FRI-UW-8714
September 1987

FISHERIES RESEARCH INSTITUTE
School of Fisheries
University of Washington
Seattle, WA 98195

Potential Mitigation of Juvenile Dungeness Crab Loss during Dredging through Enhancement of Intertidal Shell Habitat in Grays Harbor, Washington

by

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Final Report

for

Seattle District, U.S. Army Corps of Engineers
Seattle, Washington
Contract No. DACW67-85-0033

Approved

Date 10-19-87

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Director

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ACKNOWLEDGMENTS

Funding for this study was provided by a contract from the Seattle District Army Corps of Engineers (DACW67-85-0033). The authors thank Greg Jensen, Dan Doty, M.C. Howie, Laurie Bernstein, Ginger Phalen, Alex Ma, Brandt Gutermuth, Raul Palacios, Amos Black, Ed Ross, MaryLynn Jensen, Yun Bing Shi, George Williams, Brian Beckerdite and Debbie Dole for their invaluable assistance with the field work, data analysis and report preparation. The helpful coordination and and assistance of Army Corps of Engineers personnel Jim Waller, Ann Uhrich, Fred Weinmann, and Kay McGraw is gratefully appreciated. Some of the data reported on herein was collected as part of a coastal crab research program funded by Washington Sea Grant and the authors wish to thank the director, Louie Echols for his encouragement. Use of the Burroughs mainframe computer at the National Marine Fisheries Service Center in Seattle is appreciated. Tom Hayes and Mike Lynn of Coast Oyster Company were helpful throughout the project providing oyster shell, stakes, moorage, and the use of their oyster grounds for our experiments. Mike Lynn also provided helpful comments and operated the oyster dredge AMC 2 which delivered shell for our experiments. The hovercraft Falcon was provided by Sea Lease Inc. of Bainbridge Island, Washington and the authors thank Ted and Ben Huntley for operating this interesting vessel. The United States Coast Guard graciously provided moorage at their Westport facility throughout the project and helicopter overflights of Grays Harbor in August 1984 and August 1987. Marcus Duke, Carla Norwood, Maureen Phillips-Mead and Jenni Keith helped prepare the manuscript. We appreciate the conscientious review of this report given by Dr. Donald Gunderson and Charles Simenstad, Fisheries Research Institute, and Fred Weinmann, Gail Arnold, Kay McGraw, and James Waller, Army Corps of Engineers. Thanks also to Dr. Richard Wilson of Bay Center Mariculture and to members of the Crab Study Panel for their suggestions and comments.

1.0 INTRODUCTION

The Port of Grays Harbor has required maintenance dredging to deepen and stabilize navigation channels since 1905. Increasing demands for improvements to the channel in the mid 1970's led to concerns about possible environmental problems associated with dredging and initiation of studies by the U.S. Army Corps of Engineers (COE) to investigate potential environmental effects. Results indicated that the Dungeness crab, *Cancer magister*, was one of the most important species to be considered since it supports both a viable sport fishery and the most valuable commercial crustacean fishery in Washington State (PMFC 1986) and would be most impacted by dredging operations (COE 1977; Tegelberg and Arthur 1977). Interest in a major modification to the existing Grays Harbor navigation channel continued to increase, and in 1980 Congress voted to approve funds for studies on the proposed Grays Harbor Navigation Improvement Project, which would remove an estimated 14.2 million cubic yards (mcy) of sediment from the harbor and substantially increase the annual maintenance dredging from 1.5 to 2.6 mcy.

A number of studies on the potential impacts of dredging to juvenile crab populations in Grays Harbor were initiated by COE (Stevens 1981; Armstrong et al. 1982; Stevens and Armstrong 1984). An extensive amount of additional research funded by Washington Sea Grant, particularly a four-year program initiated in 1983, improved these preliminary estimates of population abundance in Grays Harbor and, for the first time, measured populations of crab along the southern Washington coast and in Willapa Bay (Armstrong et al. 1984; Armstrong et al. 1985; Armstrong and Gunderson 1985; Carrasco et al. 1985; Armstrong et al. 1986). Systematic surveys have indicated variable recruitment of young-of-the-year (YOY = 0+) juveniles to the nearshore area and consistent use of the estuaries by a major fraction of 1 year old (1+) juveniles in spring and summer of each year.

This study is part of a continuing effort by COE to investigate methods of reducing expected crab entrainment and mortality during project construction and future maintenance dredging. This investigation is the result of recommendations by the Crab Study Panel organized by COE to discuss the optimal course of action for avoidance or mitigation of potential crab losses during dredging in Grays Harbor (Pearson 1985). The panel anticipated that operational changes, particularly those involving scheduling, will have the greatest potential effect in reducing crab entrainment, and recommended that: 1) tests be run with a modified draghead; 2) crab population studies be conducted in fall and winter to evaluate movement and abundance of populations during seasons in which Sea Grant data were not available; and 3) that pilot studies be conducted to determine the feasibility of introducing intertidal shell habitat for juvenile crab as a mitigation technique. Previous work (Armstrong and Gunderson 1985) had shown a high degree of association between intertidal 0+ crab density and shell refuge.

This report covers the results of the recommended shell mitigation experiment and a field survey conducted to determine the extent and location of natural shell covered areas in Grays Harbor and the degree of utilization by 0+ crab. Specific objectives for these 2 tasks were as follows:

Shell Field Survey

1. Map the aerial distribution and amount of shell cover in Grays Harbor using a hovercraft vessel and conduct ground truthing to supplement previous helicopter surveys.

2. Determine the characteristics of shell cover best suited as crab habitat and monitor the utilization of this cover by juvenile Dungeness crab at several locations in Grays Harbor.

Shell Mitigation Experiment

1. Construct several test plots, each containing a different amount and/or configuration of shell at suitable locations in Grays Harbor, and monitor utilization by juvenile Dungeness crab.

2. Compare the results of the mitigation experiment with those from the shell field survey and develop cost estimates for a full scale mitigation effort based on crab utilization (i.e., cost per crab).

Data from previous Sea Grant intertidal surveys in 1983 and 1984 (Armstrong et al. 1984, 1985; Armstrong and Gunderson 1985) and subtidal surveys in 1985 (Armstrong et al. 1986) were utilized to place this information in the context of the total Grays Harbor crab population and to estimate the feasibility of a large scale mitigation project. The outcome of the fall and winter population study (Dumbauld et al. 1987), draghead modification experiments (McGraw et al. 1987), and studies to further quantify dredge entrainment of crab relative to trawl survey estimates (Dinnel et al 1986a; Dinnel et al. 1986b) are reported elsewhere. Results from all of these studies have been used in conjunction with the results of this study to produce a summary of the potential impacts of dredging on the Dungeness crab population based on a simulation of expected crab abundance and mortality due to dredging and natural causes (Armstrong et al. 1987).

2.0 METHODS AND MATERIALS

2.1 Shell Field Survey

2.1.1 Hovercraft and Helicopter Maps

Surveys of intertidal areas in Grays Harbor began in May 1985 with 4 trips aboard the hovercraft vessel R.V. Falcon (provided by Sea Lease, Inc.) at low tide. The hovercraft was used as a means of surveying and sampling areas otherwise inaccessible from land or by conventional small boat. Type of cover (predominantly shell and eelgrass) and estimates of percent substrate covered were recorded on a nautical chart as the vessel moved over intertidal areas. The use of transect lines to cover the entire bay, as initially designed, did not prove feasible due to topography (deep tidal creeks that could not be negotiated) and simple time/cost constraints. Therefore, cruises were designed to cover as much intertidal area as possible (Fig. 1) to supplement previous assessments made by University of Washington researchers from a helicopter in August 1984 (study funded by Washington Sea Grant and flights courtesy of the U.S. Coast Guard).

The hovercraft survey was followed by several reconnaissance trips with a 17' Boston Whaler during low tide series in May, June, and July 1985 to further document the extent of shell cover along navigable channels. Results from both of these surveys were compared and combined with those from the helicopter overflights. Helicopter flights followed east west transect lines separated by approximately 0.5 NM that covered the entire bay. Observations were made from approximately 15-30 m above the substrate and the visual field of view was estimated to cover about a 450 m swath. Type of cover and estimates of percent substrate covered were recorded on a nautical chart.

Measurements of eelgrass and shell cover from all of the surveys were grouped into four categories (heavy cover = >66%, moderate cover = ≥33% and ≤66%, light cover = >5% and <33%, and no cover = ≤ 5%) and used to create coverage maps. A digitizer provided by the National Marine Fisheries Service (NMFS) in Seattle was used to calculate total intertidal areas where each category of shell cover occurred in Grays Harbor. Areas were not calculated for eelgrass, based on preliminary findings of low crab density after initial settlement in all categories of eelgrass cover.

2.1.2 Transect Surveys

Line transect surveys were made on foot in order to equate spatial coverage estimates taken on the hovercraft and helicopter surveys with actual coverage as measured in routine crab sampling on the ground. Visual assessments of substrate cover were made using a .25 m^2 quadrat placed at 5 m intervals along several transect lines. The location of each line was randomly chosen within a representative area of each category of shell cover (as observed from the helicopter and hovercraft and recorded on the large scale map). Mean percent actual cover estimates derived from these surveys were applied as a correction factor to the calculated areas of each broad category of spatial coverage, to convert crab density measurements to total estuary population estimates (see Section 2.3).

2.1.3 Crab Survey and Site Selection

The hovercraft trips were also utilized as the first opportunity to sample intertidal populations of juvenile Dungeness crab throughout the estuary. Crab were sampled at 15 of 20 locations visited (Fig. 1) by excavating small areas (0.2 to 1.5 m^2) of substrate and associated cover (eelgrass, shell) to a depth of 2 to 5 cm. Contents were placed in a large dip net (3 mm mesh), rinsed, and sorted for crab. Several replicate samples were taken at each station.

The mean density of juvenile Dungeness crab sampled on the hovercraft trips is depicted in Figure 1. Settlement of the 1985 year class was in progress at the time of these trips since megalopae were also found in the intertidal samples and in even greater numbers in the water column (dip net samples taken in Westhaven Cove and in flotsam drift lines near the estuary mouth). All crab found were newly settled first instars. Densities ranged from 0 crab/m^2 on open mud and sand to 53 crab/m^2 in an area with moderate to heavy *Mya* shell cover, light eelgrass, and a rich benthic diatom fauna (Fig. 1).

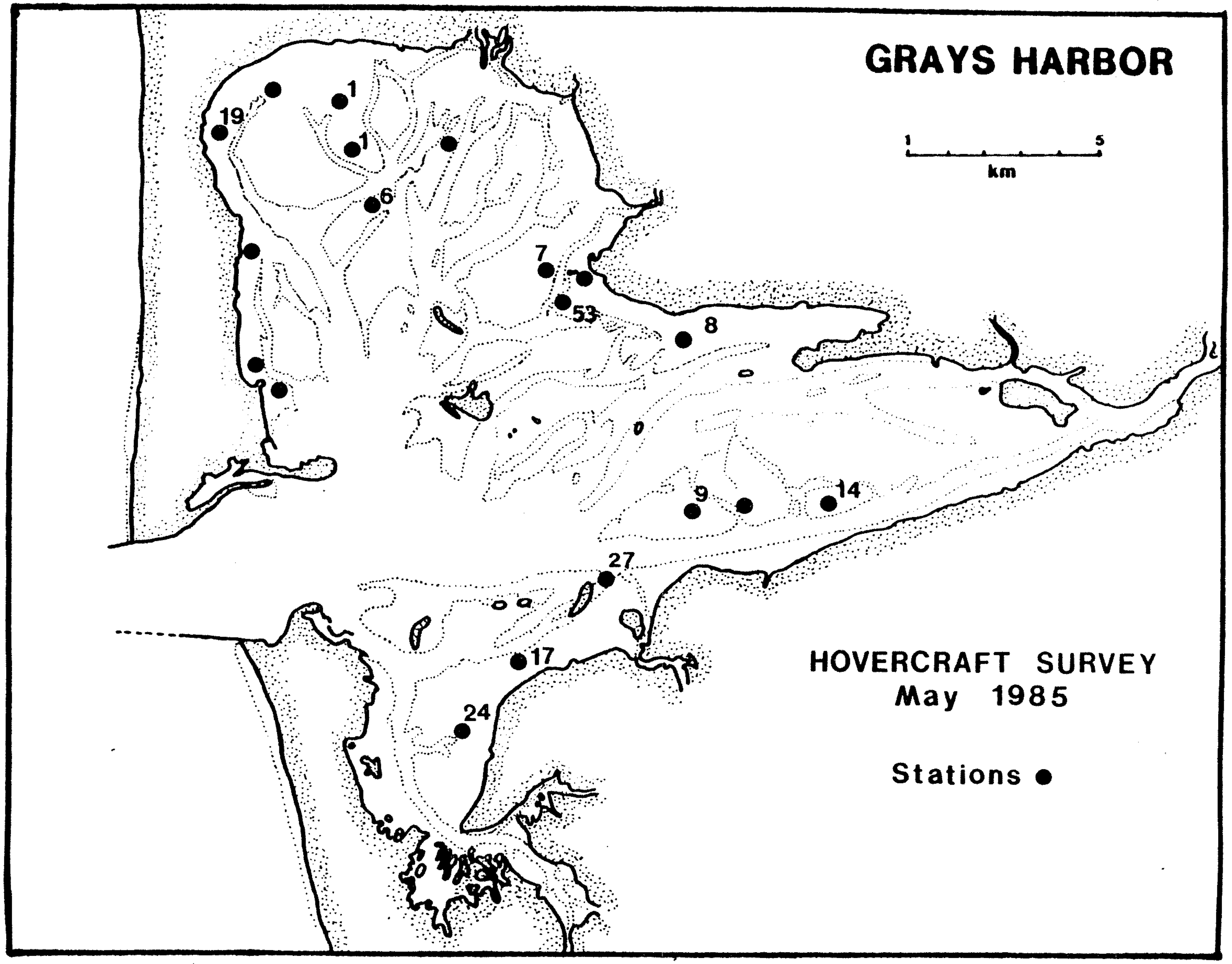

Figure 1. Locations visited by hovercraft in May, 1985. The mean density of Dungeness crab (number/m^2) is indicated at those stations where samples were taken. All crabs found were newly settled first instars.

These results were used to choose 3 stations for continued crab surveys and the experimental shell mitigation study (Fig. 2). Station 1 (South Channel Flats) was located at a site along the South Channel in an area of heavy Mya shell and high crab density. The site was located just west of a station sampled previously by the Sea Grant research team (Armstrong and Gunderson 1985). Station 2 (South Bay) was located on the edge of a commercial oyster bed in the South Bay with permission from Coast Oyster Company. Station 3 (Neds Rock) was located just south of Neds Rock in the North Bay in an area of dense Mya shell and rich diatom and algal cover where the highest density of crab was found in the hovercraft survey. Tide height was measured at each site in August 1986 using a hand held level and stakes to measure the difference between height at the site and that at low water and then interpolating between tabled values from the closest listed geographic location to get absolute height above MLLW. Station 2 was much lower (+0.8') than either Station 1 (+3.1') or Station 3 (+2.3'). All three sites had a variety of substrate cover available for sampling including open sand or mud where the experimental shell plots could be located.

Sediment samples were taken at all 3 stations in July 1985 and analyzed for volatile solids and particle size. Samples were taken from open areas where experimental shell plots were to be located. Sediments at all three sites were composed largely of sand (85% - 90%, Table 1). More silt was present at Station 2 than at the other 2 stations.

The abundance of juvenile crab was monitored at these three locations from May through September 1985, March through September 1986, and on one final occasion in August 1987 (total of 25 trips; Table 2). Between 5 and 20

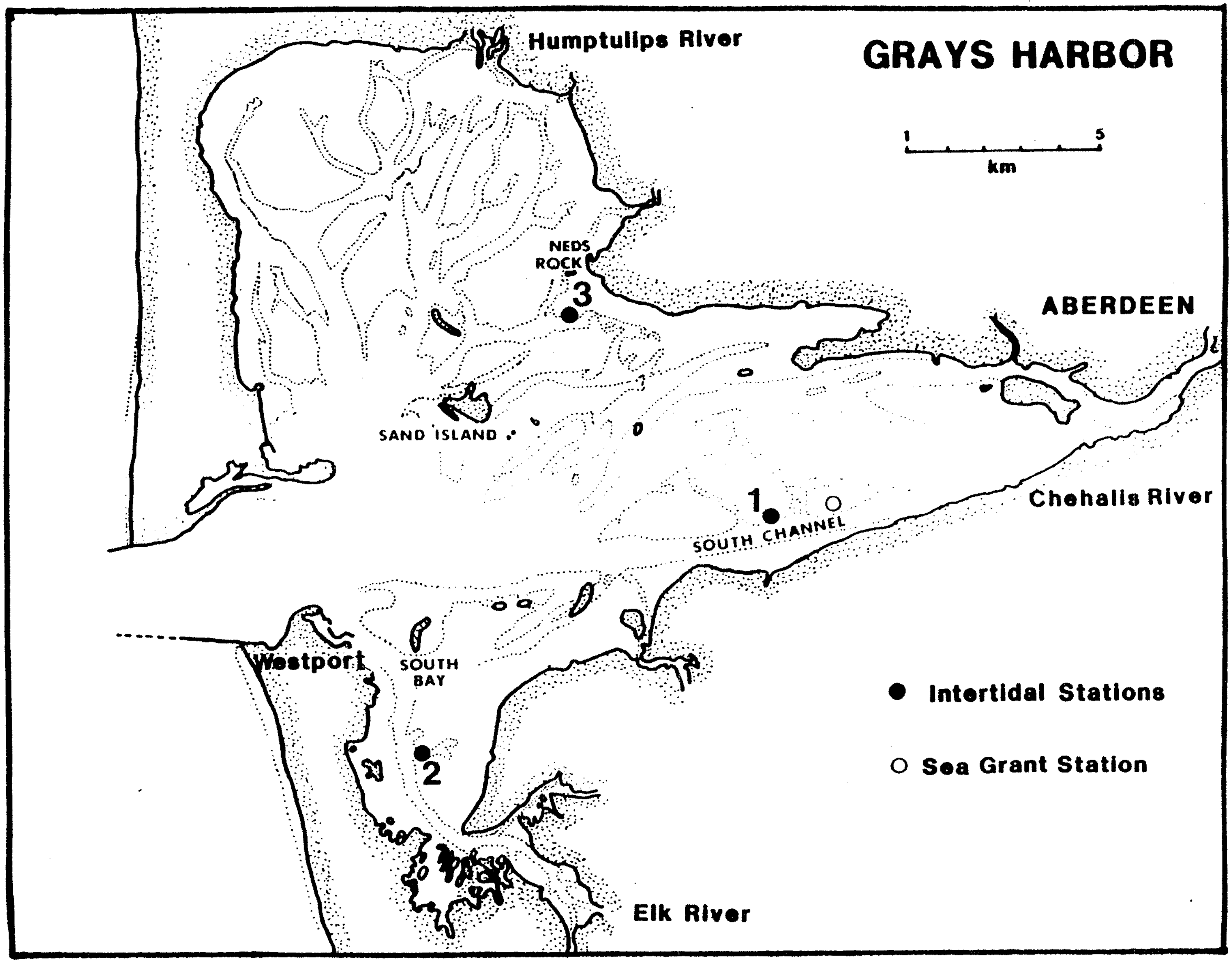

Figure 2. Station locations for the intertidal crab survey and shell mitigation experiment. Station 1 was located just west of a site along the South Channel visited by Sea Grant researchers in 1983 and 1984 (open circle). Stations 2 and 3 were located close to an oysterbed in the South Bay and just South of Neds Rock in the North Bay, respectively.

Table 1. Results of grain size analysis on sediment samples taken at the 3 locations chosen for the intertidal survey and experimental shell plots.

SEDIMENTS

Date	Station	%Dissolved Solids	%Gravel	%Sand	%Silt	%Clay
6/30/85	1	1.265	0.068	90.94	2.64	6.34
7/1/85	2	0.080	0.355	85.65	10.02	3.96
7/2/85	3	1.171	0.049	90.43	3.75	5.77

Table 2. Trip dates and total number of samples taken from experimental shell test plots and natural cover at all three stations during intertidal surveys in 1985, 1986, and 1987.

Dates	Number of Samples		
	Natural cover*	Plots	Total
1985			
5/6-5/8	48		48
5/19-5/20	9		9
6/4	5		5
6/19-6/21	21		21
6/30-7/2	31		31
7/18-7/19	16		16
7/30-8/2	20		20
8/14-8/17	31	2	33
8/28-8/30	26	18	44
9/13-9/16	18	12	30
9/27-9/29	22	6	28
Total	247	38	285
1986			
3/28-3/29	6	3	9
4/10-4/12	10	2	12
4/25-4/27	11	7	18
5/8-5/9	9		9
5/24-5/26	28		28
6/5-6/8	24	27	51
6/20-6/22	12	27	39
7/8-7/10	18	27	45
7/19-7/23	30	27	57
8/5-8/7	18	27	45
8/19-8/21	16	28	44
9/3-9/4	12	18	30
9/16-9/19	18	23	41
Total	212	216	428
1987			
8/9-8/11	24	36	60
Study Total	483	290	773

* "natural" cover was either the shell of the eastern softshell clam, *Mya arenaria*, at Stations 1 and 3 or live oysters, *Crassostrea gigas*, at Station 2.

samples were taken at each location on each trip following a stratified random sampling design. Sampling methods were standardized with the use of a 0.25 m^2 quadrat. The quadrat was randomly placed over shell until several samples had been taken from each of 4 categories based on a visual estimate of area covered by shell within the quadrat (no cover = $\leq$ 5%, light cover = >5% and <33%, moderate cover = $\geq$ 33% and $\leq$ 66%, heavy cover = >66%). A visual assessment of both shell and other forms of substrate cover within the quadrat was recorded before each sample was taken. The substrate and associated cover inside the quadrat was then excavated to a depth of 2 to 5 cm and placed in a dip net with 3mm mesh. The contents were rinsed and sorted for crab. The carapace width (CW) of each crab was measured to the nearest mm in 1985 and nearest 0.1mm in 1986 and sex was recorded for all crab measuring 15mm CW or more.

2.2 Shell Mitigation Experiment

This experiment was designed as a pilot study for a potential larger scale mitigation project to introduce shell in the intertidal as crab habitat. Cost estimates were kept in order to predict the economic feasibility of such an effort and are presented in Section 3.4.

2.2.1 Experimental Design

Previous observations on the suitability of naturally occurring clam shell (*Mya arenaria*) as crab habitat in the natural setting led us to investigate the use of shell from commercially harvested clams. Although we found a potential source of geoduck shell at no cost (King Clam, Tacoma

Washington), the scale of the pilot study alone led to prohibitive transportation costs and constraints on shell availability. The most convenient and therefore cost effective source of shell was the local oyster industry.

Three treatment plots were constructed at each location including: a) heavy shell cover (2 to several shells deep); b) light shell cover (1 shell deep or less); and c) a three dimensional pile configuration (Fig. 3). Each treatment plot measured 15 m on a side (225 m^2) and was separated from other plots by a 2 to 3 m strip with no shell.

A location with open mud and no natural shell cover was selected for construction of the experimental plots at each station. Each location was marked with stakes in order to dump shell at high tide. Oyster shell (2100 bushels) was purchased from Coast Oyster Company (Markham plant) in July 1985 and transported to the sites by oyster dredge at high tide. Seven hundred bushels of oyster shell were dumped over each site and spread by hand into the experimental arrangements (Fig. 3) during low tides in July and August.

2.2.2 Sampling Program

Preliminary sampling began on August 14, 1985 and continued through the last low tide series in September. The stations were visited to check for siltation and damage from winter storms in March 1986. A second plot was established on new and higher ground at Station 2 (S. Channel Flats) in June 1986, because of heavy siltation over the winter at the original site . A complete sampling program was initiated on June 7, 1986 after preliminary

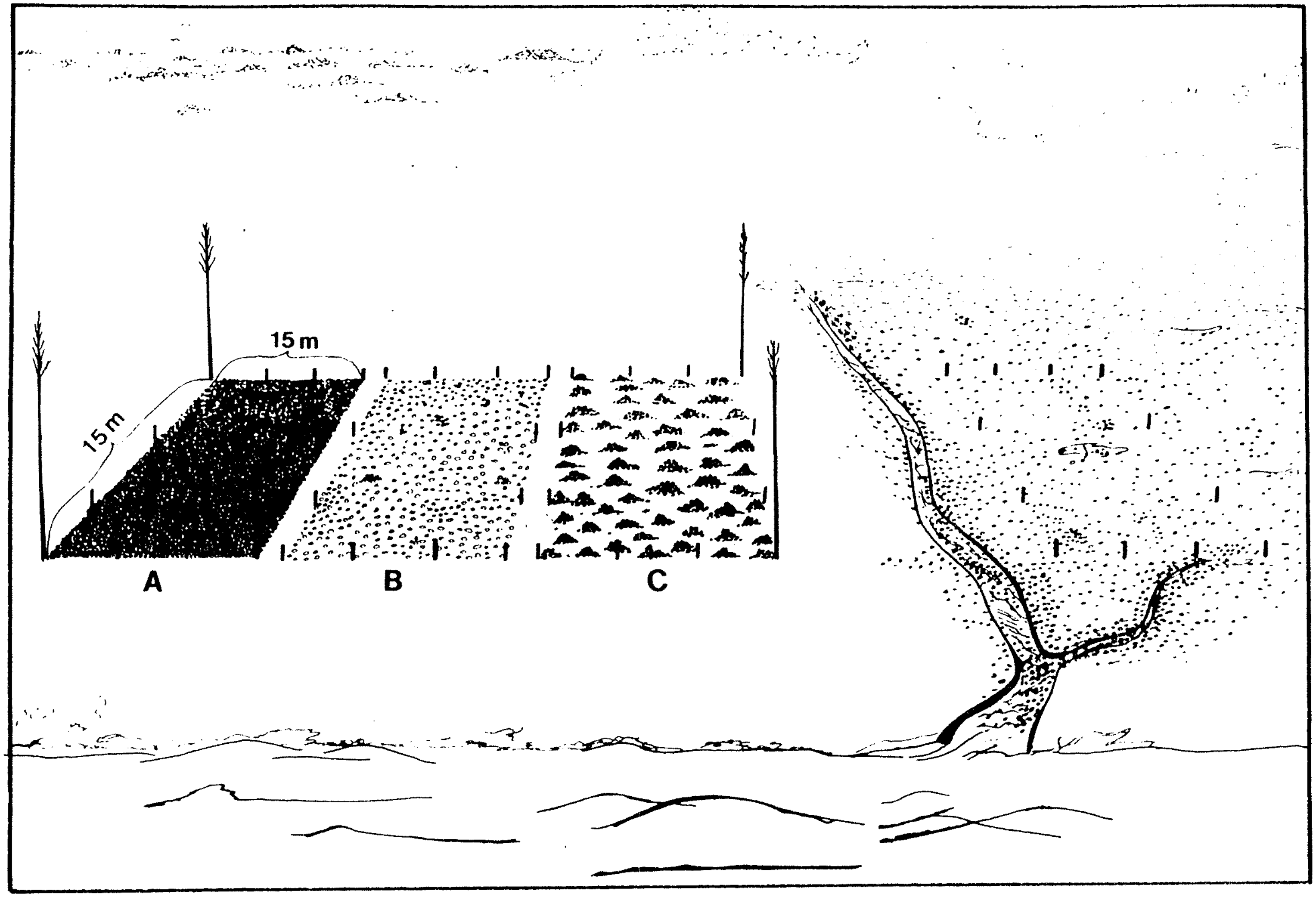

Figure 3. Schematic representation of the experimental shell plots at each station. Three treatment plots were constructed with oyster shell including: A) heavy shell cover; B)light shell cover; and C) a three dimensional pile configuration. Each treatment plot measured 15m on a side ($225m^2$) and was separated from the other plots by a 2 to 3m wide strip with no shell. Note naturally occurring Mya shell outside the plot, intertidal drainage channel on the right, and larger navigable channel in the foreground.

surveys of natural shell habitat indicated settlement of the 1986 year class had begun. Three samples were taken from each treatment plot at each station on a bimonthly basis during low tide series through September 1986. A grid of 0.25 m^2 blocks was established within each plot and sample locations were chosen randomly within the grid on each trip. Because of the proximity between samples and the potential for siltation and destruction of nearby plots by trampling, paths were set up within each plot and 1"x12"x8' planks were used to access areas between the paths. Samples were processed in the same manner as those for the regular intertidal crab survey described above (Section 2.1.3).

An additional trip to observe the condition of the experimental plots in the year after construction was made on August 9 through August 11, 1987. Four samples were taken from each treatment plot at each station to determine whether 0+ crab continue to use the plots in the year after construction. Visual assessments of the remaining shell cover were made using a 0.25 m^2 quadrat placed at 2m intervals along several transect lines across each shell plot.

2.3 Data Analyses

Data analyses were performed using database management and statistical software on an IBM microcomputer.

2.3.1 Crab Survey

The mean density of crab per unit area (m^2) was calculated for each category of actual shell cover by station and by trip. Analysis of variance procedures were then used to test for differences in mean density by location and by percent cover category and group the data for calculating population estimates. Because the data were not normally distributed, variances were not homogeneous, the design was often unbalanced, and the data was unsuited for higher level tests, non-parametric one-way Kruskall-Wallis tests and associated multiple comparison tests were used.

Because statistical test results were only conclusive for station differences (see results Section 3.1.2), new density estimates were calculated for Stations 1 and 3 grouped together. Density estimates were then combined with area estimates from the mapping survey and conversion factors from the transect surveys to produce intertidal population estimates for all of Grays Harbor as follows:

$$u_1 (a_1 c_1 + a_2 c_2 + a_3 c_3) + u_2 (a_4 c_4) = \text{population estimate}$$

where

u_1 is the mean density of crab (number/m^2) in *Mya* shell at Stations 1 and 3

u_2 is the mean density of crab (number/m^2) in oyster shell at Station 2

a_1 to a_3 represent the large scale areas of each of the 3 categories of *Mya* shell as derived from the helicopter/hovercraft mapping

a_4 is the area of ground covered by oyster shell as derived from the mapping survey

c_1 - c_3 are the correction factors for actual Mya shell cover estimated by transect surveys in 1986 (c_1 = light cover = 0.03, c_2 = moderate cover = 0.10, c_3 = heavy cover = 0.29)

c_4 is the correction factor for actual oyster shell cover estimated by transect surveys in 1986 (c_4 = 0.30)

Since crab were not sampled in oyster shell by Sea Grant researchers in 1983 and 1984, a mean monthly conversion factor was derived from 1985 and 1986 crab density information to convert from density in _Mya_ shell in 1983 and 1984 to that in oyster shell as follows:

mean density in oyster shell = mean density in _Mya_ shell * factor

where each factor represents the ratio of the mean density in oyster shell in 1985 and 1986 to the mean density in _Mya_ shell in 1985 and 1986 by month.

2.3.2 Shell Mitigation Experiment

The mean density of crab per unit area (m^2) was calculated for each treatment plot by station and trip. A non-parametric Kruskall-Wallis test and associated multiple comparisons test were used to detect significant differences in mean density between the 3 treatment groups (heavy shell, light shell, and piles).

3.0 RESULTS

3.1 Shell Field Survey

3.1.1 Hovercraft and Helicopter Mapping Surveys

Maps of shell and eelgrass, the 2 dominant forms of intertidal substrate cover in Grays Harbor, based on the results of the hovercraft survey in 1985, the helicopter survey in 1984, and ground truthing in 1985 and 1986 are presented in Figures 4 and 5. Digitized areas for shell cover were 548 ha, 817 ha, and 203 ha for light, moderate and heavy Mya shell respectively and 392 ha for oyster shell (Fig. 4). These estimates were used to derive population estimates for the estuary (see methods Section 2.3.1 and results Section 3.1.3).

The introduction of Pacific oysters, *Crassostrea gigas*, into Grays Harbor by the oyster industry has resulted in the presence of approximately 392 ha of shell and live oyster on state and privately owned lands (Figs. 4 and 6a). The location and extent of these areas shift periodically as the oysters are harvested, new seed is planted, and ground becomes unfavorable for culture. The majority of shell material found in all other areas was composed of shells from the eastern softshell clam, *Mya arenaria* (1,568 ha) and heaviest shell concentrations were found between the North and South Channels in the Inner Harbor (Figs. 4 and 6b). Shells from the cockle, *Clinocardium nutalli*, and smaller clams, *Macoma spp.*, were also present in some areas and a heavy deposit of shells from the horse clam, *Tresus capax*, was found on the south side of Sand Island. The total area covered by some

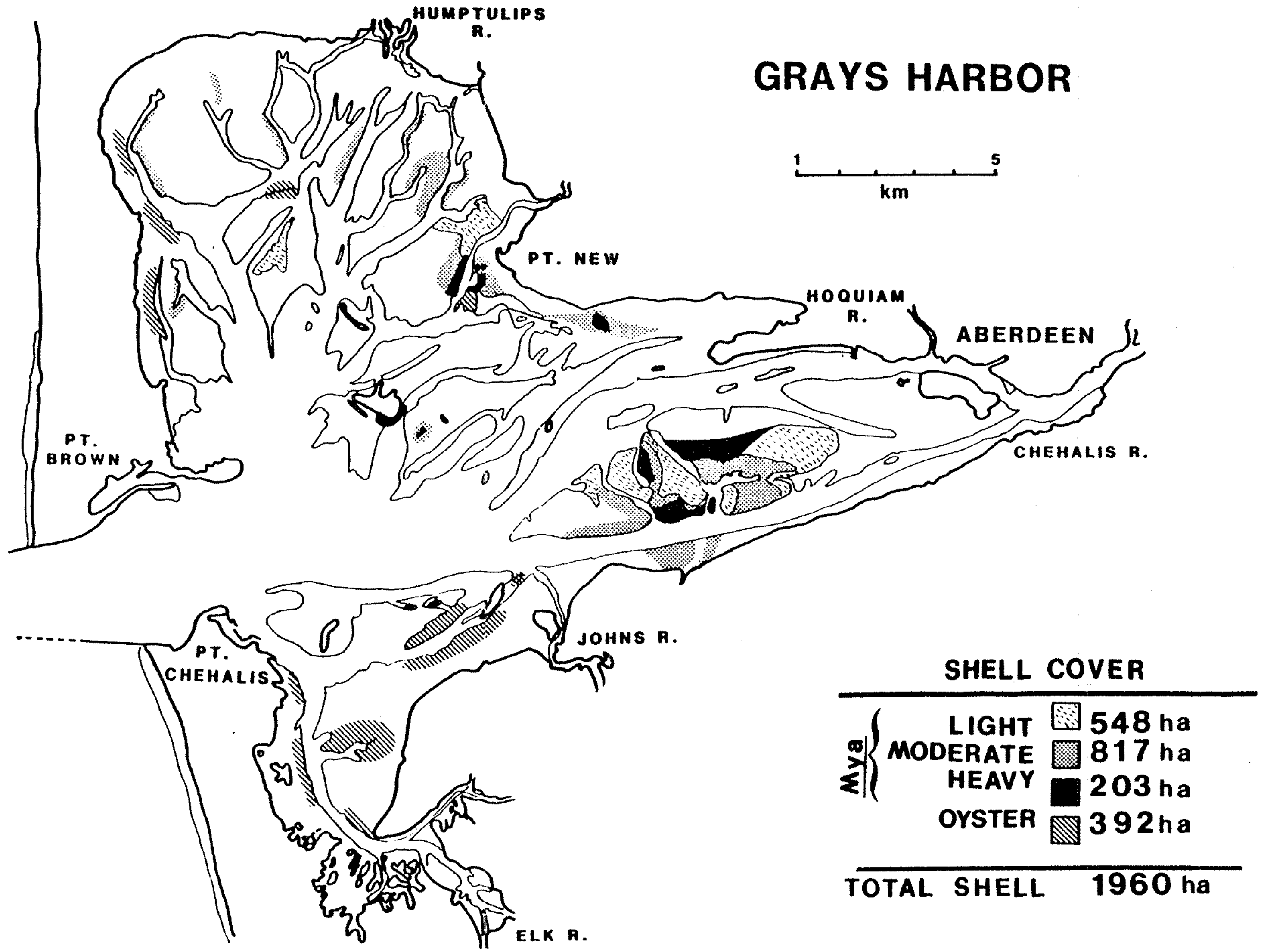

Figure 4. Map of shell substrate cover in Grays Harbor determined from helicopter overflights in August 1984, hovercraft survey in May 1985, and ground truthing in 1985. Area estimates were derived from digitizing this map. Shells of the eastern softshell clam, *Mya arenaria*, composed the major fraction of shell cover (1,568 ha) and were split into 3 categories of relative thickness. Oyster culture also contributed a significant amount of shell habitat (392 ha).

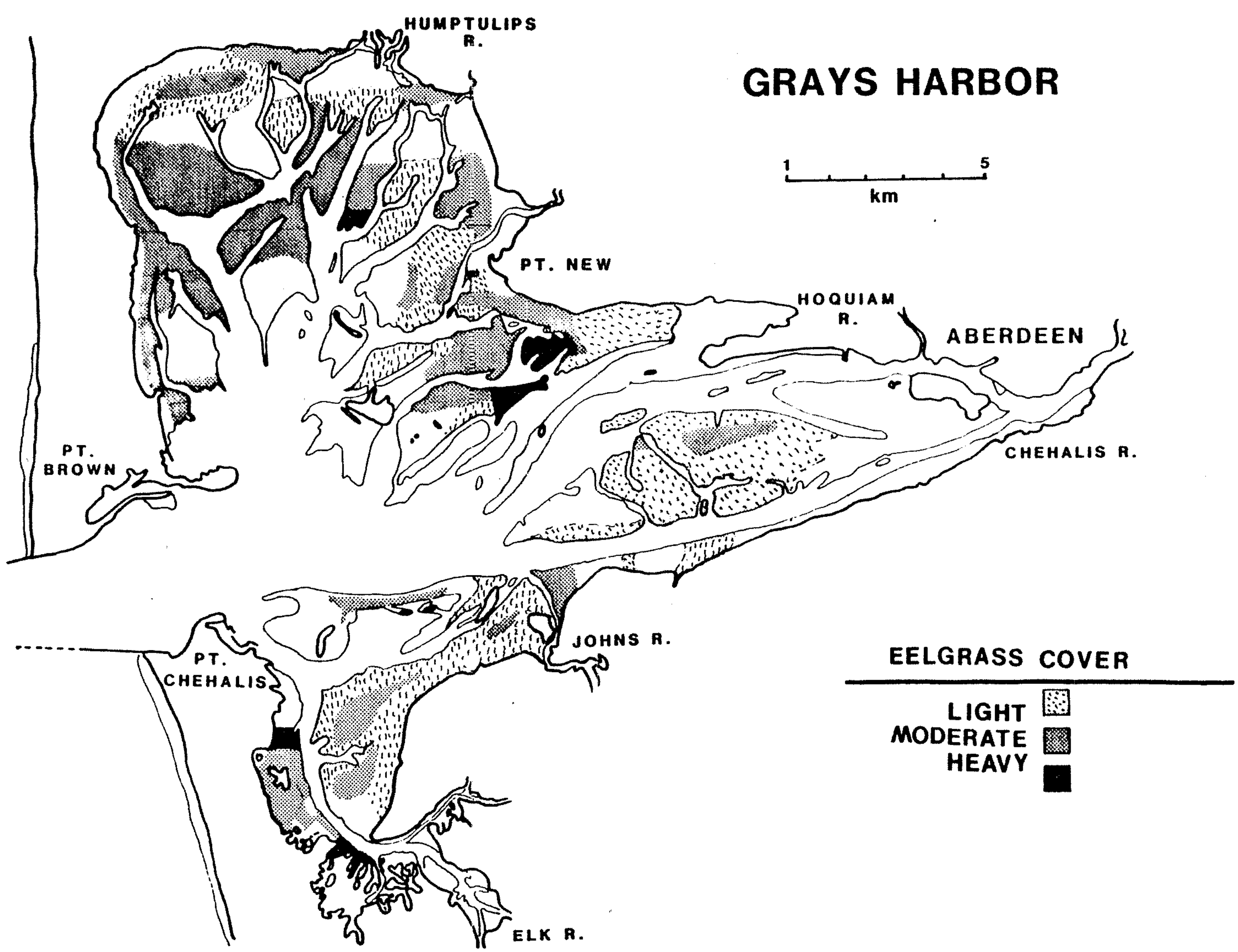

Figure 5. Map of eelgrass cover in Grays Harbor as determined from helicopter overflights in August 1984, hovercraft survey in May 1985, and ground truthing in 1985.

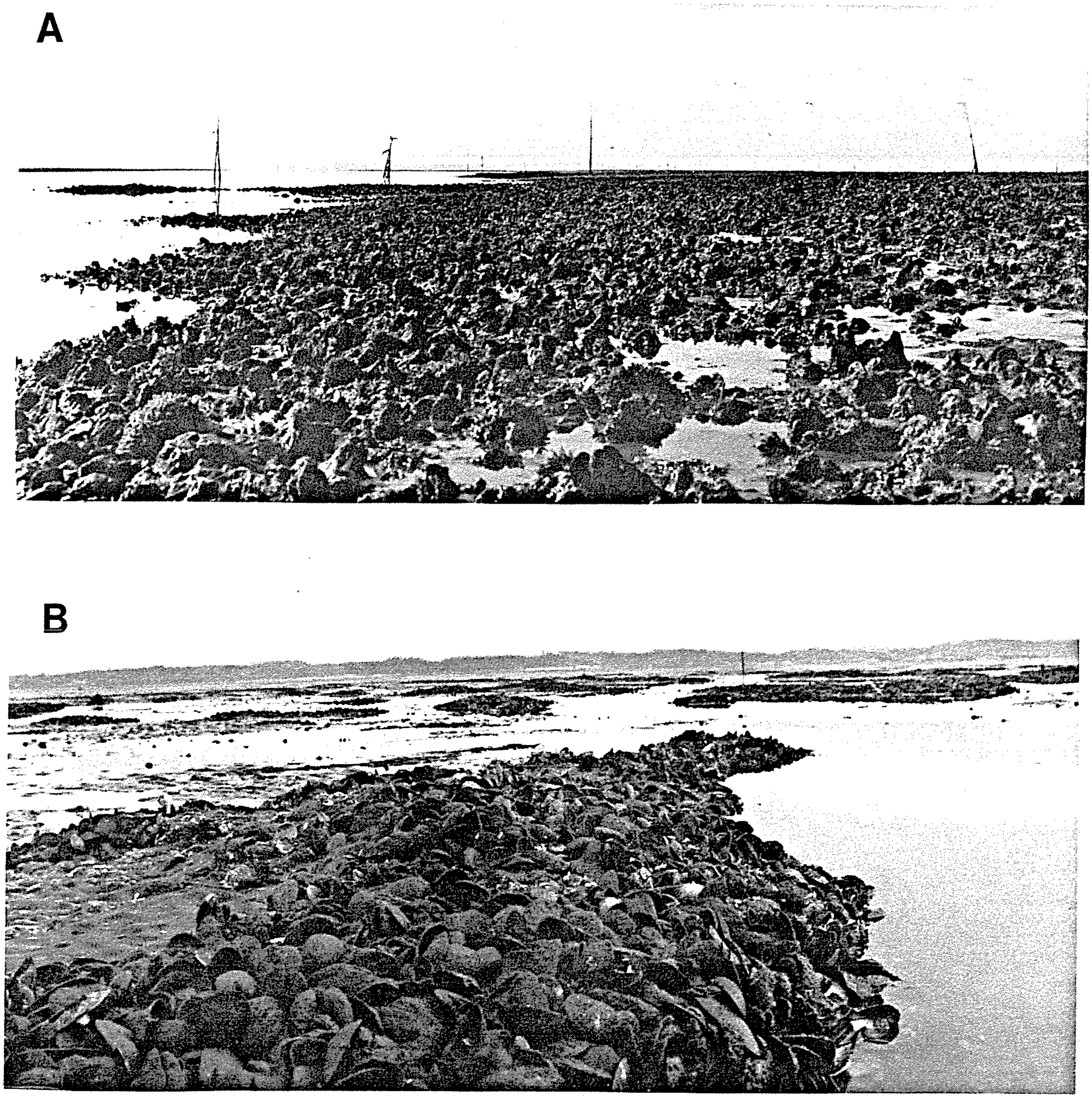

Figure 6. Intertidal shell substrate cover found in Grays Harbor consisted primarily of A) commercial live oyster beds Crassostrea gigas and B) shell deposits from the eastern softshell clam Mya arenaria.

form of shell (1,960 ha) represents about 19% of the total intertidal area in Grays Harbor as assessed from the helicopter (this value is not corrected for actual coverage determined from ground truthing, see Sections 2.1.2 and 2.3.1).

Eelgrass occurred in moderate to heavy densities over a more extensive area in Grays Harbor than did shell (Fig. 5). Zostera marina was the dominant form recorded, but Zostera noltii, a smaller bladed species, was found at higher tide levels near the perimeter of the estuary. Results from this survey were very similar to those of Smith et al. (1977) which showed eelgrass can cover up to 42% of the tideflats in Grays Harbor.

Macroalgae is also present in Grays Harbor and was generally found in association with eelgrass blades, shells, or other fixed substrate like wood debris. Several species were collected on the hovercraft trips (Table 3). Although these plants may provide cover for juvenile crab, attract potential invertebrate prey species, or serve as food themselves, we did not map their distribution due to their association with other fixed substrate cover early in the season and transient distribution as drift algae during the latter part of the sampling season. We did, however, record the presence of macroalgae in our regular intertidal crab samples.

3.1.2. Crab Density

The mean density of crab at each station (number/m^2) is given by trip in Table 4 and depicted in Figure 7. A significant difference was detected between mean crab density at Station 2 in the South Bay and that at the other

Table 3. Species of macroalgae identified from samples taken on the Hovercraft survey. Most of these algae were later found in samples taken at Neds Rock or in the South Bay, but were relatively scarce at station 1 along the South Channel.

Species	Occurrence and Relative Abundance
Polysiphonia hendryi var. deliquescens	common throughout the bay and very abundant at Station 3 (Neds Rock)
Enteromorpha crinata	attached to shells, also found in big mats later in the season
Enteromorpha linza	attached to shells
Monostroma sp.	attached to shell
Ulva fenestrata	common at both Neds Rock and in the South and North Bays attatched or associated with oyster beds and shell.
Sediment Diatoms	
Pleurosigma	very abundant
Achnanthea	very abundant
Navicula	
Synedra	
Cocconeis	
Melosira	

Table 4. Intertidal crab density estimates (number/m^2) in natural *Mya arenaria* shell cover at Stations 1 and 3 located along the South Channel and near Neds Rock, and oyster shell cover at Station 2 in the South Bay (all categories of shell cover combined; see Fig. 2. for locations).

DATE	STATION 1			STATION 2			STATION 3		
1985	MEAN DENSITY	SE	N	MEAN DENSITY	SE	N	MEAN DENSITY	SE	N
5/07	15.60	2.73	10	24.17	4.11	6	30.00	6.83	11
5/20	24.00	10.55	5	-*		0	-	-	0
6/04	28.00	10.43	5	-	-	0	-	-	0
6/20	16.89	6.34	9	7.00	2.18	4	14.00	5.23	6
6/30	30.67	12.04	9	5.45	1.87	11	11.50	3.27	8
7/19	11.33	7.08	6	3.50	1.49	8	-	-	0
8/02	9.20	3.88	11	2.40	1.01	10	17.33	5.76	3
8/16	8.73	3.67	11	1.71	0.75	7	11.56	4.24	9
8/29	8.00	3.44	10	0.00	0.00	7	10.67	4.49	9
9/14	6.29	2.12	7	3.33	1.47	6	15.20	6.34	5
9/29	6.29	2.83	8	3.00	0.94	8	10.67	5.05	6
1986									
3/28	6.67	2.18	3	-	-	0	1.33	1.09	3
4/11	4.00	1.41	4	2.67	1.09	3	2.67	1.09	3
4/26	4.00	1.89	3	4.00	3.46	4	1.00	0.87	4
5/08	0.00	0.00	3	6.67	2.88	3	2.67	1.09	3
5/25	2.91	1.16	11	0.00	0.00	6	1.45	0.58	11
6/06	6.50	3.16	8	2.29	1.27	7	5.33	0.77	6
6/21	14.40	2.15	5	-	-	0	14.00	3.62	6
7/09	8.00	5.25	6	0.00	0.00	6	3.00	1.66	4
7/20	11.79	1.38	19	0.80	0.72	5	4.80	2.09	5
8/06	5.33	0.77	6	1.33	0.77	6	2.40	0.88	5
8/18	9.33	3.36	6	1.14	1.06	7	21.33	1.09	3
9/04	4.67	3.04	6	0.80	0.72	5	-	-	0
9/17	8.80	4.44	5	0.50	0.47	8	0.00	0.00	2
1987									
8/10	14.00	3.29	8	0.50	0.50	8	15.00	2.10	8

* Some data is missing due to poor weather conditions and the use of some tide series for other tasks such as groundtruthing and plot preparation.

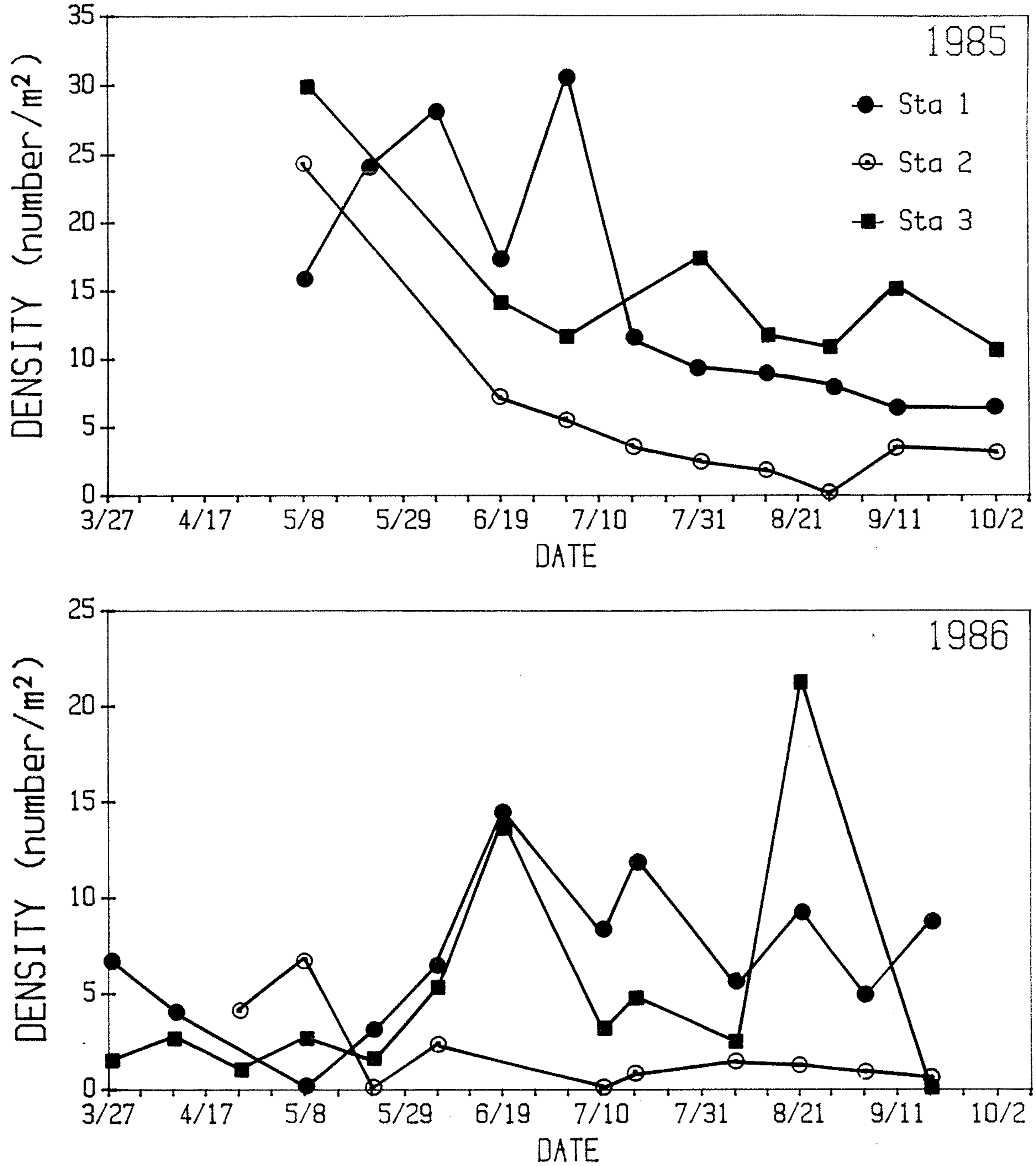

Figure 7. Comparison of mean density estimates (number/m^2) for 0+ Dungeness crab found in shell cover (all 3 percent cover categories combined) at each intertidal station in 1985 (top) and 1986 (bottom). Note the difference in numbers observed at initial settlement in May and June between years (density scale difference) and the consistently lower densities recorded in oyster shell at Station 2 in the South Bay.

two stations using non-parametric Kruskall-Wallis tests (Table 5). However, no difference could be detected between the mean density of crab at Stations 1 and 3. Further tests were run within these groups to look for differences between shell cover categories. A significant difference was found within both station groups, but the results of the multiple comparison tests were mixed showing a difference only between broader ranges of 0 to 33 percent shell cover and 33 to 100 percent cover and then only conclusively for shell at Stations 1 and 3 (Table 5).

Because significant differences were not consistently detected between crab density in the 3 categories of shell cover, densities shown in Table 4 and Figure 7 are calculated as means for all categories of shell cover combined to highlight temporal trends and differences between stations and years sampled. In 1985, two periods could be distinguished; 1) a period of initial settlement (May through mid July) when density was variable as crab settled in very large numbers, but also suffered rapid mortality and, 2) a period of more stable density as the surviving crab grew and left the intertidal (mid July through late September). Densities during the initial settlement period were a factor of 2 lower in 1986 than in 1985 (Fig. 7, note the scale difference in the 2 plots). Mean density values were lower at Station 2 in oyster shell after the initial settlement period in both years.

Density values from Mya shell cover at Station 1 along the South Channel during this survey were also compared to those from previous intertidal sampling at a similar location (Fig. 2) by Sea Grant researchers in 1983 and 1984 (Armstrong and Gunderson 1985; Armstrong et al. 1986). Initial settlement densities were an order of magnitude different from year

Table 5. Results of non-parametric Kruskall-Wallis analysis of variance tests to determine differences between crab density by station and further tests between shell cover categories. Multiple comparison test results are also indicated with a bar above factors with no detectable difference in mean rank.

Ho: crab density is the same for all factors (stations, shell types)

Factor	df	Test Statistic (H)	Tabled Value	Result	Multiple Comparisons Test (low - high)
Station (1,2,3)	2	41.44	5.991	Reject Ho	$\overline{2}\ \overline{1\ 3}$
Shell Type (H,M,L,N)*	3	69.14	7.815	Reject Ho	$\overline{N\ L}$, $\overline{L\ M}$, $\overline{H}$ (N L M H)
Shell Type at Stations 1 and 3	3	46.61	7.815	Reject Ho	$\overline{N\ L}\ \overline{M\ H}$
Shell Type at Station 2	3	23.45	7.815	Reject Ho	$\overline{N\ L\ M}$, $\overline{M\ H}$ (N L M H)

* H = heavy shell cover > 66%

M = moderate shell cover ≥ 33% and ≤ 66%

L = light shell cover > 5% and < 33%

N = no shell cover ≤ 5%

to year, but mean densities of crab found in shell from mid - July through September were very similar between years (Fig. 8, note the logarithmic scale). In May 1984, a mean density of 362 crab/m^2 was recorded at a station along the South Channel while the density recorded at Station 1 in May of 1986 was only 3 crab/m^2. By the first part of September however, these values had become 5 crab/m^2 in both years (Fig. 8).

The mean density of crab in natural Mya shell cover at Station 1 revisited in August 1987 was 14 crab/m^2 which is again comparable to previous years (Table 4, Fig. 8).

3.1.3 Transect Surveys and Population Estimates

Transect surveys to measure actual coverage of shell showed that within an oyster bed and within areas of Mya shell rated as heavy from the helicopter, the amount of actual ground covered by shell was approximately 30% of the total area (Table 6). Less than 10% of the ground was covered by Mya shell in areas recorded as having light to moderate cover when viewed from the helicopter. These values were used as correction factors to reduce the broad spatial estimates of shell cover based on aerial surveys (Fig. 4) to hectares of actual shell (Table 6). Population estimates for the entire intertidal region of Grays Harbor, derived from density estimates and these corrected area estimates, ranged from 1 billion crab in May 1984 to 18 million in June 1986, during the period of initial settlement (Table 7, Fig. 9, note the logarithmic scale). As was the case with density estimates, these numbers fell to a more narrow range of 8 to 20 million crab in August and September.

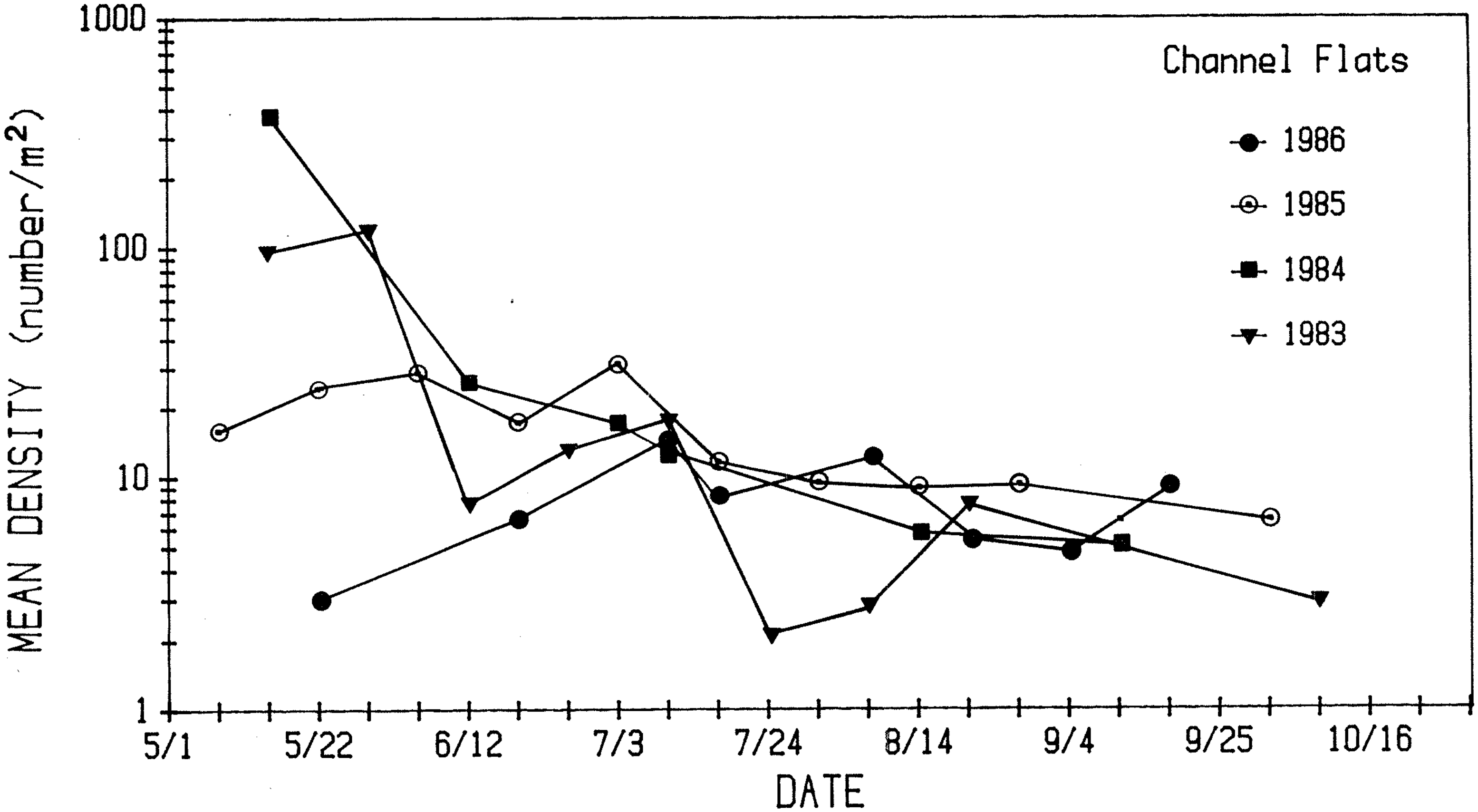

Figure 8. Comparison of mean density estimates (number/m^2) for juvenile Dungeness crab found at Station 1 along the South Channel in 1985 and 1986 (this study) and similar estimates from a nearby station (see Figure 2) sampled by Sea Grant researchers in 1983 and 1984. Note the log scale and therefore order of magnitude differences in density levels at initial settlement in May and June, but consistent values of 8 to 10 crab/m^2 by August and September.

Table 6. Results of transect surveys conducted in August 1986 to measure actual shell coverage within the 3 categories of cover used in helicopter and hovercraft mapping. Each mean cover estimate (X) is derived from (N) seperate transect survey estimates which were derived from a larger number of individual 1/4 m^2 cover observations. Also given are standard deviations for each estimate (SD), digitized aerial survey estimates of shell, and corrected estimates of actual shell in Grays Harbor.

Shell Cover Category	Transect Survey Estimates			Aerial Survey Estimate (ha)	Corrected Shell Estimate (ha)
	$\bar{X}$	N	SD		
Heavy *Mya* shell (cover > 66%)	0.29	4	0.04	203	58.9
Moderate *Mya* shell (33% ≤ cover ≤ 66%)	0.10	2	0.01	817	81.7
Light *Mya* shell (5% < cover < 33%)	0.03	4	0.01	548	16.4
Oyster shell	0.30	4	0.06	392	117.6

Table 7. Population estimates of Dungeness crab in the intertidal area of Grays Harbor derived from shell map (Fig. 4) and transect surveys (see Section 2.3). Crab population estimates for oyster shell, _Mya_ shell, and total shell are listed by month and year for 1983 through 1987. Values are expressed as millions of crab along with standard deviations (SD). Data for 1983 and 1984 are from previous Sea Grant surveys.

	Oyster		Mya		Total	
Month/Year	Mean	SD	Mean	SD	Mean	SD
5/83	*146.06	112.42	173.72	133.65	319.78	174.64
6	4.35	5.41	23.19	28.71	27.54	29.21
7	2.59	3.06	18.82	22.22	21.41	22.43
8	0.23	0.35	2.43	2.92	2.66	2.94
9	0.71	1.29	4.54	7.79	5.25	7.90
5/84	*494.27	239.41	587.65	284.66	1081.92	371.95
6	5.88	5.73	31.47	30.41	37.35	30.95
7	2.82	3.59	20.76	25.26	23.58	25.51
8	1.06	1.09	9.08	9.36	10.14	9.42
9	1.29	1.21	8.11	7.59	9.40	7.69
5/85	28.46	11.84	33.90	32.60	62.36	34.68
6	8.23	5.13	36.50	42.77	44.73	43.08
7	5.41	6.53	21.25	20.94	26.66	21.93
8	1.76	2.98	15.57	20.05	17.33	20.27
9	3.64	3.63	14.44	17.39	18.08	17.76
4/86	4.00	6.37	4.70	4.54	8.70	7.82
5	2.59	5.00	3.24	4.75	5.83	6.90
6	2.35	4.25	15.57	13.23	17.92	13.90
7	0.21	1.34	14.76	13.10	14.97	13.17
8	1.41	2.85	13.30	12.56	14.71	12.88
9	0.59	1.69	8.92	13.83	9.51	13.93
8/87	0.59	1.66	23.52	17.94	24.11	18.01

* No samples were taken in oyster shell in 1983 and 1984 so a mean monthly conversion factor based on 1985/1986 data was used to derive these estimates (see Section 2.3).

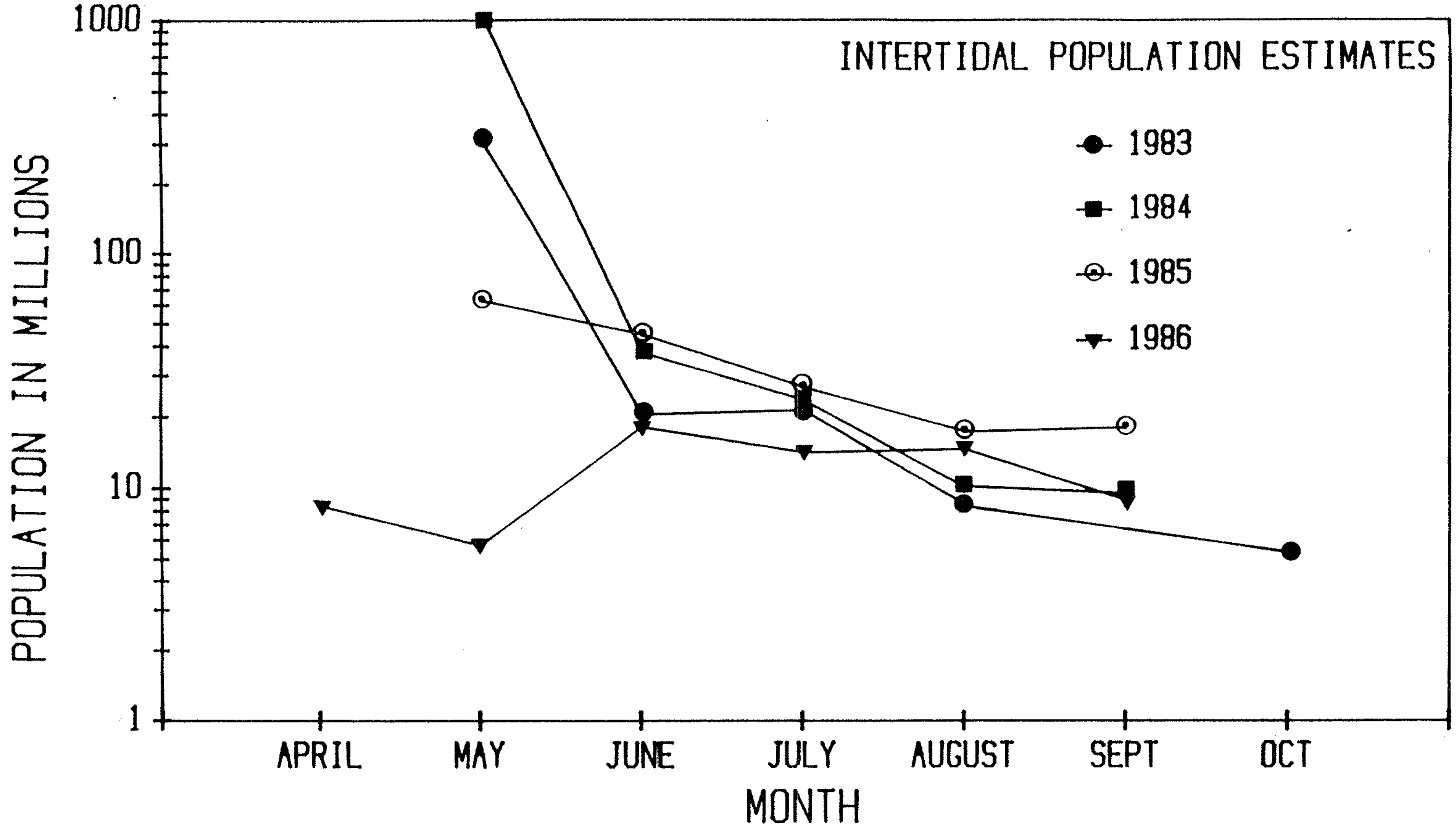

Figure 9. Comparison of population estimates for juvenile Dungeness crab in the intertidal areas of Grays Harbor from 1983 to 1986. Estimates were made using densities in Mya and oyster shell and aerial estimates for these cover types derived from the helicopter and hovercraft surveys (see Section 2.3, Fig. 4, Table 6 and Table 7). Note the log scale and order of magnitude difference in population levels at settlement in May and June, but relatively stable levels (10 million crab) reached in August and September of each year.

3.2 Shell Mitigation Experiment

3.2.1 Physical Integrity of the Experimental Plots

When first observed in March 1986 after overwintering, all experimental shell plots were in need of reconstruction to bring them back to the original experimental design. Shell plots located at Station 1 along the South Channel were covered with much more sediment than were plots at the other two locations. This was presumably due to their proximity to the channel and perhaps the higher tidal elevation at this location. It was felt that a new set of experimental plots should be set out at this location before settlement began if possible. Due to unavailability of the oyster dredge, this was not accomplished until June.

The heavy shell treatment appeared to survive the winter storms and daily tidal excursions in much better shape than did the light shell and particularly the pile configurations. Piles were rapidly spread out by the moving water and then accumulated sediment at a faster rate than the heavy shell treatment (Fig. 10). Some piles in the new plots (established June 1986) at Station 1 were completely flattened and spread out after one 24 hr period.

Similar results were observed on the final visit to the plots in August 1987. The heavy shell treatment survived best at all 3 locations. All three shell configurations were in best shape at Station 3 near Neds Rock where currents were apparently weaker and less sediment was deposited (Table 8). Shell plots at the original 1985 treatment site along the South Channel at

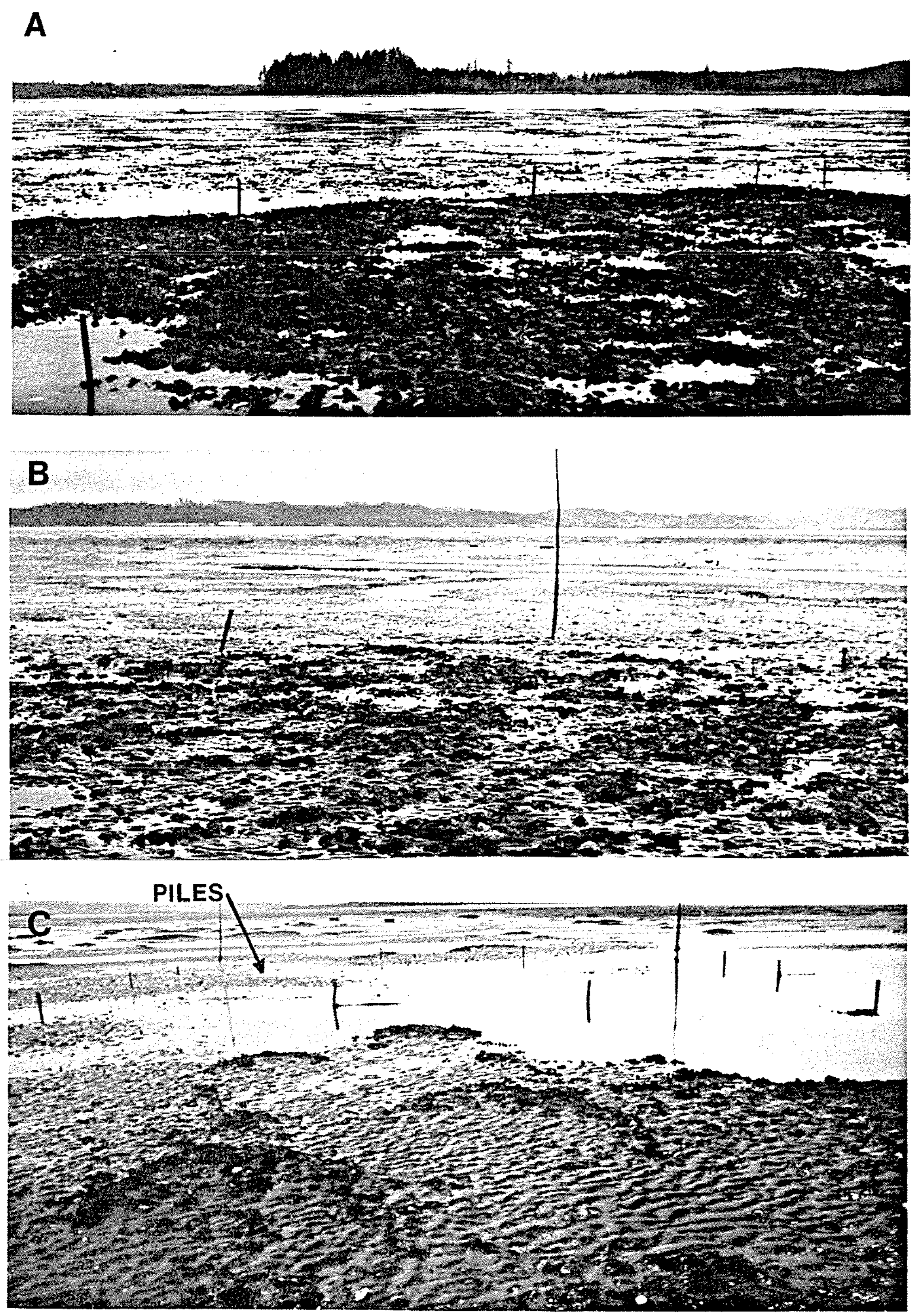

Figure 10. Examples of the physical integrity of experimental shell plots after overwintering: A) Shell was in relatively good shape in the heavy treatment at Station 3 near Neds Rock (July 85 construction viewed April 86). B) Large amounts of sediment covered the piles at Station 1 along the South Channel (July 1985 construction, viewed in May 1986). C) Shell was almost gone in the newly constructed (June 1986) heavy treatment at Station 1 when viewed in August 1987 (also note the piles configuration in the background which is completely devoid of shell).

Table 8. Results of transect surveys conducted in August 1987 to assess the condition of the experimental shell plots after overwintering. Also shown are mean crab density (number/m^2) observed in each plot and an estimate of the total number of crab found in each plot (number/225 m^2). Mean percent estimates were rounded to the nearest 5%.

STATION	TREATMENT	MEAN PERCENT SHELL COVER	MEAN CRAB DENSITY (number/m^2)	ESTIMATED TOTAL (number/225m^2)
#1 Old Plot (1985 Construction)*	Light shell	20	1	45
	Heavy shell	45	6	607
	Shell piles	20	6	270
#1 New Plot (1986 Construction)	Light shell	10	-**	-
	Heavy shell	25	4	225
	Shell piles	0	-	25
#2 (1985 Construction)	Light shell	5	1	11
	Heavy shell	40	0	0
	Shell piles	30	2	135
#3 (1985 Construction)	Light shell	30	2	135
	Heavy shell	80	8	1,440
	Shell piles	50	5	563

*Plots constructed in July 1985 were reconstructed to reflect original experimental conditions in April and May 1986.

**Samples not taken due to poor tide series and time constraints.

Station 1 were in better shape (more sediment, but less shell movement) than those at the new 1986 location further away from the channels (Fig. 10). Piles were completely gone at the new location and oyster shell had been spread over a wide area (1000 m^2). Transect surveys indicated that about 45% of the original area was still covered with useable shell habitat in the heavy shell treatment at the old location whereas only 25% of the area still had shell at the new location (Table 8). Similar surveys at Station 3 showed 80% of the original shell was still useable in the heavy shell treatment plot at that location.

3.2.2 Crab Density

Crab density estimates for each station and shell configuration used in the mitigation experiment are presented by trip in Table 9. Because the period of high initial settlement of 0+ crab had ended by the time plots were constructed in late July and August 1985, most of the crab found in the plots at this time were assumed to have moved in from surrounding areas. A single first instar crab was found in the pile configuration at Station 2 on August 28 and several second instar crab were found at all 3 stations in September, indicating some late season settlement (Table 9).

The presence of crab on the plots in March and April before settlement of the 1986 year class had occurred, demonstrated that some crab from the 1985 year class continued to use the shell plots through the winter (Table 9). Settlement did not occur as early and was not as heavy in 1986 as had been observed in 1985 and previous years (Fig. 8). Small numbers of 1st instar crab were noted outside the plots at the end of May, but no samples

Table 9. Intertidal crab density estimates (number/m^2) in experimental oyster shell plots (see Fig. 3). Data are listed by trip date for 1985 and 1986. Also shown are density estimates for single trip in August 1987.

STATION	DATE	HEAVY SHELL MEAN DENSITY	HEAVY SHELL SE	HEAVY SHELL N	LIGHT SHELL MEAN DENSITY	LIGHT SHELL SE	LIGHT SHELL N	PILES MEAN DENSITY	PILES SE	PILES N
#1	8/16/85	16.0	0.0	1	-	-	0	4.0	0.0	1
	8/29	6.0	1.4	2	2.0	1.4	2	14.0	4.2	2
South	9/14	5.3	2.2	3	0.0	0.0	2	4.0	3.3	3
Channel	9/29	6.0	4.2	2	2.0	1.4	2	10.0	1.4	2
	3/28/86	12.0	0.0	1	-	-	0	-	-	0
	4/11	6.0	1.4	2	-	-	0	-	-	0
	4/26	4.0	1.9	3	-	-	0	-	-	0
	6/06	6.7	2.9	3	4.0	3.3	3	12.0	1.9	3
	6/21	22.7	7.6	3	5.3	2.2	3	58.0	4.2	2
	7/09	18.7	1.1	3	1.3	1.1	3	17.3	6.6	3
	7/20	21.3	6.6	3	2.7	1.1	3	62.7	7.9	3
	8/06	9.3	2.9	3	2.7	2.2	3	26.7	3.9	3
	8/18	32.0	5.0	3	10.7	2.2	3	25.0	6.2	4
	9/04	8.0	3.3	3	2.7	2.2	3	8.0	1.9	3
	9/17	9.3	1.1	3	4.0	2.8	2	12.0	2.3	5
	8/11/87	6.0	3.5	4	1.0	1.0	4	6.0	1.2	4
#2	8/16/85	0.0	0.0	1	-	-	0	12.0	0.0	1
	8/29	4.0	0.0	1	8.0	3.3	3	20.0	2.8	2
South Bay	9/14	4.0	0.0	1	-	-	0	16.0	0.0	1
	4/26/86	0.0	0.0	1	-	-	0	-	-	0
	6/06	1.3	1.1	3	1.3	1.1	3	9.3	3.9	3
	6/21	1.3	1.1	3	1.3	1.1	3	2.7	2.2	3
	7/09	0.0	0.0	2	1.3	1.1	3	5.3	2.2	3
	7/20	1.3	1.1	3	4.0	1.9	3	4.0	3.3	3
	8/06	4.0	0.0	3	2.7	2.2	3	1.3	1.1	3
	8/18	0.0	0.0	3	0.0	0.0	3	2.7	2.2	3
	9/04	0.0	0.0	3	0.0	0.0	2	2.7	2.2	3
	9/17	2.0	1.4	2	2.0	1.4	2	0.0	0.0	2
	8/10/87	0.0	0.0	4	1.0	1.0	4	2.0	1.2	4

Table 9 (cont.)

STATION		HEAVY SHELL			LIGHT SHELL			PILES		
	DATE	MEAN DENSITY	SE	N	MEAN DENSITY	SE	N	MEAN DENSITY	SE	N
#3	8/29/85	0.0	0.0	2	0.0	0.0	2	14.0	1.4	2
	9/14	16.0	0.0	1	-	-	0	8.0	0.0	1
Neds Rock	3/28/86	0.0	0.0	1	-	-	0	8.0	0.0	1
	4/26	1.3	1.1	3	-	-	0	-	-	0
	6/06	4.0	1.9	3	0.0	0.0	3	5.3	2.9	3
	6/21	13.3	2.9	3	4.0	0.0	3	14.7	1.1	3
	7/09	4.0	1.9	3	2.7	2.2	3	13.3	1.1	3
	7/20	4.0	2.8	2	0.0	0.0	3	10.7	3.9	3
	8/06	4.0	1.9	3	1.3	1.1	3	9.3	4.8	3
	8/18	13.3	10.9	3	8.0	3.8	3	14.7	6.6	3
	9/04	-	-	0	-	-	0	-	-	0
	9/17	0.0	0.0	3	0.0	0.0	3	8.0	3.3	3
	8/9/87	8.0	4.3	4	2.0	2.0	4	5.0	1.0	4

from the plots were taken in that month. Throughout the summer, no consistent large peak in crab abundance within the plots was observed, but many small peaks coincident with settlement occurred (Fig. 11).

Crab continued to use the available shell habitat left in the experimental plots after another winter and early summer settlement season in 1987. Mean densities of 0 to 8 crab/m^2, realized after the initial settlement period in August 1987, were comparable to those observed in August 1986 (Table 9).

As was the case with natural cover, there appeared to be a consistent difference in crab density between stations, with generally higher densities observed at Stations 1 and 3 (Fig. 11). It thus became apparent that at least one controlling factor in intertidal crab abundance was something other than cover, because this difference occurred between plots with the same shell configuration at all three stations (particularly in the heavy shell and pile treatments, Fig. 11). Except for an early peak in June, the density of crab at Station 2 in the South Bay was always less than 5 crab/m^2 whereas at Stations 1 and 3 density was often greater than 10 crab/m^2, particularly in the heavy shell and pile treatments where peaks as high as 60 crab/m^2 were observed.

A consistent difference between treatments was found to be statistically significant using a Kruskall-Wallis nonparametric analysis of variance procedure (Table 10, Fig. 12). A subsequent multiple comparisons test showed a significant difference between the light shell and pile treatments but inconclusive results for the heavy shell treatment. When the

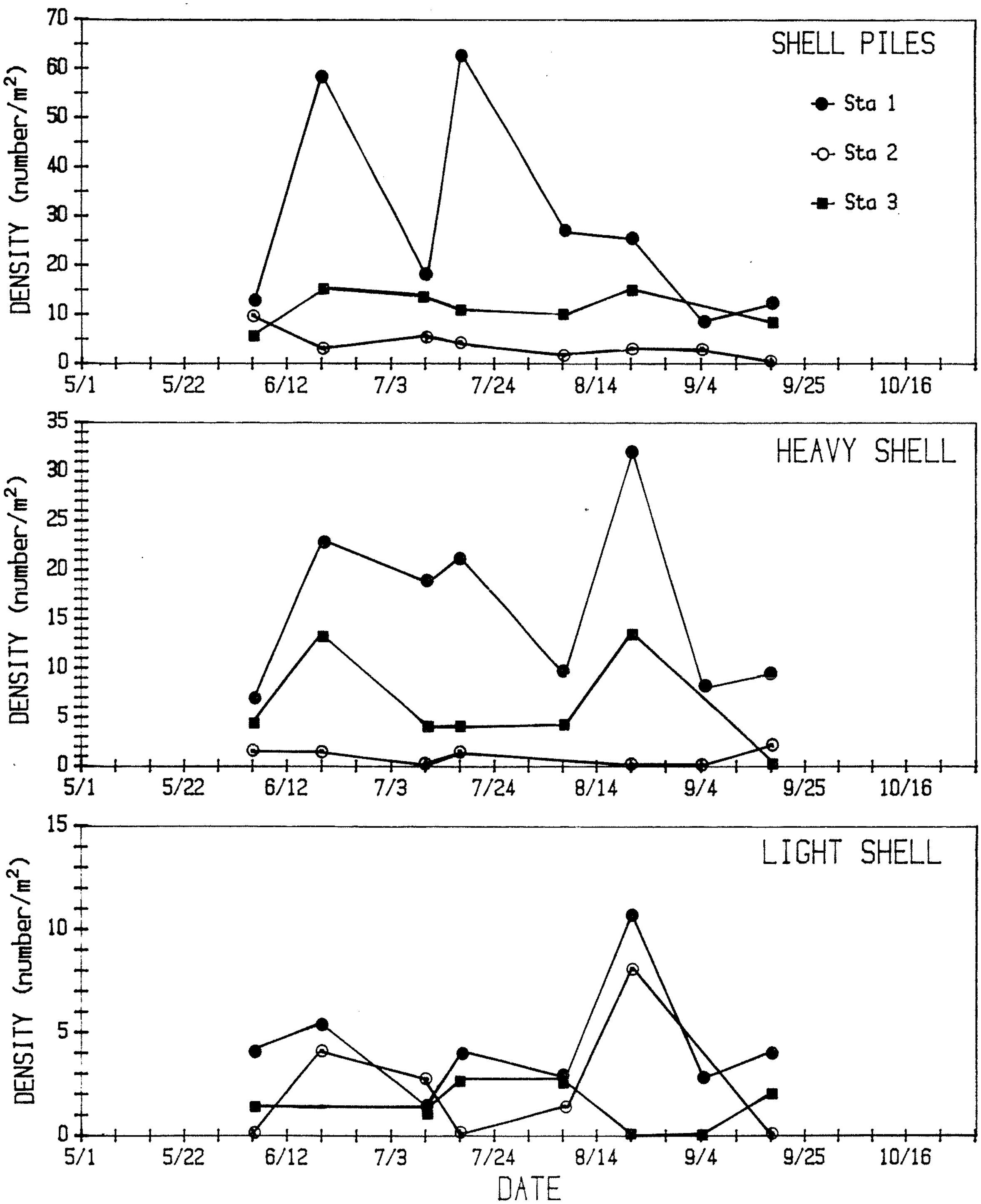

Figure 11. Comparison of mean crab density (number/m^2) at three station locations in 1986, shown separately for the piles treatment (top), heavy treatment (middle), and light treatment (bottom). Note the density scale difference and the lower densities observed at Station 2 in the South Bay in all treatments.

Table 10. Results of non-parametric Kruskall-Wallis analysis of variance tests to determine differences between crab density by treatment group. Multiple comparison test results are also indicated with a bar above factors with no detectable difference in mean rank.

Ho: crab density is the same for all treatment groups

Factor	df	Test Statistic (H)	Tabled Value	Result	Multiple Comparisons Test* (low - high)
Treatment Group	2	14.8	7.815	Reject Ho	$\overline{\text{L H}}$ $\overline{\text{H P}}$
Treatment Group at Stations 1 and 3	2	18.3	7.815	Reject Ho	$\overline{\text{L}}$ $\overline{\text{H P}}$
Treatment Group at Station 2	2	5.7	7.815	Cannot Reject Ho	

* P = piles treatment
H = heavy treatment
L = light treatment

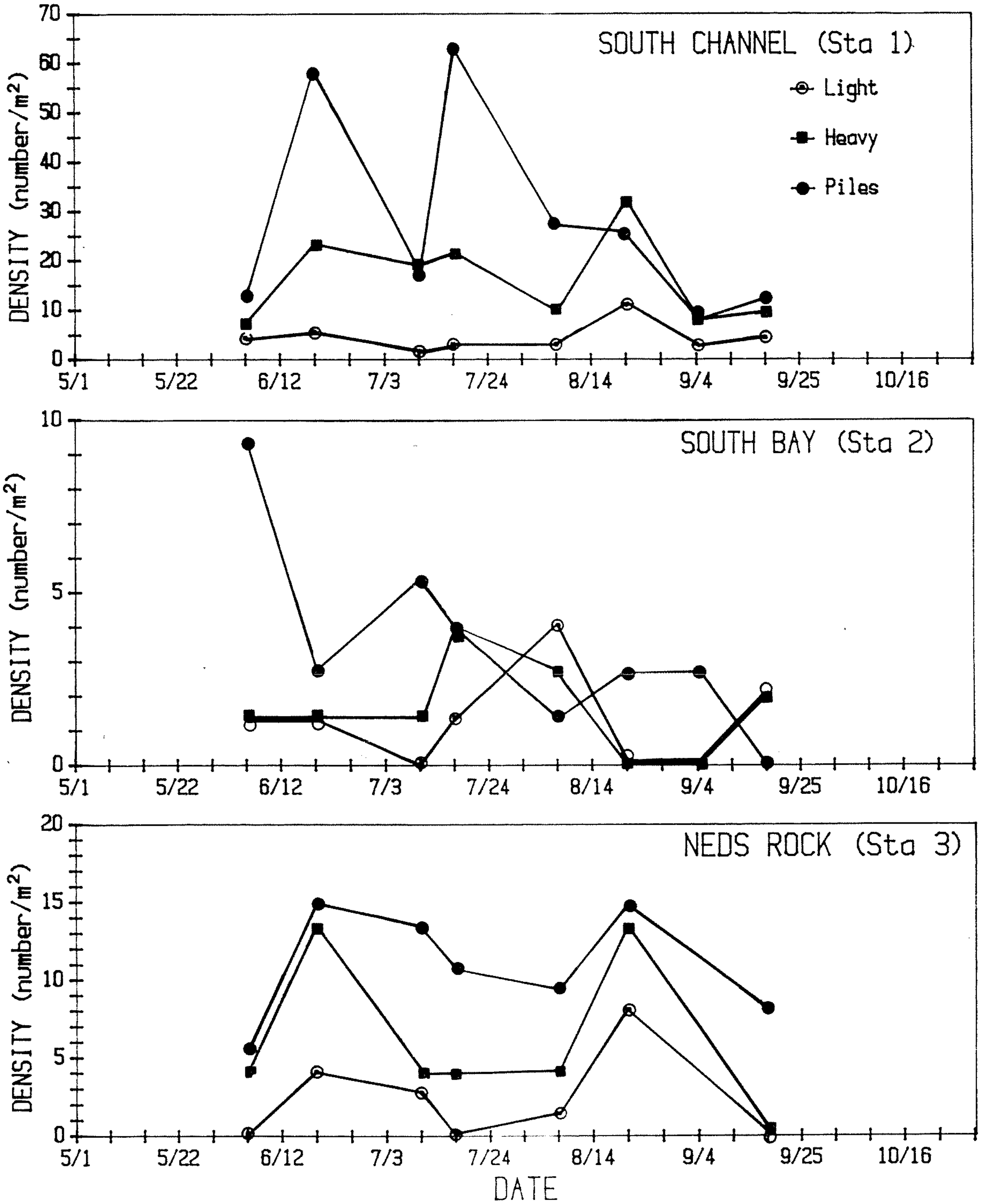

Figure 12. Comparison of mean crab density (number/m^2) in the three experimental shell treatments at each station in 1986. Note the density scale differences and generally higher densities recorded in piles and heavy treatments than those in light treatments at each of the 3 stations.

same test was performed on data from Station 2 alone, differences between treatments were not significant (Table 10). Both the heavy shell treatment and pile treatment were shown to be statistically separable from the light shell treatment at Stations 1 and 3.

The highest densities recorded on the final visit to the plots in 1987 were also at Stations 1 and 3 and in the heavy shell and piles treatments as previously observed. Because the physical integrity of the heavy shell treatment was left the most intact, greatest densities per total plot area (225 m^2) were observed in the heavy shell configuration at all stations (Table 8).

3.3 Size Composition

With the exception of 7 animals, all crab caught in the intertidal were 0+ crab less than 50mm CW. The male:female sex ratio was 51:49 for those animals over 15mm CW that were sexed. The length frequency distributions for crab sampled in the experimental plots and for those taken outside the plots over the whole season were very similar, suggesting the experimental plots were attracting the same size crab as natural shell areas (Fig. 13). The mean carapace width for the entire sampling season was 15.9mm, 17.3mm, and 15.2mm respectively for crab sampled inside the plots in 1986, outside the plots in 1986, and outside the plots in 1985. The larger mean observed in areas outside the plots in 1986 appeared to be due to mean widths of 26 to 33 mm in March and April representing crab that had settled late in 1985 and overwintered in the intertidal. Carapace widths of crab from inside the plots and outside the plots were combined for all further analyses.

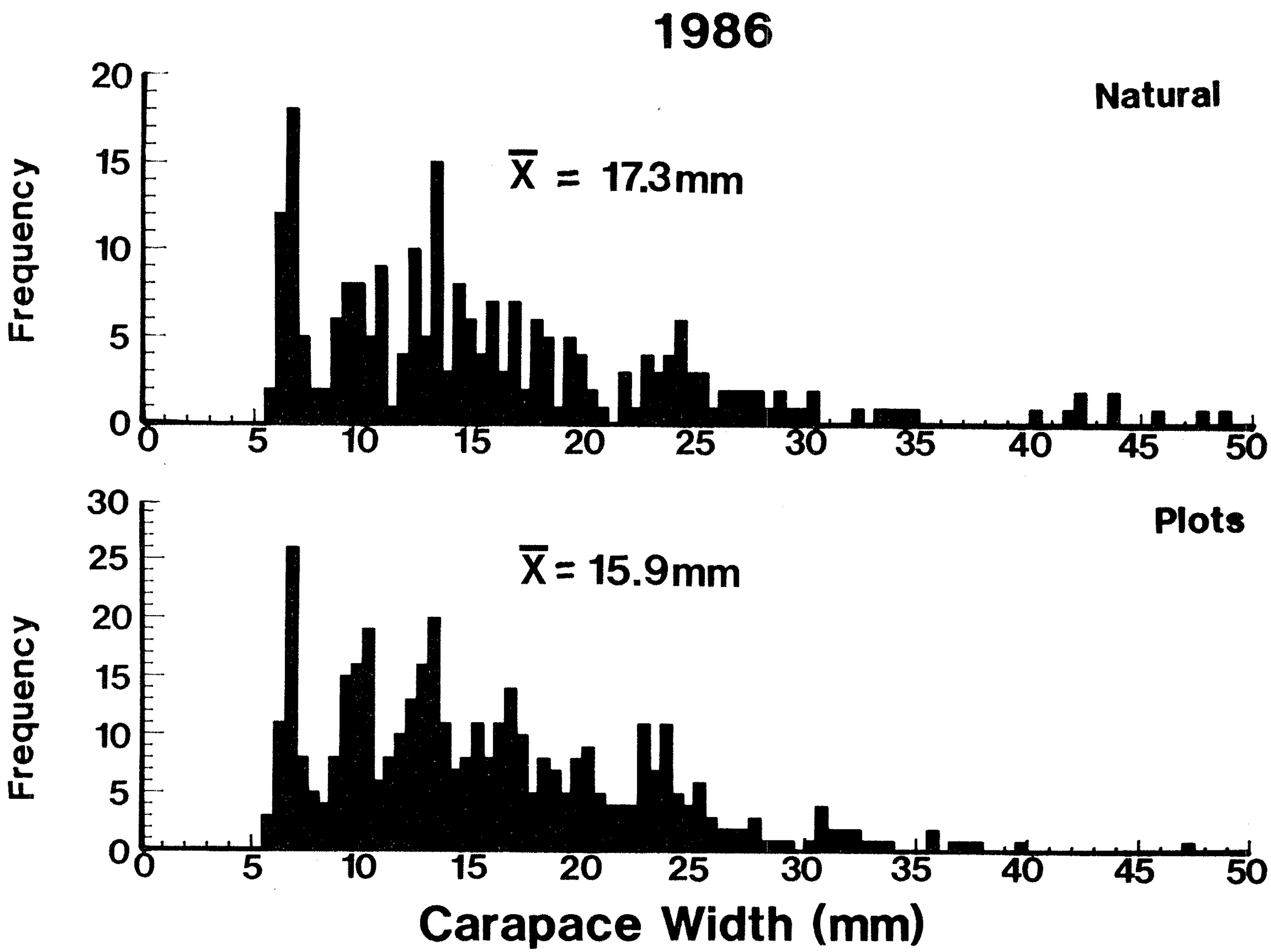

Figure 13. Comparison of size composition for Dungeness crab sampled in the experimental treatment plots and those in natural _Mya_ and live oyster shell outside the plots in 1986. Data for the entire 1986 sampling season are combined.

Although the density of crab sampled in 1985 was greater than that in 1986, patterns in length frequency distributions were very similar between years (Fig. 14). Settlement was recorded in May of both years, although crab were not measured in 1985. By the second half of June in both years, at least some of the crab that had settled in May had already reached the third instar (mean CW of 13mm). One month later in July, these crab had reached what appears to be the fifth instar (mean CW of 22mm) and by August had molted again to a mean of about 33mm CW (Fig. 14). Crab greater than 40mm CW were very rarely found, and it appears migration of these larger crab to the subtidal was taking place as early as mid July.

3.4 Cost Analysis

A simple cost analysis was performed using actual costs incurred during this pilot study, cost estimates from discussion with the oyster growers, and some information from a preliminary analysis done for the Crab Study Panel meeting in 1984 (see analysis by Fassbender, Appendix C in Pearson, 1985).

One of the first and most tenuous steps in developing a cost appraisal for a full scale mitigation program was to estimate the number of crab that would be necessary as replacements for those lost to dredge entrainment, because dredging primarily impacts 1+ and 2+ crab (Armstrong et al. 1987) while shell mitigation is directed at 0+ crab. For this analysis we have chosen to use the best and worst case figures for relative loss at age 2+ from a model of dredging impact in Grays Harbor (Armstrong et al. 1987). These figures represent the highest and lowest estimates of the equivalent

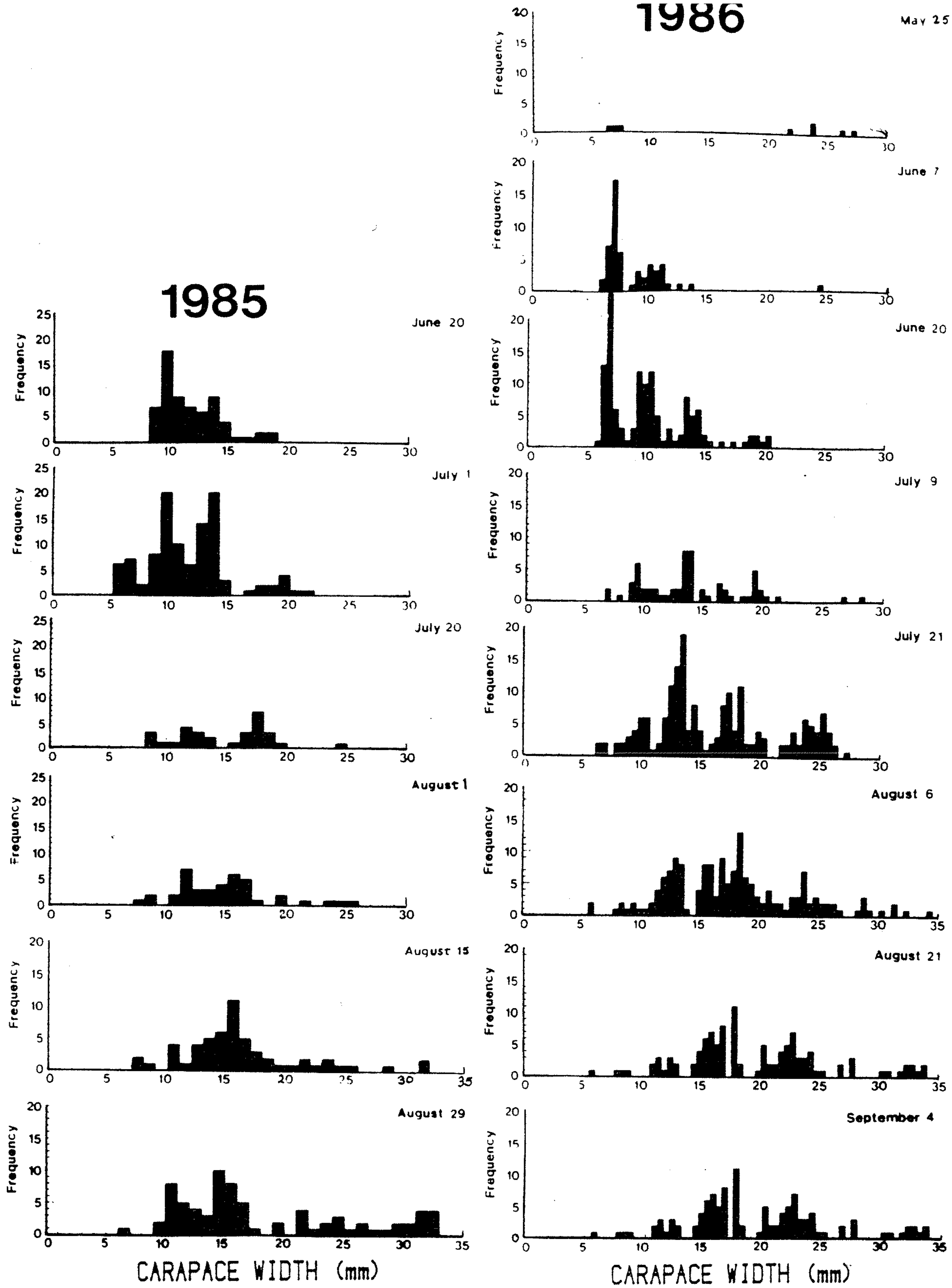

Figure 14. Size composition of intertidal Dungeness crab population in 1985 and 1986. Note that carapace width was measured to the nearest 1mm in 1985 and nearest .1 mm in 1986. Each bar in the histograms represents grouping by 1mm in 1985 and 0.5mm in 1986. Major settlement occurred in May and June of both years but some settlement continued throughout the summer. Growth was rapid and crabs reached 25mm CW by mid July. Few crabs larger than 35mm were ever recorded indicating that migration from the intertidal occurs.

number of age 2+ crab that would have to be replaced for the entire 2 year W & D project. A low estimate of 159,000 crab and a high estimate of 418,000 crab were used (Table 11). Both estimates were for a plan without confined disposal utilizing a linear entrainment function (see Armstrong et al. 1987 for assumptions and model description).

The next step was to derive a consistent estimate of the number of crab that mitigation might be able to produce. Results from the analysis of 4 years of intertidal data indicated that, on average, a density of 8 to 12 crab/m^2 was reached by July in natural Mya shell habitat (Fig. 8). Because the initial period of heavy settlement is typically over by this time, a constant can be used. Densities in natural shell were more variable in the summer of 1986, but the mean density found in all treatment plots in July was 9.5 crab/m^2. A slightly higher value of 13.2 crab/m^2 was found in the heavy shell and pile treatments when considered separately. For the final calculation, we chose a value of 10 crab produced per m^2 of shell put out on a mitigation site (Table 11). Using a survival rate of 10% to age 2+, based on values of 4.6% survival for the first year of life (July to July) and 19.5% survival for the second year of life (Armstrong et al. 1987), a simple figure of one age 2+ crab produced per m^2 of shell was derived.

Using the above figure, estimates of shell cover required for mitigation were 159,000 to 418,000 m^2 or 15.9 to 41.8 hectares (39.3 to 103.2 acres). We used 700 bushels (32.3 yds^3) per plot with 400 bushels(18.4 yds^3) on the heavy shell treatment (all area covered), 200 bushels (9.2 yds^3) on the pile treatment (half of the area covered), and 100 bushels (4.6 yd^3) on the light shell treatment. Each treatment covered 225 m^2, resulting in

Table 11. Cost estimates for a large scale shell mitigation project based on the work done in the current study and preliminary efforts by Fassbender (see Appendix C in Pearson 1985).

Biological Data and Calculations

Item	Units	Number High	Number Low
crabs to be replaced [1]	2+ crab	418,000	159,000
crabs per m^2	0+ crab/m^2	10	10
required ground [2]	hectares	41.8	15.9
shells per unit area	bushels/hectare	18,000	18,000
shell availability	bushels/year	100,000	100,000
years required to obtain shell	years	7.5	2.9

Mitigation Data and Cost Figures

Item	Units	Number High	Number Low	Unit Cost ($) High	Unit Cost ($) Low	Item Cost ($) High	Item Cost ($) Low
Shell	bushels	752,400	286,200	0.75	0.25	564,300	71,550
Shell[3] Transport	boat and operator hours	1,600	600	70	50	112,000	30,000
Shell[4] Distribution	manhours	1,600	600	12	8	19,200	4,800
Habitat Monitoring Contract (UW)	years	5	2	25,000	10,000	125,000	20,000
Total Cost						820,500	126,350

(1)Estimates are based on dredge entrainment model without confined disposal and a linear entrainment function (Armstrong et al. 1987). Figures are high and low estimates of age 2+ crabs that would have to be replaced for the entire 2 year W & D project.

(2)These figures are derived from the number of 0+ crab that mitigation could produce(10 crab/m^2) and a survival rate of 4.6% and 19.5% for the first and second years of life respectively (Armstrong et al. 1987) multiplied by the number of 2+ crab required above.

(3)Figures are based on a large barge (100,000 bushels capacity) towed by boat each requiring an operator and completing 3 to 8 trips to a site.

(4)Manhours are based on two hose operators each capable of distributing 1,000 bushels/hour.

approximately 1.8 bushels/m^2 for the heavy shell and pile treatments (18,000 bushels/ha, Table 11). At this coverage rate, a mitigation effort would require from 286,200 to 752,400 bushels of shell to complete the project.

The cost of oyster shell for this research work was $10/cubic yard or about 50 cents a bushel, but a more reasonable figure of 25 cents a bushel for a large scale project can be used (Richard Wilson Bay Center Mariculture pers. comm.; Pearson 1985). This figure could triple if transportation (e.g. from Willapa Bay to Grays Harbor) is necessary. Final cost estimates for the shell alone, therefore ranged between $71,550 and $564,300. Shell distribution and labor costs were estimated using figures obtained in discussion with oyster growers and costs incurred during this study. Figures are based on the use of a barge which would be able to transport 100,000 bushels to a site in 1 trip (high estimate of 8 trips and low estimate of 3 trips). Using a large barge would greatly reduce the manhours involved in completing the project, but more importantly, would not involve difficult scheduling for the use of the smaller oyster dredges as was encountered in this study. Each trip to the site was estimated to take 5 hours roundtrip with shell distribution taking place at 1,000 bushels/hr for a total of roughly 105 hours per trip. The figures for manhours were based on the use of 1 boat operator with one barge operator and 2 deckhands for shell distribution using a large hose or backhoe type shovel.

Habitat monitoring costs were estimated using University of Washington costs and based on a range of 1 to 4 sampling trips per year, since we believe as little as a single trip in July or August would give approximate numbers of 0+ juvenile crab that survived in the shell each year. A range of 2 to 5 years length for the monitoring program was used (Table 11).

4.0 DISCUSSION

4.1 Importance of Intertidal Areas to Dungeness Crab

Previous work by Armstrong and Gunderson (1985) showed that intertidal areas were important for newly settling 0+ Dungeness crab. With the exception of similar studies in Puget Sound (Dinnel et al. 1986c), this is the first comprehensive study of that relationship to date. Results from the hovercraft and helicopter surveys indicated that vast amounts of suitable substrate, particularly shell cover (1,960 ha, see Fig. 4), were available to YOY crab in the intertidal areas of Grays Harbor. When density estimates taken from this study and previous work in 1983 and 1984 were extrapolated to population estimates for the entire estuary (Fig. 9), the significance of the estuarine intertidal area became clear. Intertidal 0+ crab population estimates were up to an order of magnitude greater than similar estimates of 0+ crab in the subtidal portions of the estuary (as sampled with a beam trawl, Armstrong et al. 1986; Armstrong et al. 1985; Armstrong and Gunderson 1985). This was particularly true in the months right after settlement (May through July, Table 12). The difference between estimates for the subtidal and intertidal may, in part, have been due to gear inefficiency in the subtidal trawls, but similar observations of seasonally greater intertidal crab density in Puget Sound (Dinnel et al. 1986c, Dinnel et al. 1987), and the magnitude of the difference, lead us to believe it is real. The underlying reason for such a difference could be the result of number of

Table 12. Summary of population estimates for 0+ Dungeness crab in the intertidal area (IT) of Grays Harbor (quadrat samples from this study and previous Sea Grant work, see also Table 7) and those for subtidal (ST) 0+ crab derived from the Sea Grant trawl survey. Data for 4 years are given and expressed as millions of crab.

POPULATION ESTIMATES
(millions of crab)

	1983		1984		1985		1986	
Month	IT	ST	IT	ST	IT	ST	IT	ST
May	319.8	4.8	1081.9	181.8	62.4	0.3	5.8	0.0
June	27.5	1.2	37.4	5.2	44.7	0.1	17.9	0.0
July	21.4	4.7	23.6	9.0	26.7	1.1	15.0	0.1
August	2.6	7.0	10.1	10.2	17.3	3.2	14.7	0.5
September	5.3	7.1	9.4	33.0	18.1	3.0	9.5	0.7

factors, including less competition for food and space between small crab in the intertidal and perhaps more importantly, protection from predation by larger fish and cannibalism by larger crab which prefer the subtidal areas (Stevens 1981). Predator exclusion cages deployed in Puget Sound showed that predation is a major factor in the distribution of newly settled instar crab in intertidal areas. R. McMillan (University of Washington, unpublished data) found distinctly higher crab abundances within cages deployed on 3 substrates, than on similar substrates outside the cages.

By August and September, population estimates in the intertidal and subtidal areas were of comparable magnitude. Subtidal abundance of 0+ crab increased dramatically during this period in 3 of 4 years as summer progressed (1986 population levels were uniformally low). Length frequency distributions indicate that this was not due to new settlement, but apparently movement of larger individuals (25 to 35mm CW) from the intertidal into the subtidal. The mean CW of 0+ crab found in the intertidal increased from 7mm in May to 12mm June. By July, although the maximum size found was 25mm CW, new settlement resulted in a size of only 13mm CW in the intertidal. The mean size of crab found subtidally, however, increased to about 25mm in July and population estimates there had increased in all 4 years by as much as an order of magnitude (120,000 to 1 million in 1985). It has also been demonstrated that these were not individuals from coastal nearshore areas, since crab from that area are much smaller at this time of year (Dumbauld et al. 1987). In years of poor initial settlement in the estuary such as 1986, 0+ crab were not observed in the subtidal areas until late summer when this migration occurred (Table 12). Use of the intertidal by juvenile Dungeness crab during their first summer of benthic existence followed by movement into the subtidal channels has also been observed in Puget Sound, but with a different seasonal pattern (Dinnel et al. 1986c). In most areas of North Puget Sound, settlement occurs in late June and July and the majority of 0+ crab overwinter in the intertidal and move into the subtidal after growth has resumed in late spring and early summer of the following year. Movement into the subtidal at 25 to 35mm CW apparently reflects attainment of a size refuge from predators, but could also be due to simply outgrowing the shell habitat, no longer being able to find suitable prey, or agonistic behavior and displacement.

Statistical tests performed on crab density data from this survey confirm previous findings that document the importance of some type of cover, and particularly shell cover, as habitat for juvenile Dungeness crab in the intertidal (Armstrong and Gunderson 1985; Dinnel et al. 1986c). The mean density of crab found in areas with shell cover was always higher than that in comparable areas without cover. Tests showed that density in heavy cover (66-100% shell) was greater than that in light cover (5-33% shell) or no shell, but results for moderate cover (33-66% shell) could not be distinguished from heavy or light cover at some locations (Table 5).

Location was also an important factor in the observed crab densities but, due to lack of adequate statistical replication within locations sampled (pseudoreplication; Hurlbert 1984), inferential statistical tests could not be carried out. Nevertheless, the mean density of crab found in live oyster shell at Station 2 in the South Bay was distinctly lower than that in shell deposits of the eastern softshell clam *Mya arenaria*, the predominant form of shell found in all other areas of the estuary. At first this difference was thought to be solely due to the type and amount of actual habitat provided, but data from the shell plots (with identical shell treatments at all 3 stations) also displayed this pattern (Fig. 11, Table 9). One potential source of bias in the results from the plots however, was the proximity of nearby natural shell and the potential for larger crab to migrate from this shell into the plots. Several other factors could also have played a role including; 1) differences in the initial number of crab settling at each location, 2) differences in physical factors such as tidal elevation (shown to be a factor in Puget Sound, Dinnel et al. 1986c), sediments and temperature and, 3) differences in biological factors like predation (i.e., the presence of considerable numbers of *Cancer productus* at the South Bay station) and food availability.

4.2 Shell Experiments and the Feasibility of a Large Scale Mitigation Project

The results from the shell experiments show that the introduction of shell as habitat is technically feasible, at least to the extent that it creates new habitat which is used by juvenile crab. Mean densities in the shell plots were as high as 62 crab/m^2 in the pile treatment at Station 1 and averaged 5 crab/m^2 in all treatments by September (Table 9). The seasonal pattern of crab abundance in the plots followed that found in natural habitat with peak abundance in June and July 1986 due to settlement, and larger crab leaving the plots in August and September (Fig. 12). Some smaller crab remain on the plots through the winter.

Location within the estuary seemed to be important. Consistent differences in crab density were noted between stations, with the highest densities of crab at Station 1 (Fig. 11). The cause of this difference is not clear since shell habitat was the same at all sites (see discussion in Section 4.1 above). Further studies would be necessary to separate and document the importance of tidal elevation, sediment type and other biological variables, including the confounding factor of proximity of the experimental plots to areas with natural shell and the distances that small crab move.

Differences between treatment groups were also exhibited. Both heavy shell and pile configurations attracted more crab per unit area than the light shell treatment with scattered shell. This is probably due to the structural complexity of usable habitat created and suggests that a large scale project should utilize some form of three dimensional arrangement. Fortunately, practical considerations with regard to the labor involved in spreading shell are also consistent with such a design. Large quantities of shell loaded on a barge could conceivably be shoveled overboard with a backhoe bucket or washed overboard with a firehose, as was done in this study. As long as the barge was moving slowly during this process, depth of the shell deposition could probably be controlled. Another factor to be considered in such an operation would be location with respect to currents and sediment transport. Although the shell pile treatment was most successful in terms of number of crab supported, it also was most susceptible to alteration by the currents and sedimentation. Locations with naturally occurring shell deposits nearby would presumably be best, but preliminary studies of current patterns and velocities such as that done on dredge disposal site E in Grays Harbor (Barrick 1975), might be advisable.

Cost estimates for shell materials necessary for a full scale mitigation project (Table 11) are much lower than preliminary estimates by Fassbender (Pearson, 1985). This is primarily due to refined estimates of the number of crab to be replaced (taken from a dredge entrainment impact model; Armstrong et al. 1987) and our estimates of the amount of shell necessary to produce a given density of crab per unit area. Cost estimates for transport and distribution of the shell were also reduced based on the smaller quantity of shell and reduced need for costly distribution found in this study. Based on a University of Washington study with fewer sampling days required to document results, overall costs for habitat monitoring were less than initially estimated. As a result of these revisions the final estimates of project cost ($113,750 to $820,500, Table 11) are much lower than those reported by Fassbender (Pearson 1985; $779,157 to $10,866,064).

The primary obstacle to the feasibility of a large scale mitigation project however, may be the availability of shell since most of the shell produced by the oyster industry is reused in the hatchery for spat collection. According to the oyster growers (Tom Hayes, Coast Oyster Company, pers. comm.) 100,000 bushels of shell would be available per year. At this rate, at least 3 years, and as many as 7 years, would be necessary to complete the mitigation project.

One important factor that was not incorporated in our cost estimates is the longevity of the shell plots. Results from the followup study in the summer of 1987 indicated that crabs continue to recruit to shell plots in the second year, especially to the heavy shell treatment plots, which remained intact at most of the stations revisited. Depending on the site selected for mitigation, this could conceivably be true for much longer periods of time. Therefore, estimates of the amount of shell required could be adjusted down to allow for crab recruited in subsequent years.

4.3 Recommendations for Further Research

Suggestions for future research based on the results of this pilot study are as follows:

1. It is highly recommended that sampling continue at the experimental shell plots already in place for one more year to determine their longevity and long-term benefits to crab recruitment. Such a benefit became apparent in the followup study and will be significant in terms of the total amount of shell necessary for a large scale mitigation effort. Cost estimates could be refined to reflect this result and the amount of field work necessary to document one more year would be minimal and limited to 1 or 2 sampling trips.

2. When results from the intertidal crab survey were analyzed statistically, a problem with lack of station location replication was noted. In any future study this could easily be remedied. Instead of taking a large number of replicate samples at a limited number of locations, it would be statistically preferable to replicate locations with fewer samples. Time constraints would still limit the number of wide area locations (e.g. North Bay, South Bay) that could be visited, but obtaining data from a number of

smaller scale sites within each area, such as separate oyster beds in the South Bay or Mya shell patches along the South Channel, would produce better estimates of estuary populations. Results from this study also suggest that sampling should be limited to, at most, 2 categories of shell cover at each location (heavy shell, 33 to 100% cover and light shell, 0 to 33% cover). A number of locations with live oysters and Mya shell should be sampled in order to test for differences between the suitability of each of these habitats for crab.

3. In the experimental plots, the problem of statistical replication could be handled by sampling a number of smaller treatment plots placed in more areas (i.e., replicating treatments not samples). Location of each plot should be far enough away from natural shell to minimize the possibility of migration from these areas into the experimental plots.

4. Further documentation of the growth rate and conclusive evidence for movement of 0+ crab into the subtidal as summer progresses would be necessary to unequivocally determine the benefit of intertidal areas to the Dungeness crab population. More detailed length frequency analysis, coordinated trawl and intertidal sampling in a given area, and tagging studies could further define growth patterns, timing of migration into subtidal channels, the size at which crab move, and distances traveled on a small scale.

5. Define the role of predation in determining intertidal crab distribution using predator exclusion cages such as those used in Puget Sound studies (R. McMillan, thesis project, Univ. of Washington) and inclusion

cages in which predators (eg. sculpins, larger crab, etc.) are enclosed with the crab. Analysis of stomach contents from both juvenile Dungeness crab and their predators would help clarify simple food chain linkages in the intertidal environment.

6. Better estimates of natural mortality of 0+ crab are needed in order to obtain the number of 1+ and 2+ crab it will be necessary to replace and hence the amount of shell a mitigation effort will require to reconcile these losses. This would include a more detailed length frequency analysis of the 1983 through 1987 catch records for 0+ crab.

7. Experimental efforts to catch megalopae or first instar crab in nearshore coastal waters and transport them to naturally occurring shell deposits in the estuary could increase survival and growth of a year class especially during years of poor settlement in the estuary.

5.0 SUMMARY

1. Results from the hovercraft and helicopter surveys indicated that about 19% (1568 ha) of the intertidal area in Grays Harbor was covered with some type of naturally occurring shell, primarily that of the Eastern softshell clam, *Mya arenaria*. A significant amount of intertidal area in Grays Harbor is used for oyster culture, which also provides crab habitat (392 ha). The density of juvenile Dungeness crab observed in shell substrate was greater than that in areas without shell, especially after the initial settlement period. Both location and configuration of shell influenced the density of crab found.

2. Crab density estimates from one location, sampled for 4 years, varied by an order of magnitude between years during the period of initial settlement (May, June). Subsequent mortality reduced these densities to relatively similar levels later in the summer (July through September). This was even true for 1986, when initial settlement densities were very low.

3. Virtually all crab sampled in the intertidal were 0+ crab that settled in May and June, grew to 25-35mm and apparently moved to the subtidal channels in August and September. Some settlement occurred throughout the summer in both years of the study and these crab appeared to overwinter in the intertidal.

4. Comparison of intertidal 0+ crab population estimates for the entire estuary (derived from density estimates and area conversions) with similar subtidal estimates (derived from beam trawl samples) indicated that a large portion of the 0+ year class resides in the intertidal during the summer months. This is especially important in years of poor overall settlement and recruitment to the estuary. Also apparent was the increase in 0+ populations in subtidal areas in late summer and early fall, presumably due to movement from intertidal areas.

5. Crab recruited to the experimental shell plots. Densities observed (5-10 crab/m^2) were comparable to those found in natural shell. Statistically significant differences were noted between shell treatments, with the highest densities found in a three-dimensional pile configuration. The heavy shell treatment plots (thick layer completely covering the plot) best survived sedimentation processes and currents. Differences between density at the 3

station locations were also observed, indicating something other than the amount of shell present contributed to the number of crab recruited.

6. Rather than cost, the primary obstacle to a large scale mitigation effort may be the quantity of shell available for such an effort. Cost estimates based on this study and the dredge impact model work were much lower than previously estimated, primarily because of lower estimates for the amount of shell necessary and for the number of crab to be replaced.

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