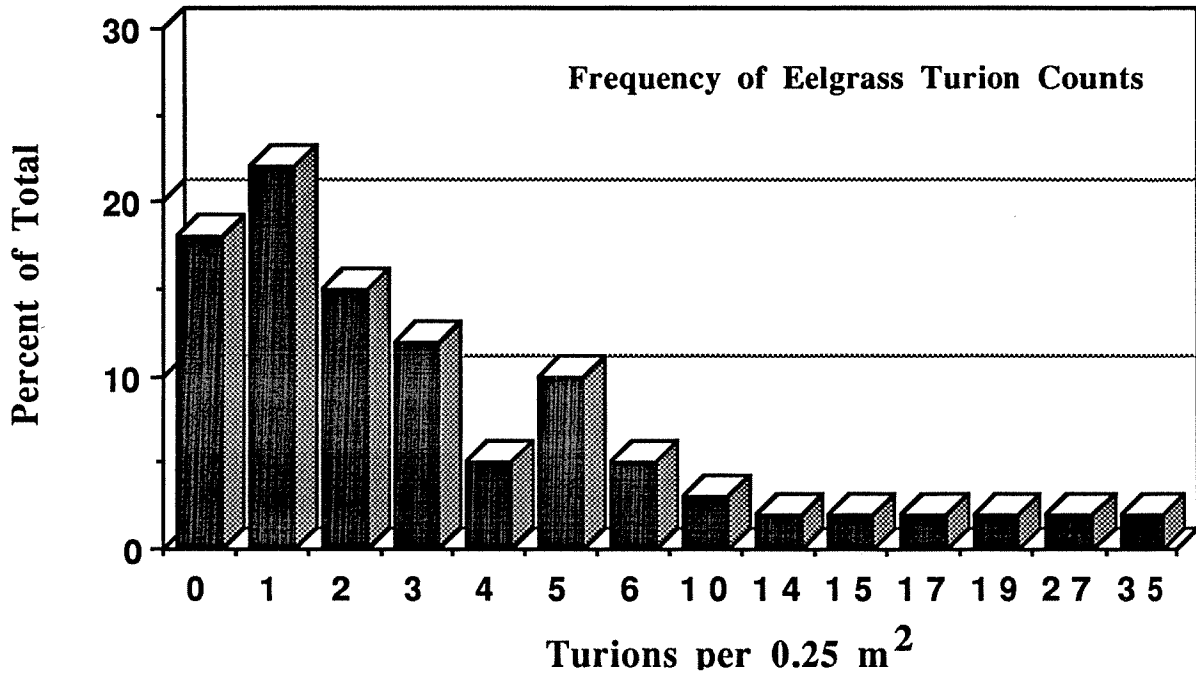


Figure 12. Frequency distribution of eelgrass turion counts/0.25 m² in a control plot next to Site 11 (Pacman) in March 1991.

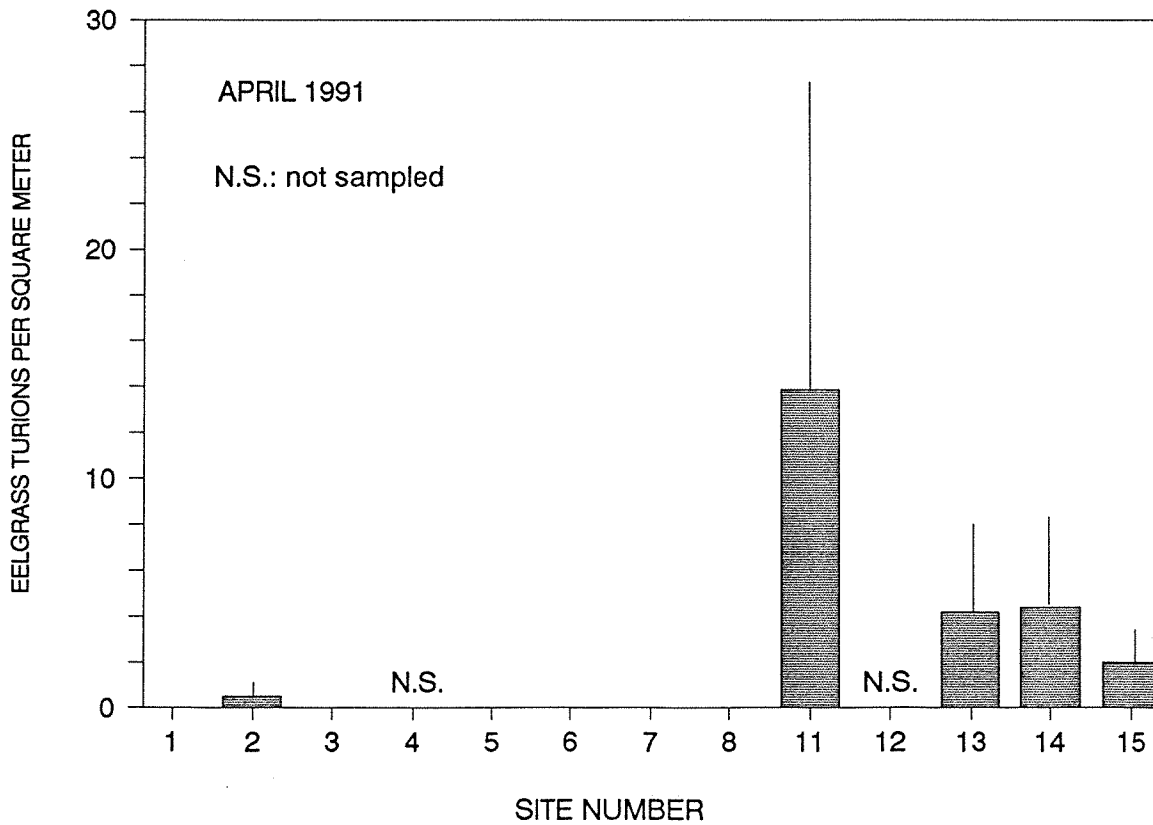


Figure 13. Eelgrass density (mean turions/m² ± 1 standard deviation) estimated from control plots next to each of the shell sites. Sites 1, 3, 5, 6, 7, and 8 = zero.

Table 1. Mean number and standard deviations of epibenthic organisms/m² estimated from pump and excavation samples collected in 1991 from two areas of Grays Harbor, Washington.

Sample type	Shell		Mud	
	Mean	SD	Mean	SD
Campbell Slough				
Pump	32,000	17,000	38,000	37,000
Excavation	61,000	32,000	119,000	75,000
South Channel				
Pump	20,000	11,000	12,000	9,000
Excavation	87,000	39,000	210,000	110,000

Table 2. Diversity (Shannon-Weiner H') indices and taxa richness for excavation and pump samples taken from shell and mud habitats at Campbell Slough and South Channel, Grays Harbor, Washington.

Sample site/Type	S-W diversity		Taxa richness		J (Evenness)	
	Shell	Mud	Shell	Mud	Shell	Mud
Campbell Slough						
Pump	3.16	2.90	61	45	1.77	1.75
Excavation	4.46	3.54	78	27	3.36	2.48
South Channel						
Pump	2.72	2.66	54	39	1.57	1.67
Excavation	2.72	2.33	50	24	1.60	1.69

South Channel pump samples from the shell plot had a higher mean total number of epibenthic organisms and total taxa than corresponding mud samples (20,000/m² and 54 categories vs. 12,000 organisms/m² and 39 categories, respectively; Tables 1 and 2). Shell samples were dominated by copepod nauplii (37% frequency of occurrence) and *Leimia vaga* (45%) (Table 3; all life history categories combined). Mud samples were dominated by *L. vaga* (56%) and copepod nauplii (29%). Campbell Slough pump samples from mud had more organisms than the shell samples (38,000/m² vs. 32,000/m²) but fewer taxa (45 vs. 61; Tables 1 and 2). Mud samples were dominated by copepod nauplii and *L. vaga* (38% each); shell was dominated by copepod nauplii (42%) and *L. vaga* (30%) (Table 4).

Table 3. Average density, standard deviation, and % numerical occurrence of epibenthic organisms collected by pump sampling at South Channel, Grays Harbor, during 1991.

Species	Shell			Mud		
	Mean (#/sq. m)	SD	% Numerical occurrence	Mean (#/sq. m)	SD	% Numerical occurrence
Podocopida	706	345	3.46	244	212	1.98
Copepoda (nauplii)	7494	4426	36.74	3578	2793	29.05
<i>Acartia</i> sp. (adult)	83	112	0.41	672	357	5.46
<i>Acartia</i> sp. (copepodid)	978	665	4.79	56	69	0.45
Ectinosomatidae (adult)	100	82	0.49	61	89	0.50
Ectinosomatidae (copepodid)	28	39	0.14	11	35	0.09
Ectinosomatidae (gravid female)	39	59	0.19	2489	2225	20.21
<i>Leimia vaga</i> (adult)	2789	1595	13.67	3994	3652	32.43
<i>L. vaga</i> (copepodid)	6106	4424	29.93	344	331	2.80
<i>L. vaga</i> (gravid female)	333	347	1.63	67	141	0.54
<i>L. vaga</i> (mating pair)	122	206	0.60	6	18	0.05
<i>Dactylopodia</i> sp. (copepodid)	6	18	0.03	11	35	0.09
<i>Dactylopodia crassipes</i> (adult)	22	39	0.11	6	18	0.05
<i>D. crassipes</i> (copepodid)	17	53	0.08	11	35	0.09
<i>D. crassipes</i> (gravid female)	6	18	0.03	6	18	0.05
<i>Leucon</i> sp. (juvenile)	11	35	0.05	11	35	0.09
<i>Cumella vulgaris</i> (juvenile)	39	74	0.19	6	18	0.05
<i>C. vulgaris</i> (gravid female)	11	23	0.05	6	18	0.03
<i>C. vulgaris</i> (female)	6	18	0.03	6	18	0.05
<i>Eogammarus confervicolus</i> (juvenile)	61	67	0.30			

Table 4. Average density, standard deviation and % numerical occurrence of epibenthic organisms collected by pump sampling at Campbell Slough, Grays Harbor during 1991.

Species	Shell			Mud		
	Mean (#/sq. m)	SD	% Numerical occurrence	Mean (#/sq. m)	SD	% Numerical occurrence
Copepoda (nauplii)	13361	8043	41.65	14278	21568	37.77
Calanoida (copepodid)	689	608	2.15	3861	3006	10.25
Ectinosomatidae (juvenile & adult)	1567	1637	4.88	694	1162.2.	1.84
<i>Harpacticus arcticus</i>	6	18	0.02	406	493	1.08
<i>Microarthridion littorale</i> (adult)	1039	1220	3.24	339	752	0.90
<i>M. littorale</i> (copepodid)	367	421	1.14	667	751	1.77
<i>M. littorale</i> (gravid female)	211	264	0.66	422	683	1.12
<i>Tachidius triangularis</i> (adult)	1333	1076	4.16	200	286	0.53
<i>T. triangularis</i> (copepodid)	917	704	2.86	222	276	0.59
<i>T. triangularis</i> (gravid female)	94	105	0.29	267	572	0.71
<i>Huntsmannia jadensis</i> (juvenile & adult)	411	247	1.28	944	790	2.51
<i>Leimia vaga</i> (adult)	2994	2357	9.33	5800	7318	15.40
<i>L. vaga</i> (copepodid)	5794	3911	18.06	6939	7717	18.42
<i>L. vaga</i> (gravid female)	456	351	1.42	1361	1903	3.61
<i>L. vaga</i> (mating pair)	233	289	0.73	100	152	0.27
<i>Schizopera knabeni</i>	328	244	1.02	22	39	0.06
<i>Dactylopusia crassipes</i> (adult)	17	38	0.05			
<i>D. crassipes</i> (juvenile & adult)	67	128	0.21			
<i>D. crassipes</i> (copepodid)	50	92	0.16			
<i>D. crassipes</i> (gravid female)	6	18	0.02			
<i>Leucon</i> sp. (juvenile)	22	29	0.07			
<i>Cumella vulgaris</i> (juvenile)	11	35	0.03			
<i>Corophium</i> sp. (juvenile)	6	18	0.02			
<i>Eogammarus confervicolus</i> (juvenile)	22	54	0.07			

Excavation samples from the mud habitat had higher total averages, but lower taxa richness than the shell habitat at both sites. South Channel mud samples had 210,000 animals/m² and 24 taxa (Table 2), which were dominated by *L. vaga* (83%), while shell had 87,000 organisms/m² and 50 taxa with *L. vaga* (73%) and copepod nauplii (10%) dominant (Tables 1 and 5). Campbell Slough shell had an average total of 61,000 organisms/m² and 78 taxa, which were dominated by *L. vaga* (27%), copepod nauplii (16%), and *Dactylopodia crassipes* (8%). Mud had 119,000 organisms/m² and 27 taxa, which were dominated by *L. vaga* (45%) and the family Ectosomatidae (16%) (Table 6).

The numerically dominant groups and (all juvenile salmonid prey) selected for statistical analyses (Figs. 1 and 2) were as follows: the harpacticoid copepods *L. vaga*, *Dactylopodia crassipes*, *Harpacticus* sp., and Family Ectosomatidae, the cumaceans *Leucon* spp. and *Cumella vulgaris*, and amphipod groups *Eogammarus confervicolus* and total Gammaridea.

In pump samples, *D. crassipes* and the family Ectosomatidae were the only harpacticoid groups to have significant differences between shell and mud and between Campbell Slough and South Channel. Specifically, *D. crassipes* had significantly higher density in shell than in mud ($p = 0.0001$; Table 7, Fig. 1). Ectosomatidae densities were significantly different between the two sites, with more at Campbell Slough than at South Channel ($p = 0.0001$). In the non-harpacticoid groups, *Cumella vulgaris*, *Eogammarus confervicolus* and total Gammaridea were significantly more abundant in the shell compared to the mud ($p < 0.001$, Table 7). For these groups, South Channel had significantly higher numbers of *Cumella vulgaris* and *Eogammarus confervicolus* (Table 7, Fig. 1).

For excavation samples, the harpacticoids *D. crassipes* and *Harpacticus* sp. were significantly more abundant in excavated shell compared to mud ($p < 0.05$), but *Leimia vaga* was significantly less abundant in shell (Table 6, Fig. 2). Ectosomatidae numbers were not significantly different in shell and mud excavation samples. Excavation densities of all four harpacticoid groups were significantly different between South Channel and Campbell Slough (Table 7, Fig. 2). For non-harpacticoid groups, *Cumella vulgaris*, *Eogammarus confervicolus*, and total Gammaridea had significantly higher numbers in shell than in mud excavation samples. *Leucon* sp. density was similar on both substrates. No significant difference in densities of these four species occurred between South Channel and Campbell Slough (Table 7, Fig. 2).

DISCUSSION

Work and results reported for 1991 conclude the experimental phase of mitigation habitat research in Grays Harbor estuary; beginning in spring 1992, larger-scale mitigation will be initiated. While we have verified the technical feasibility of intertidal shell mitigation as viable habitat enhancement for 0+ crab, the durability and integrity of the shell habitat in certain regions of the estuary and over periods of years is still equivocal.

Table 6. Average density, standard deviation and % numerical occurrence of epibenthic organisms collected by excavation sampling at Campbell Slough, Grays Harbor during 1991.

Species	Shell			Mud		
	Mean (#/sq. m)	SD	% Numerical occurrence	Mean (#/sq. m)	SD	% Numerical occurrence
<i>Bivalvia</i> (juvenile)	618	623	1.02	4750	5945	3.98
<i>Bivalvia</i>	68	118	0.11	1250	3173	1.05
Halacaridae	3801	3181	6.28	14500	9846	12.16
Podocopida	955	948	1.58	19500	8233	16.35
Copepoda (nauplii)	9802	12889	16.20	4500	8233	3.77
Harpacticoida	64	123	0.11	1250	2125	1.05
Harpacticoida (copepodid)	614	745	1.02	1250	2430	1.05
Ectinosomatidae (juvenile & adult)	3140	2099	5.19	500	1054	0.42
<i>Harpacticus uniremis</i>	13	40	0.02	500	1054	0.42
<i>H. arciticus</i>	54	99	0.09	2500	4249	2.10
<i>Harpacticus</i> sp. <i>uniremis</i> group (copepodid)	24	50	0.04	8750	8101	7.34
<i>Microarthridion littorale</i> (adult)	2138	1477	3.53	23750	24812	19.92
<i>M. littorale</i> (copepodid)	464	427	0.77	15750	20448	13.21
<i>M. littorale</i> (gravid female)	591	505	0.98	11250	12816	9.43
<i>M. littorale</i> (mating pair)	25	79	0.04	2500	3536	2.10
<i>Tachidius triangularis</i> (adult)	483	438	0.80	1250	1768	1.05
<i>T. triangularis</i> (copepodid)	333	487	0.55			
<i>T. triangularis</i> (gravid female)	144	162	0.24			
<i>Paralaophonte congenera</i> (adult)	1101	663	1.82			
<i>Hunismannia jadensis</i> (juvenile & adult)	935	1065	1.54			
<i>H. jadensis</i> (copepodid)	14	45	0.02			
<i>Leimia vaga</i> (adult)	7983	4525	13.20			
<i>L. vaga</i> (copepodid)	5434	2940	8.98			
<i>L. vaga</i> (gravid female)	2435	979	4.03			
<i>L. vaga</i> (mating pair)	471	397	0.78			
<i>Amphiascus parvus</i>	3874	2113	6.40			
<i>A. parvus</i> (gravid female)	260	573	0.43			
<i>Schizopera knabeni</i>	2297	2099	3.80			
<i>Dactylopodia vulgaris</i> (adult)	13	40	0.02			
<i>Dactylopodia crassipes</i> (adult)	1580	409	2.61			
<i>D. crassipes</i> (copepodid)	2860	1980	4.73			
<i>D. crassipes</i> (gravid female)	516	300	0.85			

Table 6—cont.

Species	Shell			Mud		
	Mean (#/sq. m)	SD	% Numerical occurrence	Mean (#/sq. m)	SD	% Numerical occurrence
<i>Balanomorpha</i> (nauplius)	123	389	0.20			
<i>Balanomorpha</i> (juvenile)	2114	1162	3.49			
<i>Balanomorpha</i> (cypris)	914	550	1.51			
<i>Leucon</i> sp. (juvenile)	24	51	0.04			
<i>Cumella vulgaris</i> (juvenile)	15	47	0.02			
<i>C. vulgaris</i> (juvenile & adult)	228	256	0.38			
Gammaridea (juvenile)	24	74	0.04			
<i>Corophium</i> sp. (juvenile)	165	209	0.27			
Gammaridae (adult)	15	47	0.02			
<i>Eogammarus confervicolus</i> (juvenile)	80	95	0.13			
<i>E. confervicolus</i> (adult)	25	54	0.04			
<i>E. confervicolus</i> (juvenile & adult)	47	149	0.08			
<i>E. confervicolus</i> (gravid female)	13	40	0.02			
<i>Eobroligus spinosus</i>	13	40	0.02			

Table 7. Summary of two-way ANOVA analysis for eight selected epibenthic species. Species is significantly ($p < 0.05$) more abundant (+), not significantly different (NS), or depressed (-) in shell vs. control mudflat and South Channel vs. Campbell Slough comparisons.

Species	Excavation		Pump	
	Shell vs. mud	South Channel vs. Campbell Slough	Shell vs. mud	South Channel vs. Campbell Slough
<i>Leimia vaga</i>	-	+	NS	NS
Dactylopodia	+	-	+	NS
Ectosomatidae	NS	-	NS	-
<i>Harpacticus</i> sp.	+	-	NS	NS
<i>Leucon</i> sp.	NS	NS	NS	NS
<i>Cumella vulgaris</i>	+	NS	+	+
<i>Eogammarus confervicolus</i>	+	NS	+	+
Gammaridea	+	NS	+	NS

SHELL HABITAT INTEGRITY

In all intertidal shell mitigation studies conducted since 1986, we have learned that several processes worked to reduce the functional features of shell as crab habitat. Primarily such reductions are caused by sinkage into the substrate or substantial sedimentation, which fills the matrices of the shell habitat and eliminates use by young-of-the-year crab. Dumbauld and Armstrong (1987) reported that - scale test plots constructed at South Channel in 1985 had to be reconstructed the following year because substantial portions of the habitat were lost through the winter. Best retention and durability of shell habitat was at test plots constructed near Ned's Rock on the eastern edge of North Bay, relatively close to the Pacman site of 1991. Test plots constructed in North Bay in 1990 at Campbell Slough and two locations east of Goose Island were disappointing since percent cover was quickly reduced to 10-30% by June of that year (Armstrong et al. 1991). Similarly the more extensive effort to construct a number of test plots throughout North Bay in 1991 was not productive since most habitat was quickly lost within one to two tidal cycles after construction. Particularly striking in these results is the extent to which shell sinks; as has been stated by the oyster industry, this seems to be due to presence of high densities of burrowing shrimp at these same locations. Our data indicate that shell mitigation will not be successful at intertidal regions of the estuary where infaunal shrimp density is in excess of 150-200 animals/m². In summary, shell habitat mitigation and durability seem highest at areas of the South Channel and the eastern edge of North Bay between Ned's Rock and Pacman.

CRAB DENSITY

The 1991 Dungeness crab year class recruited to the estuary and settled to shell habitat in May and June, as has been reported in a number of previous years (Gunderson et al. 1990). Density, as measured by the "excavation" method, was also high in 1991 and ranged between 100 to 300 crab/m² shortly after settlement, comparable to densities reported in 1990 (Armstrong et al. 1991). It is puzzling to compare and interpret these data in light of earlier values of crab density reported by Dumbauld and Armstrong (1987), who used calculations done in order to determine the extent of intertidal shell habitat required as mitigation following subtidal dredging and loss of older juveniles as a primary component of crab mitigation. Stemming from this earlier work based on the QRC method, a mean density of 10 crab/m² was used as the benchmark for calculations of full mitigation habitat required. The QRC density data from South Channel in 1990, for example, were 40 decreasing to about 20 crab/m², and in that year excavation data showed densities between 50 to 100 crab/m². If we assume that the QRC method is only half as efficient in capturing small crab as the excavation method, then the data reported by Dumbauld and Armstrong would only be about 20 crab/m² if corrected for the years 1986 and 1987. Whether these years simply had lower recruitment compared to 1990 and 1991 or there was yet another inherent sampling problem not yet identified is unknown at this time. It seems unreasonable, however, to use a value as low as 10 crab/m² as the basis of calculating required mitigation and we suggest that a more accurate summer density value is around 40 crab/m². In August 1991, 0+ crab density at all three South Channel sites was in excess of 50 crab/m², even though animals by that time were largely J4 to J6 instars and presumably had begun their migration off the intertidal to subtidal channels.

SUBTIDAL CRAB RECRUITMENT

The subtidal crab recruitment experiment confirmed that 0+ crab can utilize subtidal shell habitat, as suggested by numerous trawl samples taken throughout Grays Harbor in the past. However, the amount of sediment deposited in the trays in a 1-month period indicates that many subtidal shell plots would be covered by sand and rendered useless in a short amount of time. At minimum, subtidal areas in Grays Harbor where shell might survive burial would have to be identified and tested to determine durability of shell habitat and crab recruitment. Another conceptual problem with using subtidal shell for 0+ crab recruitment is that these young recruits might be displaced or cannibalized by 1+ crab of the previous year (at about 30 mm CW) that have moved off the intertidal flats and normally reside in the channels, especially in natural shell deposits. Because of these factors, we presently recommend against deployment of any mitigation shell in subtidal areas.

EELGRASS DENSITIES

Eelgrass densities at all newly established sites in North Bay (other than Site 11, Pacman) were essentially zero in 1991. Eelgrass density at Site 11 averaged 14 to 17 turions/m² in 1991. Although such density is low, resource agencies still stated concern about impacts caused by shell placement. Unfortunately, firm guidelines regarding eelgrass habitat and densities below which mitigation projects might be approved are presently lacking in Washington State. Eelgrass densi-

ties at Sites 13 and 14 (South Channel) were less than half that at Site 11 in 1991. Both Pacman and South Channel areas had relatively low densities of ghost shrimp and substrates that are firm enough to support full mitigation (~8 ha) shell plots. Usable area at Pacman, however, is only about half that required for full mitigation when the thickest eelgrass areas and accumulations of *Mya arenaria* shell (which now serve as "natural" crab habitat) are avoided. South Channel has an extensive usable area of low eelgrass density, but this attribute is offset by concerns about possible pulp mill pollution (especially dioxin and related organic compounds) from upcurrent sources.

Results of the eelgrass transplants at Site 4 (Campbell Slough) are encouraging. In areas where shallow ponds remained between the shell piles, eelgrass grew and produced turion counts four times greater than when originally transplanted in summer 1990. Eelgrass could possibly be transplanted into the full-scale mitigation plots to compensate for loss of eelgrass caused by shell deployment over existing plants. However, a more plausible scenario is that the large shell plots will help stabilize the substrate, reduce burrowing shrimp density, and provide conditions conducive to natural regeneration of eelgrass within the shell plots (which will slowly fill in with sediments). The chance to monitor the basic ecological changes in relation to eelgrass, burrowing shrimp, and the relative habitat values of both eelgrass and shell (and combinations thereof) should not be lost.

EPIBENTHIC COMMUNITY

In general, the major taxa and taxa richness found in the shell and mud habitats investigated in this study were similar to those found on Grays Harbor mudflats in earlier studies (Cordell and Simenstad 1981; Simenstad and Eggers 1981). However, dominant species were different than those described by these authors, which may be due to different sampling sites and frequency (we sampled only once in April in both North and South Bay, while the 1981 studies consisted of multiple sampling over the entire spring, and concentrated on South Bay sites only).

If one assumes that the neoprene-collared pump adequately sampled the shell habitat, then pump samples may be interpreted as representative of the zooplankton community present during initial flooding of the mudflat after low tide, and excavation samples as the community of the mudflat during low tide. In this light, samples taken from both exposed and flooded habitats showed the same trends when comparing shell relative to bare mudflat. Specifically, the total number of plankton categories and diversity for both flooded and intertidal habitats were greater in shell habitats of both Campbell Slough and South Channel (Figs. 14 and 15). Increased diversity of fauna in shell relative to mud habitats may be attributed to a number of factors including enhancement of several habitat components that are important to epibenthic organisms such as relative mobility, nutrient and oxygen availability, and refugia. Decho et al. (1985) concluded that aggregations of meiofauna are largely passive and driven by microphysical environments such as changes in surface topography. Increased surface heterogeneity of the shell habitat may increase drag, slow water flow, and cause planktonic organisms to passively settle into the shell habitat. Organic content of the shell habitat is undoubtedly higher than barren mudflat due to increased diatom and algal growth on the shells and increased fecal material from other larger epibenthic invertebrates. This in turn may result in enhancement of some harpacticoid species. Decho (1988) found that mean grain size, % silt-clay, and organic content were the most important factors

PUMP SAMPLES

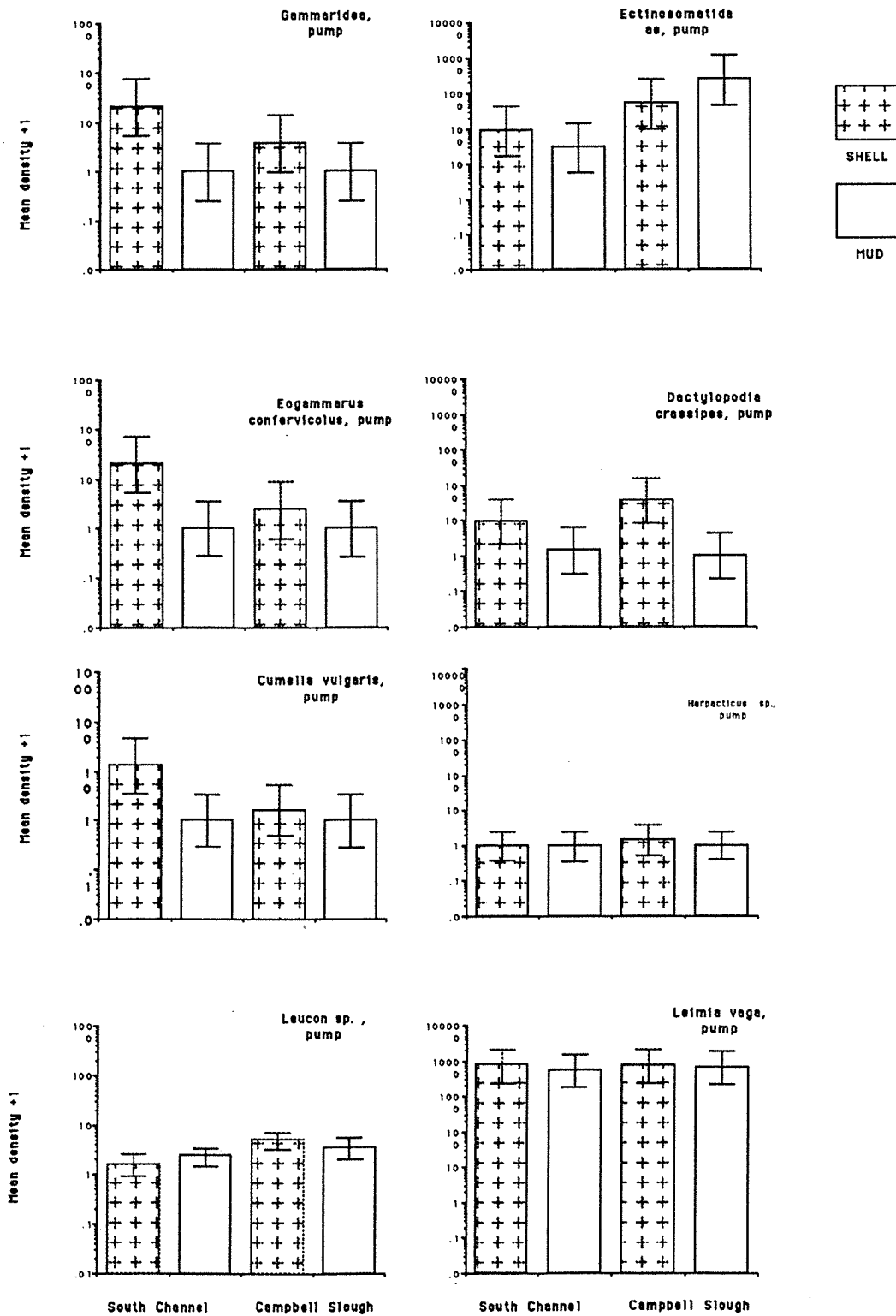


Figure 14. Average densities (#/m² + 1) and 95% confidence intervals for selected harpacticoid and non-harpacticoid taxa from *pump* samples collected over shell and mud.

EXCAVATION SAMPLES

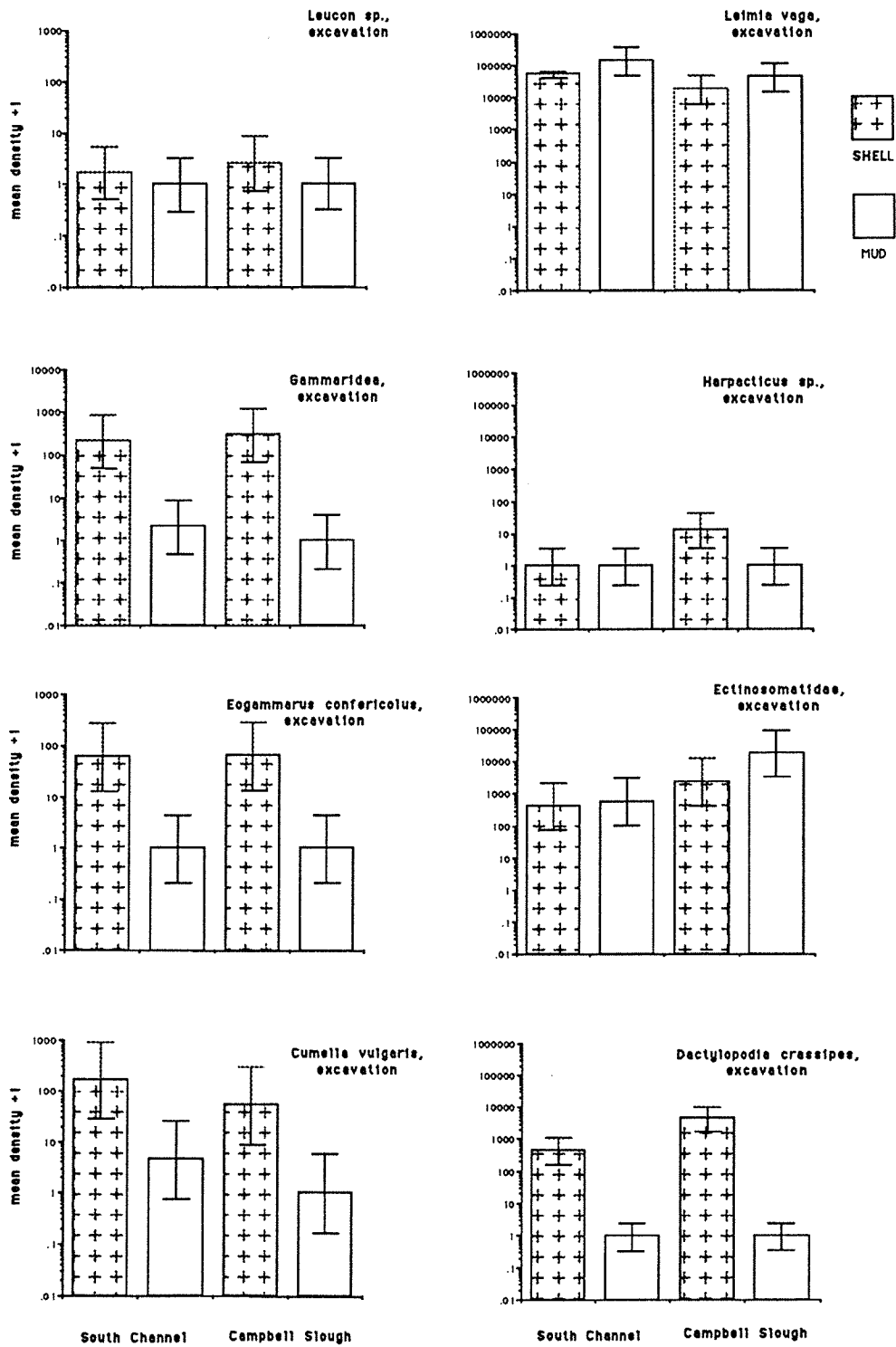


Figure 15. Average densities ($\#/m^2 + 1$) and 95% confidence intervals for selected harpacticoid and non-harpacticoid taxa from "excavation" samples collected from shell and mud.

affecting harpacticoid species distribution; larger grain size increases habitat heterogeneity, while accumulation of smaller particles reduces pore space and potential carrying capacity of the habitat.

Comparison of the intertidal and flooded habitat reveals some differences. The higher species richness, lower diversities, and absolute densities of epifauna on flooded mudflat relative to the dewatered intertidal may be attributed to structural differences in the two habitats and differences in organisms that use them. Simenstad (1981) and Decho (1988) found that epibenthic organisms are resuspended in the water column as the mudflat floods, and spatial patterns of epibenthic mud-dwelling copepods appear to be disrupted with each tidal cycle by active and passive resuspension processes. Enhanced species richness and decreased densities and diversity of fauna over the flooding mudflat relative to habitats sampled at low tide (dewatered) indicates that harpacticoid distribution in Grays Harbor is passive and tidally driven. These effects, however, differ somewhat from those reported by Simenstad and Eggers (1981), who described an increase in harpacticoid densities with flooding tide.

The enhancement of larger benthic organisms and species-specific effect on harpacticoid groups witnessed in this study is in general agreement with other habitat enhancement studies that involved the deposition of coarser material onto unvegetated mudflat. Simenstad et al. (1991) found radically different responses to gravel placed on unvegetated mudflats of an exposed and a protected bay. In the more exposed bay (Bywater Bay, north Hood Canal), harpacticoid response was species-dependent, amphipods were only briefly enhanced, and cumaceans were depressed. At this bay, the mud habitat had more diverse fauna than the graveled habitat. In the more protected bay (Oakland Bay, south Puget Sound), gravel habitat was always enhanced and had a higher diversity relative to control. Taxa richness was higher on the gravelled plots in both bays. The authors concluded that the influence of adding gravel was highly dependent on taxa and substrate of the natural littoral flat.

Results of this study are in general agreement with other research. For some harpacticoid taxa the shell habitat had higher densities than adjacent unvegetated mudflat, but these increases appeared temporary, lasting only until the area was reflooded. Larger, less planktonic species, such as amphipods and cumaceans, are not as prone to tidally driven distribution fluctuations. For these groups, the shell habitat appears enhanced relative to the bare mudflat, which is possibly due to shell offering more habitat niches and carbon resources than surrounding mudflat. How these changes in epifaunal mudflat communities translate to other components of the Grays Harbor mudflat ecosystem, such as juvenile salmonids and flatfish, is not presently known. Increased prey abundances may or may not translate to increased prey availability and may be mediated by increased prey refugia offered in the shell habitat.

REFERENCES

- Armstrong, D.A., B.G. Stevens and J.C. Hoeman. 1982. Distribution and abundance of Dungeness crab and *Crangon* shrimp, and dredging-related mortality of invertebrates and fish in Grays Harbor, Washington. Tech. Report for Washington Department of Fisheries and U.S. Army Corps of Engineers, Seattle District by School of Fisheries, University of Washington, Seattle. 349 p.
- Armstrong, D.A., D.R. Gunderson and J.L. Armstrong. 1985. Juvenile Dungeness crab population dynamics in the offshore of the Grays Harbor estuary, spring and summer 1984. Final Report to the Seattle District, U.S. Army Corps of Engineers, Seattle, WA. 59 p.
- Armstrong, D.A., J.L. Armstrong and D.R. Gunderson. 1986. Juvenile Dungeness crab population dynamics in Grays Harbor and Willapa Bay and along the adjacent coast, spring and summer, 1985. Final Report to the U.S. Army Corps of Engineers, Seattle District by Aquatic Resources Consultant Services, Seattle, Washington.
- Armstrong, D.A., T.C. Wainwright, J. Orensanz, P.A. Dinnel and B.R. Dumbauld. 1987. Model of dredging impact on Dungeness crab in Grays Harbor, Washington. Final Report to Battelle Pacific Northwest Laboratories and U.S. Army Corps of Engineers, Seattle District Office. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8702. 167 p.
- Armstrong, D.A., L. Botsford and G. Jamieson. 1989. Ecology and population dynamics of juvenile Dungeness crab in Grays Harbor estuary and adjacent nearshore waters of the southern Washington coast. Final Report to the U.S. Army Corps of Engineers, Seattle District. 140 p.
- Armstrong, D.A., O. Iribarne, K.A. McGraw and R. Palacios. 1991. Intertidal shell mitigation and community composition in Grays Harbor Estuary, 1990. Chapter 2, pp. 21-35 in Construction Dredging Impacts on Dungeness Crab, *Cancer magister*, in Grays Harbor, Washington and Mitigation of Losses by Development of Intertidal Shell Habitat, D. A. Armstrong, et al., Principal Investigators. Final Report for Seattle District, U.S. Army Corps of Engineers. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-9110. 63 p.
- Cordell, J.R. and C.A. Simenstad. 1981. Community structure and standing stock of epibenthic zooplankton at five sites in Grays Harbor. Final Report to the Seattle District Corps of Engineers, Contract # DACW 67-PO-R-0009.
- Decho, A.W. and J.W. Fleeger. 1988. Microscale dispersion of meiobenthic copepods in response to food-resource patchiness. J. Exp. Mar. Biol. Ecol. 118:229-243.
- Decho, A.W., W.D. Hummon and J.W. Fleeger. 1985. Meiofauna-sediment interactions around subtropical seagrass sediments using factor analysis. J. Mar. Res. 43:237-255.
- Dinnel, P.A., D.A. Armstrong and B.R. Dumbauld. 1986a. Impact of dredging and dredged material disposal on Dungeness crab, *Cancer magister*, in Grays Harbor, Washington during

- October, 1985. Final Report to the U.S. Army Corps of Engineers, Seattle District Office. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8606. 30 p.
- Dinnel, P.A., D.A. Armstrong, B.R. Dumbauld and T.C. Wainwright. 1986b. Impact of dredging and dredged material disposal on Dungeness crab, *Cancer magister*, in Grays Harbor, Washington during August, 1986. Final Report to the U.S. Army Corps of Engineers, Seattle District Office. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8611. 34 p.
- Dinnel, P.A., D.A. Armstrong, A. Whiley, T.C. Wainwright and K.A. McGraw. 1991. Impact of 1990 Grays Harbor construction dredging on Dungeness crab, *Cancer magister*. Chapter 1, pp. 3-20 in D.A. Armstrong, et al., Construction Dredging Impacts on Dungeness Crab, *Cancer magister*, in Grays Harbor, Washington and Mitigation of Losses by Development of Intertidal Shell Habitat. Final Report for Seattle District, U.S. Army Corps of Engineers. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-9110. 63 p.
- Dumbauld, B.R. and D.A. Armstrong. 1987. Potential mitigation of juvenile Dungeness crab loss during dredging through enhancement of intertidal shell habitat in Grays Harbor, Washington. Final Report to U.S. Army Corps of Engineers, Seattle District. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8714. 64 p.
- Dumbauld, B.R., D.A. Armstrong and A.R. Black. 1987. Distribution and abundance of Dungeness crab, *Cancer magister* in Grays Harbor, Washington, and in adjacent nearshore during fall/winter 1985/1986. Final Report for U.S. Army Corps of Engineers, Seattle District. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8616. 85 p.
- Dumbauld, B., D. Armstrong, P. Dinnel and T. Wainwright. 1988. Impact of dredging on Dungeness crab, *Cancer magister*, in Grays Harbor, Washington, during August 1987. Final Report to U.S. Army Corps of Engineers, Seattle District Office. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8820. 25 p.
- Gunderson, D.R., D.A. Armstrong, Y.-B. Shi, and R.A. McConnaughey. 1990. Patterns of estuarine use by juvenile English sole (*Parophrys vetulus*) and Dungeness crab (*Cancer magister*). *Estuaries* 13:59-71.
- McGraw, K.A., L.L. Conquest, J.O. Waller, P.A. Dinnel and D.A. Armstrong. 1988. Entrainment of Dungeness crab, *Cancer magister* Dana by hopper dredge in Grays Harbor, Washington. *J. Shellfish Res.* 7(2):219-231.
- McClain, D.H. 1974. Drawing contours from arbitrary data points. *The Computer J.* 17:318-324.
- Pearson, W.H. 1987. Qualitative assessment of impacts on Dungeness crabs from disposal of dredged materials from Grays Harbor, Washington. Final Report for U.S. Army Corps of Engineers, Seattle District. Battelle Marine Research Laboratory, Sequim, WA. 29 p.
- Pearson, W.H. and D.L. Woodruff. 1987. Effects of dredged materials from Grays Harbor on bait odor response in Dungeness crab (*Cancer magister*). Final Report for U.S. Army Corps of Engineers, Seattle District. Battelle Marine Research Laboratory, Sequim, WA. 48 p.

- Pearson, W.H., D.L. Woodruff, P. Wilkinson and J.S. Young. 1987. Data report for the 1984-1985 ocean surveys to investigate potential ocean disposal sites off Grays Harbor, Washington. Final Report for U.S. Army Corps of Engineers, Seattle District. Battelle Marine Research Laboratory, Sequim, WA. 183 p.
- Simenstad, C.A. and D.M. Eggers, editors. 1981. Juvenile salmon and baitfish distribution, abundance, and prey resources in selected areas of Grays Harbor, Washington. Final Report. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-8116.
- Simenstad, C.A., J.C. Cordell and L. Weitkamp. 1991. Effects of substrate modification on littoral flat meiofauna: assemblage structure changes associated with adding gravel. Technical Report to the Washington State Department of Fisheries. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-9124.
- Stevens, B.G. 1981. Dredging related mortality of Dungeness crabs associated with four dredges operating in Grays Harbor, Washington. Washington Dept. of Fisheries Report to U.S. Army Corps of Engineers No. DA-79-45.
- Tegelberg, H. and R. Arthur. 1977. Distribution of Dungeness crabs (*Cancer magister*) in Grays Harbor, and some effects of channel maintenance dredging. Appendix N in Maintenance dredging and the environment of Grays Harbor, Washington. Final Report to U.S. Army Corps of Engineers, Seattle District, Seattle, WA. 94 p.
- U.S. Army Corps of Engineers. 1982. Interim Feasibility Report and Final Environmental Impact Statement, Grays Harbor, Chehalis, and Hoquiam Rivers, Washington, Channel Improvements for Navigation. Seattle District, U.S. Army Corps of Engineers, Seattle, Washington. 800 p.
- U.S. Army Corps of Engineers. 1989. Final Environment Impact Statement Supplement. Grays Harbor, Grays Harbor Navigation Improvement Project. Seattle District, U.S. Army Corps of Engineers. Seattle, WA. 115 p.
- Wainwright, T.C., K.A. McGraw, D.A. Armstrong, B.R. Dumbauld and L.L. Conquest. 1990. Impact of dredging on Dungeness Crab, *Cancer magister*, in Grays Harbor, Washington, during August 1989. Final Report for U.S. Army Corps of Engineers, Seattle District. Univ. Washington, School of Fisheries, Fish. Res. Inst. FRI-UW-9905. 18 p.
- Wainwright, T.C., D.A. Armstrong, P.A. Dinnel, J.M. Orensanz and K.A. McGraw. 1992. Predicting effects of dredging on a crab population: an equivalent adult loss approach. Fish. Bull. (U.S.) 90:171-812.
- Wilkinson, L. 1988. SYGRAPH. SYSTAT, Inc., Evanston, Ill.