FRI-UW-9110
July 1991

FISHERIES RESEARCH INSTITUTE
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CONSTRUCTION DREDGING IMPACTS ON DUNGENESS CRAB, *CANCER MAGISTER*, IN GRAYS HARBOR, WASHINGTON AND MITIGATION OF LOSSES BY DEVELOPMENT OF INTERTIDAL SHELL HABITAT

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FINAL REPORT

for

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

Contract No. DACW67-85-C-0033

Approved

Submitted 9-30-91 R. C. Francis
Director

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ACKNOWLEDGEMENTS

Funding for this study was provided by a contract (DACW67-85-C-0033) from the Seattle District, U.S. Army Corps of Engineers and was augmented by a grant through Washington Sea Grant (#NA 86 AA-D-SGO44). The authors thank B. Brun, L. Scudder, and Dr. J.O. Waller of the Corps of Engineers, and Dr. F. Weinmann, Region X EPA, formerly Chief, Environmental Resources Section, Seattle District Corps of Engineers, for their support and coordination efforts. Field and laboratory assistance was provided by J. A. Shaffer, C. Adkins, V. Souze, J. Larsson, M. Elger, J. Rodakowsky, K. Feldman, J. Fuerstenberg, A. Whiley, R. McConnaughey, D. Herren, and Y. Bing Shi. Advice on survey design was provided by Dr. L. Conquest, Center for Quantitative Science, University of Washington. Research vessel support was provided by Vern Heikkila, captain of the F/V *Karelia*, Westport, Washington.

KEY WORDS

Dungeness crab, dredging, Grays Harbor, intertidal, mitigation, oyster shell, trawling.

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, begin in April 1990, 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); 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 previously listed field studies, 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 avoidance of entrainment by modifying dredging equipment. Because this method was unsuccessful in field tests, a combination of other approaches was considered based on (1) a Dredge Impact Model (DIM, Armstrong et al. 1987) used to calculate theoretical crab loss under different scenarios of seasonal and spatial abundance, and (2) 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, we monitored crab densities in the navigation channel from April through December 1990 (Chapter 1). The resulting information was integral for revising the original impact predictions provided by DIM and, ultimately, the amount of mitigation necessary to compensate for crab losses.

Because the creation of intertidal oyster shell habitat for 0+ crab was shown to be an effective and feasible technique for increasing the abundance of this age class (Dumbauld and Armstrong 1987), it was chosen as the primary method to mitigate for loss of 1+ and 2+ crab in the subtidal. 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 of construction dredging. However, due to time constraints, uncertainty about shell retention and shell deployment techniques, and some controversy regarding site selection, shell placement for 1990 was reduced to four experimental sites of 0.4 ha of shell each. We monitored those sites from May through August 1990 for the density of 0+ crab, percent shell cover, and other invertebrate fauna that recruited to the shell habitat. The results of that portion of the study are found in Chapter 2.

Finally, concern about impacts of shell deployment on eelgrass (*Zostera marina)* prompted the additional need to study eelgrass/shell interactions. Those findings are discussed in Chapter 3.

CHAPTER 1. IMPACT OF 1990 GRAYS HARBOR CONSTRUCTION DREDGING ON DUNGENESS CRAB, *CANCER MAGISTER*

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A Dredge Impact Model (DIM, Armstrong et al. 1987, Fig. 1–1) was designed to integrate several variables associated with dredging and Dungeness crab (*Cancer magister*) population parameters to produce an estimate of loss from the resource (age 2+) and from the commercial fishery. The DIM evolved from a series of dredging/crab entrainment studies in Grays Harbor (see Tables 3.1 and 3.2 in Armstrong et al. 1987) that investigated entrainment or mortality (or both) associated with various dredging gear, schedules, and disposal practices. From these studies evolved an entrainment regression (ER, Armstrong, et al. 1987, McGraw et al. 1988) that described in quantitative terms the number of Dungeness crab entrained by the dredging process per unit of dredged material. Subsequent to its original publication (Armstrong et al. 1987, McGraw et al. 1988) the ER has been refined to include results of additional entrainment studies by Dumbauld et al. (1988) and Wainwright et al. (1990).

The ER provides an estimate of crab entrained during dredging but not necessarily killed; thus the next step in the DIM (Fig. 1–1) incorporates estimates of mortality based on gear type, crab age and supporting data from previous studies in Grays Harbor (see Table 3.3 in Armstrong et al. 1987) to yield an estimate of immediate loss of crab of all ages and both sexes. The DIM further incorporates estimates of natural mortality up to sexual maturity (2+) and harvestable size (3+) to finally provide estimates of fishery loss due to dredging alone (Fig. 1–1).

Construction monitoring work reported herein was designed to provide real-time estimates of crab loss based on crab sampling during the construction process. The construction monitoring data used in the DIM to calculate final project losses were as follows:

- **Dredge volumes**
    - by location
    - by month
    - by gear type and disposal method

and

- **Dungeness crab densities**
    - by month
    - by location
    - by size (age)

MATERIALS AND METHODS

Construction dredging impacts on Dungeness crab were monitored by monthly trawl sampling at 12 to 15 stations (Fig. 1–2). Trawl operations were conducted on board the chartered fishing

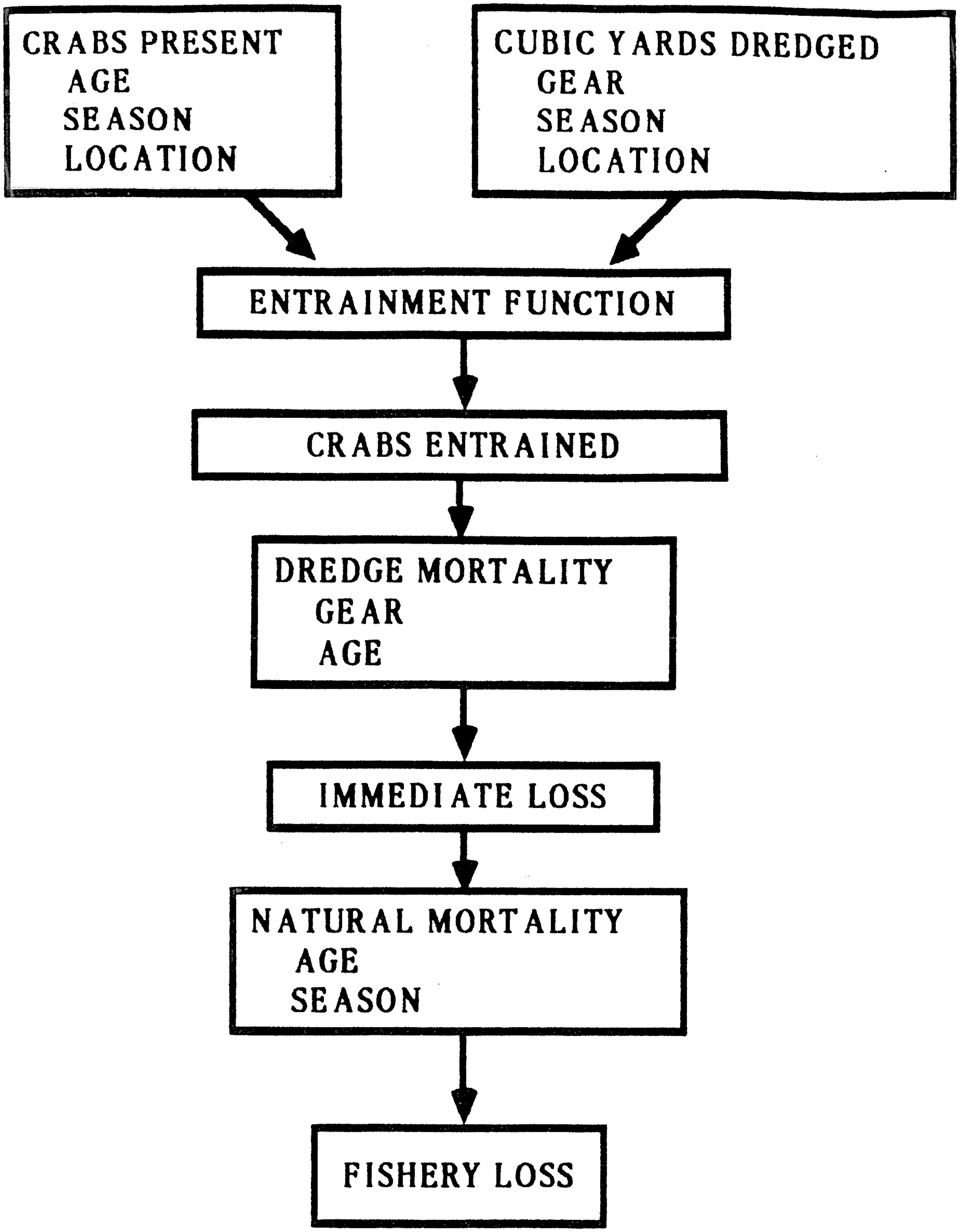


Figure 1–1. Summary digram of the Dredge Impact Model (DIM).

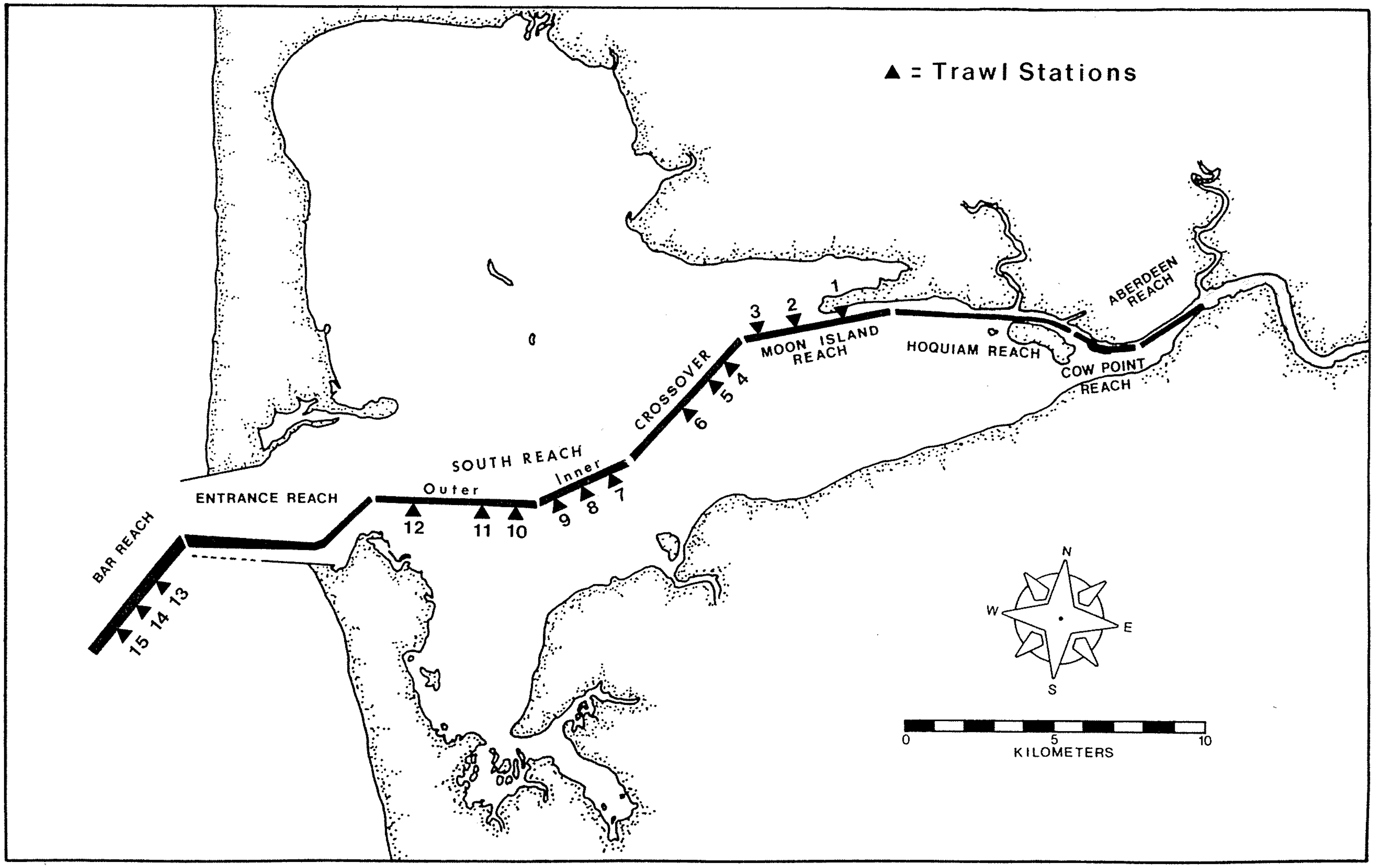


Figure 1–2. Trawl station locations (▲) in Grays Harbor during the 1990 construction monitoring.

vessel *Karelia* out of Westport, Washington. Crab were sampled with a 3-m beam trawl (Gunderson and Ellis 1986), which has been used in other Dungeness crab studies in Grays Harbor (Armstrong and Gunderson 1985, Armstrong et al. 1987), Willapa Bay (Armstrong et al. 1986), and Puget Sound (Dinnel et al. 1985, 1986c, 1988).

All trawl stations were selected via a stratified random sampling plan. Three stations were allotted to each trawlable reach of the navigation channel under construction, and the exact station locations within each reach were selected randomly from a grid of 20 to 30 cells within each reach. The location of each station is recorded in Appendix 1. The target tow distance at each station was 274 m (300 yds) at a target speed of 1.5 knots. The 3 m beam trawl has an effective fishing width of 2.3 m; thus, the target area swept by the net was 631 m^2. Trawls occasionally varied in length since boat navigation was affected by winds, currents or other vessel traffic. Trawl stations were located each cruise either via Loran C (latitude and longitude) readings; radar range readings to buoys, fixed navigation markers, or points on shore; or both. Trawl paths and distances were determined by radar ranges to the same fixed markers.

Trawl catches from each tow were sorted for crab, and notes were made on proportions of the substrate material (shell, wood debris, algae) caught in the net. All Dungeness crab from each tow were counted, sexed, measured, and returned live to the general area of capture. Generally, crab greater than about 75 mm carapace width (CW) were tagged prior to their release with a numbered Floy® anchor tag inserted through the epimeral line (molt suture) running along the posterior side of the carapace. Tagging was conducted to gather information on crab movements within the estuary and was not intended to be used for population estimates since a specific tag recapture program was lacking. Surface and bottom water temperatures and salinities were measured at each reach on each cruise via a hand-held thermometer and a temperature-compensated refractometer.

Data Analyses

Dredging data for the DIM were provided to the University of Washington staff by the U.S. Army Corps of Engineers (COE) and its contractors. Dungeness crab spatial, temporal, density and size data were collected during the trawl work described previously. Estimated crab densities were adjusted to the standard unit of crab/hectare (ha) based on tow lengths and the fishing width of the net (2.3 m). Crab ages were estimated based on size-frequency data and size mode analyses.

RESULTS

Crab Densities

A total of 5,380 Dungeness crab were caught in 124 successful beam trawl tows during the nine months of construction monitoring. Average calculated crab density for all 124 tows was 678 crab/ha with a range of 0 to 9,796 crab/ha for individual tows. Crab densities, relative proportions of substrate materials caught in the tows, and temperature/salinity data are summarized for each station and cruise in Appendix 2.

Crab catches varied considerably between adjacent reaches and stations and between cruises for a given station or reach. Average calculated densities for each reach (n = 3) by cruise (month) ranged from a low of 26 crab/ha at the Moon Island reach in December to a high of 4,106 crab/ha at the Moon Island reach in October (Fig. 1–3). Of special note are occasional tows that caught exceptionally high numbers of crab (e.g., Moon Island reach Station 3 with individual tow catches of 618 and 447 crab/tow; Fig. 1–3). These extremely high catches were typically associated with concomitant catches of clam and oyster shells. Indeed, calculated crab densities exceeding about 1,500 crab/ha were all associated with a high percentage (≥60%) of shells in the catches (Fig. 1–4). Average crab densities for all stations combined (n = 12 or 15; the Bar was not sampled October–December) for each month ranged from about 225 (July and December) to almost 2,000 in October (Fig. 1–5). The unusually high average density in October was largely driven by one high catch (618 crab = 9,796 crab/ha) at Station 3 (Moon Island reach), where an abundance of shell was also caught in the net.

Sex Ratios

The sex ratio was essentially 1:1 in the inner-most (Moon Island) reach and gradually increased to a higher proportion of males in the direction of the harbor entrance (Fig. 1–6), with a sex ratio of almost 4:1 in favor of the males. However, samples from the Bar consisted of only about 40% males overall, a substantial difference from the outer portion of Grays Harbor (Fig. 1-6).

Crab Sizes

Crab size tended to increase from inner to outer harbor (Fig. 1-7). Moon Island and Crossover reaches contained the smallest crab (mostly 1+ age class); both sexes were still misted in equal proportions (Fig. 1–6), and both sexes exhibited essentially equal sizes, which indicated equal growth up to 60 mm CW. Crab size averaged about 30 mm greater at the South reach as compared to the Moon Island/Crossover reaches (Fig. 1–7), and males were noticeably more abundant and larger by about 10 mm. The location(s) of the females apparently absent from South reach are presently unknown although early migration out of the harbor is one possibility.

The apparent segregation of crab by age class between the inner and outer portions of Grays Harbor is illustrated by the size-frequency plots in Fig. 1–8. The 1+ crab were dominant at the Moon Island/Crossover reaches whereas 2+ crab were the most abundant age group at South reach. The younger 1+ crab are essentially absent from the offshore Bar reach despite the fact that settlement did take place in this area (as indicated by the high 0+ peak for the 1990 cohort; Fig. 1–8).

Post-Larval Recruitment and Growth

In 1990, Dungeness crab megalopae settled in Grays Harbor in late May and June (0+ in Fig. 1–9) and grew to about 35-40 mm CW by December 1990. Crab that settled in about June of 1989 (1+ in Fig. 1–9) averaged about 25-30 mm in April 1990 and grew rapidly to ~90–115 mm by December 1990. Growth information on the 1987 and 1988 cohorts is vague in this data set because many of these animals have probably emigrated from the estuary. Some of the 3+ males will probably grow enough to enter the commercial fishery (minimum legal size = 159 mm CW) by winter 1990 (Armstrong et al. 1987).

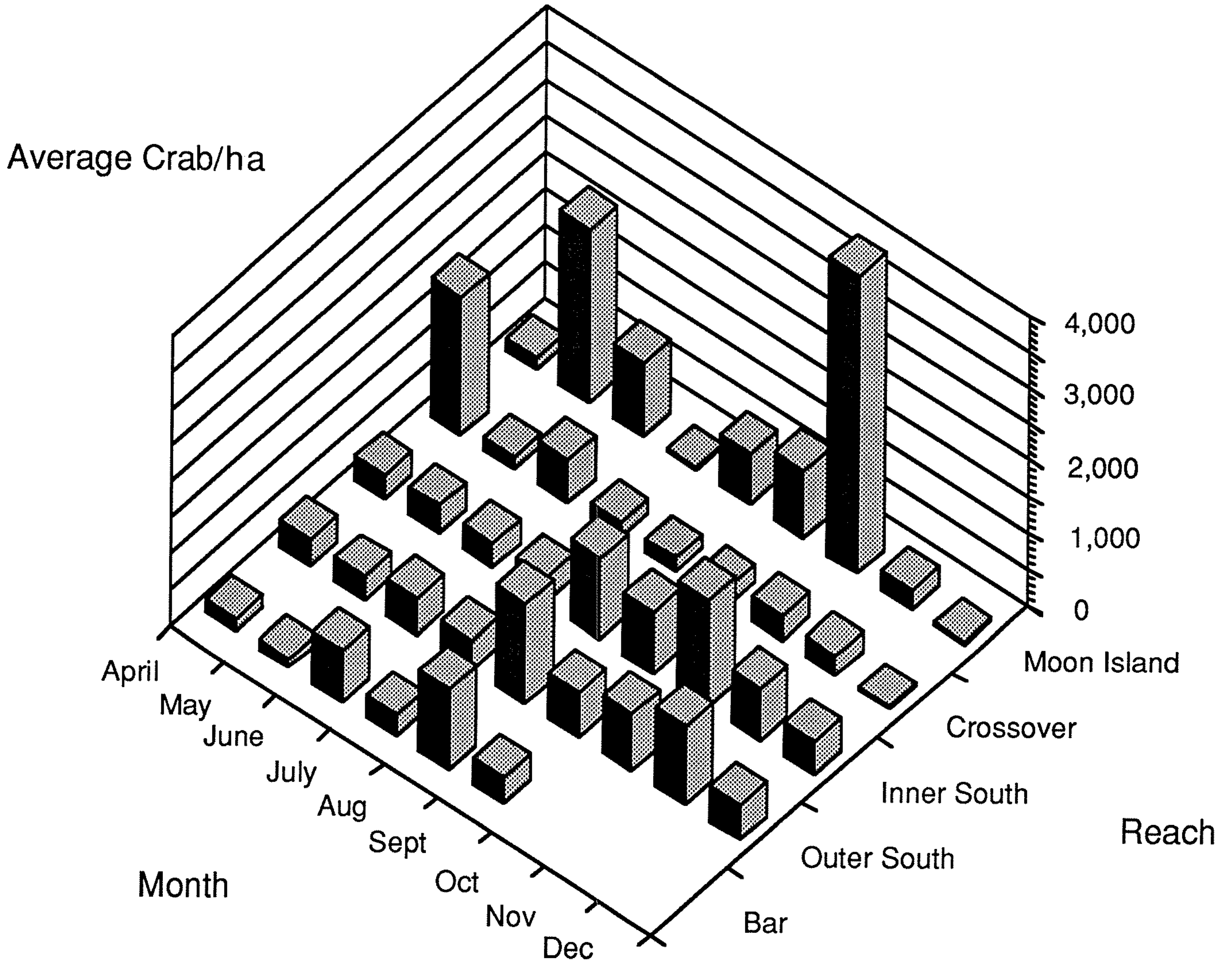


Figure 1–3. Average crab densities calculated for each reach (n = 3 stations each) for each month for the Grays Harbor construction monitoring trawl sampling. The Bar was not sampled Oct.–Dec.

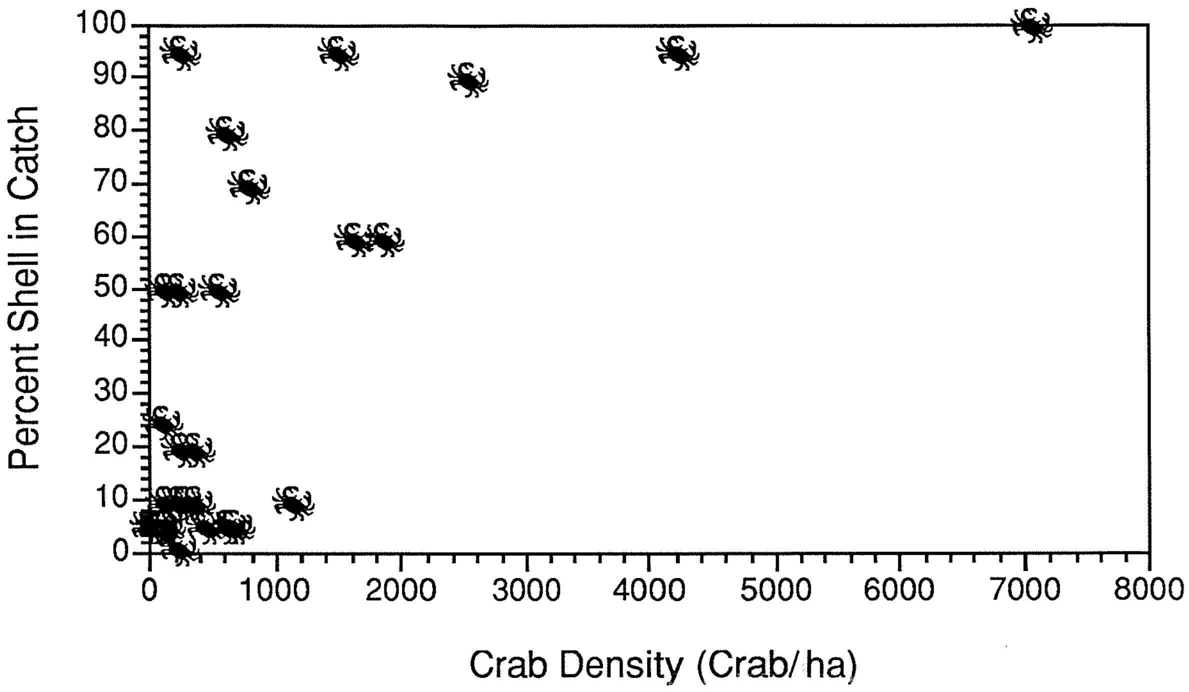


Figure 1–4. Relationship between calculated crab densities and the proportion of shell caught in the net.

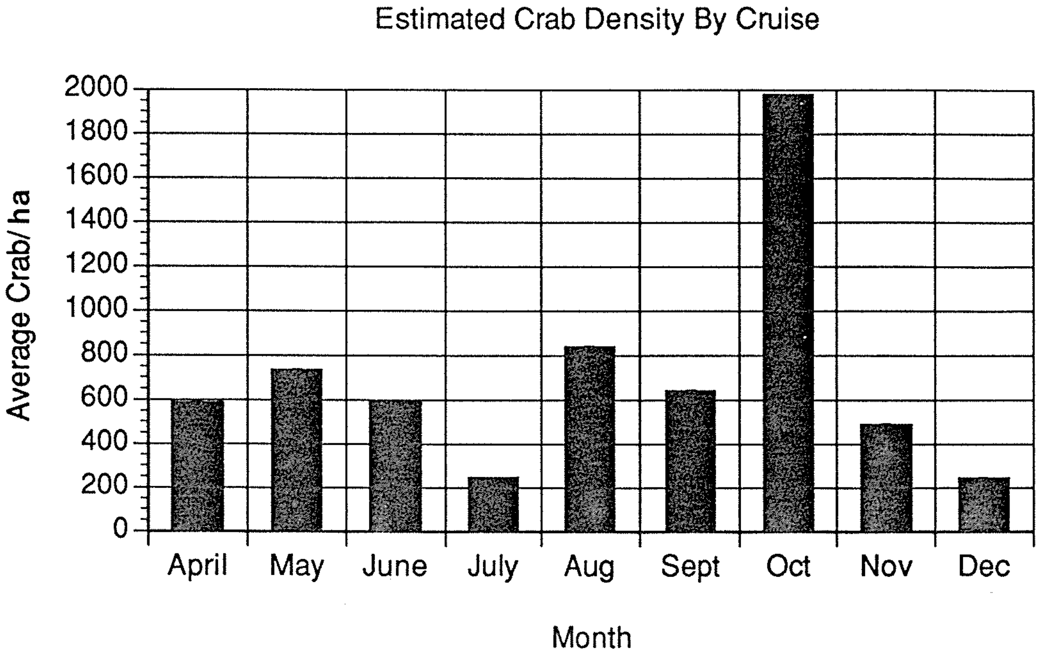


Figure 1–5. Average crab densities by month for all stations combined.

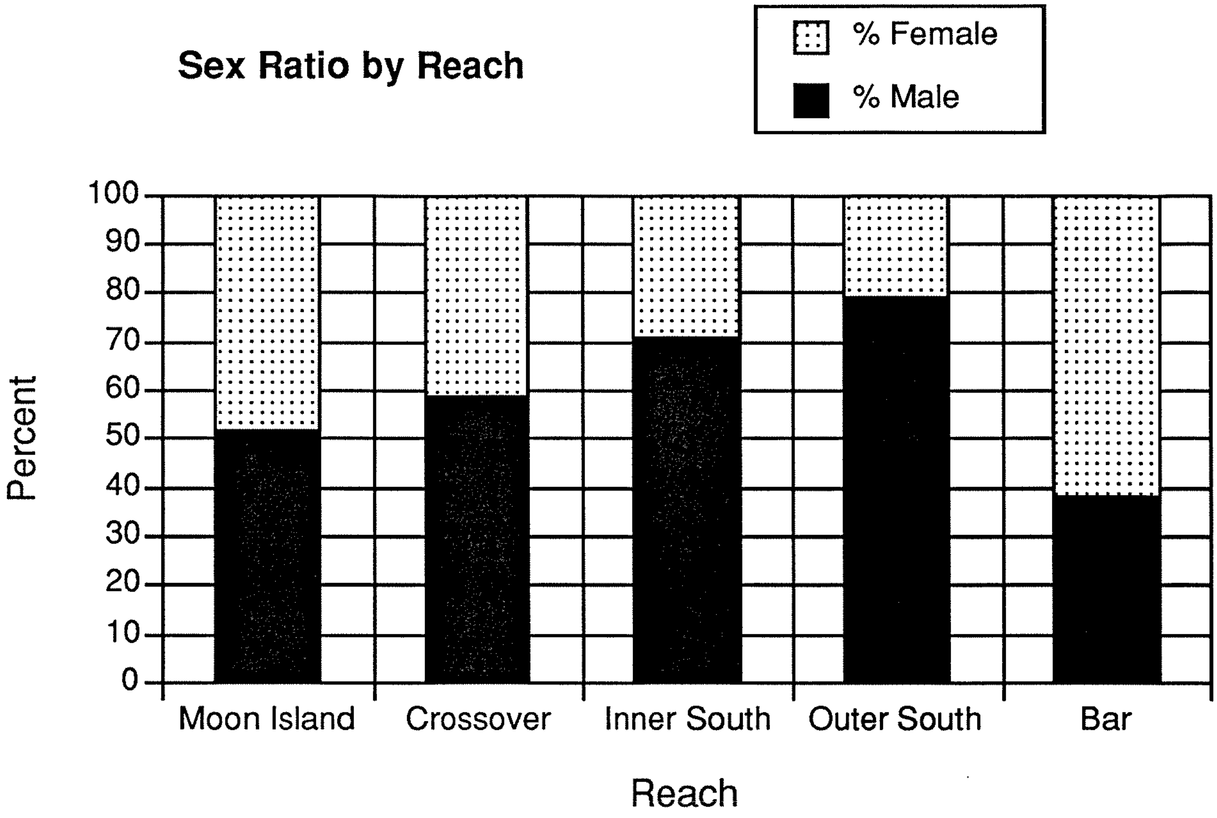


Figure 1–6. Ratio of male:female crab by reach, all sample months combined.

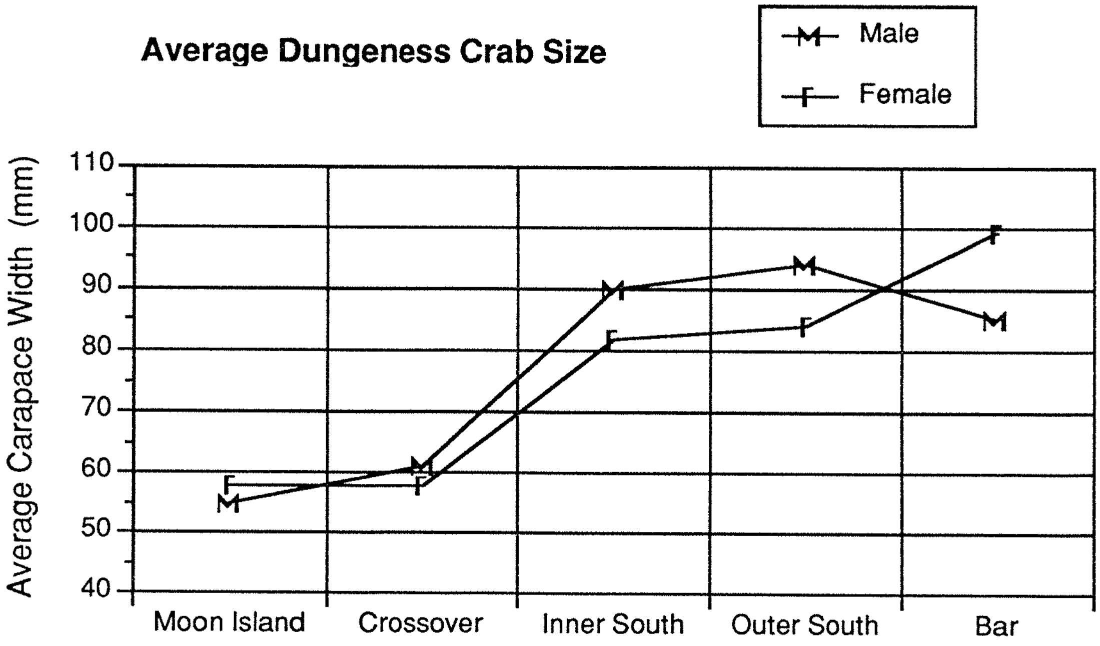


Figure 1–7. Average crab size for each reach, all sample months combined.

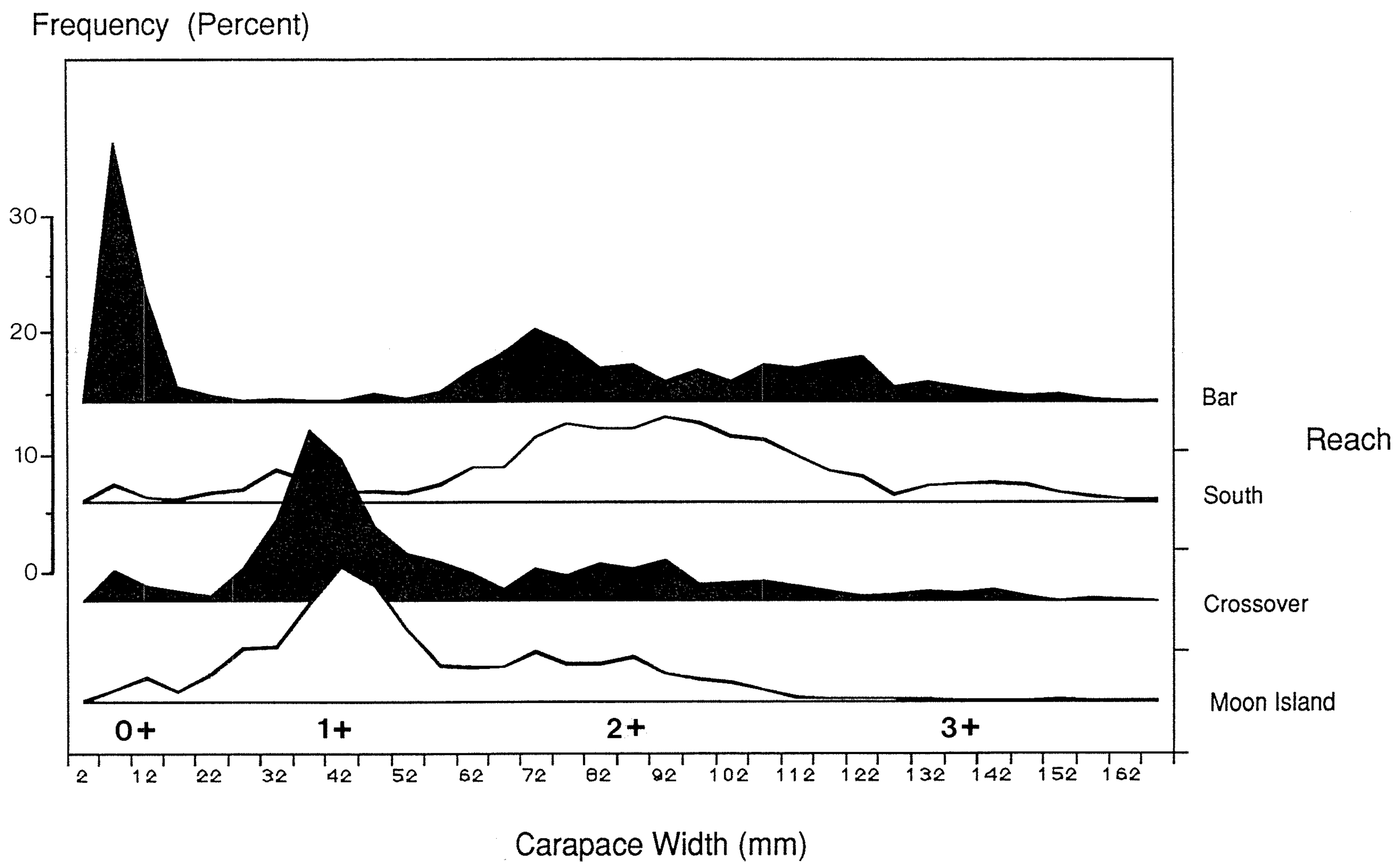


Figure 1–8. Dungeness crab size-frequencies by reach, all sample months combined. The various peaks are labeled by approximate crab age at the bottom.

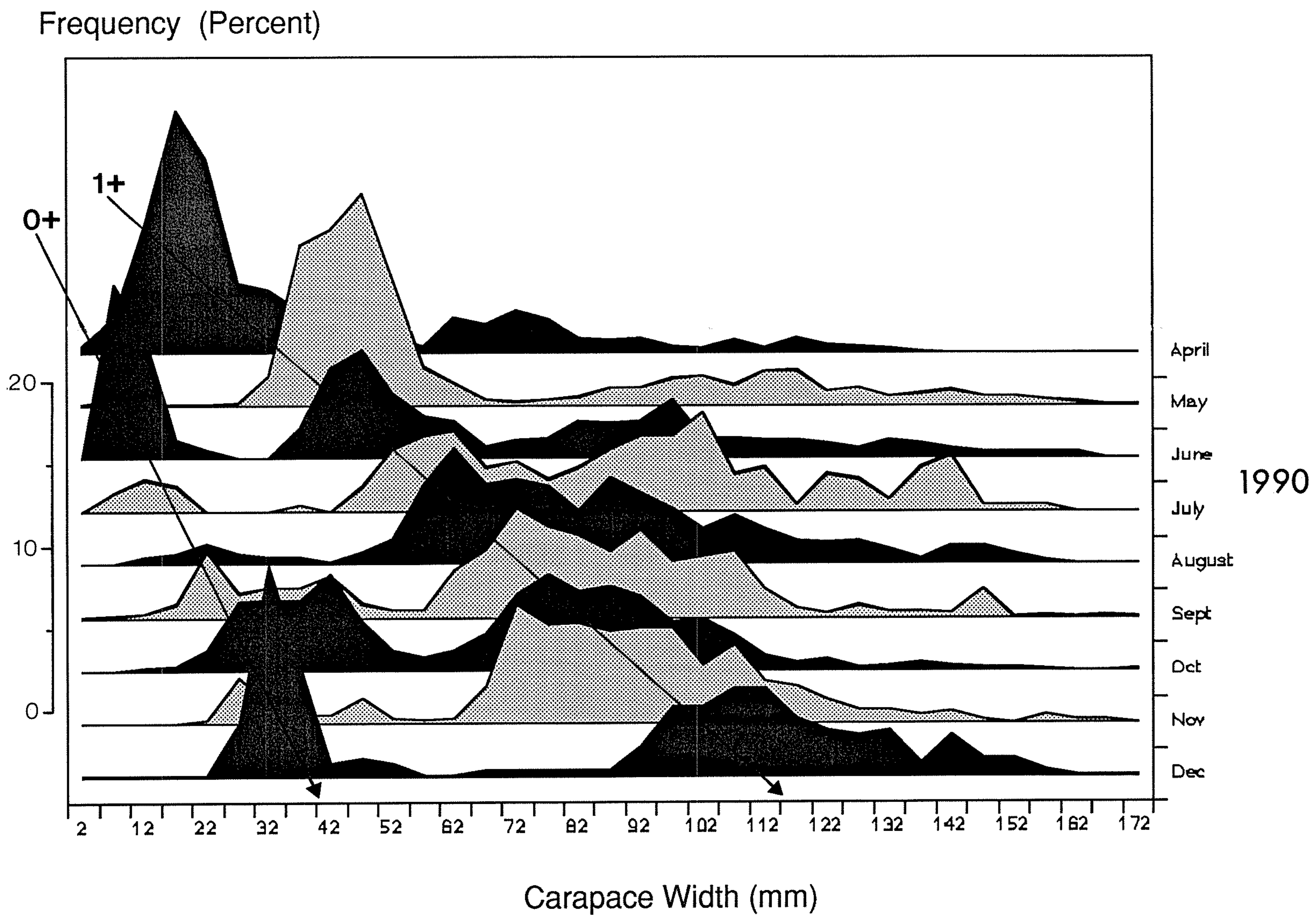


Figure 1–9. Dungeness crab size-frequency plots by month, all stations combined, showing approximate growth of each age class.

Crab Movements

Data presented in this report plus previous reports and publications on Grays Harbor crab studies leave little doubt that Dungeness crab move out of the estuary and into the Pacific Ocean as they grow and mature. However, this pattern of emigration has been constructed largely based on indirect evidence of size-frequency distributions by location. To provide more direct evidence of this movement, most of the older (i.e., >75 mm CW) crab caught during the 1990 construction monitoring were tagged with Floy® anchor tags, which should remain with the crab through one molt. Unfortunately, no tagged crab were recovered by our trawling operations and only two crab were caught by commercial/sport fishermen. Both of these crab were legal sized males tagged and released at South reach. One crab was caught 71 days later in a cove just inside the south jetty at a distance of about 4 km west of the release site (Fig. 1–2). The second crab was caught outside the harbor 26 days following its release in the South reach. Its exact capture location is unknown as this crab was recovered in landings at a Westport processor (these landings were reported to be only from boats fishing off-shore pot strings).

Temperature and Salinity

Water temperatures in Grays Harbor followed a normal seasonal cycle with low temperatures in December 1990 of about 8–10°C and high temperatures of about 18–20°C in August (Fig. 1–10). Bottom temperatures at the Moon Island reach tended to average a few degrees warmer than South reach waters during spring and summer, but they were similar to South reach during the rest of the year (Fig. 1–10).

Because of its closer proximity to river inputs, bottom water salinities at the inner Moon Island reach were almost always lower than South reach. Moon Island bottom salinities varied between about 22 and 28‰ whereas South reach bottom salinities ranged from 26 to 33‰ (Fig. 1–11). For the Moon Island reach, surface and bottom salinities were sometimes identical owing to turbulent mixing (tides and/or winds) and minimal freshwater inputs. On other occasions, the bottom and surface salinities were widely divergent with differences as high as about 17‰ (bottom salinity = 5‰ in December 1990; Fig. 1–12).

Crab Entrainment and Mortality During Construction

The primary objective of the crab sampling during construction dredging was to measure crab abundances and sizes directly associated with the actual dredging efforts. These summarized data were then inserted into the DIM (Armstrong et al. 1987) to provide a real-time assessment of crab losses.

The following section describes the parameters and variables used for the construction impact analyses.

Parameters

1. Hopper dredge Entrainment Rate (ER) = 0.27. This is a constant, based on several years of comparisons, that relates number of crab entrained/kcy dredged to the number of crab/ha caught by trawling.

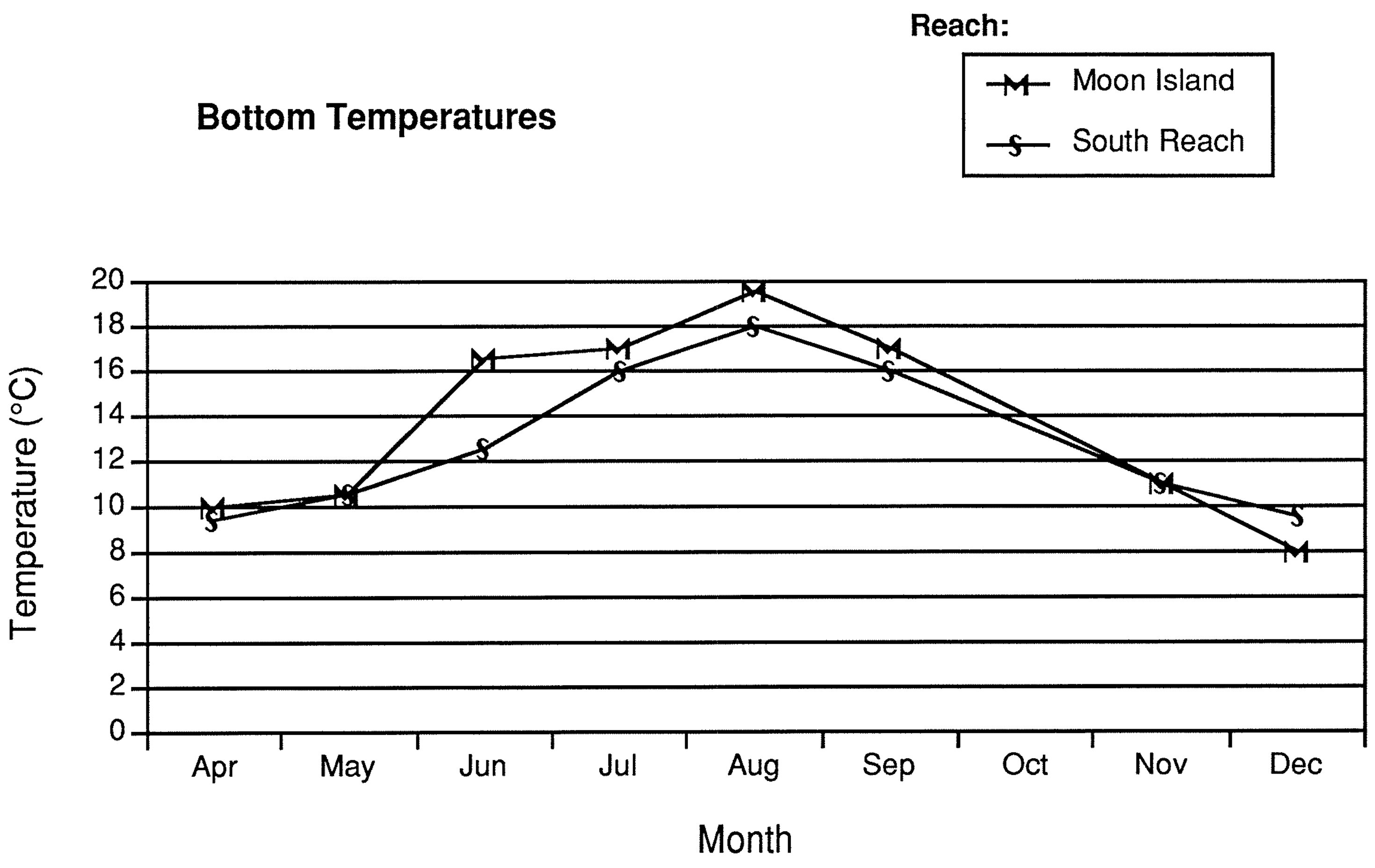


Figure 1-10. Monthly bottom temperatures recorded at Moon Island and South reaches.

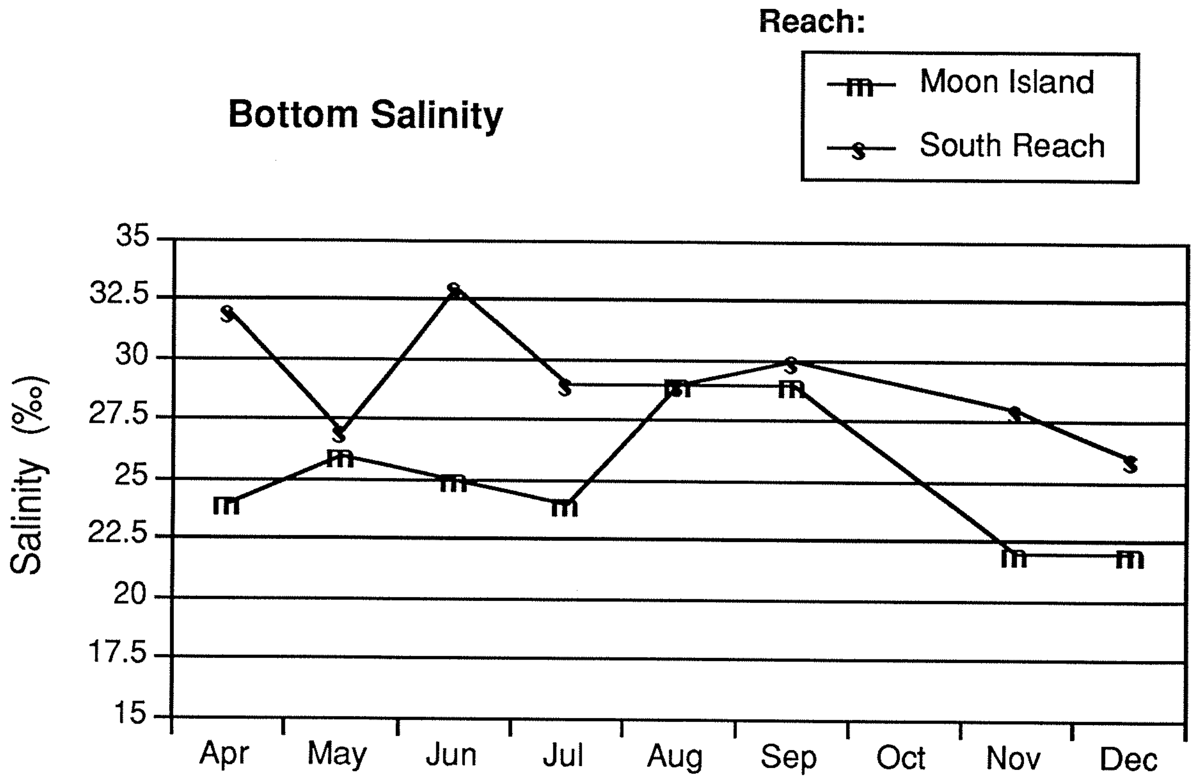


Figure 1–11. Monthly bottom water salinities recorded at the Moon Island and South reaches.

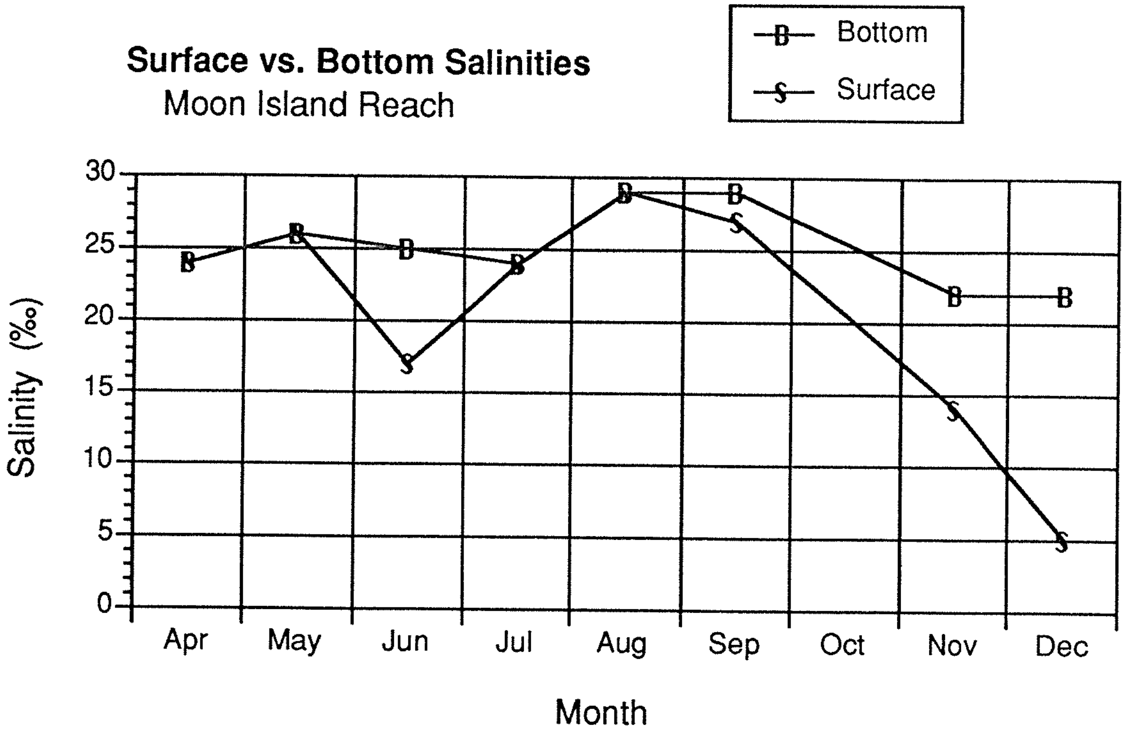


Figure 1–12. A comparison of surface and bottom water salinities recorded at the Moon Island reach.

2. Entrainment Factors (EF) (as percent of a hopper dredge):
   - hopper dredge = 100%
   - pipeline suction dredge = 100%
   - clam shell = 5%

3. Loss Factors (LF), which are the % crab killed of those actually entrained:
   - hopper dredge = 5% to 86% depending on crab size
   - pipeline = 100%, since all crab entrained are deposited in upland fill
   - clam shell = 10%

The LFs for hopper and clam shell dredges were established from previous studies by Stevens (1981) and Armstrong et al. (1982).

4. Crab natural survival to their 2+ winter (survival varies by crab age and season):

Season	0+	1+	>1+ & <3+
April–May	0.9%	10.7	53.2
June–September	1.7	16.0	64.9
October–December	3.4	25.5	81.9
January–March	6.6	38.0	100.0

(For example, only 1.7% of the 0+ crab alive between June and September of their settlement year will survive to winter 2+ age).

Further, for calculations of crab actually lost to the fishery at an age of 3+ years, a survival factor of 45% can be applied for crab in their 2+ → 3+ year. This factor is not a component of the DIM (which only calculates loss to 2+ years), but it can be applied to the DIM output.

5. Reach groupings:
   - Moon Island and Crossover reach crab densities are averaged together (n = 6), and this average applies to all reaches from Crossover → eastward.
   - Inner and outer South reach densities are averaged together (n = 6), and this average applies to all of South reach.
   - The Bar densities are based on the average of the three Bar stations.
   - The Entrance reach densities are based on the average of the outer South reach and the Bar (n = 6) because this area could not be trawled successfully.

Dredging Volumes and Crab Population Variables

1. Dredge volumes (kcy) were determined by COE and its contractors by month, reach, and gear, and entered as such into the DIM.
2. Crab densities (average crab/ha) were calculated for each month by reach groupings as noted previously. Since some dredging occurred in January 1991 when a trawl survey was not conducted, December 1990 crab data were applied without correction to January 1991.

3. Crab ages for any given month were determined by visual examination of the size-frequency data, and percentage 0+, 1+ and >1+ were determined for each month and reach grouping and inserted into the model.

The DIM output (Appendix 3) is given in terms of number of crab entrained, number of crab killed, and as equivalent age 2+ loss by month, by reach, and by crab age (0+, 1+, >1+). A final column gives the total equivalent age 2+ loss by month and reach and, finally, a summation of total 2+ loss for the whole project. The 2+ crab loss for the 1990/1991 construction dredging is estimated to be 161,600 Dungeness crab.

In viewing the DIM output, one should recognize that the estimate of 2+ crab killed by dredging was derived by an equation that accounts for degrees of entrainment and mortality by gear, abundances of crab in relation to dredging locations, and the application of natural mortality rates to each age of crab killed. High crab entrainment or mortality in a given reach does not necessarily result in high losses of 2+ crab. For instance, in a reach being dredged by a clamshell dredge, a crab will be 10X less likely to be entrained as compared to a hopper dredge. Similarly, a hopper dredge will only kill 5%-40% of the 0+ crab as compared to almost 90% for 1+ to 2+ crab (see the "Parameter" section of Appendix 3).

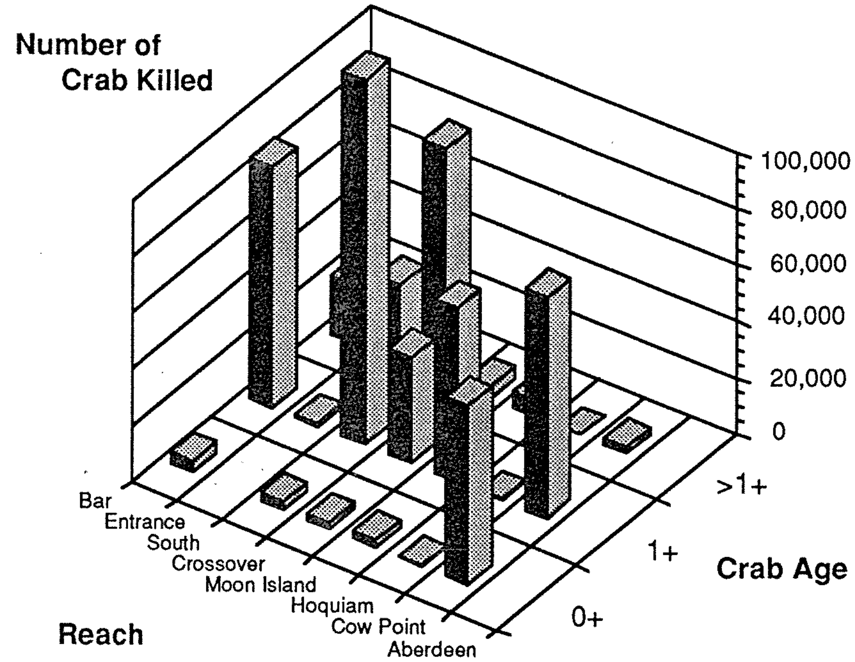
Another important DIM factor is that the death of a young crab represents less of a loss than that of an older crab since natural mortality of 0+ crab is much higher than for older crab. To illustrate this point, Fig. 1–13 (top) shows a high number of 0+ crab killed at the Cow Point reach, but the equivalent number of 2+ crab killed (Fig. 1–13, bottom) shrinks to a low number because few 0+ crab would naturally be expected to survive to age 2+ despite the dredging. This point is further illustrated for the 1+ and >1+ crab at South reach, where higher numbers of 1+ crab were killed (Fig. 1–13, top), but there was a higher 2+ equivalent loss of the >1+ crab due to a higher survival rate for the larger animals (and, hence, a higher probability of entering the fishery).

The “Total” row of Fig. 1–13 (bottom), which is a summation of normalized 2+ loss for all ages, shows that the greatest dredging impact on crab was at the South reach, an area where high abundances of larger crab are typically found.

DISCUSSION

The output of the DIM indicates that construction dredging killed approximately 161,600 age 2+ Dungeness crab. Loss at age of recruitment to the fishery (age 3+) will equal (2+ loss) X (an estimated survival of 45%), or 72,700 crab. Further, one-half of these crab are females, which are not part of the fishery. However, for purposes of mitigation, COE has agreed to mitigate for female loss as equivalent to male loss since there may be some loss of reproductive/juvenile recruitment capacity, although there is no present way to measure this. In terms of recent historical crab abundances in Grays Harbor, 1990 was roughly an average year. Sea Grant-sponsored annual trawl surveys of Dungeness crab at 18 stations in Grays Harbor from 1983 to 1990 have shown that average August crab densities throughout the estuary have ranged from a low of 900 crab/ha in 1986 to a high of 2,952 crab/ha in 1983, with an 8-year average of 1,750 crab/ha. The 1990 Sea Grant survey produced an estimated density of 1,488 crab/ha, a value very close to the 8-year average (Fig. 1–14).

Previous projections of crab losses due to dredging were made by Armstrong et al. (1987) as part of the efforts to “construct” the DIM. On the basis of a scenario without confined disposal, as essentially implemented by COE during actual construction dredging, and a linear entrainment rate,



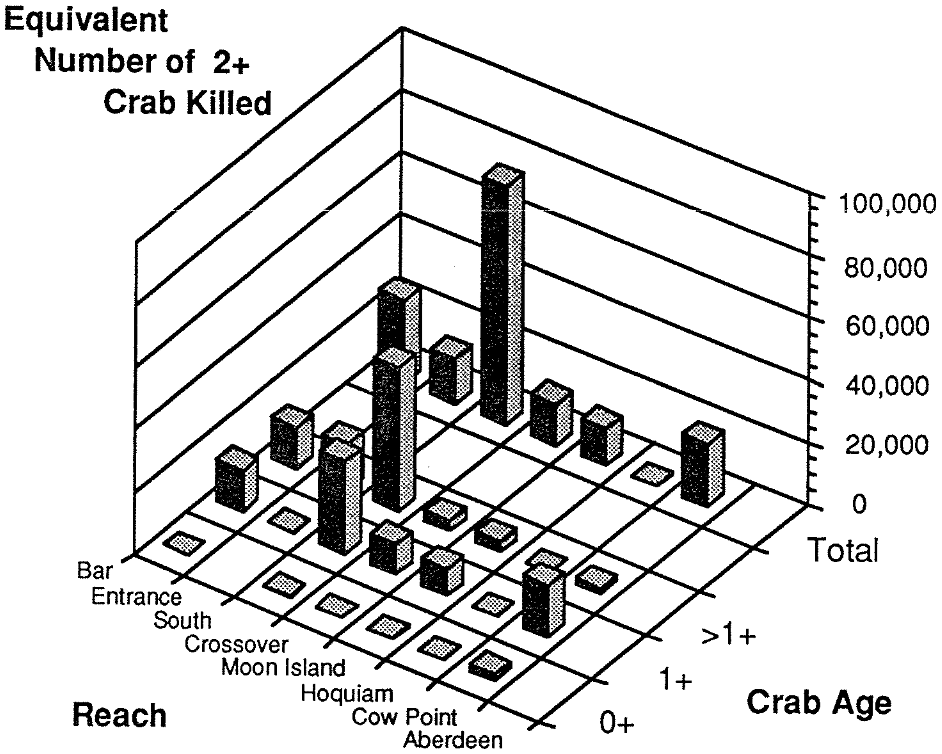


Figure 1–13. Estimated number of crab killed by age group and reach during 1990 construction dredging (top); estimated number of crab killed when normalized to age 2+ (bottom).

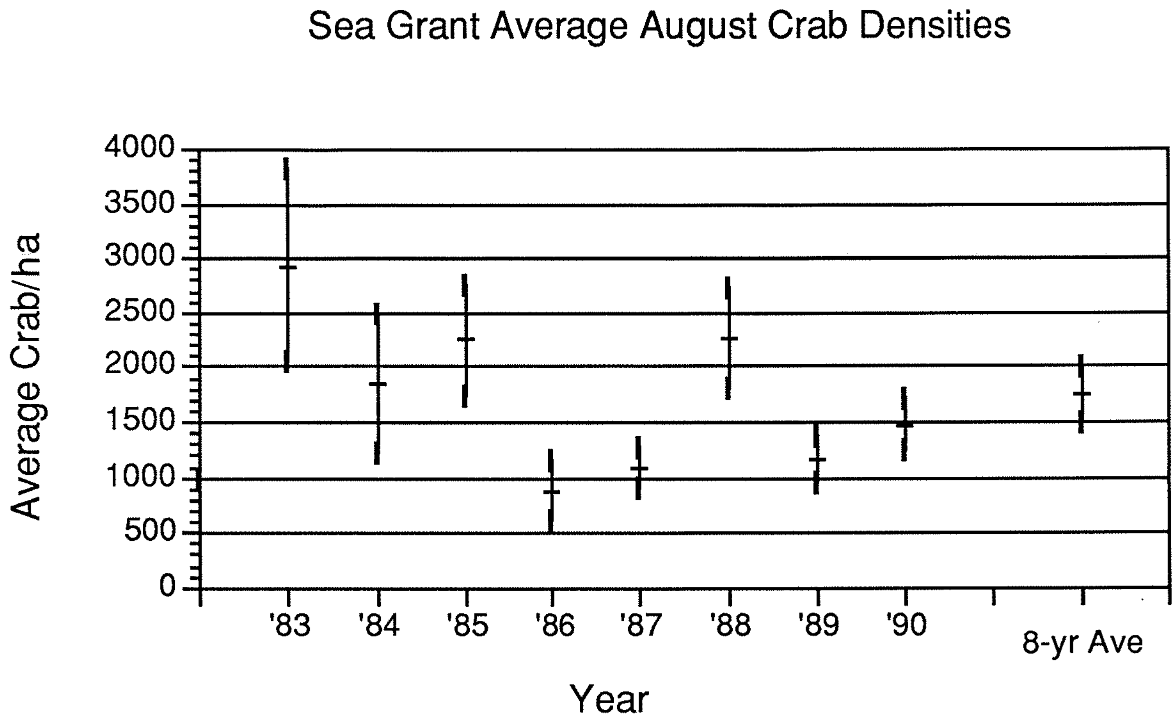


Figure 1-14. Average (with standard error bars) August crab densities in Grays Harbor from 1983 to 1990 as calculated from beam trawl sampling at 18 permanent stations. The 8-year average is shown on the right.

losses projected at that time for age 2+ crab ranged from a low of 108,000 to a high of 778,000. Most of the interannual variability depends on the abundance of the 1+ and 2+ age groups, which are at greater risk in the dredge program, and closer to the 2+ normalized impact value. Our present estimate of equivalent 2+ loss for 1990 of 161,600 crab is near the lower end of the range projected by Armstrong et al. (1987).

As indicated in other parts of this report, crab losses will be mitigated by deploying oyster shell beds in intertidal areas to increase survival of juvenile 0+ crab. The crab losses cited previously, in conjunction with data collected on juvenile crab survival in shell, will serve as the basis to calculate the amount of shell to be deployed in future years.

Crab Ecology

The same basic pattern of crab settlement, growth, movements, and aggregations were evident during this study as has been observed in past Grays Harbor studies. Briefly, crab settle to the benthos during May and June in both intertidal and subtidal areas. Highest survival of the juvenile instars is associated with protective habitats, especially shell rubble in Grays Harbor. The 1+ year old crab prefer the channel areas of Grays Harbor and are again especially plentiful in areas with shell or wood debris that provide subtidal hiding places. As crab mature at about age 2+, they move to the outer, deeper portions of the estuary and subsequently emigrate from Grays Harbor, where males enter the commercial fishery and females mate and produce eggs.

Continuing observations that highest trawl catches are associated with large amounts of shell reinforces the concept of mitigation for crab loss via shell deployment. Further, it suggests that shell deployment in subtidal areas (and perhaps even offshore) may also be as effective as intertidal plots, especially if subtidal shell plots are less prone to burial or disruption by currents.

CHAPTER 2. INTERTIDAL SHELL MITIGATION AND COMMUNITY COMPOSITION IN GRAYS HARBOR ESTUARY, 1990

D.A. ARMSTRONG, O. IRIBARNE, K.A. MCGRAW, AND R. PALACIOS

The study was carried out in Grays Harbor, an estuary located on the southern Washington coast (Lat. 47°N, Long. 124°W). The estuary is approximately 24 kilometers (km) long and 17 km wide, with a water surface area ranging from 235 km^2 at mean higher high water (MHHW) to 98 km^2 at mean lower low water (MLLW). Grays Harbor estuary is characterized by mudflats, which comprise 63% of the surface area at MLLW and are interspersed with a dendritic pattern of subtidal channels formed by numerous rivers and creeks as well as tidal discharge.

Several potential mitigation sites in intertidal areas were evaluated between 1988 and 1989 by University of Washington biologists, resource agency representatives, and U.S. Army Corps of Engineers (COE) personnel. The general selection criteria used were as follows: (1) public (i.e., state-owned) property; (2) reasonably firm substrate (i.e., relatively low density of infaunal shrimp affecting compaction); (3) relatively flat surface; (4) accessibility to a barge at high tide; and (5) absence or low density of eelgrass (*Zostera marina).* A total of four sites—3 in the North Bay area and 1 along South Channel (Fig. 2–1)—were selected, and designated as Campbell Slough (CS), Grass Creek Slough North (GCN), Grass Creek Slough South (GCS), and South Channel (SCh).

The four mitigation sites were monitored from May through August 1990. The primary objectives of the study were to (1) assess crab densities within each plot, (2) estimate the amount (percent cover) of shell remaining at each site, and (3) develop and implement an appropriate experimental design for data collection.

MATERIALS AND METHODS

One test plot consisting of oyster shell, and one control plot (undisturbed) each of 4000 m2 (0.4 ha), were established at each of the four sites. The amount of shell placed at each plot was intended to make a uniform layer about 6 cm deep (about 2-3 shells deep), which was previously shown by Dumbauld and Armstrong (1987) to support a mean crab density of about ten 0+ crab/m2.

Each plot was divided into 40 equal-sized sampling units (10 m x 10 m) and assigned a numeric code. On each trip, ten randomized units were sampled in both the control and shell plots. Three strata were defined in each shell plot: no-shell (open mud within the shell plot), wet shell (shell in ponds at low tide) and dry shell (shell exposed at low tide). Only two of these (wet shell and dry shell) were sampled continuously since crab densities on open ground were virtually zero after settlement. Additional random numbers (c.f., sampling units) were selected for more sampling units if both strata were not present in the first 10. This sampling scheme was designed to provide sufficient sampling units for 10 replicates per stratum. However, this level of replication was not always possible to obtain due to extensive sedimentation over exposed shell.

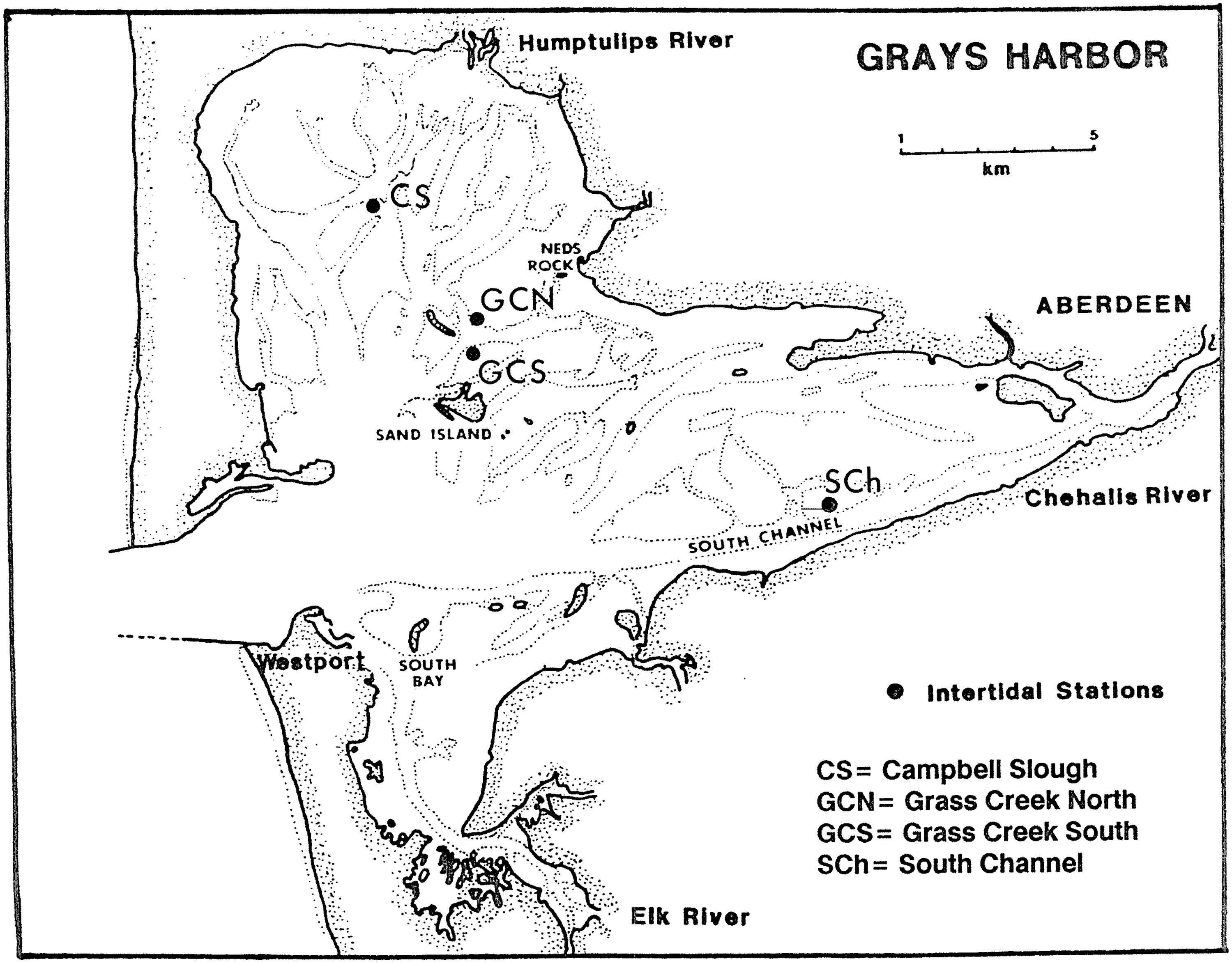


Figure 2-1. Map of Grays Harbor showing location of intertidal stations (●). Tidal elevations (in m) above mean lower low water (MLLW) and average eelgrass densities (turions/m^2) prior to shell placement are as follows. CS: 0.4–0.6 m, 13 turions/m^2; GCN: 0.4–0.6 m, 0.2 turions/m^2; GCS: 0.7–0.9 m, 1.1 turions/m^2; SCh: 0.6–0.9 m, 0.8 turions/m^2.

Sampling Procedure

Two different sampling methods were used: one for a relative measure of crab density based on a quadrat-rake-count (QRC method) designed to provide many samples in the brief period of low tide; and a second, more labor intensive “excavation” method, which involved a smaller quadrat and careful excavation of all shells to retrieve organisms.

QRC Samples

Within each randomly selected 10 X 10 m unit in the test plot, a three-sided 0.25 m^2 quadrat was placed over either dry or wet shell. A total of 10 samples were taken, if possible, for each substrate in the test plot. All shell and substrate down to a depth of 5 cm within the quadrat were quickly raked into a large dipnet of 3 mm mesh. A smaller dipnet of the same mesh size was used to scour the raked area inside the quadrat and capture any crab missed by raking. All shell and sediment were scraped into the large net, washed, transferred to a wooden sieve box with a screen mesh bottom (mesh size 3 mm), and sorted to remove most shells. All megalopae and small instar crab were sorted from the shellhash, and crab were measured just anterior to the 10th anterolateral spine to the nearest 0.1 mm using Vernier calipers, and sexed if over 20 mm carapace width (CW). Data for megalopae were used only to denote presence or absence of this stage and were not included in crab density calculations.

Sampling in the control plots consisted of one sample in each of 10 randomly selected units, collected by raking the top 5 cm of sediment into a large net (3 mm mesh), washing the sample, and examining remaining sediment and/or vegetation for crab.

Shell cover: Four independent visual estimates of the area covered by shell (wet plus dry) were recorded in each 10 x 10 m sample unit during each trip. The visual estimation technique was chosen for efficiency, but it proved to be robust across individual estimates and accurate when compared with a photographic survey. The four independent estimates of shell cover for the 10 units were averaged for each site monthly. Differences in extent of shell cover over time were tested using a two-way (site, trips) ANOVA with a Tukey *a posteriori* test to isolate differences.

Crab analysis: Crab abundance per site was estimated by multiplying the mean number of crab per site times the mean area covered by shell. To account for variances (shell coverage and crab density), the Delta method of variance approximation (Seber 1982) was used to estimate the variance of the crab population in each site.

If $y = f(x_1, x_2)$, with x_1, x_2 random variables, then the approximate variance [Var(y)] is:

$$\mathrm{Var}\ (y) = (\sigma f/x_i)^2 \ \mathrm{var}\ x_1 + (\sigma f/x_i)^2 \ \mathrm{var}\ x_2 + \mathrm{Cov}\ (x_1, x_2),$$

where y = mean crab density,
x_1 = percentage of area covered by shell in the same sampling unit,
x_2 = crab density in each sampling unit, and $(\sigma f/ x_i)^2$ is the partial derivation with respect to x_i.

A correlation analysis between proportion of shell cover and crab density was carried out for each site and each sampling trip. If x_1, x_2 are independent, uncorrelated random variables, then the approximate variance is as follows:

$$\mathrm{Var}\ y = (\sigma f/x_i)^2\ \mathrm{var}\ x_1 + (\sigma f/x_i)^2\ \mathrm{var}\ x_2$$

Two-way analysis of variance (ANOVA, Zar 1984) was used to test for differences in crab density among sites through time. Appropriate transformations were performed to meet the assumption of the linear model (Zar 1980).

Excavation Samples

During August 1990, benthic invertebrate fauna were sampled within shell at three sites—CS, GCS and SCh; no samples were taken at GCN due to time constraints). Sampling units in the oyster shell treatments consisted of excavating a 30 x 30 cm area through the shell plus 5 cm into the substrate beyond the shell-sediment interface. Excavation depth (shell depth in cm) was measured for each sample. Shell material was carefully removed, washed in a bucket containing estuarine water, and the elutriate filtered through a 1-mm mesh-size screen. All specimens retained on screens were sorted, identified, and counted. Additional samples were taken similarly from eelgrass and open areas.

<u>Amphipod analysis</u>: The total dry weight of amphipods was obtained from six subsamples of 30 amphipods each, dried at 60°C for 4 days, and ash free dry weights (AFDW) were then obtained from the same samples combusted at 500°C for 24 h. The weights of the amphipod subsamples were expanded to the total amphipod count from each excavation sample.

<u>Effects of shell packing</u>: An experiment was carried out at the South Channel site from August 20 to September 5, 1990 to determine if animal density corresponded to the relative surface area of shell-per-unit-volume of space (i.e., shell loosely or densely packed). Five cages (35 x 35 x 10 cm in depth) containing fragments of oyster shell and five cages containing entire oyster shells were buried within broad shell piles at the mitigation site. Cages were constructed with chicken wire (5 cm screen), which allowed free movement of the most common epifaunal species. Empty space within cages was estimated by measuring the equivalent volume of water displaced. The sampling procedure was as described above for the excavation sampling. Cages were retrieved on 5 September and all animals found in each cage were sorted and counted. Owing to the differences in variances, Welch's approximate t-test (t_c; Davenport and Webster 1975) was used to compare both treatments.

<u>Sediment Analyses</u>

Sediment samples were obtained at each station for determining grain size composition. Samples were collected to a depth of 10 cm using a section of PVC pipe with an inside diameter of 5 cm. Three strata were defined in shell treatment plots at each site for sediment analysis: open mud, pools, and underneath shell piles. Four samples were taken from each strata of the shell plot and four from the control. Grain size was analyzed according to the standard methodology described by Krumbein and Pettyjohn (1938). Results are reported as Phi values for each of the following sediment fractions: smaller than silt (<0.004 mm), silt (0.063–0.004 mm), 4(0.063 mm), 3(0.125 mm), 2(0.25 mm), 1(0.5 mm), 0(1.0 mm) and -1(>1.0 mm).

RESULTS

Shell Coverage

In April 1990, shell was deployed from barges onto experimental plots. Because of logistical constraints, we did not measure the amount of area covered by shell within the 0.4-ha plots immediately after deployment, but the Eelgrass Survey Team provided a visual estimate of 60-70% shell coverage. By May 20, approximately 2 weeks after shell placement, a large proportion of each shell plot had been covered by sediment in CS, GCN, and GCS; sediment accumulation was less at South Channel (Fig. 2–2A). The extent of shell cover at South Channel remained constant at about 60-70% during summer, significantly higher than at the other mitigation sites in North Bay (ANOVA on ln transformed data: $P<0.05$, see Appendix 4). Shell "loss" was due mainly to sediment accumulation, although some shell may have sunk into the substrate at certain locations (e.g., GCN). Transport of shell off plots by current and wave action played a negligible role in shell loss. Some shell was exposed in ponds during the summer, but for estimation of crab abundance this stratum, called "wet shell," was deleted as negligible (usually less than 2% of the total shell coverage).

Dungeness Crab

Major post-larval recruitment of crab occurred in mid-May through early June, with only a few megalopae detected in June. Crab densities (QRC method) were highest in June, with some decrease towards the end of the summer (Fig.2–2B). Densities in June were comparable between SCh and two sites in North Bay (GCN, GCS) at about 20-40 crabs/m^2, but were significantly lower (<10 crab/m^2) at CS (Fig. 2–2B). Within a site through time (June-August), densities changed by less than 2X. Juvenile crab densities in open areas (controls) were usually zero with few exceptions. There were no differences in crab size between individuals sampled in the two shell strata within plots (ANCOVA: $P>0.05$; Fig. 2–3). Size frequency data showed a preponderance of 1st stage juvenile (J1) instars (~ 7.5 mm CW) in June, and a range up to J4 through August (Fig. 2–3). Juvenile crab in the "dry" shell substratum were somewhat lethargic during low tide and generally hidden in the moist shell-mud interface; few animals were on the shell in the vertical dimension. Crab living in shell ponds were active and moved rapidly when disturbed.

Using crab densities determined by the QRC method, we estimated abundance per plot by month as a function of total coverage (Fig. 2–2C). Because of high crab density and higher shell coverage at SCh, abundance was greatest at this location and declined from about 85,000 to 40,000 crab over the test plot from June through August. Data analyses (Table 2–1) showed no definite relationship between between crab density and percent shell remaining on a plot, although there were a few cases of significant correlation.

Similarly, excavation samples showed no correlation between shell depth (or sample volume) and crab density at any of the three study sites sampled during August 1990 (Fig. 2–4B; SCh: $r^2 = 0.002$, $n = 30$, $P>0.05$; GCS: $r^2 = 0.02$, $n = 7$, $P>0.05$; CS: $r^2 = 0.03$, $n = 8$, $P>0.05$). Crab density was significantly higher (ANOVA: $P<0.05$, 95 % Tukey HSD intervals, Appendix 5) at SCh ($\bar{x} = 71 \pm 35$, $n = 30$) than at CS ($\bar{x} = 54 \pm 42$, $n = 8$) and GCS ($\bar{x} = 35 \pm 19$, $n = 7$). These densities were approximately two or three times greater than those determined by the QRC method (compare Figs. 2–2 and 2–4).

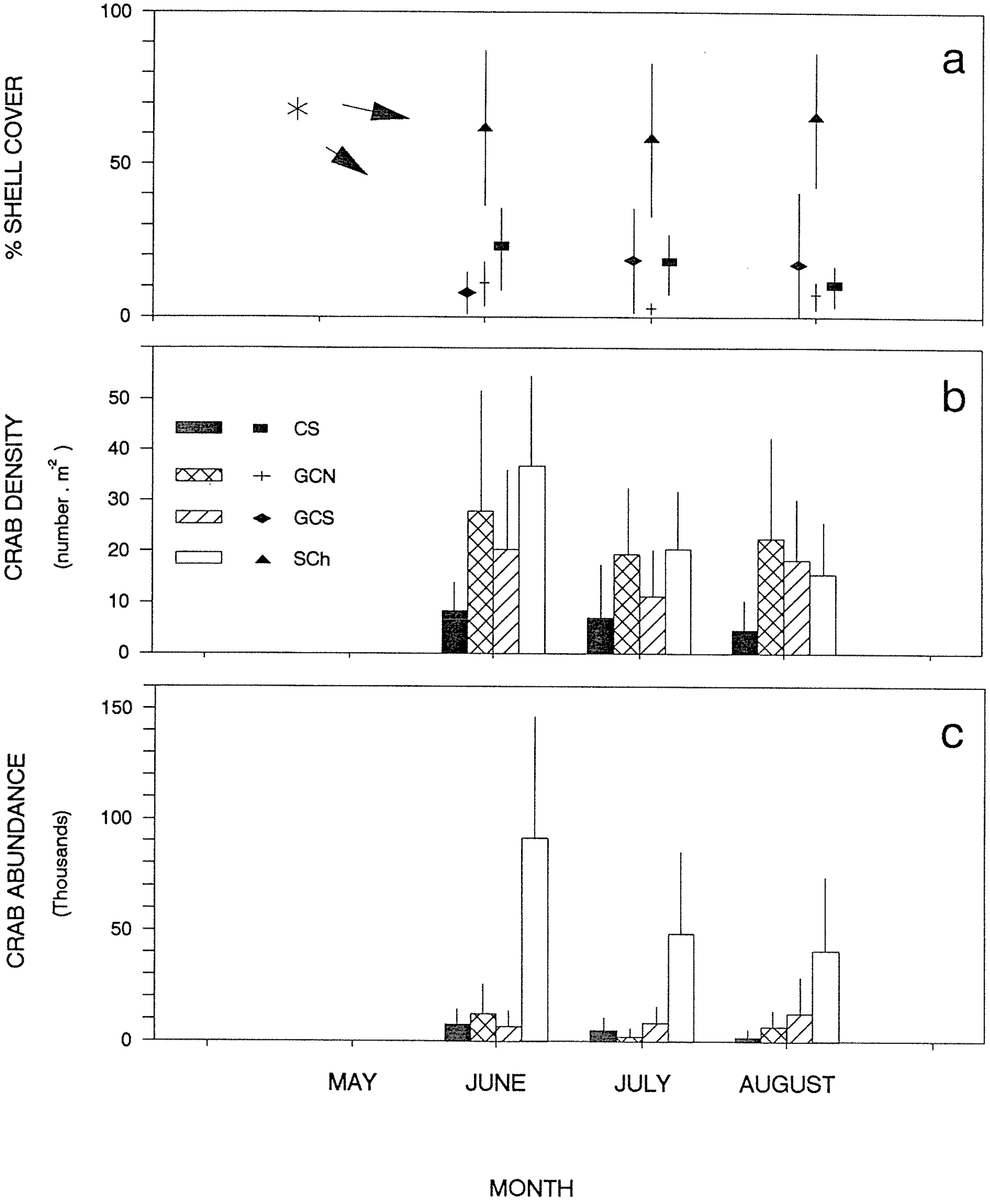


Figure 2–2. A. Proportion of 0.4-ha experimental plots covered by shell at the four different mitigation sites; initial coverage was 70%. B. Mean crab density (±1 S.D.) in each site (QRC method). C. Crab abundance at each site. CS: Campbell Slough; GCN: Grass Creek North; CGS: Grass Creek South; and SCh: South Channel.

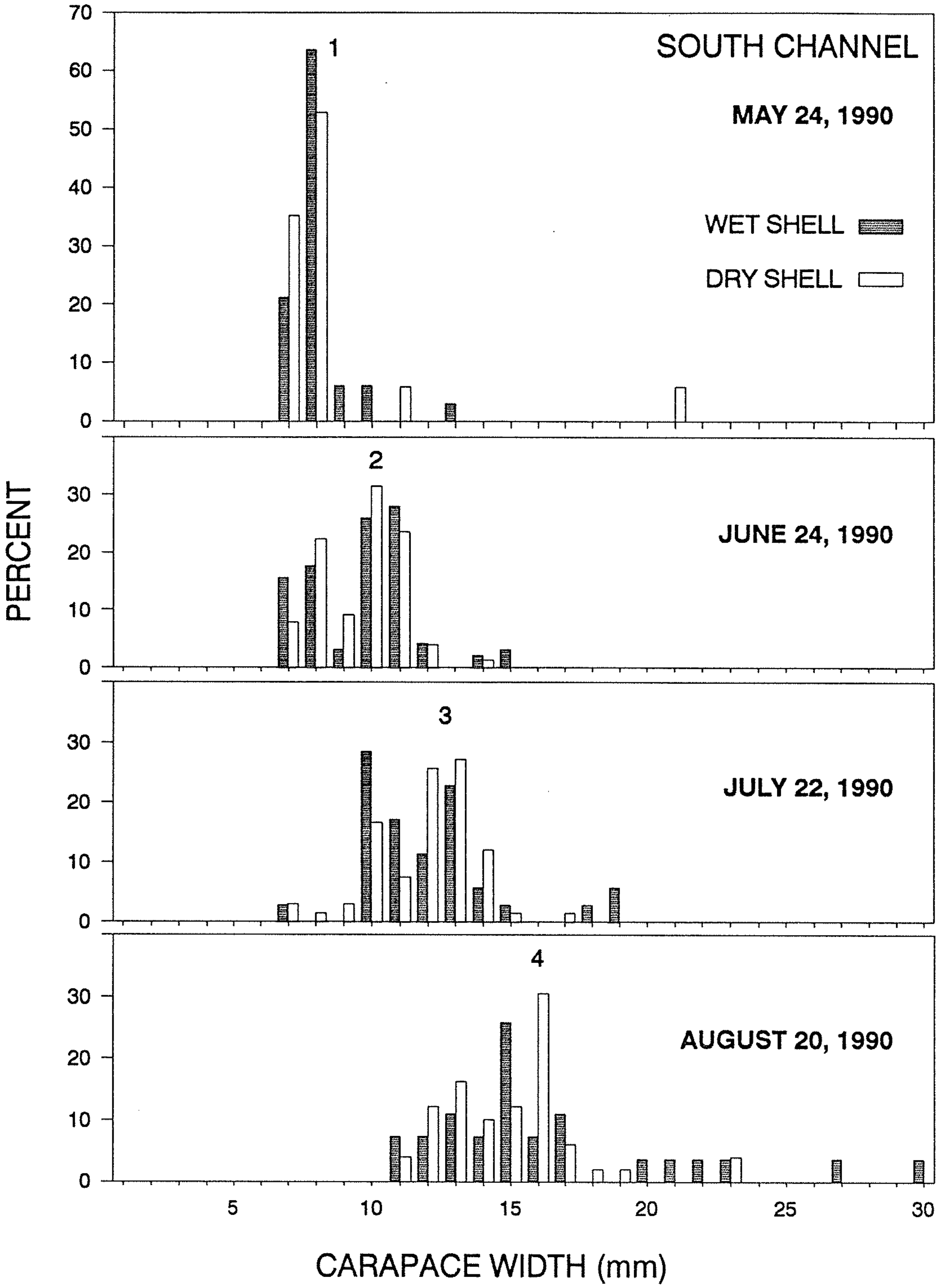


Figure 2–3. Size frequency distribution of crab collected in wet shell and dry shell strata at the South Channel mitigation site.

Table 2-1. Correlation analysis between percent of area of each plot covered by shell and corresponding crab CPUE (crab/0.25 m^2). Sites: CS = Campbell Slough; GCN = Grass Creek North; GCS = Grass Creek South; SCh = South Channel. N = Number of samples; r^2 = Coefficient of determination; P = probability; * = significant at 0.05 level, and NS = non-significant.

	CS			GCN			GCS			SCh		
Date	r^2	P	N	r^2	P	N	r^2	P	N	r^2	P	N
June-90	0.01	NS	18	0.21	*	18	0.27	*	18	0.01	NS	18
Jul-90	0.17	NS	18	0.85	*	10	0.23	NS	12	0	NS	18
Aug-90	0.21	NS	9	0.05	NS	5	0.53	NS	4	0.11	NS	18

Community Characteristics from Excavation Samples in August 1990

Principal species found in the excavated shell matrix at CS, GCS and SCh were amphipods (*Eogammarus confervicolus*) (Fig. 2–4A), Dungeness crab (*Cancer magister*), shore crab (*Hemigrapsus* sp.), hermit crab (*Pagurus hirsutiusculus*), gunnels (*Pholis* sp.), and mussels (*Mytilus edulis*) (Fig. 2–5). Bivalve species found in soft-bottom areas covered by shell were the bivalves *Mya arenaria* and *Cryptomya californiana*; those found in open mud areas were primarily the bivalves *Macoma balthica, M. arenaria*, and *C. californiana.*

Amphipods were the most abundant group, and analysis showed a significant correlation between density and shell depth or volume at SCh ($r^2 = 0.73$, n = 30, $P<0.005$; Fig. 2–4A). However, there were no such correlations at GCS ($r^2 = 0.48$, n = 7, $P>0.05$) and CS ($r^2 = 0.11$, n = 8, $P>0.05$; Fig. 2–4A). Average amphipod density was significantly greater at SCh (from 1,000-7,000/m^2 depending on shell depth; Fig. 2–4A) compared to the other two sites (ANOVA: $P<0.005$). Amphipod densities were not statistically different between GCS and CS (95% Tukey HSD intervals) at 500-1000/m^2. In terms of biomass, amphipods ranged from 1 to 15 g dry weight, or up to 5 g AFDW (Fig. 2–4A).

The experiment on the effect of shell packing produced some interesting results. Cages with fragments of oyster shell, which had an average empty space volume of 8.8 liters (l) per cage (n = 5), had a mean amphipod density of 417 (±88) per cage. Amphipod density was much lower ($\bar{x} = 51 \pm 11$ per cage) in cages with whole shell, which had a mean empty space volume of 10.8 l per cage (n = 5).

Mussels were the most common bivalve species in the shell matrix (Table 2–2). Densities were higher in GCS than in SCh and CS. Densities in the control and eelgrass sites were zero. Densities of *M. balthica* and *M. arenaria* were higher in shell at CS and SCh; however, the cockle, *Clinocardium nuttalli,* tended to have higher densities in control than in shell samples. Unlike amphipods, mussel densities were not correlated with shell depth at any mitigation sites (SCh: $r^2 = 0.25$, d.f. = 28, N.S.; GCS: $r^2 = 0.55$, d.f. = 5, N.S.; CS: $r^2 = 0.04$, d.f. = 6, N.S.); this was also true for the density of the other species (r always non-significant, $P>0.05$).

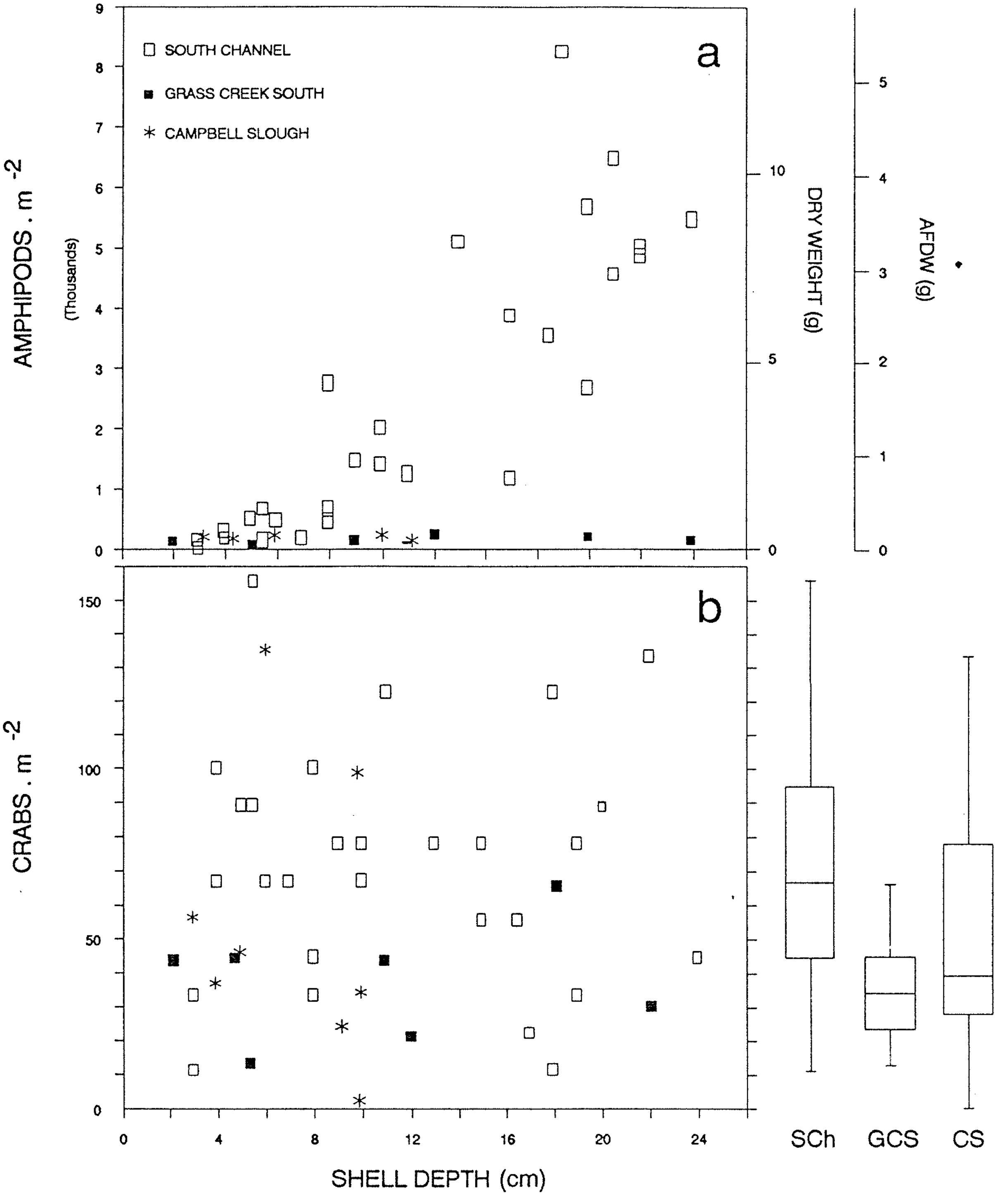


Figure 2–4. Amphipod and crab densities in excavation samples, August 1990. A. Amphipod (*Eogammarus confervicolus*) density in relation to shell depth; B. Crab density in relation to shell depth. Box plots at the right show the *median* value (center horizontal line) and quartiles (edge of the central box). SCh: South Channel; GCS: Grass Creek South; and CS: Campbell Slough. AFDW: Ash free dry weight.

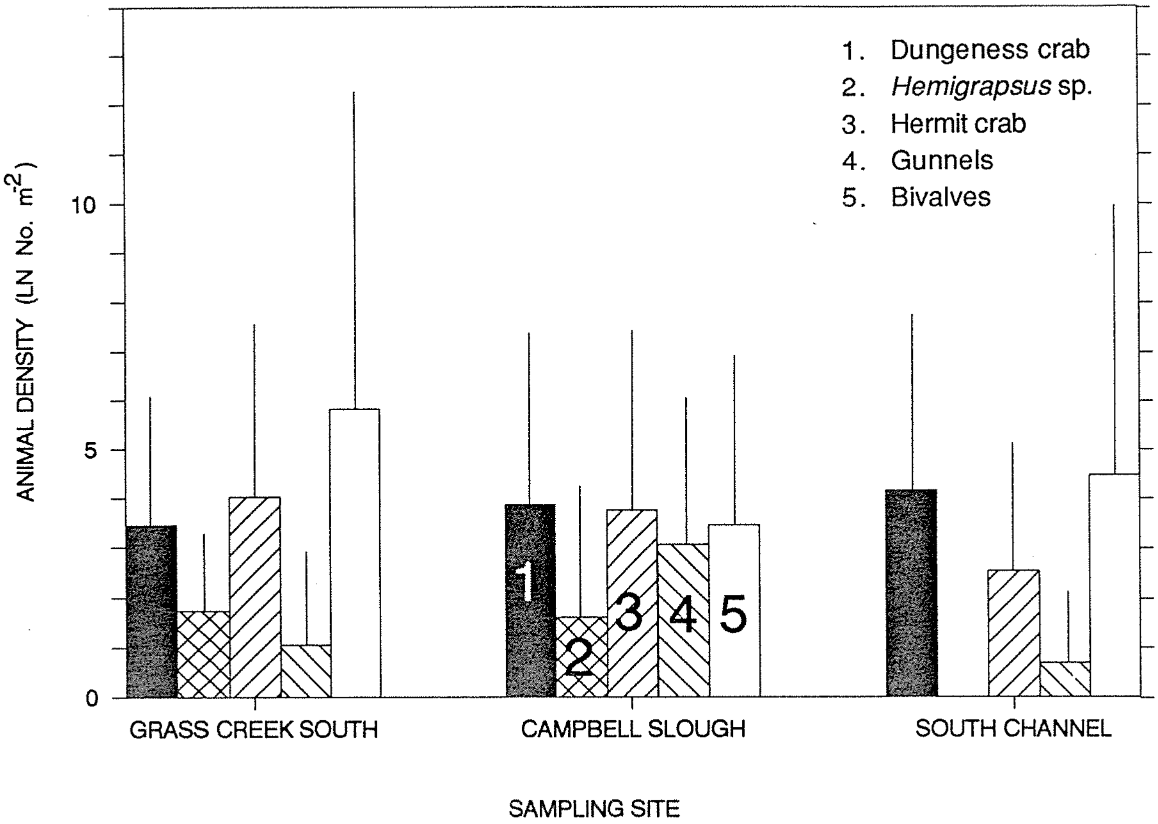


Figure 2–5. Other species (excluding amphipods) found in the shell matrix. Densities are expressed as Ln/m^2 ± 1 S.D.

<u>Sediment Analyses</u>

The proportion of silt in sediment samples from SCh was higher than at the other three sites (Fig. 2–6). However, there were no important differences within strata at different sites (i.e., ponds, underneath shell piles, open mud within shell area, or the control). The predominant grain size at all sites was 0.125 mm, or a Phi value of 3.

DISCUSSION

Results of the 1990 program indicate that intertidal shell habitat will work as mitigation for loss of crab caused by subtidal dredging, but there are several outstanding problems that stem from physical processes and resource agency concerns, both of which bear on the future viability of the mitigation program. Issues centered on the durability of shell and effects of physical processes, as well as crab recruitment and survival in several distinctly different shell configurations, are being addressed in further small-scale studies during the 1991 field season. Whether environmental issues of concern to resource agencies (impact of shell on eelgrass; proximity of shell mitigation to point source pollution; possible propagation of smooth cordgrass, *Spartina alterniflora*, via importation of shell) are under study is not known to us at present.

Table 2-2. Bivalve density (in number/m^2) measured with excavation samples (0.10 m^2 quadrat). CS = Campbell Slough, GCS = Grass Creek South, SCh= South Channel. $\bar{x}$ = Average ± standard deviation (SD); n = sample size.

Species/Site	Shell plot		Control plot	
	$\bar{x}$ ± SD (No./m^2)	n	$\bar{x}$ ± SD (No./m^2)	n
Mytilus edulis				
CS	9.6 ± 10.2	8	0	8
GCS	355.0 ± 533.0	8	0	10
SCh	70.7 ± 106	30	0	10
Macoma balthica				
CS	15.0 ± 16.0	8	3.9 ± 1.7	8
GCS	1.5 ± 3.7	7	7.3 ± 4.2	10
SCh	14.0 ± 18	30	9.0 ± 2.5	8
Mya arenaria				
CS	2.7 ± 4.7	8	0	8
GCS	3.1 ± 7.6	7	2.8 ± 5.2	10
SCh	9.5 ± 17.1	30	5.0 ± 3.5	30
Clinocardium nuttalli				
CS	6.8 ± 11.0	8	2.2 ± 0.2	8
GCS	15.7 ± 15.4	7	24.2 ± 33.7	10
SCh	2.2 ± 5.2	30	3.3 ± 0.3	8

Shell Durability

A paramount objective of the 1990 field program was to learn the fate of intertidal shell placed at a variety of intertidal sites. "Durability" connotes both the length of time over which the shell functions as usable habitat for 0+ crab (i.e., months or years), and the spatial extent of cover-per-unit-area (i.e., whether 100% or a lesser amount of each hectare) of habitat constructed with shell. The small-scale research of Dumbauld and Armstrong (1987) suggests that shell several layers thick provides the best habitat for 0+ crab, and in the small experimental plots the authors used, coverage was set at 100% per-unit-area.

The most surprising and informative aspects of habitat construction and durability during 1990 were as follows: (1) the high percentage of open ground within mitigation plots resulting from heterogeneous displacement of shell off barges; (2) the extreme variability in thickness of shell coverage, which ranged from a single layer to mounds up to 50 cm deep; (3) substantial change in the topography of intertidal flats from essentially level ground with very shallow depressions (less than 5 cm) to a broken, more three-dimensional terrain of pools and mounds; and (4) the rapid loss of usable shell habitat caused by sedimentation, sinkage, or transport of shell off the mitigation sites. Data shown in Fig. 2–2A indicate that only one of the four mitigation sites (South Channel) persisted through the summer as extensive, viable shell habitat for 0+ crab. The 70% coverage recorded for that site is probably acceptable, but the extensive loss of habitat that reduced North Bay sites to a range of cover from 10-20% seems unacceptable. At these sites, that most "lost"

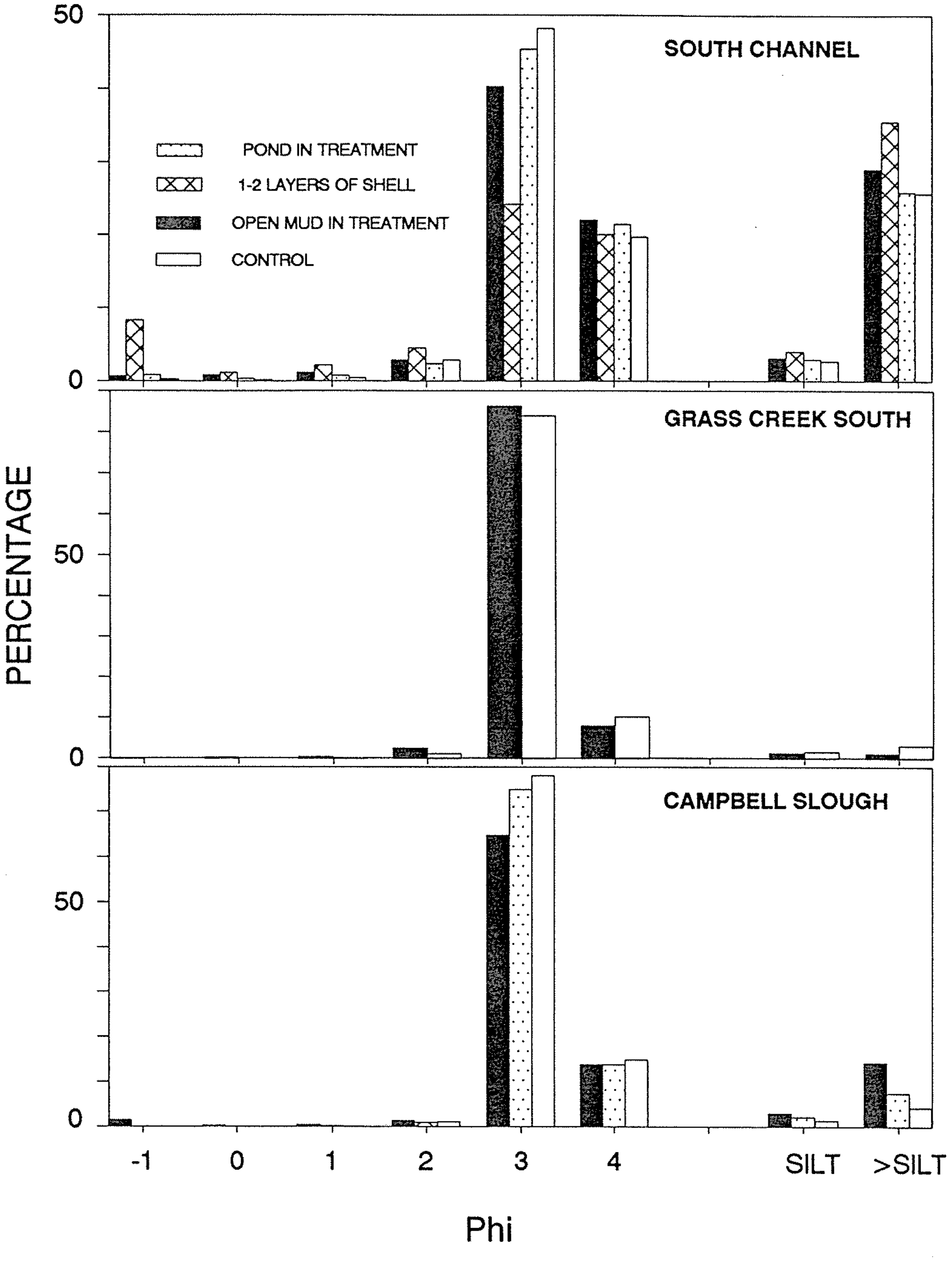


Figure 2–6. Grain-size analysis (phi values are described in Chapter 2 Materials and Methods).

shell habitat appeared to be due to heavy sedimentation and burial of the shell rather than physical transport off-site.

As a consequence of severe turbulence caused by the prop wash of barges hovering over the sites during placement of shell at high tide, the topography changed substantially, resulting in deep pools (20-50 cm) and large mounds of shell. We discussed the data on percent shell cover with two faculty in the University of Washington School of Oceanography, Drs. Peter Jumars and Arthur Nowell, who felt the high sedimentation rates and subsequent coverage of shell were consistent both with our description of extreme change in topography at the North Bay sites and our guess that current speed and turbulence were lower at those sites than at the South Channel site. Sedimentation rates will increase in areas of greater three-dimensional topography as well as lower current velocity, both of which enhance sedimentation rather than promote scouring. Jumars and Nowell believe that habitat should be constructed such that the most uniform shell layer possible is created, which minimizes three-dimensional features of the intertidal terrain. Missing from the program in 1990 was support to measure current speeds and sedimentation rates at any of the mitigation sites in order to improve our ability to predict likelihood of shell durability at other sites selected in the future.

The significant decrease of shell coverage on the scale of hectares will badly impact the total abundance of 0+ crab recruited into new mitigation habitat. The overall goal of the mitigation project is to work backwards in age-class from subtidal crab killed during dredging to an amount of habitat required for 0+ crab, based on estimates of natural mortality for replacement of older subtidal juveniles lost during construction. A substantial reduction in percent cover can only be offset by either higher density of 0+ crab/m^2 or greater aerial deployment of shell in excess of the original estimate (about 35 ha) or both, but the second option is probably not economically feasible. Sites where shell durability and retention are high should be given greatest priority for full-scale mitigation in order to maximize use of shell as crab habitat and minimize cost. Whether such sites can be found in North Bay is a primary objective of the 1991 program.

<u>0+ Crab Densities</u>

At most of the mitigation sites, densities of the 1990 crab year-class were substantially higher than measured during past studies. Although the percent coverage of shell was generally low, crab densities as determined by the QRC method were on the order of 15 to 25 crab/m^2, and based on the excavation method were typically between 30 to 100 crab/m^2 through the summer (see Figs. 2–2B, 2–4B). Estimates of full-scale mitigation have generally been based on a crab density value of 10 animals/m^2, so results of 1990 indicate this value might reasonably be increased by a factor of two- to fourfold. Also of interest was the finding that crab density did not seem to increase linearly with shell depth (Fig. 2–4B). This finding should be taken as evidence that extensive piles deeper than 10 cm are not necessary in the context of crab abundance, but the data should not be interpreted in the other direction that layers down to a single shell thickness are adequate refuge or proper shell habitat. During careful excavation of samples in shell piles, most crab were found at the shell-sediment interface rather than within the shell on the vertical plane. This may imply that 0+ crab are predominantly treating shell as a two-dimensional habitat gauged by density, but the three-dimensional configuration may provide increased foraging space within the refuge of the shell habitat, and most likely an increased amount of prey.

The Shell Community

Of great interest in the 1990 study were data that showed substantial recruitment of several major invertebrate taxa to the shell and high densities through the summer. Numbers of amphipods (thousands/m^2) and high biomass suggest they are important prey for resident 0+ crab within the shell, and other prey certainly include small bivalves that recruited at high densities (Fig. 2–5). We intend further studies of invertebrate communities within the shell habitat to better define species composition, population dynamics, and standing stock as part of the community perspective of shell habitat. These data should be weighed carefully against similar information (to the extent available) on communities within the light to sparse eelgrass that is common over much of the Grays Harbor intertidal, since the issue of shell impact on eelgrass is so pervasive and controversial at this time. Our admittedly limited data collected within eelgrass during 1990 show very low densities of epibenthic invertebrates or complete absence (e.g., *Hemigrapsus* sp., hermit crab).

RECOMMENDATIONS

As experts on estuarine crab ecology and as advisors in the mitigation program from its inception, we consider it important to go on record as advising COE in several respects pertinent to the overall mitigation program. As of this writing, construction dredging has been completed and any resultant impact on the crab resource has occurred. It therefore seems imperative to us that mitigation proceed as rapidly as possible, and that studies be focused on outstanding environmental issues to resolve the different perceptions of whether or not certain impacts might result from intertidal shell mitigation. The following recommendations summarize our sense of the most promising aspects of actual habitat construction as well as the hope and need to resolve certain controversies.

1. COE should regard the South Channel site as the most promising location for mitigation and be prepared to construct extensive habitat in this area in 1992.
2. COE should work in concert with resource agencies as they have done to this time to resolve whether or not pollution in any form is excessive at the South Channel site compared to other potential mitigation sites in Grays Harbor. At this time there are no data to substantiate concerns and it seems to us unnecessary to eliminate such a promising location with no basis in data on dioxin or other contaminants.
3. COE should request standards and criteria by which resource agencies ascertain and judge the relative importance of eelgrass over a spectrum of density as essential or not from a community perspective. We believe that the best mitigation sites as determined from the combined 1990-91 studies will inevitably be proximate to or on intertidal locations with low eelgrass density. We would be willing to work in concert with colleagues in resource agencies to compare data on community structure (species composition, relative density) in shell versus eelgrass. We take a perspective that shell habitat is ecologically sound and possibly of greater importance to a variety of estuarine organisms than the extremely light eelgrass cover over much of Grays Harbor. As well, the spatial scale of shell mitigation is very slight in comparison to the expanse of intertidal flats throughout this estuary.
4. COE should support and encourage work and participate in measurements designed to characterize current velocity and sedimentation rates at a variety of the small-scale mitiga-

tion sites studied in 1991. We consider it inadvisable to finish 1991 studies with only presence/absence data on crab and shell durability, with no predictive sense of whether or not shell will endure across a variety of intertidal locations given currents and sediment loads.

CHAPTER 3. EELGRASS (*ZOSTERA MARINA* L.) STUDIES ASSOCIATED WITH CRAB MITIGATION IN GRAYS HARBOR ESTUARY, 1990

R.M. THOM[1] AND L. HALLUM

The Seattle District, U.S. Army Corps of Engineers (COE), intends to use oyster shell plots to mitigate for Dungeness crab (*Cancer magister*) mortalities caused by dredging in Grays Harbor, Washington. In April 1990, experimental shell test plots, 1 acre (0.4 ha) in size, were established to further evaluate the proposed mitigation method. Because some of the selected plots contained eelgrass, general concern arose regarding the impact of shell placement on natural stands of eelgrass. The present study addressed the question "Does the 1990 experimental shell placement affect eelgrass survival in the plots?"

The objective of this study was to sample eelgrass density within shell plots and adjacent control plots before and after shell placement in order to quantitatively assess the effects of shell piles on eelgrass survival. To help assess potential for recovery of eelgrass in plots that may have been significantly affected, we also conducted eelgrass transplanting experiments in the shell plots. Because the shell placement would probably result in a general disturbance of sediment processes (e.g. nutrient cycling, sediment-associated metabolism), we measured chlorophyll *a* and phaeopigment concentrations in the surface sediments in the plots. If disturbance were significant, we hypothesized that sediment-associated primary producers would be affected, as would the microbial system that results in the production of the phaeopigments from the breakdown of chlorophyll. Specifically, increased perturbations would change phaeopigment and chlorophyll *a* concentrations.

MATERIALS AND METHODS

Study Sites

The experimental plots were located in Campbell Slough (CS), on the northern (GCN) and southern (GCS) sides of the Grass Creek channel, and in South Channel (SCh) (Fig. 2–1). These sites were chosen to maximize shell plot stability, to cover minimal stands of eelgrass, and to maximize the probability of crab settlement. In April 1990, rectangular 0.4 ha (40 x 100 m) shell and control plots (adjacent to the shell plots) were established at each site. Scientists, including personnel from resource agencies, the University of Washington, and the COE, selected the position of the test plots so that they appeared qualitatively to contain less eelgrass compared with the control plot. The plots were marked with wooden stakes and floats to facilitate shell placement and relocation for crab and eelgrass sampling.

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Sampling Methods

Each plot was sampled in March or April 1990 prior to the placement of shell and then in May, June, July, and August. Samples, consisting of eelgrass shoot densities and percentage cover of shell, were collected from within a 0.25-m^2 quadrat at 15 randomly located sites within each plot during low tides. The percentage cover of shell was estimated from 35-mm color slides taken vertically over each quadrat. The slides were projected onto a grid of 50 random points, and the number of points covered by shell was recorded. These counts were converted to a percent. At five random sites, 1-cm diameter x 1-cm deep cores were collected for sediment pigment analysis. All sediment samples were frozen and transported to the laboratory for analysis. Chlorophyll *a* and phaeopigments were determined using a fluorometer (Turner). Sediment pigment sampling was carried out only during the post-shell placement trips in May–August.

Transplanting Methods

In April and May 1990, we transplanted eelgrass shoots with attached roots and rhizomes into ponds created by the placement of shell in the plots. Initial depth varied among ponds; however, individual pond depth also varied through time, probably as a result of sediment accumulation. In general, eelgrass is confined to areas of standing water on the flats, and we reasoned that plants placed in ponds would have a higher probability of surviving compared with plants placed on flat areas that were more prone to desiccation. Most of the plantings were done by bundling 10 eelgrass shoots around a metal wire. The shoots were secured to the wire with a plastic-covered metal twist tie. The wire, which protruded below the rhizomes approximately 10-15 cm served as an anchor for the shoot bundles. Material for the transplants was gathered immediately adjacent to the plot to minimize handling time and exposure of the below-ground parts to air. A total of 16 experimental ponds in the four test plots received 50-150 shoots each. Individual shoots or shoot bundles were planted with 10-20 cm spacings. In August, we recorded the number of shoots per pond, pond depth and other observations on events that may have affected the survival of the plants.

RESULTS AND DISCUSSION

Initial shell cover was not measured quantitatively, but visual estimates made at CS and GCS the day after shell placement indicated that shell covered approximately 60% of the plots. Shell was generally distributed in piles up to 50 cm thick, with areas of relatively uniform thickness of 1–2 shell layers. Areas of standing water (i.e., ponds), with little or no shell cover, were evidently created by the placement of shell. Percent shell cover at the end of the summer (August) for CS, GCN, GCS and SCh was 1.1, 4.5, 0.1, and 24.8%, respectively. This suggested that shell was either removed from the sites or buried relatively rapidly (i.e., within a 1–4 month period) following placement. Note that percent shell cover estimates for the eelgrass study were derived from a different method than that used for the crab sampling study. Locations of samples did not coincide between the two studies and, therefore, the estimates may vary both in magnitude and space.

Eelgrass occurred in fairly discrete patches in all of the plots. Mean density prior to shell placement in March ranged from 0-13 shoots/m^2 (Figs. 3–1 to 3–4). Mean density was greater in the shell plots as compared with the control plots at CS and GCS (Figs. 3–1, 3–3). However, the variance was great at these two sites because of the patchiness of the eelgrass, and the difference

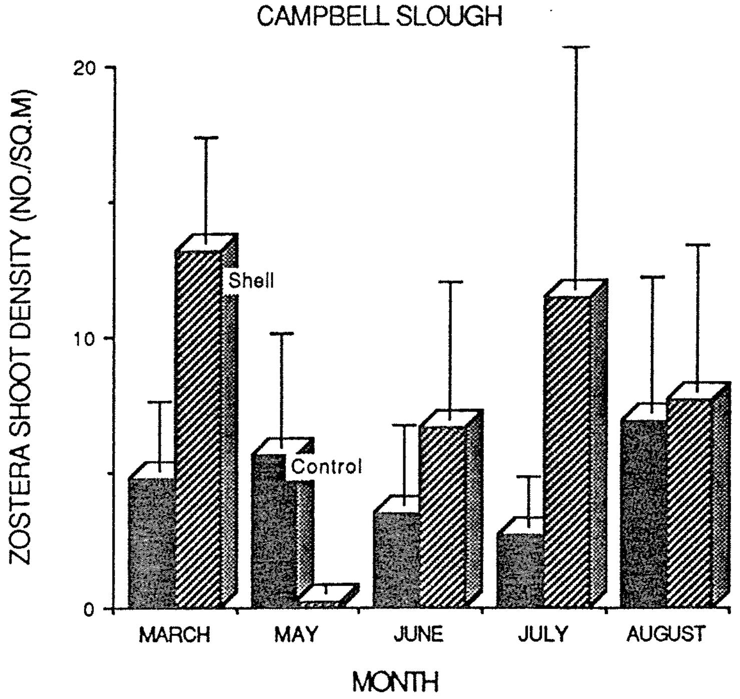

Figure 3–1. Temporal variation in mean eelgrass shoot density (± S.D.) at Campbell Slough shell and control plots.

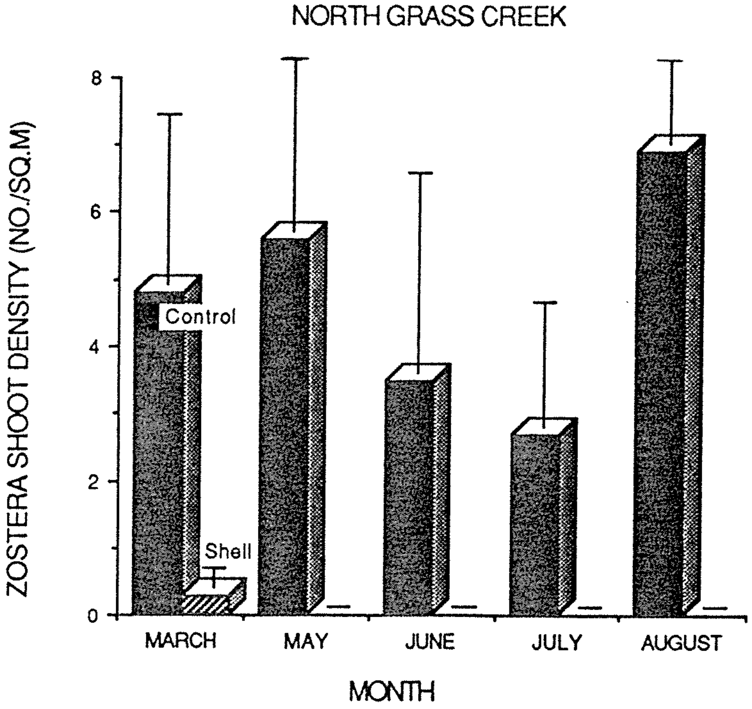

Figure 3–2. Temporal variations in mean eelgrass shoot density (± S.D.) at North Grass Creek shell and control plots.

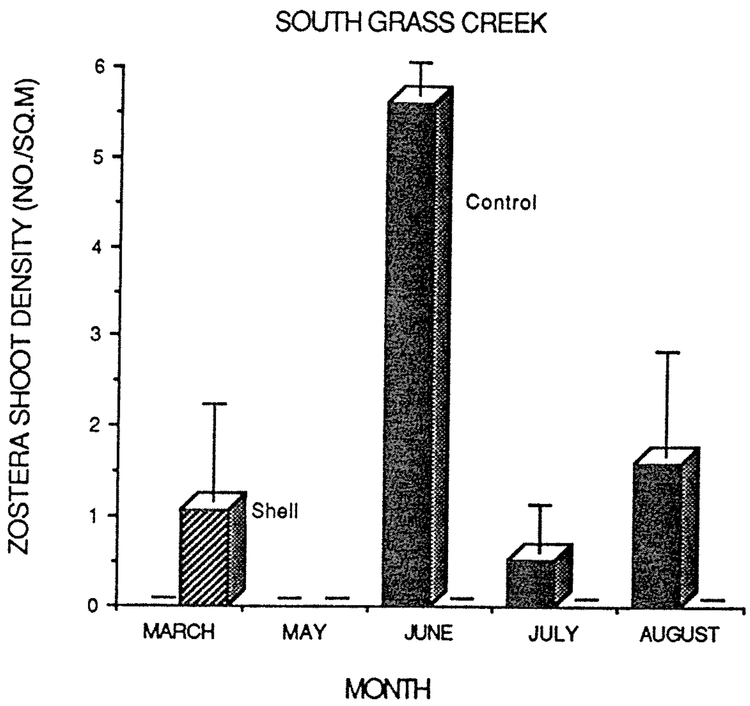

Figure 3–3. Temporal variations in mean eelgrass shoot density (± S.D.) at South Grass Creek shell and control plots.

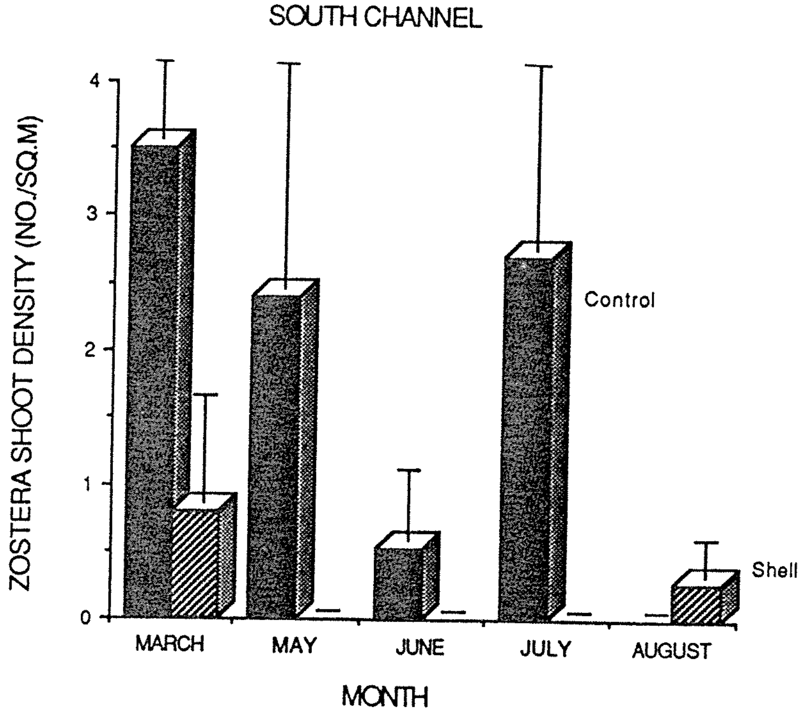

Figure 3–4. Temporal variations in mean eelgrass shoot density (± S.D.) at South Channel shell and control plots.

between mean density at the two plot types was not significant (p = 0.05) prior to shell placement.

The data portrayed in Figs. 3–1 to 3–4 suggested that (1) eelgrass density was as great in March as it was in August (except at GCS) as evidenced by samples taken in the control plots; and, (2) eelgrass was extremely patchy. Also, apparently shell placement significantly affected the mean density of eelgrass only at SCh and perhaps at GCS. However, mean shoot density at the plots was very low (ca. 1 shoot/m^2) initially. Because our sampling design was random, we probably did not effectively sample individual patches of eelgrass with our limited sample size. We did note that individual patches, which contained shoot densities of 50-100/m^2, were destroyed by the shell piles.

As a test of the null hypothesis that shell placement had no affect on eelgrass density, we compared all post-shell placement samples from the shell plots with all post-placement samples from the control plots. Since shoot density did not change significantly through the study period, we felt that combining data from all samples was acceptable. Furthermore, pre-placement sampling showed that eelgrass density in shell and control plots did not differ significantly. The results of the comparison indicated that the density of eelgrass in the combined shell plots did not differ significantly from that in the combined controls (Table 3–1).

Chlorophyll *a* concentration varied considerably at all of the sites (Figs. 3–5 to 3–8) as did phaeopigment concentration (Figs. 3–9 to 3–12). No trends with regard to treatment or month were discernable. Mean chlorophyll *a* concentration for all samples taken in the shell plots (141.7 mg/m^2, SD = 126.2, n = 78) was not significantly different from mean concentration (115.7 mg/m^2, SD = 105.8, n = 79) in the control plots. Similarly, mean phaeopigment concentrations did not differ significantly between the shell plots (321.7 mg/m^2, SD = 278.8, n = 78) and the control plots (333.3 mg/m^2, SD = 262.3, n = 79). These results suggest that (1) shell placement did not significantly disrupt sediment microbes in areas where shell did not cover the sediments (i.e., samples were collected from exposed sediments only and not under shell), and (2) sediments contain relatively high concentrations of sediment microalgae. These microalgae could contribute significantly to the food web in terms of carbon fixation on the flats. The average shell

Table 3-1. Comparison of post shell placement eelgrass shoot densities (no. m^{-2}) in shell and control plots (all stations combined). C.V.= coefficient of variation.

	Shell plots	Control plots
N	240	239
Mean Density	1.6	2.8
S.D.	11.7	10.6
C.V.	7.1	3.8

t-Test Results:

t = -1.159
DF= 238
Prob.= 0.248 (not significant)

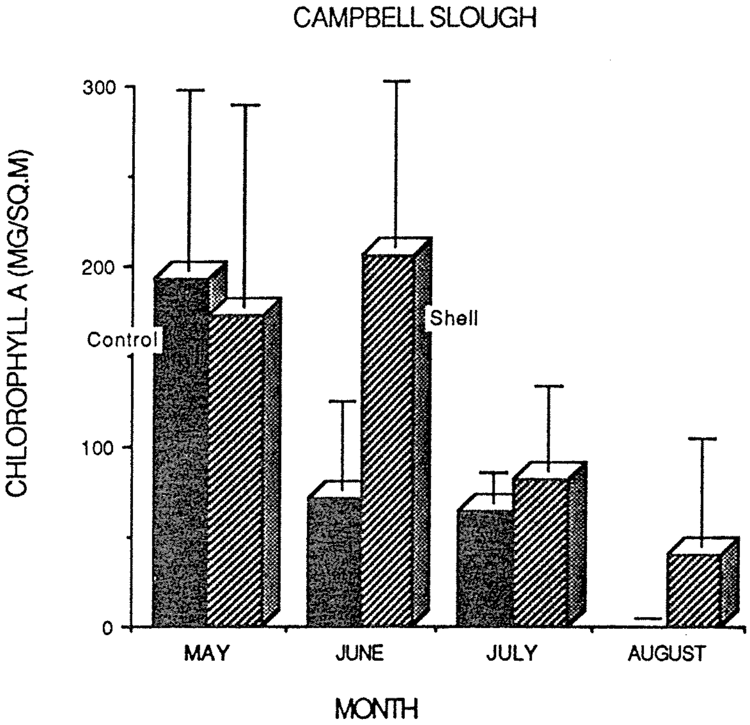

Figure 3–5. Temporal variations in mean chlorophyll *a* concentration (± S.D.) at Campbell Slough shell and control plots.

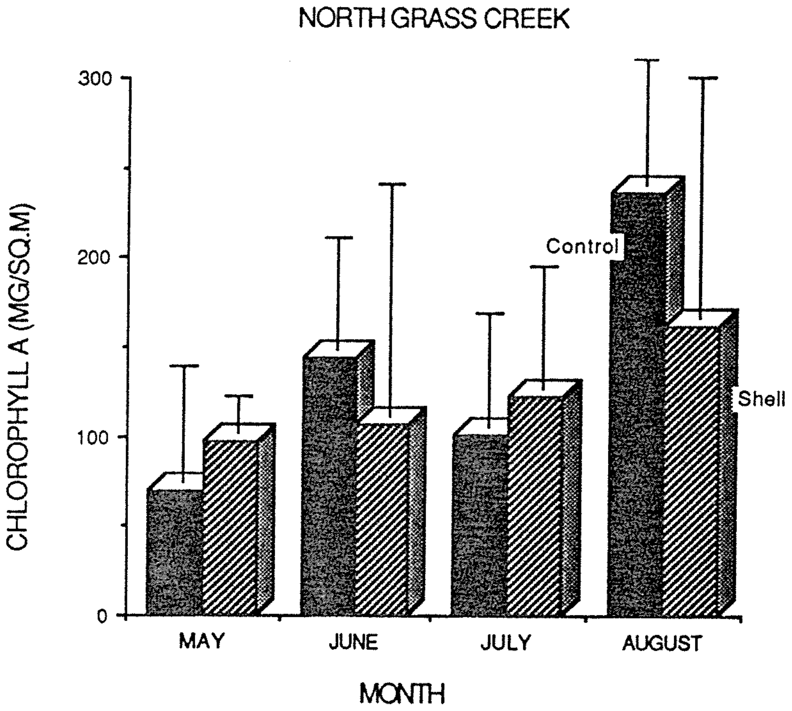

Figure 3–6. Temporal variations in mean chlorophyll *a* concentration (± S.D.) at North Grass Creek shell and control plots.

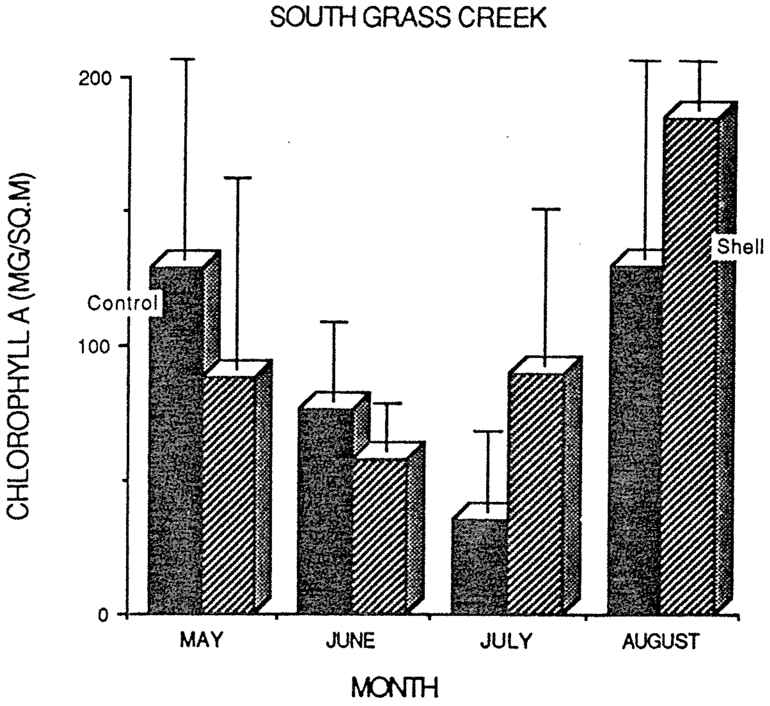

Figure 3–7. Temporal variations in mean chlorophyll *a* concentration (± S.D.) at South Grass Creek shell and control plots.

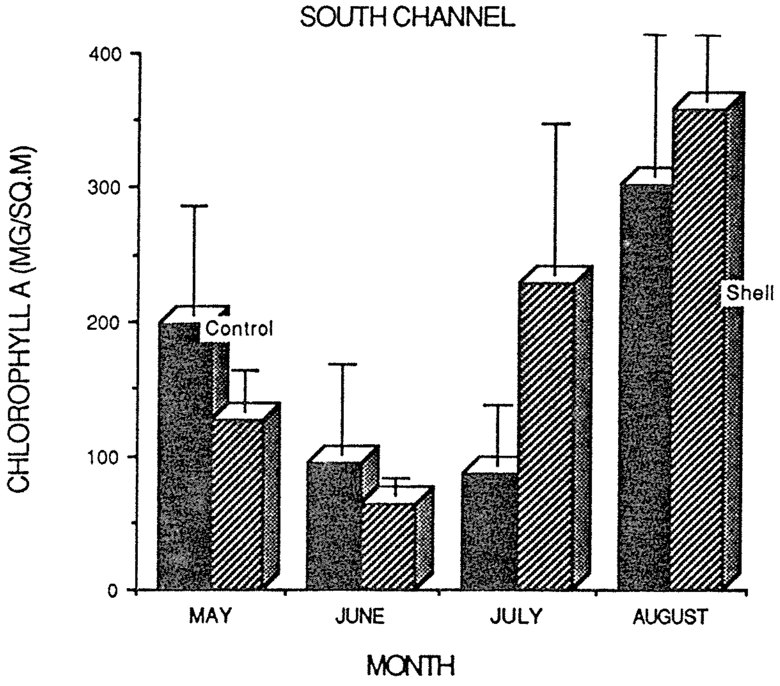

Figure 3–8. Temporal variations in mean chlorophyll *a* concentration (± S.D.) at South Channel shell and control plots.

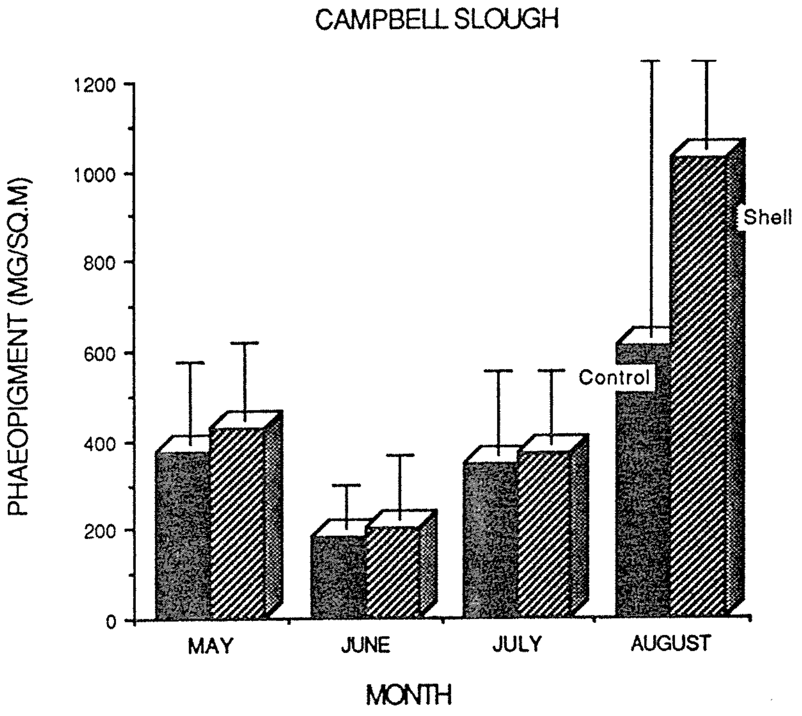

Figure 3–9. Temporal variations in mean phaeopigment concentration (± S.D.) at Campbell Slough shell and control plots.

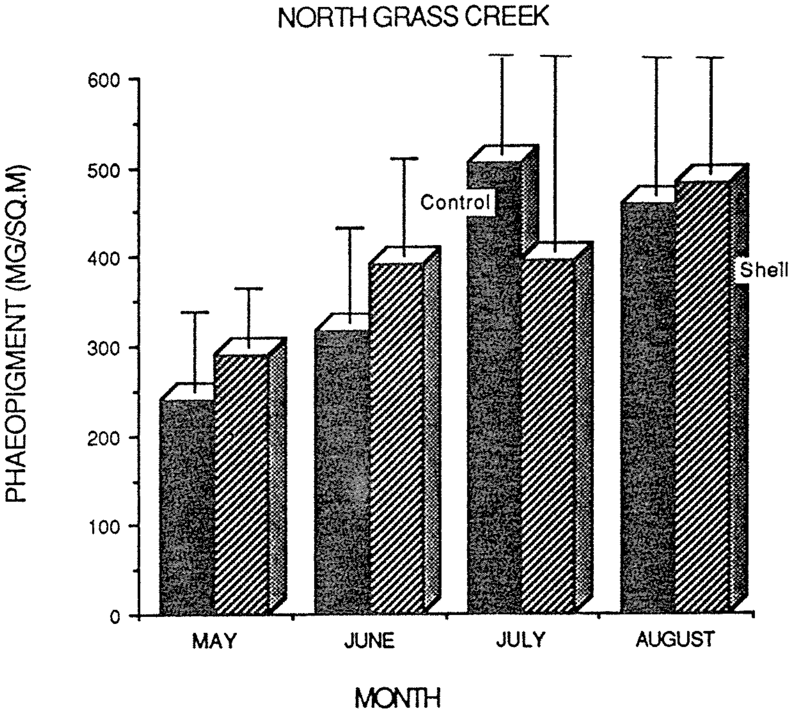

Figure 3–10. Temporal variations in mean phaeopigment concentration (± S.D.) at North Grass Creek shell and control plots.

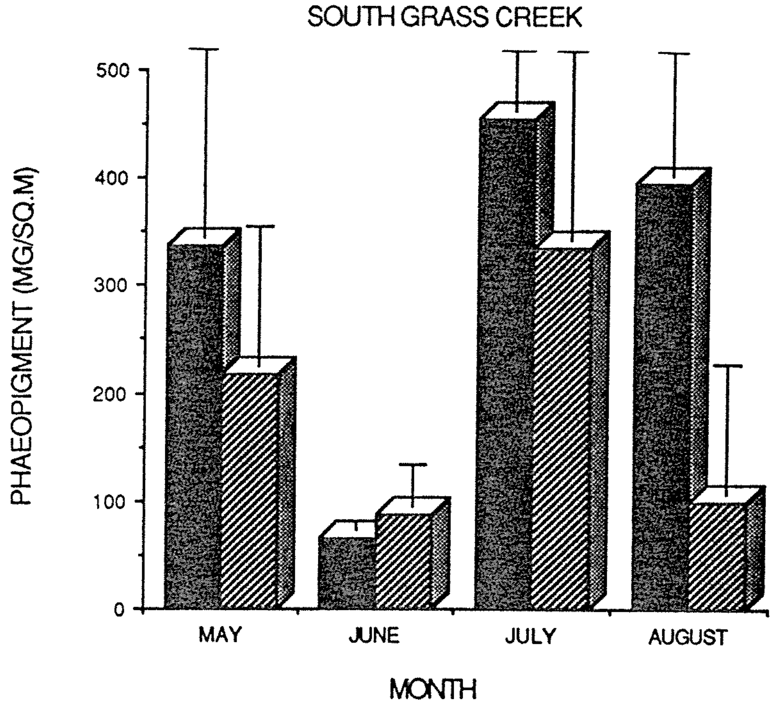

Figure 3–11. Temporal variations in mean phaeopigment concentration (± S.D.) at South Grass Creek shell and control plots.

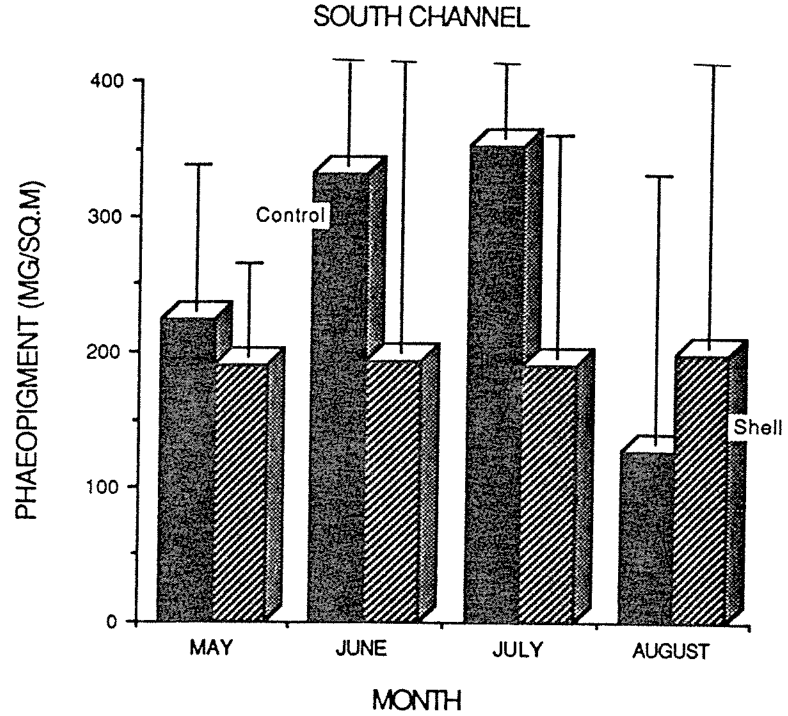

Figure 3–12. Temporal variations in mean phaeopigment concentration (± S.D.) at South Channel shell and control plots.

cover in the shell plots was very low (i.e., 0.1 to 4.5% in GCS, CS, GCN, respectively) in three of the four plots. The total standing stock of chlorophyll was not affected by shell placement. However, the GCS plot had 24.5% cover of shell in August, which probably reduced the total standing stock of sediment-associated chlorophyll by about 25%. We did notice a diatom film developing on the shell which may have eliminated much of the decrease in sediment-associated chlorophyll caused by shell placement.

Eelgrass transplanting provided some interesting data regarding the initial utility of this method for establishing eelgrass within shell plots for the purpose of increasing habitat diversity and remediating damage of shell placement to eelgrass beds. Mean survival, calculated as number of shoots in August divided by the number initially transplanted in April-May, was 106.2% (SD = 96.3) and ranged from 0 to 358%. The plants in the plots showing highest survival appeared healthy and had similar shoot lengths as compared to natural stands. In general, survival was poorest at GCS where ponds tended to fill with sediment during the study period (Fig. 3–13). Pond depth showed a positive relationship with shoot survival (Fig. 3–14). Deeper ponds may have inhibited survival due to light attenuation or other factors. However, more deep ponds would be needed to evaluate this latter conclusion. The long-term fate of these transplants is of interest in predicting the feasibility of employing eelgrass transplantation in shell plots.

CONCLUSIONS AND RECOMMENDATIONS

Eelgrass was very patchy on the flats where shell was placed. The sampling methodology we employed, which assessed the mean eelgrass density for each plot, resulted in a high variance. To reduce the variance, sampling could be confined to individual patches. Within a plot, the number and area of each patch could be measured, and the density of eelgrass within each patch determined using replicated samples. The total area of the plot covered by eelgrass, as well as the mean shoot density and total abundance for the plot, could then be calculated.

Although we could not quantitatively document significant overall effects of shell placement on the eelgrass or sediment microalgae, it was obvious that patches of eelgrass and sediment algae were lost under the deeper shell piles. Shell cover declined rapidly at all sites over the 5-month period between placement and the last sampling in August. We did not notice recruitment of new plants to newly-exposed or deposited sediments in the areas which lost shell, but there may have been some recruitment. Transplanting of eelgrass showed some promise initially for rehabilitating shell plots and for possibly increasing habitat diversity in shell plots. This appeared to depend upon the existence of shallow pools of standing water in which eelgrass would be protected from desiccation during low tides. According to oyster growers (T. Hayes, M. Lynn, Coast Oyster Company, personal communication), eelgrass is commonly found growing amongst planted oysters, and can reach densities great enough to interfere with oyster growth by smothering the oysters. Hence, recruitment of eelgrass into the shell plots should be expected with time.

The long-term fate of shell on these plots, recruitment of eelgrass into the plots, and the persistence of transplanted eelgrass can only be assessed through subsequent measurements. We recommend that sampling of these parameters be conducted once during the summer of 1991 to evaluate the long-term fate of eelgrass and shell.

The shell changes the physical structure of the system which likely affects the metabolic processes of the benthic community. Deposition of organic matter, changes in the production and respiration rates of the community, and changes in the flux of nutrients between the water column and the sediments all are probably altered by the shell. In order to better understand the effect of

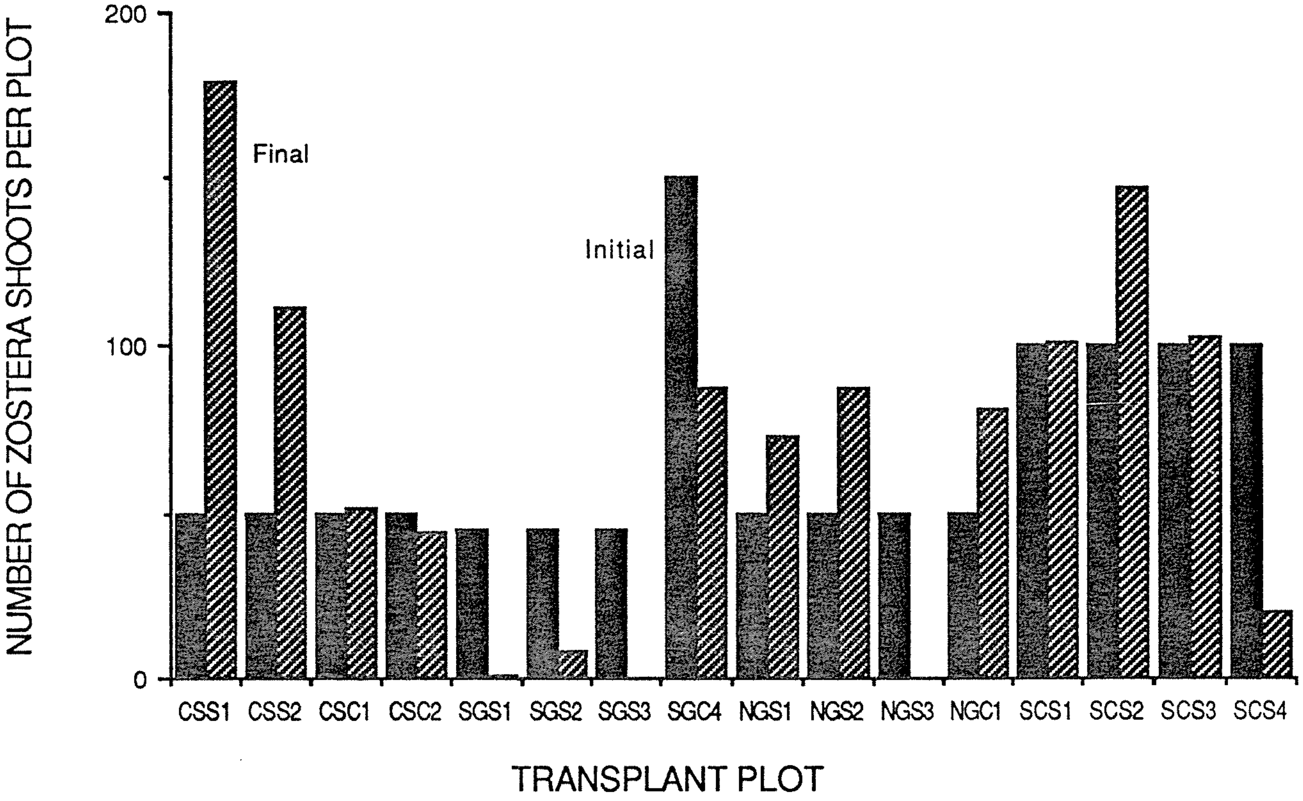

Figure 3–13. Number of eelgrass shoots transplanted initially in April-May and the final number of shoots counted in August in the transplant plots. Plots are numbered serially within each shll plot. CSS = Campbell Slough shell plot; CSC = Campbell Slough control plot; SGS = South Grass Creek shell plot; SGC = South Grass Creek control plot; NGS = North Grass Creek shell plot; NGC = North Grass Creek control plot; SCS = South Channel shell plot.

shell placement on the major benthic processes, we strongly recommend studies on net primary productivity, respiration, and nutrient flux in shell piles. These processes indicate the primary functions of the benthos in the system, and alteration of these processes should be of interest in fully assessing the impact of shell placement on the system. The shell plots could be contributing significantly more energy to the system than bare mud.

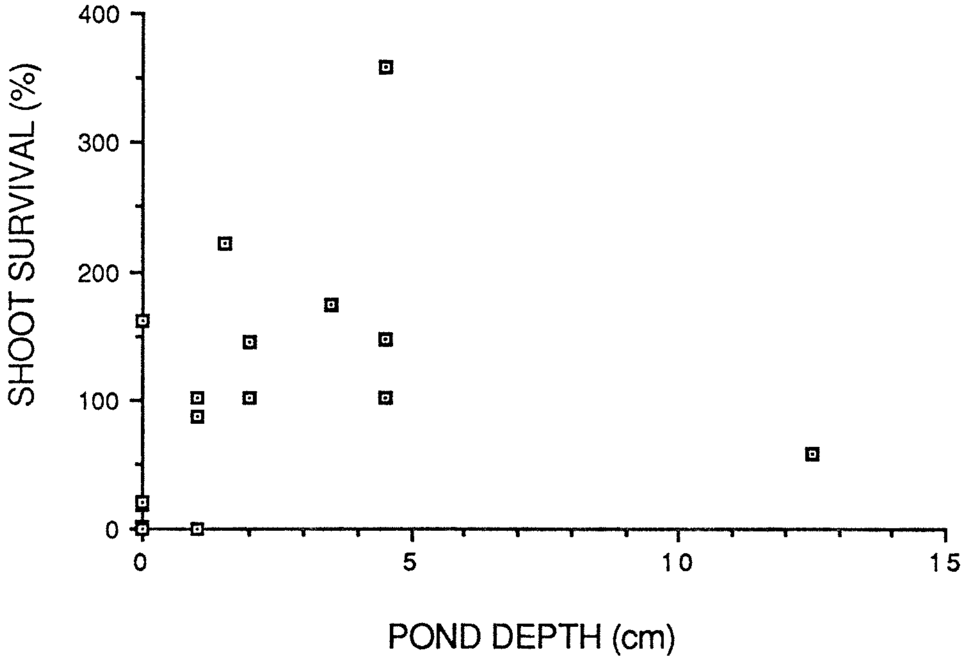

Figure 3–14. Percent transplant shoot survival vs. final pond depth.

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APPENDICES

Appendix 1. 1990 construction monitoring station location data (as recorded in April 1990).

Station No.	Reach	Depth (m)	Latitude	Longitude
1	Moon Island	12	46° 57.63'	123° 56.77'
2	Moon Island	10	46° 57.41'	123° 58.14'
3	Moon Island	12	46° 57.33'	123° 58.84'
4	Crossover	11	46° 56.67'	124° 00.01'
5	Crossover	11	46° 56.39'	124° 00.39'
6	Crossover	12	46° 55.98'	124° 08.80'
7	Inner South	7	46° 55.22'	124° 02.66'
8	Inner South	9	46° 55.11'	124° 02.92'
9	Inner South	11	46° 54.89'	124° 03.56'
10	Outer South	9	46° 54.83'	124° 04.20'
11	Outer South	10	46° 54.87'	124° 05.05'
12	Outer South	10	46° 54.89'	124° 06.21'
13	Bar	10	46° 53.69'	124° 12.19'
14	Bar	12	46° 53.61'	124° 12.28'
15	Bar	14	46° 53.24'	124° 12.36'

Appendix 2. Summary of crab and substrate catches and temperature/salinity data collected during all nine construction monitoring cruises in 1990.

Cruise No.	Station No.	Date	Tow Depth (meters)	Est. Density (crab/hectare)	Substrate (%)			Temperature (°C)		Salinity (‰)	
					Shell	Wood Debris	Algae	Bottom	Surface	Bottom	Surface
1	1	4/23/90	12	428		100					
1	2	4/23/90	10	16		100		10.0	10.0	24	24
1	3	4/23/90	12	95		100					
1	4	4/23/90	11	1,046		80					
1	5	4/23/90	11	460	5	90		10.0	10.0	25	25
1	6	4/23/90	12	4,248	95	5					
1	7	4/24/90	7	111		100					
1	8	4/24/90	9	127	50	50		9.9	10.0	30	31
1	9	4/24/90	11	174		75					
1	10	4/23/90	9	634		100					
1	11	4/23/90	10	824		100		9.4	10.0	32	32
1	12	4/23/90	10	143		100					
1	13	4/23/90	10	16		1					
1	14	4/24/90	12	238	10			7.8	9.4	35	30
1	15	4/24/90	14	254		1					
2	1	5/21/90	11	16	5	80					
2	2	5/21/90	10	95	5	95		10.5	11.1	26	26
2	3	5/21/90	13	7,085	100						
2	4	5/21/90	9	63	5	80					
2	5	5/21/90	10	317		75		10.5	10.5	27	26
2	6	5/22/90	11	95		50					
2	7	5/22/90	8	206		50	50				
2	8	5/22/90	12	174				10.5	11.6	27	27
2	9	5/22/90	12	666		100					
2	10	5/22/90	9	143		100					

Appendix 2–cont.

Cruise No.	Station No.	Date	Tow Depth (meters)	Est. Density (crab/hectare)	Substrate (%)			Temperature (°C)		Salinity (‰)	
					Shell	Wood Debris	Algae	Bottom	Surface	Bottom	Surface
2	11	5/22/90	9	840		100		10.5	10.5	27	27
2	12	5/22/90	10	317		100					
2	14	5/21/90	14	143		100		10.0	10.5	28	25
2	15	5/21/90	16	119	25	75					
3	1	6/25/90	9	174		90					
3	2	6/25/90	9	380	20	40		16.5	17.5	25	17
3	3	6/25/90	10	2,552	90						
3	4	6/26/90	7	293	10						
3	5	6/26/90	7	666	5	20					
3	6	6/26/90	8	808	70			15.5	16.5	27	23
3	7	6/26/90	8	571		30	30				
3	8	6/26/90	9	143	10			15.5	16.5	30	25
3	9	6/26/90	9	460		20	30				
3	10	6/25/90	13	491		10					
3	11	6/25/90	13	95		10		12.5	12.5	33	
3	12	6/25/90	13	222		40					
3	13	6/25/90	13	380	10						
3	14	6/25/90	15	625	80			12.0	14.0	34	33
3	15	6/25/90	16	1,087							
4	1	7/24/90	10	0				17.0	17.8	24	24
4	2	7/24/90	9	0							
4	3	7/24/90	10	111							
4	4	7/24/90	9	127	5	35	60				
4	5	7/24/90	9	95		50	50				
4	6	7/24/90	9	365	10	40	50	15.0	16.0	29	30
4	7	7/25/90	10	32							
4	8	7/25/90	8	254		80					
4	9	7/25/90	9	254	1	80		16.0	16.5	29	27

Appendix 2–cont.

Cruise No.	Station No.	Date	Tow Depth (meters)	Est. Density (crab/hectare)	Substrate (%)			Temperature (°C)		Salinity (‰)	
					Shell	Wood Debris	Algae	Bottom	Surface	Bottom	Surface
4	10	7/25/90	10	650		95					
4	11	7/25/90	11	254		90					
4	12	7/25/90	12	634	5	80					
4	13	7/24/90	13	367							
4	14	7/24/90	14	258	20	5		9.5	12.5	33	33
4	15	7/24/90	17	258	95						
5	1	8/19/90	12	206			20				
5	2	8/19/90	13	16			5				
5	3	8/19/90	13	1,886	60			19.5	18.5	29	29
5	4	8/19/90	9	143			95				
5	5	8/19/90	10	159				17.0	18.0	28	28
5	6	8/19/90	12	238							
5	7	8/20/90	11	32							
5	8	8/20/90	10	1,141	10						
5	9	8/20/90	10	523							
5	10	8/19/90	10	824				18.0	19.0	29	28
5	11	8/19/90	10	2,853							
5	12	8/19/90	9	1,173			1				
5	13	8/20/90	13	1,522	95						
5	14	8/20/90	13	747							
5	15	8/20/90	15	1,101							
6	1	9/23/90	13	713							
6	2	9/23/90	13	460				17.0	17.0	29	27
6	3	9/23/90	14	1,648	60		20				
6	4	9/23/90	11	48	5		30				
6	5	9/23/90	11	222			50				
6	6	9/23/90	11	476				16.0	17.0	30	28
6	7	9/23/90	13	539							

Appendix 2–cont.

Cruise No.	Station No.	Date	Tow Depth (meters)	Est. Density (crab/hectare)	Substrate (%)			Temperature (°C)		Salinity (‰)	
					Shell	Wood Debris	Algae	Bottom	Surface	Bottom	Surface
6	8	9/24/90	9	713				16.0	16.0	30	
6	9	9/24/90	12	935		20	5				
6	10	9/24/90	12	1,506		30		16.0	17.0		
6	11	9/24/90	12	539		80					
6	12	9/23/90	13	745		70					
6	13	9/23/90	13	269							
6	14	9/23/90	16	238							
6	15	9/23/90	16	555							
7	1	10/27/90	12	697							
7	2	10/27/90	10	1,826							
7	3	10/27/90	13	9,796							
7	4	10/27/90	9	618							
7	5	10/27/90	9	79							
7	7	10/27/90	9	1,141							
7	8	10/27/90	10	1,236							
7	9	10/27/90	13	3,963							
7	10	10/27/90	13	1,744							
7	11	10/27/90	13	95							
7	12	10/27/90	10	571							
8	1	11/20/90	13	32		100					
8	2	11/20/90	12	174		100		11.0	9.5	22	14
8	3	11/20/90	13	571	50	50					
8	4	11/20/90	11	491			100				
8	5	11/20/90	10	95		100		11.0	10.0	25	20
8	6	11/20/90	10	254	50	50					
8	7	11/20/90	13	143		100					
8	8	11/20/90	12	238	10	90		11.0	11.0	26	24
8	9	11/20/90	12	523		100					

Appendix 2–cont.

Cruise No.	Station No.	Date	Tow Depth (meters)	Est. Density (crab/hectare)	Substrate (%)			Temperature (°C)		Salinity (‰)	
					Shell	Wood Debris	Algae	Bottom	Surface	Bottom	Surface
8	10	11/20/90	12	2,679		100					
8	11	11/20/90	13	507		100		11.0	11.5	28	28
8	12	11/20/90	12	159		100					
9	1	12/19/90	12	48			100				
9	2	12/19/90	10	32			100	8.0	5.0	22	5
9	3	12/19/90	12	0							
9	4	12/19/90	9	95		100					
9	5	12/19/90	10	0		100					
9	6	12/19/90	13	63		20	80	8.0	6.0	22	14
9	7	12/19/90	12	254		100		8.0	7.0	23	14
9	8	12/19/90	12	777		100					
9	9	12/19/90	11	174		90	10				
9	10	12/19/90	12	428		90	10				
9	11	12/19/90	12	777		100		9.5	7.0	26	17
9	12	12/19/90	10	269		90	10				

Appendix 3. Input and output of the Grays Harbor Dredge Impact Model (DIM) for the 1990 construction dredging.

Run title:
1990 Construction Monitoring, by month, Crossover + Moon Island grouped, All South Reach grouped, Bar stands alone, Entrance = Average of Bar + Outer South Reach

Parameters

Entrainment regression constant (ER):
0.27 (ha/kcy)

Entrainment factors (EF) (% of Hopper Entrainment):

CS	HP	PL
5%	100%	100%

Loss factors (LF):

Age	Season	CS	HP	PL
0+	Apr-May	10%	5%	100%
	Jun-Sep	10%	10%	100%
	Oct-Dec	10%	20%	100%
	Jan-Mar	10%	40%	100%
1+	Apr-May	10%	60%	100%
	Jun-Sep	10%	60%	100%
	Oct-Dec	10%	86%	100%
	Jan-Mar	10%	86%	100%
>1+	Apr-May	10%	86%	100%
	Jun-Sep	10%	86%	100%
	Oct-Dec	10%	86%	100%
	Jan-Mar	10%	86%	100%

Survival to age 2+ (SURV):

	From Age Class:		
Season	0+	1+	>1+
Apr-May	0.9%	10.7%	53.2%
Jun-Sep	1.7%	16.0%	64.9%
Oct-Dec	3.4%	25.5%	81.9%
Jan-Mar	6.4%	38.0%	100.0%

Notes

Dredge Types:
CS--Clamshell
HP--Hopper
PL--Pipeline

Input

		Construction Schedule			Population Data			
		Volume dredged (kcy)			Density	Year class percentages		
Season	Reach	CS	HP	PL	(Ave. No./ha)	Age 0+	Age 1+	Age >1+
April	Aberdeen	0	0	0	1049	0.0%	91.0%	9.0%
	Cow Pt.	0	0	0	1049	0.0%	91.0%	9.0%
	Hoquiam	0	0	0	1049	0.0%	91.0%	9.0%
	Moon Isl.	0	0	0	1049	0.0%	91.0%	9.0%
	Crossover	0	0	0	1049	0.0%	91.0%	9.0%
	South	0	461	0	336	0.0%	8.0%	92.0%
	Entrance	0	0	0	351	0.0%	24.0%	76.0%
	Bar	0	0	0	169	0.0%	3.0%	97.0%
	Total	0	461	0				
May	Aberdeen	0	0	0	1279	0.0%	92.0%	8.0%
	Cow Pt.	0	0	0	1279	0.0%	92.0%	8.0%
	Hoquiam	0	0	0	1279	0.0%	92.0%	8.0%
	Moon Isl.	159	144	0	1279	0.0%	92.0%	8.0%
	Crossover	0	0	0	1279	0.0%	92.0%	8.0%
	South	0	501	0	391	2.0%	17.0%	81.0%
	Entrance	0	396	0	312	0.0%	6.0%	94.0%
	Bar	0	0	0	131	18.0%	0.0%	82.0%
	Total	159	1041	0				
June	Aberdeen	0	0	0	812	31.0%	66.0%	3.0%
	Cow Pt.	131	0	4	812	31.0%	66.0%	3.0%
	Hoquiam	0	0	0	812	31.0%	66.0%	3.0%
	Moon Isl.	193	379	0	812	31.0%	66.0%	3.0%
	Crossover	0	0	0	812	31.0%	66.0%	3.0%
	South	0	164	0	330	47.0%	34.0%	19.0%
	Entrance	0	0	0	484	2.0%	27.0%	71.0%
	Bar	0	0	0	698	98.0%	0.0%	2.0%
	Total	324	543	4				
July	Aberdeen	0	0	0	116	9.0%	84.0%	7.0%
	Cow Pt.	352	0	112	116	9.0%	84.0%	7.0%
	Hoquiam	188	0	0	116	9.0%	84.0%	7.0%
	Moon Isl.	0	47	0	116	9.0%	84.0%	7.0%
	Crossover	0	0	0	116	9.0%	84.0%	7.0%
	South	0	46	0	346	0.0%	65.0%	35.0%
	Entrance	0	0	0	403	7.0%	74.0%	19.0%
	Bar	0	323	0	294	27.0%	19.0%	54.0%
	Total	540	416	112				
August	Aberdeen	0	0	0	441	17.0%	82.0%	1.0%
	Cow Pt.	221	0	188	441	17.0%	82.0%	1.0%
	Hoquiam	394	0	0	441	17.0%	82.0%	1.0%
	Moon Isl.	0	0	0	441	17.0%	82.0%	1.0%
	Crossover	0	0	0	441	17.0%	82.0%	1.0%
	South	0	64	0	1091	5.0%	81.0%	14.0%
	Entrance	0	0	0	1370	1.0%	81.0%	18.0%
	Bar	0	455	0	1123	24.0%	71.0%	5.0%
	Total	615	519	188				

Appendix 3–cont.

September	Aberdeen	0	0	0	594	48.0%	51.0%	1.0%
	Cow Pt.	0	0	198	594	48.0%	51.0%	1.0%
	Hoquiam	448	0	0	594	48.0%	51.0%	1.0%
	Moon Isl.	0	0	0	594	48.0%	51.0%	1.0%
	Crossover	0	0	0	594	48.0%	51.0%	1.0%
	South	0	99	0	830	4.0%	93.0%	3.0%
	Entrance	0	0	0	642	3.0%	83.0%	14.0%
	Bar	0	428	0	354	4.0%	89.0%	7.0%
	Total	448	527	198				
October	Aberdeen	0	0	0	2603	56.0%	43.0%	1.0%
	Cow Pt.	0	0	118	2603	56.0%	43.0%	1.0%
	Hoquiam	51	0	0	2603	56.0%	43.0%	1.0%
	Moon Isl.	0	0	0	2603	56.0%	43.0%	1.0%
	Crossover	0	174	0	349	16.0%	84.0%	0.0%
	South	0	315	0	1458	7.0%	88.0%	5.0%
	Entrance	0	0	0	803	17.0%	78.0%	5.0%
	Bar	0	0	0				
	Total	51	489	118				
November	Aberdeen	0	0	0	270	19.0%	70.0%	11.0%
	Cow Pt.	36	0	82	270	19.0%	70.0%	11.0%
	Hoquiam	0	0	0	270	19.0%	70.0%	11.0%
	Moon Isl.	0	0	0	270	19.0%	70.0%	11.0%
	Crossover	0	441	0	270	19.0%	70.0%	11.0%
	South	0	15	0	708	18.0%	77.0%	5.0%
	Entrance	0	0	0	1115	6.0%	91.0%	3.0%
	Bar	0	0	0				
	Total	36	456	82				
December	Aberdeen	0	0	0	40	20.0%	67.0%	13.0%
	Cow Pt.	0	0	0	40	20.0%	67.0%	13.0%
	Hoquiam	0	0	0	40	20.0%	67.0%	13.0%
	Moon Isl.	0	0	0	40	20.0%	67.0%	13.0%
	Crossover	0	418	0	40	20.0%	67.0%	13.0%
	South	0	5	0	447	61.0%	32.0%	8.0%
	Entrance	0	0	0	491	24.0%	70.0%	6.0%
	Bar	0	0	0				
	Total	0	423	0				
January	Aberdeen	0	0	0	40	20.0%	67.0%	13.0%
	Cow Pt.	0	0	0	40	20.0%	67.0%	13.0%
	Hoquiam	0	0	0	40	20.0%	67.0%	13.0%
	Moon Isl.	0	0	0	40	20.0%	67.0%	13.0%
	Crossover	0	617	0	40	20.0%	67.0%	13.0%
	South	0	0	0	447	61.0%	32.0%	8.0%
	Entrance	0	0	0	491	24.0%	70.0%	6.0%
	Bar	0	0	0				
	Total	0	617	0				
	Grand Total	2173	5492	702				

Appendix 3–cont.

Output

		Numbers entrained			Numbers lost			Equivalent age 2+ loss			
Season	Reach	Age 0+	Age 1+	Age >1+	Age 0+	Age 1+	Age >1+	Age 0+	Age 1+	Age >1+	Total
April	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	0	0	0	0	0	0	0	0	0	0
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	0	3,346	38,476	0	2,007	33,090	0	215	17,604	17,818
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	0	3,346	38,476	0	2,007	33,090	0	215	17,604	17,818
May	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	0	0	0	0	0	0	0	0	0	0
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	0	48,275	4,198	0	27,702	3,443	0	2,964	1,832	4,796
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	1,058	8,991	42,841	53	5,395	36,844	0	577	19,601	20,179
	Entrance	0	2,004	31,398	0	1,202	27,002	0	129	14,365	14,494
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	1,058	59,271	78,437	53	34,299	67,289	0	3,670	35,798	39,468
June	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	717	1,527	69	316	674	31	5	108	20	133
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	26,414	56,237	2,556	2,641	33,044	2,150	45	5,287	1,395	6,727
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	6,868	4,968	2,776	687	2,981	2,388	12	477	1,550	2,038
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	33,999	62,732	5,402	3,645	36,699	4,568	62	5,872	2,965	8,899
July	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	365	3,410	284	321	2,993	249	5	479	162	646
	Hoquiam	26	247	21	3	25	2	0	4	1	5
	Moon Isl.	132	1,237	103	13	742	89	0	119	58	176
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	0	2,794	1,504	0	1,676	1,294	0	268	840	1,108
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	6,930	4,877	13,860	693	2,926	11,919	12	468	7,736	8,216
	Total	7,454	12,564	15,772	1,030	8,362	13,553	18	1,338	8,796	10,151
August	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	4,029	19,435	237	3,828	18,464	225	65	2,954	146	3,165
	Hoquiam	399	1,923	23	40	192	2	1	31	2	33
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	943	15,271	2,639	94	9,162	2,270	2	1,466	1,473	2,941
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	33,116	97,969	6,899	3,312	58,782	5,933	56	9,405	3,851	13,312
	Total	38,487	134,598	9,799	7,274	86,600	8,431	124	13,856	5,472	19,451

Appendix 3–cont.

September	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	15,243	16,195	318	15,243	16,195	318	259	2,591	206	3,056
	Hoquiam	1,724	1,832	36	172	183	4	3	29	2	35
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	0	0	0	0	0	0	0	0	0	0
	South	887	20,633	666	89	12,380	572	2	1,981	371	2,354
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	1,636	36,408	2,864	164	21,845	2,463	3	3,495	1,598	5,096
	Total	19,491	75,069	3,883	15,667	50,603	3,356	266	8,096	2,178	10,541
October	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	46,442	35,661	829	46,442	35,661	829	1,579	9,093	679	11,352
	Hoquiam	1,004	771	18	100	77	2	3	20	1	25
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	2,621	13,761	0	524	11,834	0	18	3,018	0	3,036
	South	8,680	109,123	6,200	1,736	93,845	5,332	59	23,931	4,367	28,357
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	58,747	159,315	7,047	48,802	141,417	6,163	1,659	36,061	5,048	42,768
November	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	1,161	4,276	672	1,138	4,194	659	39	1,069	540	1,648
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	6,108	22,504	3,536	1,222	19,354	3,041	42	4,935	2,491	7,468
	South	516	2,208	143	103	1,899	123	4	484	101	589
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	7,785	28,988	4,352	2,463	25,446	3,824	84	6,489	3,132	9,704
December	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	0	0	0	0	0	0	0	0	0	0
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	903	3,025	587	181	2,601	505	6	663	413	1,083
	South	368	193	48	74	166	42	3	42	34	79
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	1,271	3,218	635	254	2,767	546	9	706	447	1,162
January	Aberdeen	0	0	0	0	0	0	0	0	0	0
	Cow Pt.	0	0	0	0	0	0	0	0	0	0
	Hoquiam	0	0	0	0	0	0	0	0	0	0
	Moon Isl.	0	0	0	0	0	0	0	0	0	0
	Crossover	1,333	4,465	866	267	3,840	745	9	979	610	1,598
	South	0	0	0	0	0	0	0	0	0	0
	Entrance	0	0	0	0	0	0	0	0	0	0
	Bar	0	0	0	0	0	0	0	0	0	0
	Total	1,333	4,465	866	267	3,840	745	9	979	610	1,598
	Grand Total	169,624	543,564	164,669 0	79,454	392,041	141,565	2,231	77,282	82,049	161,561

Age 2+ loss = 161,561

Appendix 4. ANOVA for LN transformation of shell cover.

Source	SS	df	F	Sig. level
Main effects	71.385	5	13.82	0.00
Plot	70.23	3	22.66	0.00
Month	2.090	2	1.04	0.36
Interaction	17.749	6	2.95	0.012
Residual	118.806	115		
Total	207.941			

Appendix 5. ANOVA for crab density using only dry shell strata.

Source	SS	df	F	Sig. level
Main effects	984.29	6	10.59	0.00
Station	520.11	3	11.19	0.00
Month	526.73	3	11.33	0.00
Interaction	242.79	9	26.97	0.08
Residual	2322.62	150		
Total	3549.71	165		

Multiple range analysis for crab by station: 95 % Tukey HSD intervals.

	Average	Homogeneous group
Campbell Slough	2.14	*
Grass Creek North	3.68	*
Grass Creek South	6.13	*
South Channel	6.20	*

Multiple range analysis for crab by month: 95 % Tukey HSD intervals.

	Average	Homogeneous group
May	2.20	*
August	4.19	**
July	4.95	**
June	7.07	*