Grays Harbor Shell Mitigation Project

2011 Annual Dungeness Crab Production and Status of Live Oyster Habitat

FINAL REPORT
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Executive Summary

The most significant findings as of 2011 are that within assumptions of the model and based on the best dredge data we have been able to access, mitigation efforts have fully compensated for construction and maintenance dredge impacts. Secondly, that a million J4 Dungeness crab were produced by the shell plots this year. Crab production for summer 2011 of 1.04 $\pm$ 0.35 million J4 juvenile Dungeness crab production units was above the average annual juvenile crab production for old shell habitat of 0.88 million J4s. Total cumulative production of mitigation efforts over the 22-year project history is now up to 31.3 $\pm$ 7.6 million Dungeness crabs. Settlement of Dungeness crab megalopae in summer 2011 was protracted over the first two months of sampling, rather than exhibiting a steep peak in May as is often the case. The second cohort of settling megalopae which is often observed in July, yet does not typically enjoy strong survival, was not evident in 2011 data, except for on the 2006 West shell plot. Timing of settlement and sampling was such that crab densities were relatively flat over the shortened sampling period of three months and mortality rates appear relatively low. Because of lengthy settlement period, crab densities in June were higher than in May.

While percent shell cover on live oyster plots is slightly higher than plots without live oysters, these differences are not statistically separable due to low sample size and inherent variability of shell cover data. Crab utilization of the live oyster refuge habitat, however, was significantly higher in August when compared with crab densities on plots with only inert oyster shells. Juvenile crabs were more abundant on live shell. This difference has been indistinguishable in the past and another year of comparison is required to confirm efficacy of live oyster seeding of mitigation plots. Trends over the past two years suggest that effectiveness of live oyster habitat is surpassing that of inert shell, particularly as the season progresses. The limited sample size makes statistical detection of differences problematic given the variability inherent in biological field data. It seems that after five years of growth and development of three-dimensional structure, live oyster habitat is emerging as a more beneficial refuge space for juvenile Dungeness crab. Continued monitoring will hopefully

resolve the question of live oysters as a strategy to enhance habitat longevity, and fits within the context of standard annual mitigation sampling regime without additional effort or cost.

Juvenile Dungeness crab production on mitigation plots exhibits the lack of recent shell placement with productivity plateauing without peak yields. Continued decline of production is expected as shell sinkage continues and habitat quality declines. When shell placement becomes feasible, priority locations will be overlaying historically good locations to enhance stability and thus habitat longevity.

By far the highest priority for field budget allocation for Dungeness crab habitat mitigation efforts in Grays Harbor should be trawl surveys to update the 30 year old dataset that dredging impact estimates are based upon. With the channel navigation improvement (deepening) project likely to occur within the next 3-4 years, discussion of impact and corresponding mitigation is likely to be renewed. Since the ultimate goal of crab mitigation is to match or exceed estimates of impact on the estuarine Dungeness crab population, reasonably current data is necessary to attempt this mandate. Since no crab sampling will occur summer 2012, it is important that May through August sampling is budgeted for 2013 sampling efforts. Emerging differences in live and inert oyster habitat, as well as the need for annual plot specific mortality estimates, all stress the importance of including an August sampling period in the summer schedule. With impact & production estimates equitable, the mitigation project has met its goals thus far.

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1. Scope and Objectives

Goals for summer 2011 field efforts were similar to those of past sampling seasons: computation of annual juvenile Dungeness crab production as a measure of mitigation success and monitoring status of live oyster habitat with regard to its contribution toward increased longevity and consequent enhanced crab productivity. Production of juvenile Dungeness crab by the intertidal mitigation plots in South Channel of Grays Harbor was estimated by continuing the excavation sampling scheme practiced since mitigation project inception in 1990. Monthly densities and size composition of juvenile crab less than 25 mm carapace width and amount of intertidal area covered with oyster shell refuge habitat serve as input for a growth model incorporating natural mortality and estimating crab production for each functional plot during the 2011 summer field season. Output of the model is J4 juvenile Dungeness crabs produced by mitigation plots each month during the intertidal phase of their early life history, which are summed over the summer intertidal period to obtain an annual estimate.

The longevity of oyster shell refuge habitat is a limiting factor for productivity of mitigation plots, with generally one or more years of high yield before empty oyster shells cease to remain on the surface of the mudflat and sinkage rates correspond to decreased percent shell cover, requiring labor and cost intensive construction of new shell habitat to maintain juvenile crab production. The experimental attempt to increase shell longevity was initiated by seeding existing empty shell habitat with patches of live oyster spat. Oyster shells with live spat were distributed on 5 subplots of the 2003 Up plot in late March 2006 and survival and growth of these live oysters continue to be monitored with respect to functionality as refuge habitat for juvenile crabs. Enhanced sediment stability caused by presence of these live oysters may eventually compensate for sedimentation and sinkage of shells, not only helping maintain percent shell cover relative to the subplots without live oysters, but creating a more three dimensional substrate with reef-like functionality, perhaps even supporting higher densities of juvenile crab and extending the frequency of new shell habitat construction.

2. Background

2.1 History

Although periodic dredging of the shipping channel through Grays Harbor estuary has taken place since the early 1900's, controversy over Dungeness crab *(Cancer magister)* mortality due to dredge entrainment did not become an issue until the late 1980's. The Army Corps of Engineers (ACOE) plan, authorized by Congress in 1986, to widen and deepen the shipping channel into Aberdeen as part of the Grays Harbor Navigation Improvement Project (McGraw et al. 1988, Wainwright et al. 1992, Dinnel 1996), brought environmental and economic concerns to the fore. Mitigation was deemed necessary by state and federal agencies and in 1990, the ACOE adopted the current mitigation strategy, which includes strategies to minimize the impact such as timing of dredging activities and gear choice, as well as compensation for unavoidable impact. This agreement was last revised in 1998. Despite efforts by the ACOE to select gear type and plan timing of operations to minimize impacts, an estimated 26% of resident crab in the hopper dredge path become entrained (Wainwright et al. 1992), which can represent 1-4% of the annual crab fishery in Grays Harbor. Construction of intertidal juvenile habitat by depositing empty oyster shells on the surface of the mudflat was initiated in 1990 to increase survival rates during the first summer of growth (Dumbauld et al. 1993), and thereby compensate for dredging losses to the crab population by increasing juvenile crab survival through a vulnerable period of their life history. By 1994, South Channel was chosen as the sole location of mitigation efforts after comparisons throughout Grays Harbor estuary. Several years of efforts in both South Channel and North Bay indicated that shell longevity and productivity, as well as construction and sampling feasibility were greatest in South Channel (Armstrong et al. 1991). The entrainment impact, or estimated crab mortality, is determined for each dredging project using the Dredge Impact Model (Armstrong et al. 1987, Wainwright et al. 1992), which uses crab population density, the volume of sediment dredged, and a regression function to give the number of crabs lost to the population. After accounting for natural mortality over the growth period from juvenile legal fishery sized crab, the

requirement for impact compensation was determined. Thus the initial target goal for mitigation of the widening and deepening project became 9 million fourth instar juveniles (J4). Until this target construction impact goal was met in 2001, shell placement occurred annually (1990-2000, except 1993), but since current mitigation efforts are undertaken to offset the more minor ongoing operation and maintenance impacts, spacing between shell placement events is wider (2000, 2003, 2006). Budget constraints precluded 2009 or 2010 shell placement. Total cumulative crab production attributable to mitigation efforts to date (1990-2010) is 30.3 million ($\pm$ 7.3 million) J4 juvenile Dungeness crabs.

2.2 Ecology and Life History

Dungeness crab megalopae select flood tide currents as transport mechanisms into Grays Harbor and settle into intertidal areas during late spring and early summer. They subsequently metamorphose into first juvenile instars (J1; 6-9 mm carapace width), with initial densities often 100-200 crabs per m^2 (Visser and Armstrong 1998). Megalopae and early juvenile instars select shell habitat and survive better in shell than either bare sediment or eelgrass (Fernandez et al. 1993, Eggleston and Armstrong 1995). Artificial shell mitigation plots and relic deposits of *Mya arenaria* (eastern softshell) serve as important refuge habitat (Armstrong et al. 1992, Palacios 1994) throughout the first summer. By early fall, the juvenile Dungeness crab migrate to subtidal regions and no longer make extensive use of the shell refuge habitat (Gutermuth and Armstrong 1989, Gunderson et al. 1990, Wainwright and Armstrong 1993). By this time, the crabs have reached the fifth juvenile instar (J5: 20-26 mm carapace width, Figure 1) and shell habitat no longer seems to be crucial refuge habitat for them, having outgrown their phase of highest vulnerability to predation. Thus the shell mitigation concept is to provide effective habitat during this critical phase of life history in order to increase the number individuals with carapace widths greater than 25mm entering the subtidal population.

Figure 1. Juvenile *Cancer magister* found in excavation samples: counterclockwise from top: megalopae, J1, J2, J3, J4 and J5, representing discrete size classes and increasing molt intervals.

Purple shore crabs, *Hemigrapsus oregonensis* colonized the shell mitigation plots after initial construction, to the detriment of juvenile Dungeness crab production (Visser 1997, Dumbauld et al. 2000, Visser et al. 2004). For 1992-1997, the typical pattern was high productivity as evidenced by high densities of *Cancer magister* during the initial year after shell plot construction followed by much lower densities of Dungeness crab and much higher abundance of *Hemigrapsus* during subsequent years. Competitive dominance by *Hemigrapsus oregonensis* for refuge space in intertidal habitats seemed to play the major role in the interaction between the populations during early years of the mitigation project (Visser 1997, Banks and Dinnel 2000, Visser et al. 2004). These competitive interactions, as well as some predation on settling Dungeness megalopae by resident adult *Hemigrapsus*, combined with loss of shell cover due to bioturbation and sediment destabilization by burrowing shrimp, *Neotrypea pugetensis* and mudshrimp, *Upogebia californiensis*, led to lost effectiveness of shell plots after their initial year of construction, at least as measured in terms of Dungeness crab productivity. During 1998-present, the pattern has changed due to an apparent recruitment failure of *Hemigrapsus* (Visser et al. 2004, C. Roegner unpubl. data), and very few *H. oregonensis* have been

collected in South Channel excavation samples in the past eight years compared to previously when interspecific competition played a significant role. Insufficient *H. oregonensis* population data exists to determine whether this is a reproductive failure or a recruitment and population distribution issue, since our sampling regime is limited to South Channel mitigation plots. While Dungeness crab productivity is still greatest on new shell, production per square meter on shell mitigation plots ≥ 1 year post-construction is much greater than before 1998, and habitat longevity issues are of greater focus as the limiting factor on post-settlement Dungeness crab productivity in the absence of significant competition for refuge space. The ongoing challenge of the habitat mitigation project continues to be accurate assessment of the number of juvenile Dungeness crabs being produced by the current habitat, optimization of areas for shell placement and monitoring of live oyster patches on the 2003 Up mitigation plot as a potential strategy for extended habitat longevity and decreased mitigation costs.

Pacific oysters, *Crassostrea gigas*, are native to northeast Asia, including Japan, and have been introduced and spread widely throughout many countries, including the UK, France, USA, Canada, Korea, China and New Zealand, for aquaculture. This species was introduced from Japan to the western coast of the United States in 1903 (Pauley et al. 1988). While Pacific oyster survival can occur over a wide temperature range (4-24 degrees C) precluding prolonged periods of desiccation or exposure to dinoflagellate blooms, their spawning success requires fairly specific water temperature criteria (Chavez-Villalba et al. 2003, Fabioux et al. 2005). Because spawning depends on a rise in water temperatures above 18 -19 degrees C, it spawns naturally only erratically in west coast estuaries (Pauley et al. 1988), and therefore, cultured 'spat' is generally used to seed commercial oyster beds.

When spawning or 'natural set' does occur, it occurs primarily in July and August. Once the spawning temperature has been reached, spawning is synchronous. This species is highly prolific and an average market-sized female (3 inches long) can broadcast 50-100 million eggs in a single spawning (Gouletquer et al. 1997) for fertilization in the estuarine water column. The larvae are planktonic and free swimming, feeding on phytoplankton and growing for 2-4 weeks and approximately a size of 0.30 mm before later stage larvae settle out of the water column, group together, and crawl

along the bottom, searching for a suitable hard substratum in lower intertidal areas upon which to cement their lower shell valves (Pauley et al. 1988). Although they usually attach to rocks, debris or adult oyster shells, they can also settle in muddy or sandy areas, where they attach to small stones, shell fragments or other debris in the lower intertidal areas of estuaries (Emmet et al. 1991). A very small percentage of oysters survive this phase; those that do are called spat.

The sessile juvenile and adult *Crassostrea gigas* are filter feeders that sort food particles by size using mucus secretions. They ingest a wide variety of phytoplankton, bacteria, protozoa, larval forms of other invertebrate animals, detritus and some inorganic material (Pauley et al. 1988). Pacific oysters thrive in the brackish waters of sheltered estuaries in the intertidal and shallow subtidal zones, to a depth of about 3 meters although they can tolerate a wide range of salinities (10-42 ppt -Shatkin et al 1997, 34-36 ppt optimum -Coleman 1996, Mann et al. 1991) and can occur offshore. Pacific oysters can live for 10 years or more (Matthiessen 2001) and reach an average size of 150-200 mm. Average growth rates are about 25 mm/year, with a maximum growth around 50 mm/year (Lukenbach et al. 1999). *Crassostrea gigas* can thus exceed 75 mm only 18 months post-settlement (Matthiessen 2001). Growth is faster during the warmer months (Bayne 2002) and sexual maturity is reached during the first year (Matthiessen 2001). Like most oyster species, *Crassostrea gigas* is sequentially hermaphrodidic, functioning as separate male or female animals in any given reproductive season (Fabioux et al. 2005). They are male during their first spawning, and about half remain male for their second spawning.

Crabs (*Cancer magister, C. productus,* and *C. gracilis*) as well as starfish can be serious predators upon both young and adult *Crassostrea gigas*. They are also preyed on by the Japanese oyster drill (*Ocinebra japonica*) and by the predatory flatworm (*Pseudostylochus ostreophagus*). Parasites include copepods (*Mytilicola orientalis*), boring sponges (*Cliona celata*) and sea worms *(Plydora ciliata*). Mud shrimp *(Neotrypea pugetensis* and *Upogebia californiensis)* burrow construction can retain water at low tide and destabilize the sediment, compromising oyster survival (Pauley 1988), however competition for space and overgrowth on the hard substrate is arguably the most important source of mortality (Quayle 1988).

3. Methodology

3.1 Field Protocol

The historical sampling protocol was again utilized to obtain juvenile *Cancer magister* and other resident crab density and size composition data. Plots were surveyed in early May to determine which sites would be sampled and to measure boundaries, as well as map and mark the plots chosen for 2011 summer field efforts. Then three monthly sampling series were conducted during the spring tide series each month beginning in May. The seven plots sampled during 2011 were the 1995 Island, 2000 East, 2003 Up, 2003 Down, and 2003 East, 2006 East, and 2006 West plots (Figure 2). Plots are named according to the year of initial construction. Since percent shell cover strongly affects juvenile Dungeness crab survival in the intertidal (Dumbauld et al. 1993, Visser and Armstrong 1998), any previously constructed shell plot with < 20% shell cover remaining on top of the mud surface before larval settlement was not chosen for monitoring efforts this year. Although these scantly covered plots may be adding to overall juvenile crab production, their importance relative to plots with greater habitat quality and refuge area does not merit the manpower investment to quantify their minor contribution.

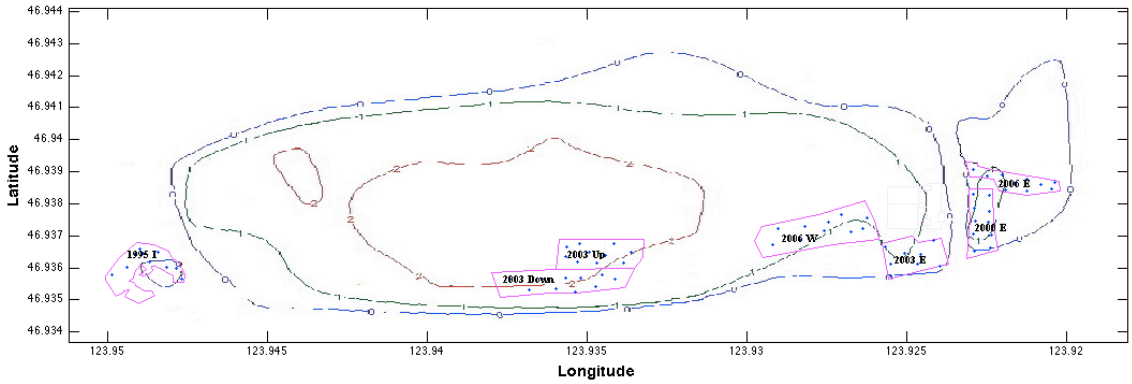

Figure 2. Map of South Channel shell mitigation site and plots sampled in summer 2011 showing tidal elevation contours and shell plot boundaries for seven plots.

A sampling crew consisting of 6-9 excavation samplers and two additional shell estimators was transported to the shell mitigation plots by personnel aboard the Army Corps of Engineers survey vessel Shoalhunter during low spring tides each month (Table

1). About 2 hours before low tide, the crew was delivered to the mudflats to begin sampling. Four to ten replicate excavation samples were taken monthly from each of the seven plots sampled in 2011 to obtain plot specific monthly crab density and size composition data.

Table 1. Sampling dates, approximate times, and estimated tidal heights during data collection during summer 2011 at South Channel crab mitigation sites. The initial May tide was for field site preparation, and each month's sampling was completed in two or three field days.

Date	Low tide time	Low tide height (ft)
May 17	7:30AM	-2.6
May 18	8:18	-2.7
May 19	9:04	-2.4
May 20	9:50	-2.0
June 16	8:01	-2.5
June 17	8:45	-2.3
June 18	9:27	-1.8
July 14	7:08	-1.9
July 15	7:51	-1.9
July 16	8:30	-1.8

Note: Times and heights given are based on computer estimation of tides at Markham, WA (predicted from actual readings at Aberdeen and Westport, WA, see Port of Grays Harbor Tide Tables).

Collection of these samples consisted of haphazardly placing a 0.1 m^2 quadrat on a section of 100% shell cover within the plot to be sampled. All shell material from within the quadrat was removed, including all sediment to 5 cm below the shell layer, sorted by hand, and seived through a 3 mm mesh screen (Figure 3). All crabs retained by the screen were placed into bags to be identified to species and measured to the nearest 0.1 cm carapace width back on the Shoalhunter after the tide rose, recorded, and returned to the estuary alive. Gender and ovigery status for females was also recorded when *Hemigrapsus oregonensis* were collected.

Figure 3. Collection of excavation samples in the field. Metal quadrat in the left of photo defines the 0.1 m^2 area to be excavated. Material is placed in wooden screen, sorted and rinsed by hand, and all crabs in sample are taken back to the ship for measurement before being returned live to the field.

Estimates of amount of refuge area available within each plot are necessary in order to translate the crab density data (on a per meter squared basis) into total number of crabs produced over the hectares of shell mitigation area of differing habitat qualities and age. Total amount of refuge space was computed by multiplying plot size for each of the eight plots by average percent shell cover for the individual plot. These percent shell cover estimates were taken by 3 to 6 observers visually studying each of four to ten fixed and marked subplots (20m x 20m) throughout each of the seven mitigation plots sampled in 2011 (Figures 2 and 4). The amount of shell remaining above the surface of the mud and therefore representing refuge space available to the juvenile crabs was estimated and recorded. Thus, the overall monthly shell cover estimate for each plot was based on 12-50 individual independent estimates, giving mean and standard deviation for production model input.

Figure 4. Landscape view of shell mitigation plots showing patchiness of habitat and crew members taking excavation samples and making visual estimates for shell cover.

Although shell provides the optimal refuge habitat for very young juvenile Dungeness crabs, both as evidenced by survival rates and by habitat preference experiments (Figure 5, Fernandez et al. 1993), eelgrass *(Zostera marina)* serves as habitat and provides some protection as well. Part of the mitigation strategy in Grays Harbor has been to avoid placing shell in areas where eelgrass flourishes in order not to disturb any natural refuge function within the estuary, thereby making mitigation productivity additive rather than substitutional. Mitigation credit would not be accurate if these plots were replacing otherwise viable refuge habitat. On plots where eelgrass beds flourish, original shell placement was therefore intentionally patchy. Part way along the 22 year mitigation history, percent cover estimates for eelgrass were added to the mitigation sampling scheme so that trends in eelgrass coverage can be tracked. Eelgrass distribution

and abundance may be correlated with enhanced sediment stability caused by shell placement over the long term.

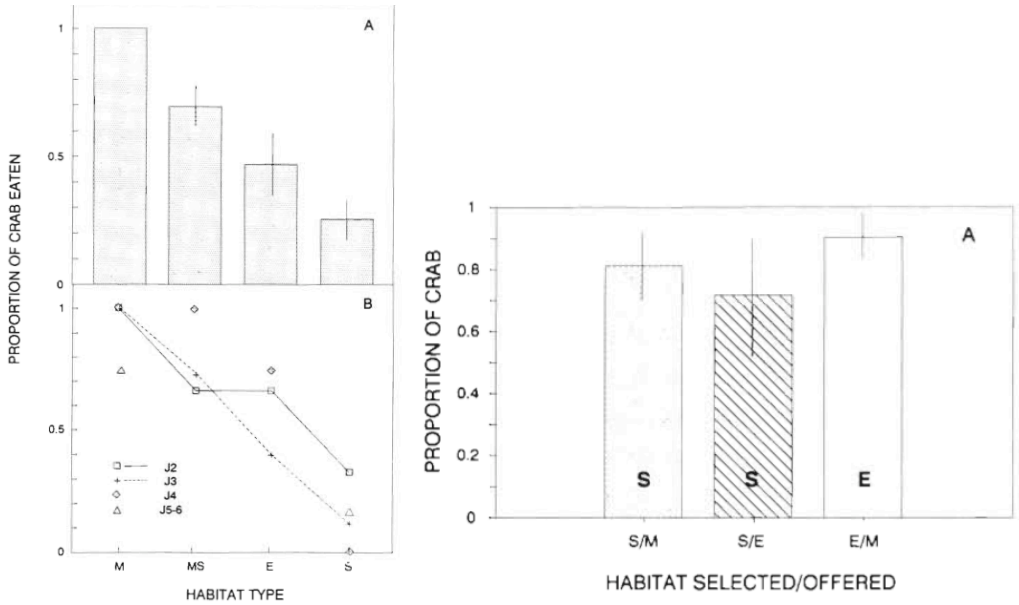

Figure 5. Juvenile Dungeness crab survival and habitat preference differences between habitats (from Fernandez et al1993). Mortality in the field was highest on mud habitat, then mixed mud/shell, then eelgrass, and lowest in shell habitats. In laboratory comparisons, juvenile crabs prefer shell over mud, shell over eelgrass, and eelgrass over mud, in keeping with field findings of risk.

Eelgrass supports much lower densities of crabs than does shell, as evidenced by doubled mortality rates in eelgrass compared to oyster shell habitat (Figure 5). Because eelgrass is a naturally occurring phenomenon rather than a direct result of mitigation efforts, estimates of eelgrass coverage neither factor into the production model nor contribute to the production units reported here. The conceptual basis of the mitigation project considers production estimates from shell plot sites as additional crabs produced in Grays Harbor above and beyond natural recruitment and survival as a direct result of the artificial habitat created by mitigation efforts. Inherent in the project concept is the assumption that this production is linearly additive with natural production from other habitats within the estuary and that the natural relationships among the populations within

Grays Harbor are not altered by the addition of these crabs. The detailed long term dataset from these mitigation efforts combined with fishery catch data and updated trawl surveys of juveniles, particularly 1+ Dungeness crabs in their second summer, may address some of these questions about long term population trends within Grays Harbor and how production of young of the year on the intertidal mitigation plots translates to enhanced populations of older size classes.

3.2 Data Analysis

Crab size and abundance per quadrat as well as shell and eelgrass cover estimates from the field were entered into field books on the ship and later transferred into Microsoft Excel spreadsheets, analyzed using the production model originally developed by Armstrong et al. (1995) and modified by Visser and Armstrong (1998). This model applies a plot-specific mortality function to the crab density data over an instar-based molt interval. Density of J2 instars are used as input for the model since J1 density is extremely variable, especially at the beginning of the summer depending on how the timing of specific settlement events correlates with the timing of the initial sampling period in any given year. The timing of first sampling date and whether it coincides with the major spring settlement pulse, predates megalopal influx to the estuary, or occurs 1-2 weeks after the peak settlement dramatically effects numbers of first instars collected. Survival of J1s is low and highly variable, while J2 densities and survival rates are much more stable relative to that of J1s and therefore J2 density is preferable as an input value for the production model. When J3 instars are present at the first sampling date, they are treated as early settlers and inputted into the model as well, using the annual plot-specific mortality function computed for that location, but over the shorter period of time a J3 instar takes to reach the J4 size class. This strategy corrects for the possibility of missing juvenile crabs that settled earlier than peak and were missed by the J2 input function. Mortality rates for each plot are computed annually by fitting an exponential function to the declining Dungeness crab density data for each field season. In some years the data require computing the mortality function without the initial settlement peak of J1 instars (J2 mortality) so that the high initial mortality rate is not averaged into the more average rate for juveniles throughout the summer growth period, thereby applying an initial

phenomenon over the entire summers population pattern. This adjustment was not necessary for 2011 data, since sampling did not coincide with peak larval settlement and sampling data did not evidence a precipitous decline after initial population measures. Standard curve fit protocol of r^2 values were applied to these mortality rate computations; thus curves with a significance of less than .90, explaining less than 90% of the observed variation, were discarded in favor of average mortality rate values from past years on comparable habitat. Commensurate with the decision to drop the August sampling date was a loss of one degree of freedom for population decline over the summer, and lower significance. Average historical mortality functions from shell habitat greater than one year post construction are applied to population data rather than plot specific annual mortality rates when annual estimates are insignificant.

Multiplying the density of surviving crabs by the effective refuge area (the product of total habitat area constructed and percent shell cover) gives the number of crabs produced by each plot for each month over the summer. Thus,

$$\text{Production} = J2 * e^{-35k} + J3 \bullet e^{-20k} \bullet \% \bullet A$$

where J2 is the average monthly density of second instar juveniles on the plot, k is the daily mortality rate experienced by juvenile crabs on the plot, J3 the average density of third instar juveniles that would have been missed by sampling regime based on timing of settlement, % is average percent cover for the shell plot, and A is the total area of the shell plot. The J4 instar serves as the accepted production unit, as per the agreement by ACOE and agency personnel. By the time the crabs reach J5 instars, they are no longer as vulnerable to risk of predation and begin to move to subtidal areas, making their intertidal densities a poor measurement of population abundance within the estuary. Thus, the computed mortality rate is applied over a 35 day interval for J2 instars and a 20 day interval for J3 instars, the time it takes for each instar to reach the fourth juvenile instar, J4 or 16-19 mm carapace width. Results in the form of production of crabs per plot and annual comparisons, crab density and instar composition, and shell cover, as well as eelgrass abundance and mortality rates are presented and discussed. Since

intertidal juvenile Dungeness crab densities in areas with no shell or eelgrass refuge are less than 5 crabs • m^{-2} and generally zero, all crabs produced on the shell mitigation plots are attributed to the mitigation efforts. The sampling regime does not test the possibility that the mitigation plots attract crabs that may otherwise be settling elsewhere within the Grays Harbor system. Nor does it consider the carrying capacity of the subtidal channels and whether or not enhanced production of intertidal juveniles actually translates through the next stages of life history into increased number of legal adults entering the fishery three to four years later.

3.3 Live Oyster Monitoring

Potential differences in crab usage and shell cover between subplots with live and inert oyster shells were measured and recorded within the context of the standard excavation sampling regime and visual estimation of percent shell cover on all the shell mitigation plots. Quality of habitat over time was measured by comparing crab density per meter squared between plots with and without live oysters, and the test of increased shell longevity will be evaluated over time as a comparison of percent shell cover over time relative to existing plots of the same age without live oysters.

4. Results and Discussion

4.1 2011 Production

The South Channel shell mitigation plots yielded 1.04 million ($\pm$ 0.35 million) J4 production units during summer 2011. This level of production is within one standard deviation of the historical average combined production for old shell plots of 0.88 million per year. Of this total for 2011 summer, 0.50 million $\pm$ 0.16 million or 48% was contributed by the two 2006 plots, East and West. The overlay method of plot construction, where new shell habitat placement occurs over the top of previously constructed shell habitat, was employed in the most recent placement event, 2006, for both East and West plots with the goal of enhancing sediment stability and thus long term

crab productivity relative to plots without underlying shell. This expectation seems to continue to be being met, with an average percent shell cover of 47-78% shell still remaining on the mud surface five years after plot construction. The three plots constructed in 2003 contributed 0.32 ± 0.11 million J4 production units, which represents 31% of the 2011 annual total (Figure 6, Table 2). Habitat constructed in 2000 contributed 0.12 ± 0.05 million or 11% of the annual total, while the 1995 habitat contributed 0.11 ± 0.03 million representing 10% of total annual production.

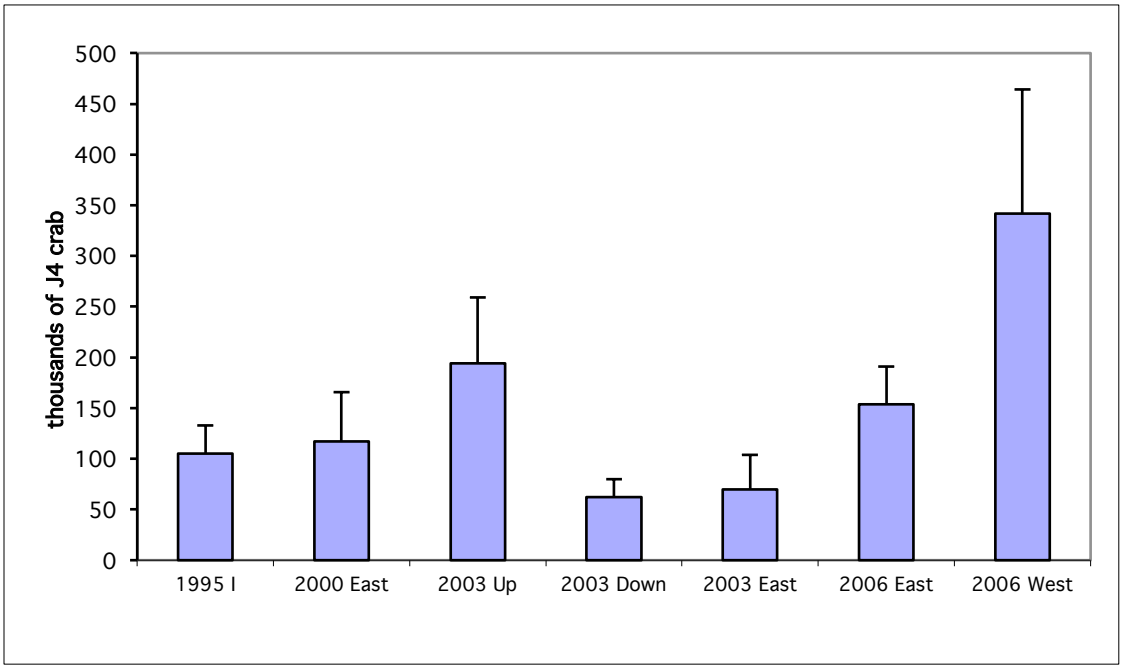

Figure 6. Summed annual production over the three-month sampling period during summer 2011 for each of the seven plots sampled this season.

Table 2. Monthly J4 Dungeness Production by plot for 2011 sampling season.

Plot	Month	Total crab density	J2 instars	st.dev.	Mortality	Plot size (m2)	Shell cover %	st.dev. %	Production	Annual prod (J4)	st.dev.
1995 I	May	16	1.56	9.00	0.0217	13336	0.50	0.29	4861	105179	28155
	June	30	10.94	13.80	0.0217	13336	0.51	0.26	84114		
	July	19	6.25	3.78	0.0217	13336	0.42	0.24	16204		
2000EAST	May	14	1.23	7.87	0.0217	10956	0.23	0.29	1480	117219	48572
	June	61	33.33	14.96	0.0217	10956	0.34	0.25	101473		
	July	20	7.41	11.35	0.0217	10956	0.37	0.28	14266		
2003UP	May	21	0.00	18.89	0.0217	20145	0.49	0.14	0	193753	64568
	June	55	31.00	8.16	0.0217	20145	0.41	0.16	178087		
	July	54	4.00	9.94	0.0217	20145	0.42	0.14	15666		
2003DOWN	May	20	12.50	9.57	0.0217	6648	0.21	0.07	8214	61798	18267
	June	45	50.00	5.00	0.0217	6648	0.21	0.10	41271		
	July	18	12.50	0.00	0.0217	6648	0.32	0.11	12313		
2003EAST	May	20	0.00	8.66	0.0217	12901	0.32	0.27	0	69601	34258
	June	34	14.81	21.08	0.0217	12901	0.38	0.30	58593		
	July	27	4.94	9.28	0.0217	12901	0.37	0.28	11007		
2006EAST	May	32	3.00	16.19	0.0217	12004	0.58	0.07	9812	154140	37414
	June	42	20.00	10.59	0.0217	12004	0.71	0.17	135532		
	July	27	2.00	6.99	0.0217	12004	0.78	0.06	8796		
2006WEST	May	40	4.00	21.11	0.0217	32603	0.46	0.27	28318	342334	121520
	June	41	20.00	17.16	0.0217	32603	0.48	0.26	250037		
	July	37	9.00	10.54	0.0217	32603	0.47	0.31	63979		
										1,044,022	352,753

Settlement was protracted over May and June sampling periods, even extending into July for 2006 plots. Although early settlement was not a significant factor as far as settlement occurring before first sampling in 2011, but instar composition data indicated a significant number of juveniles that were missed by standard J2 production estimates, so these individuals were added in as J3s. Contribution of these crabs accounted for

almost a third of the annual production. Although peak megalopal influx into the estuary tends to occur on spring tides in late April or early May, Dungeness crab megalopae do migrate into Grays Harbor during neap tides as well. Thus the contribution of early settlement, defined as crabs reaching J3 instar before the first sampling session of the year, is greater on years when sampling first occurs in late May such as 2009, and less significant when first sampling occurs in mid May, such as 2008, 2010 and 2011. Some larval settlement during the 2011 season occurred before May sampling efforts, but settlement was protracted throughout the first two months of the summer, and did not show evidence of a sharp peak. Historically, June has shown the greatest percentage of annual crab productivity, and 2011 was no exception, this difference being particularly distinct in these data. May efforts contributed only 5% of the annual total, with 0.05 million crabs. June sampling efforts contributed 0.51 million juvenile crabs utilizing the shell habitat, which was 49% of summer 2011 production. The July sampling data contributed 0.14 million juvenile crabs utilizing shell mitigation habitat or 14% of summer productivity. In normal years, August sampling data typically produce only 2-7% of annual crab production, and this sampling trip was cancelled for 2009 - 2011 summers due to budget constraints. As juvenile crabs are beginning emigration to subtidal habitat by August, having outgrown the most vulnerable phase of their life history and most stringent habitat requirements, low intertidal abundances and low August mitigation productivity result. When low tides fall at the end of the month, the probability of August contributions being negligible increases. While many years show protracted or a late settlement pulse in July or early August, the contribution of this second cohort of settling crabs to total productivity is minor due to cannibalism and intraspecific competition for refuge space. Size lends its advantage to the individuals settling early in the summer and these late settlers suffer poor survival rates. While it is interesting biologically to see the data from late August samples, the recommendation to drop later August sampling dates in light of cost:benefit ratio of conducting field efforts at diminishing production return remains despite occasional significant contribution of August sampling efforts, such as in 2008. Summer 2012 tides fall at the beginning of the month, increasing the probability that juvenile crabs will still be utilizing plots in August.

Timing of upcoming low tides as well as the need for periodic comparisons of annual plot specific mortality rates leads to the necessity of an August sampling period in 2012.

Average production per unit of refuge area for summer 2011 was 5.95 crabs per square meter of habitat (Figure 7). This is just below the average production rates for old shell of 6.36 crabs/m^2 since refuge space competition with *Hemigrapsus oregonensis* ceased to be a major factor on mitigation habitat utilization by juvenile Dungeness crab in 1998. The patchy shell placement, particularly on the west end of the 2006 West plot may have contributed to lower per meter squared production since this 2006 plot averaged 4.54 crabs/m^2, while the 2006 West plot did better at 5.48 crabs/m^2. The best performing plots by unit shell habitat were the 2003 Down and 2000 East plots, at 10.39 and 7.79 crabs/m^2, respectively. Only the 2003 Down and 2000 East plots were above the historical old shell average production rate of 6.36 crabs/m^2 or the average 2011 per meter squared production rate of 5.95 crabs/m^2. Below the 2011 annual average per meter squared production rate were the 2003 Up, 2006 West, 2006 East, 95 Island, and 2003 East plots in declining order of crab production. The 2003 Up plot yielded 5.88 crabs/m^2 while the 2006 West plot produced 5.48 crabs/m^2, the 2006 East plot showed 4.54 crabs/m^2 while the 95 Island plot yielded 4.02 crabs/m^2 and the 2003 East plot supported the lowest juvenile crab numbers per area at 3.57 crabs/m^2. This year showed typical production per meter squared rates (Figure 7), which were considerably lower than rates for 2009 summer, but slightly higher total production in 2011 relative to 2010 yields (Figure 8). This discrepancy exists because less habitat area was available for sampling in 2010 and 2011 since no new shell habitat has been created since spring 2006. All plots showed low production rates, with 2011 numbers surprisingly increased over 2010 production rates, even with older shell habitat (Figure 8). While historically, shell cover has played a determining role in crab productivity, patterns in the past several years seem to have been defined by larval supply issues. Our data does not include direct measures of larval supply, so we are unable to differentiate between the effects of larval supply and early post-settlement survival and displacement issues. Live oyster shell shows evidence of better habitat longevity, which may partially account for improved production rates in 2011.

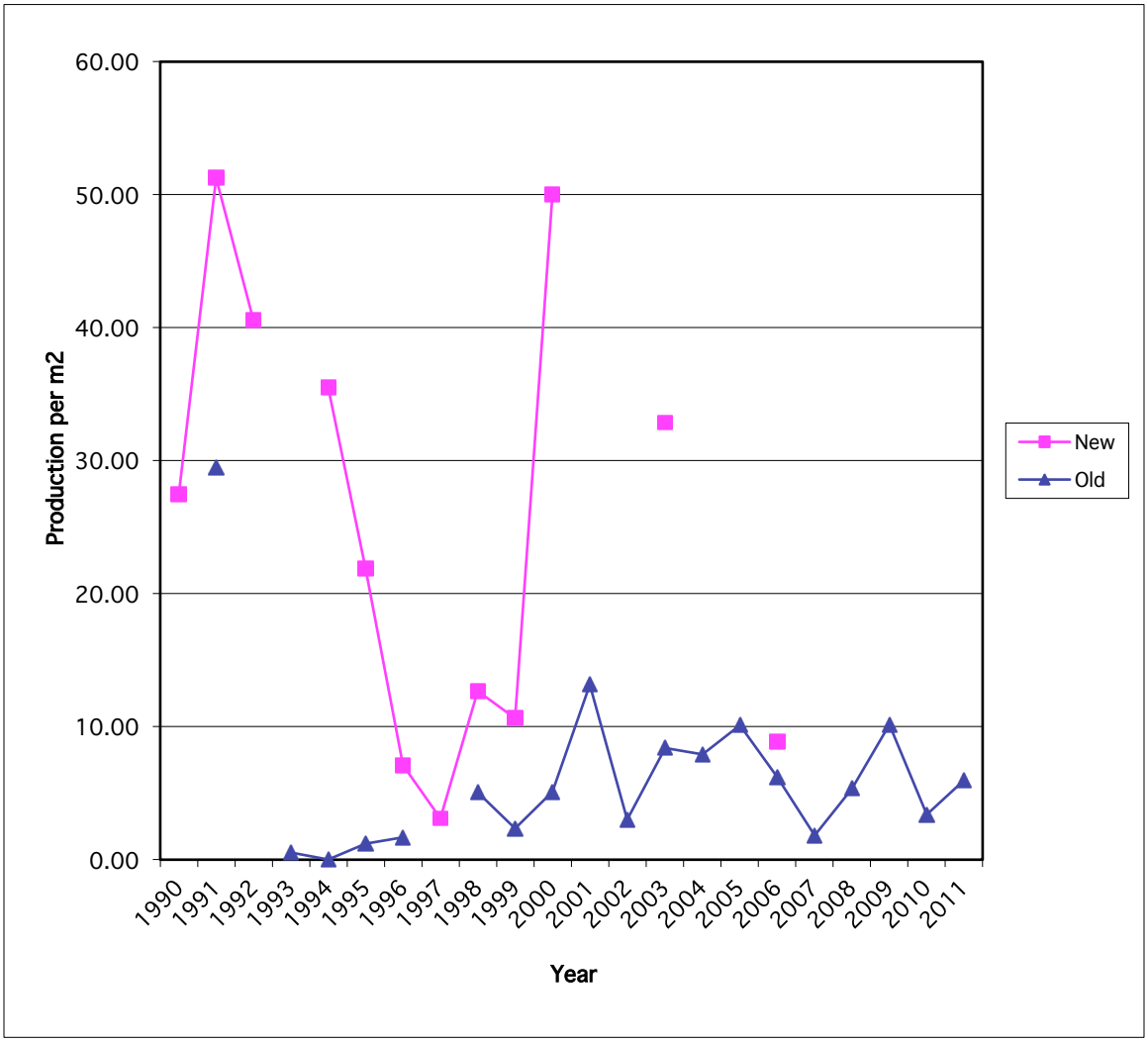

Figure 7. Total production for all years since initiation of mitigation efforts, showing contribution of new and old shell. Note high production of 'old' 1990 shell sampled in 1991, and relatively low productivity of 'new' 1996, 1997, and 2006 shell habitat.

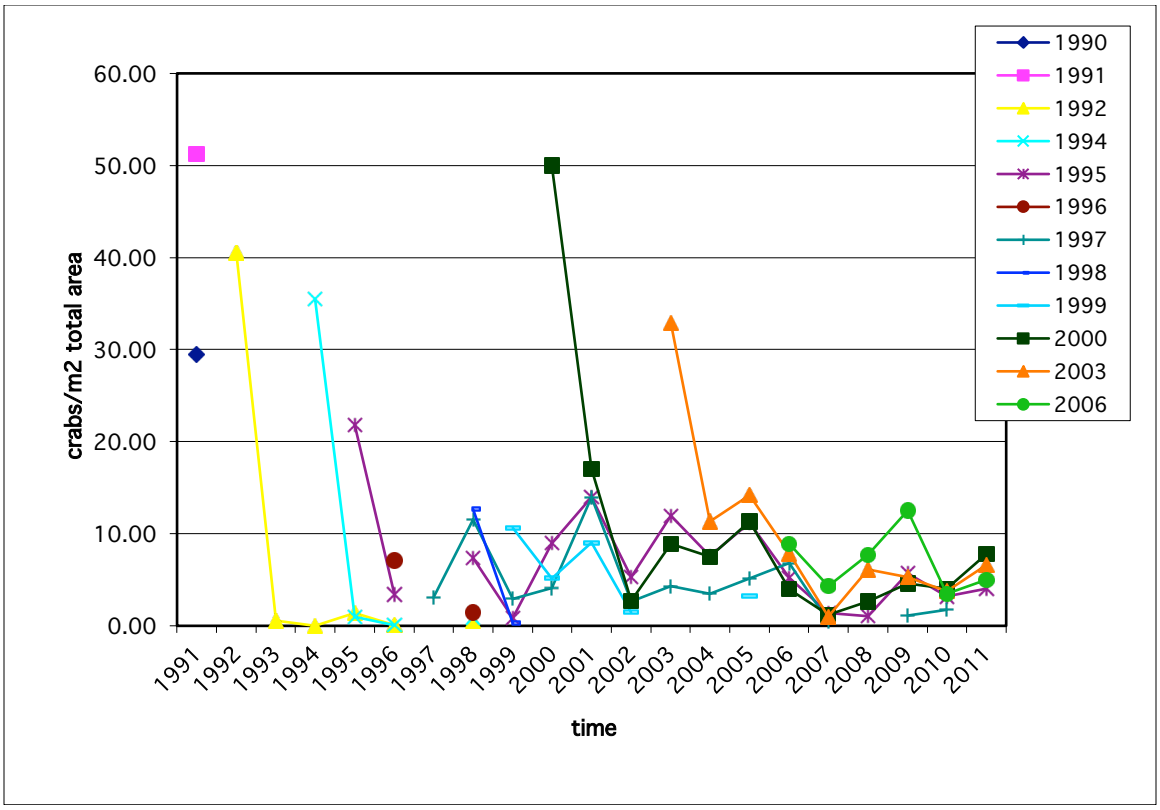

Figure 8. Historical production of J4 Dungeness crab per square meter of shell mitigation habitat created, separated by habitat. For example, the orange triangles show the average production rate of the three shell plots constructed in 2003 and sampled nine consecutive years 2003 - 2011.

Within year variation between plots shows the four plot groupings by age (2006, 2003, 2000 and 1995 shell) comprising respectively 41%, 37%, 10% and 12% of total area, ordered by increasing age. When scaled in this way for area, 2006 shell produced 48% of annual total on 41±13% of the total area sampled. Shell habitat constructed in 2003 likewise contributed 31±7% of crab productivity on 37% of total area sampled during 2011 field efforts. The 2000 shell produced 11% of total annual yield in Dungeness crab productivity on 10% of total area and the 1995 habitat continues to provide effective refuge, producing 10% of juvenile crabs on 12% of the total area. The 1996/97 plot performed poorly in 2010 and did not have enough remaining shell cover to merit sampling efforts over 2011 field season. 2006 West and 2003 Up were statistically greatest producers, 2006 East, 2003 Up, 2000 East, and 1995 Island were in the second

statistical grouping (at .05 confidence level), while the third and lowest statistically separable group included 2003 Down, 1995 Island, 2000 East, and 2003 East plots.

4.2 Cumulative Production

Total estimated production of juvenile Dungeness crab from shell mitigation habitat is 30.3 ± 7.3 million crabs as of the end of the 2010 sampling season. The 0.93 million crab produced in summer 2010 is about the 0.88 million average yield for old shell over the 21 year project history (Figure 9). 2010 ranked 14/21 overall and 5/9 of years when no new shell habitat was placed. Comparing 2010 production with other old habitat production yields, places it in the top third, 7/21 years. Shell habitat is aging and this is the longest duration of no shell placement since project inception in 1990. Production of shell mitigation plots can be expected to decrease or plateau without additional shell habitat construction soon.

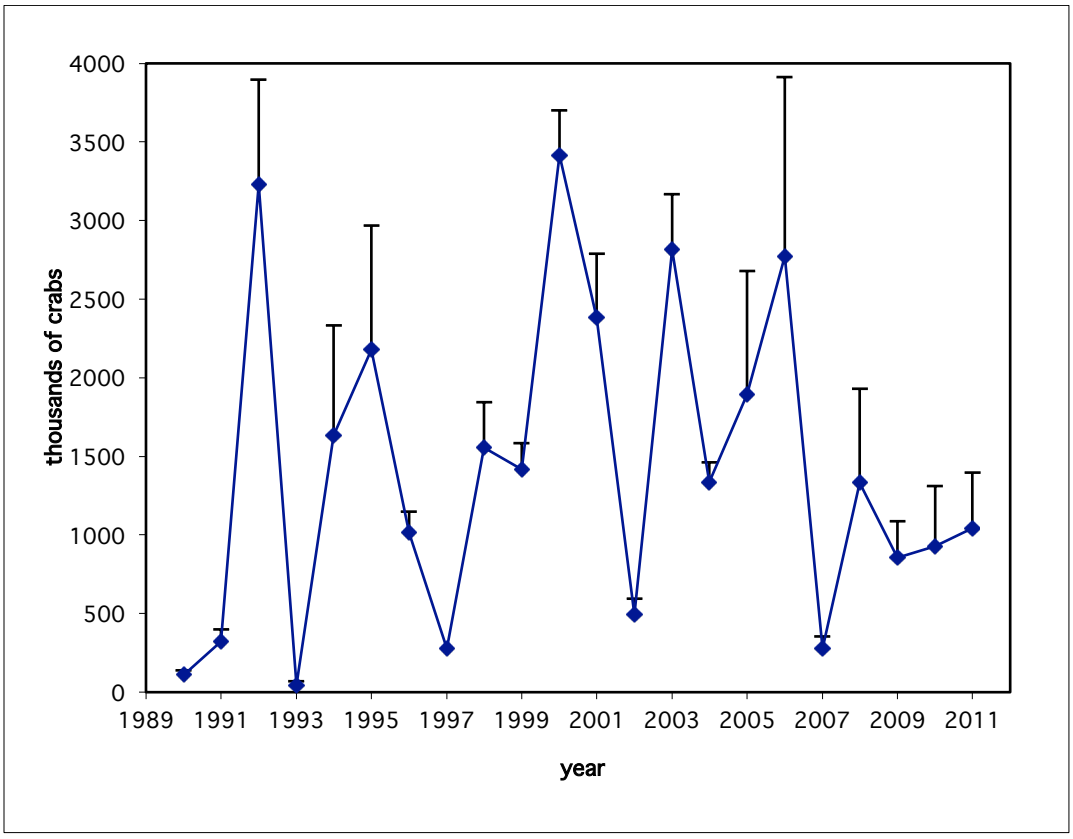

Figure 9. Historical annual yields of J4 juvenile Dungeness crabs by sampling season. Note that all plots sampled within the year are summed in this graph so that data are by year of sampling rather than the shell habitat constructed in a given year.

Of the total 31.3 million crabs produced to date (Table 3), 49.2% comes from the 12 plots constructed in their initial year (12 plot•years, or about 450 excavation samples) and 50.8% from all plots summed over all subsequent years sampled (167 plot•years, or over 7700 samples). New shell is typically much more productive than old shell, although that difference has narrowed since 1998 when interspecific competition with *Hemigrapsus oregonensis* ceased to play a role in Dungeness crab behavior and habitat usage within shell plots (Figure 10). Although shell habitat functionality is of greater duration than in early stages of the mitigation project thanks to increased habitat longevity as well as absence of *Hemigrapsus oregonensis*, periodic deposition of new shells remains necessary for high yields of juvenile Dungeness crab. Only twice in the 20 years since large scale (greater than 4000 m^2) shell plots have been created on the South Channel mudflats has new shell failed to produce over 500,000 juvenile Dungeness crab.

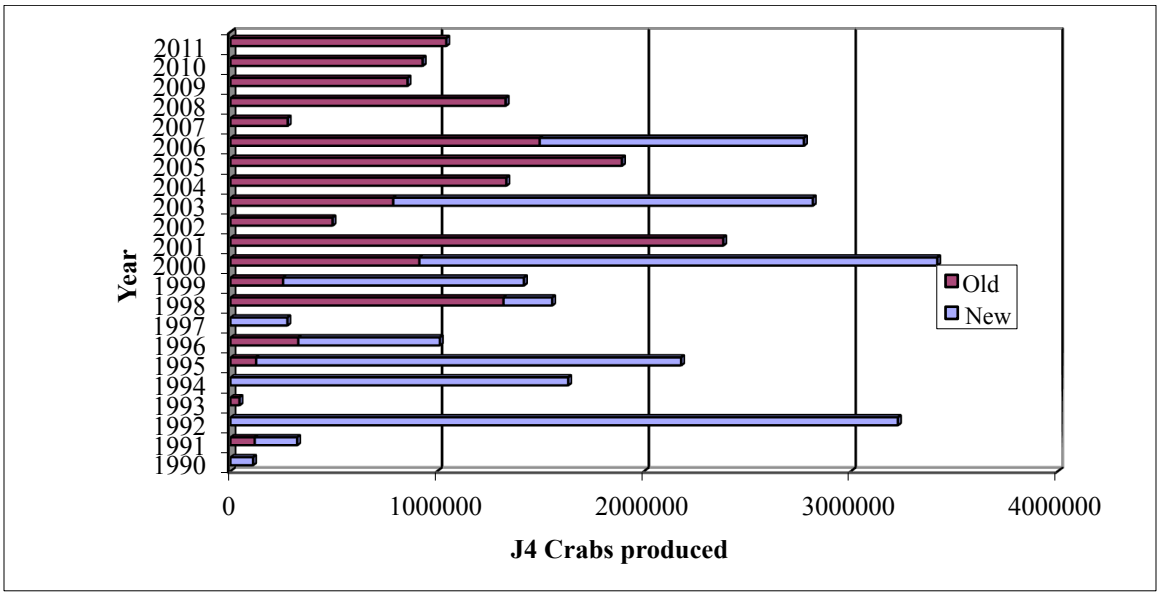

Figure 10. Historical production yields by year of sampling, separated into contribution of new and old shell habitat. No new shell habitat was created in 1993, 2001, 2002, 2004, 2005, or 2007-2011 so there are no blue colored portions of the bars for these years. Likewise, old shell was not sampled in 1992, 1994 or 1997 thus contribution of old shell cannot be quantified for these years.

Less than half the time does the sum of all previously constructed plots (≥72000 m^2) reach 500,000 crabs over a much greater area. New shell attracts and supports a greater number of juvenile crabs. Low levels of productivity can be continued without new habitat and may even be able to keep up with maintenance dredging, but the higher yields to meet impact of deepening will probably require new shell placement. The contribution live oyster habitats to total productivity of mitigation project seems to be increasing as crab utilization of shell increases.

Table 3. Annual production by new and old shell plots sampled since the beginning of the shell mitigation project. Note that unlike other tables, 'year' here is year of sampling, rather than year of plot construction.

Year	New	Old	Total	st.dev.
1990	109,710	N/A	109,710	29,172
1991	204,984	117,987	322,971	77,615
1992	3,226,965		3,226,965	670,204
1993	N/A	44,222	44,222	27,042
1994	1,633,038	0	1,633,038	701,685
1995	2,054,273	124,945	2,179,217	788,633
1996	684,584	328,064	1,012,648	136,052
1997	275,729		275,729	
1998	235,167	1,320,398	1,555,565	287,290
1999	1,164,115	254,838	1,418,953	167,137
2000	2,503,377	913,513	3,416,889	285,964
2001	N/A	2,382,476	2,382,476	408,102
2002	N/A	493,780	493,780	100,899
2003	2,028,516	787,181	2,815,697	352,682
2004	N/A	1,334,419	1,334,419	128,541
2005	N/A	1,892,976	1,892,976	786,935
2006	1,277,192	1,495,301	2,772,493	1,140,425
2007	N/A	277,461	277,461	75,608
2008	N/A	1,330,796	1,330,796	500,594
2009	N/A	856,557	856,557	230,653
2010	N/A	929,514	929,514	381,557
2011	N/A	1,044,022	1,044,022	352,753
Total	**15,397,650**	**15,928,449**	**31,326,097**	**7,629,544**

4.3 Crab Density and Instar Composition

Crab density and instar composition data from all plots sampled in 2011 show classic trends of increasing size and decreasing numbers following settlement (Figures 11-17). Some large instar crabs remaining on the plots from late 2009 settlement, or recolonization can be seen in May samples on each of the seven plots, showing up as red bars for greater than 25mm carapace crabs on each of the plots. Particularly on the 2006 plots where the later cohort of megalopae tends to have better survival, the overwintering instars are evident at higher abundance. The top section of all instar composition bars in May show crabs greater than 25 mm carapace width (Figures 11-17) that could not have settled in spring 2011 and grown to that size by the first sampling date of May 17th. High abundances of larger crabs from the previous season may contribute to poor survival of the initial cohort of young of the year due to a combination of cannibalism on molting individuals by larger instars as well as competitive advantage of larger instars over more recently settled smaller juvenile crabs. An elevated mortality function would have confirmed this, but due to a shortened sampling regime, lack of August data points, and consequential decreased statistical power and insignificance of curve fit, it was necessary to use the average mortality rate due from historical data set. Settlement of the second cohort in July on the 2006 West plot is notable, as it has been a reliable historical pattern, and was not evident in 2010 data.

The three shell mitigation plots with the highest productivity were the 2006 West, 2003 Up, and 2006 East plots, none of which demonstrated particularly high shell coverage. Percent shell coverage within the 40-70% coverage range, which includes shell plots sampled in 2010 and 2011, was not a good indicator of productivity. Neither was there was a correlation between rank order of productivity and average percent shell cover among plots. This lack of relationship was particularly evident between the 2006 plots where the higher performing 2006 West plot had ~47% shell cover during summer 2011 while the same aged 2006 East plot had ~70% cover yet yielded less than half as many crabs. Due to shell sinkage and adjustment of plot boundaries as a result of decreased area of habitat functionality, the size range among plots is greater than it has been historically, which changes the relative importance of shell cover to the total end

productivity result. Since all of the 2011 data were from plots 5+ years old, all from quadrats with 100% shell and from shell plots within a fairly narrow shell coverage range, the lack of correlation does not address or contradict the long-standing finding that crabs survive better in shell habitat compared non-shell habitats.

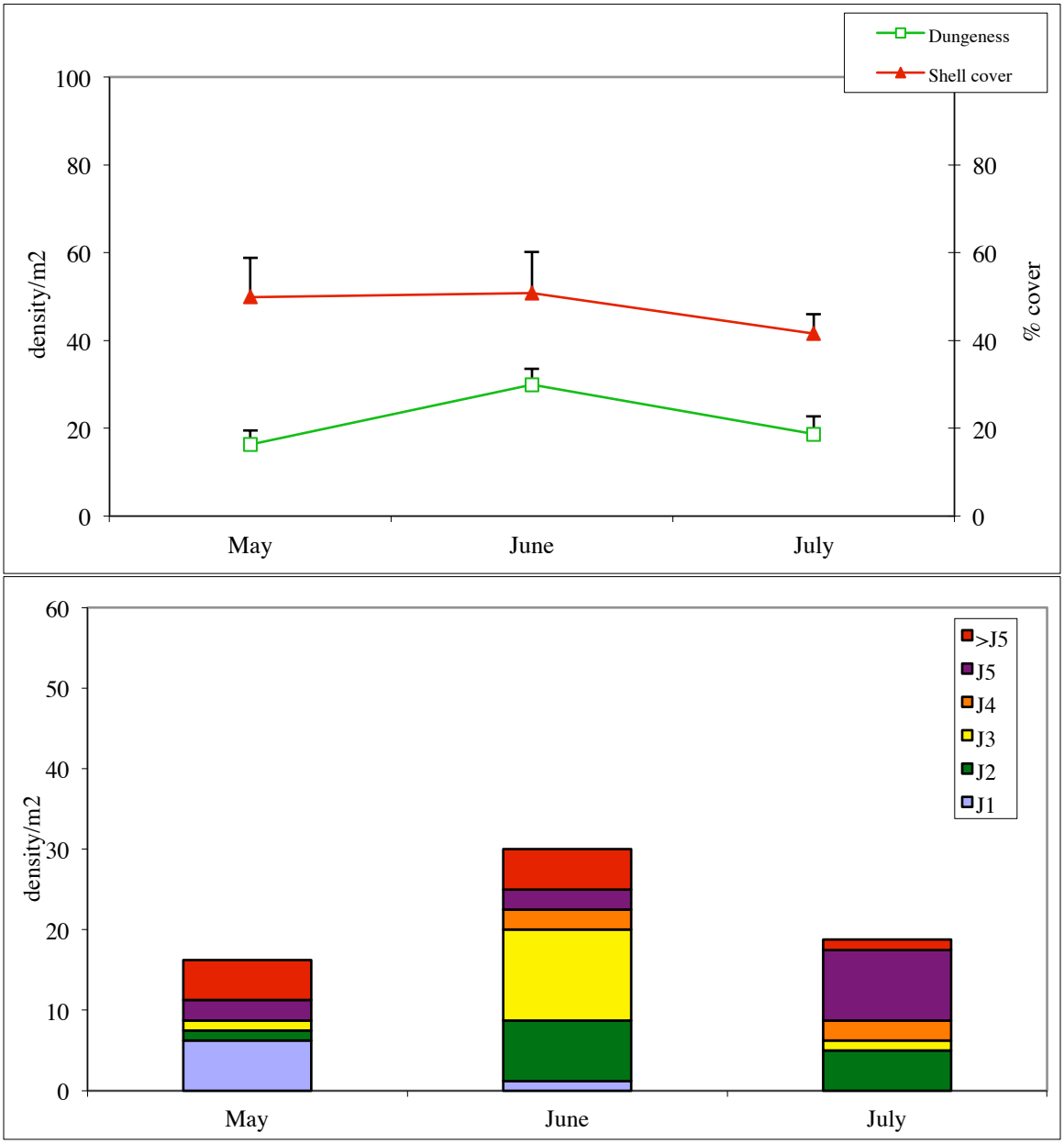

Figure 11. Summer 2011 crab data from 1995 Island plot: abundance compared with shell cover and instar size composition.

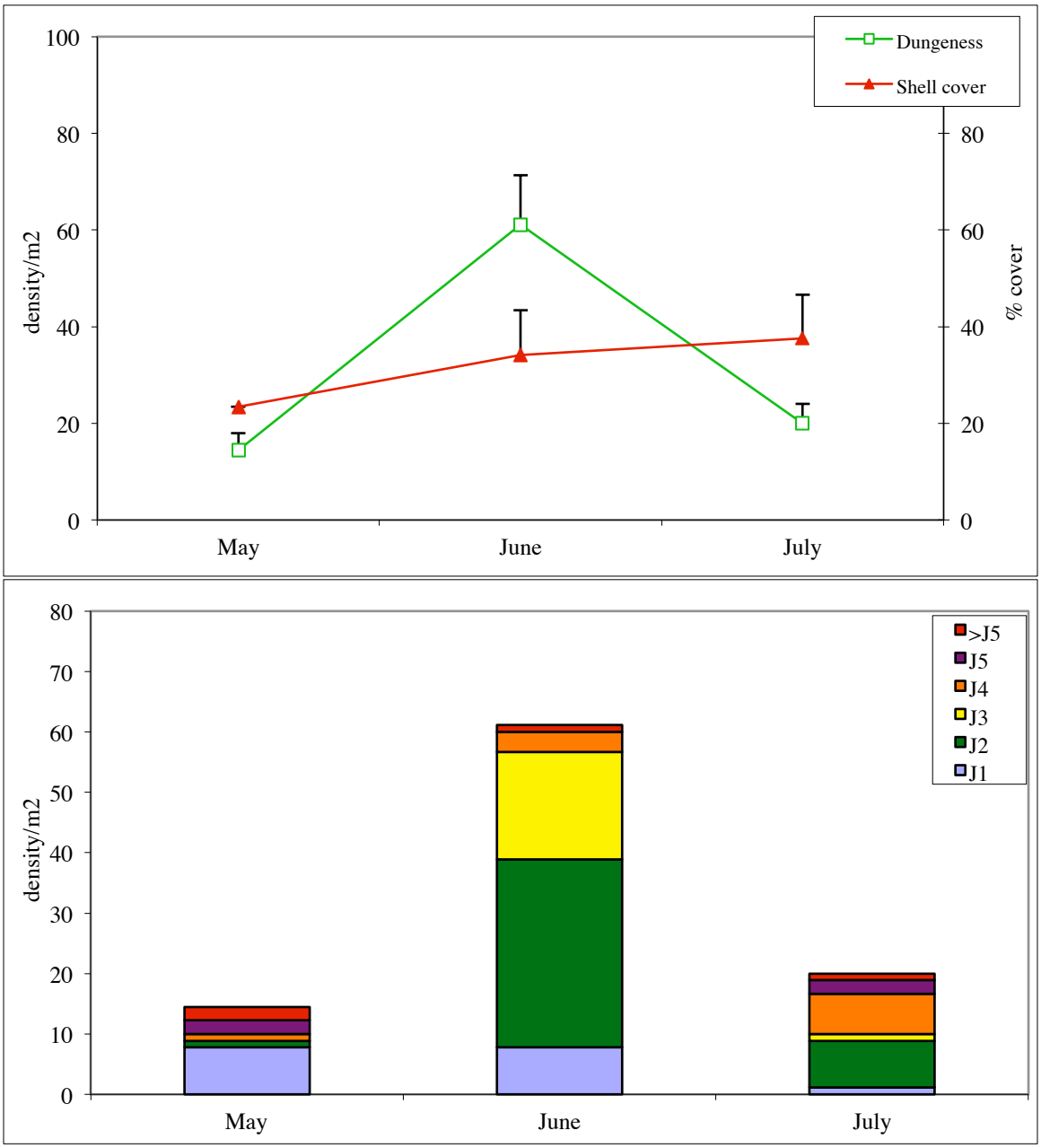

Figure 12. Summer 2011 crab data from 2000 East plot: abundance compared with shell cover and instar size composition.

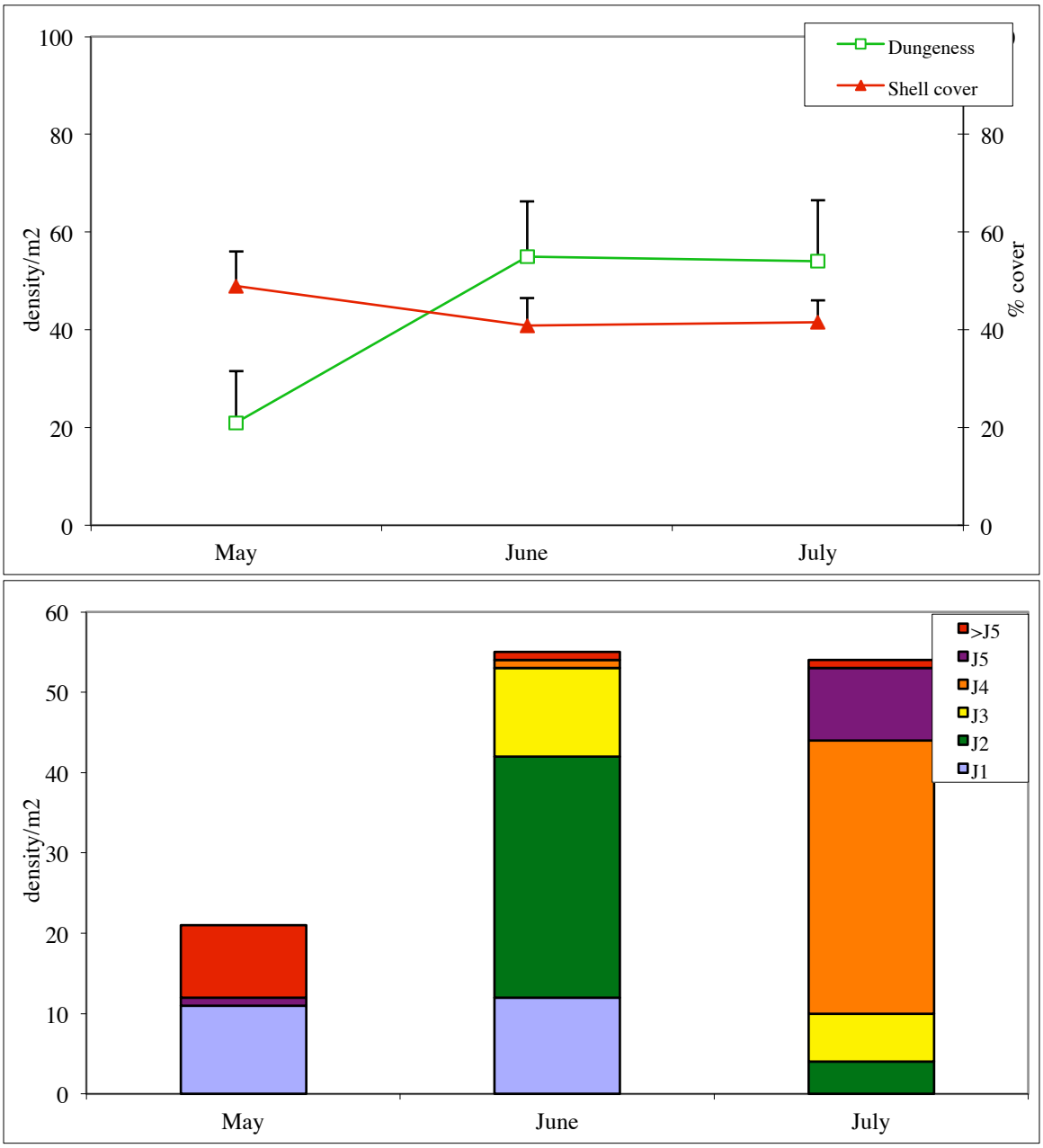

Figure 13. Summer 2011 crab data from 2003 Up plot: abundance compared with shell cover and instar size composition.

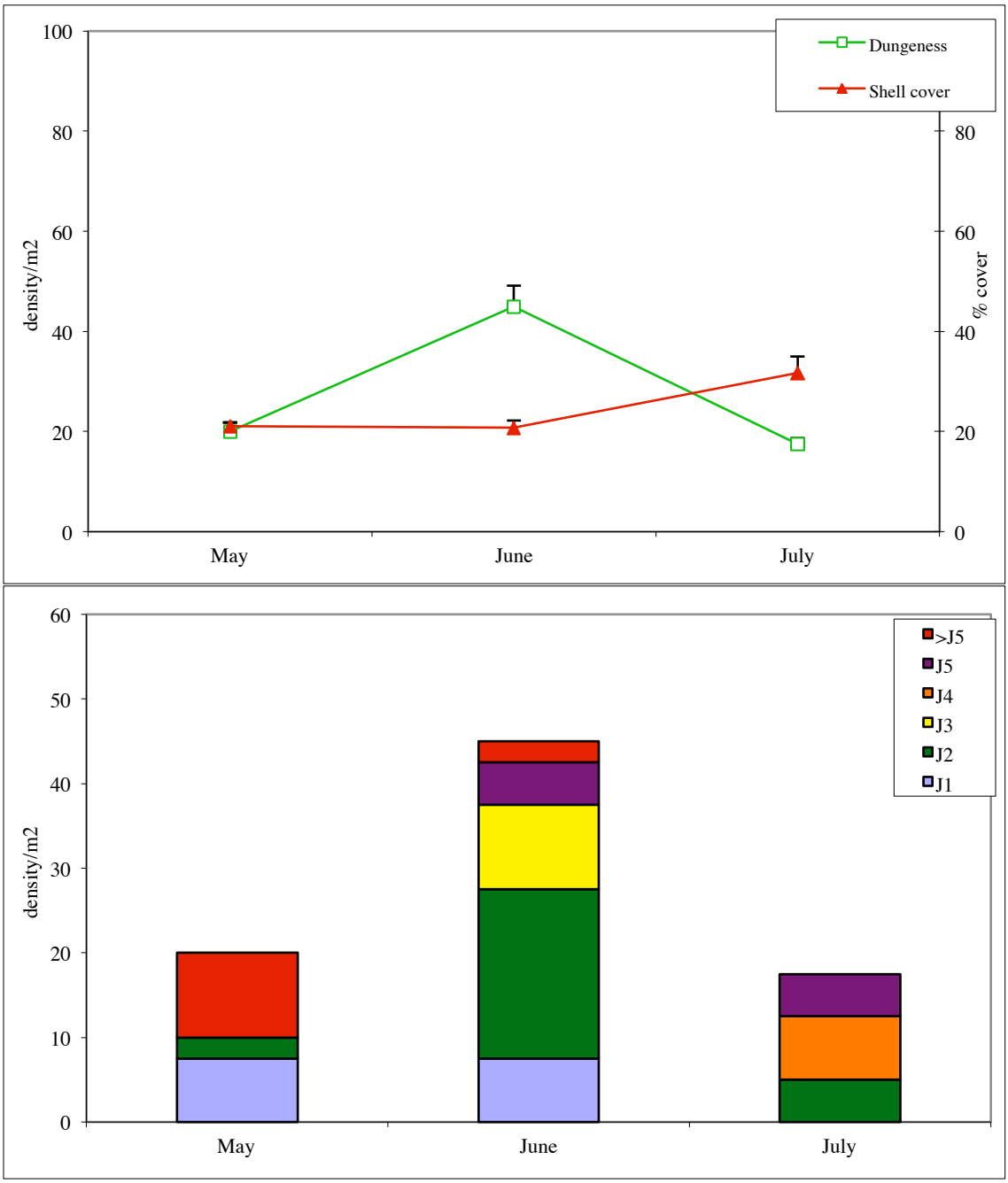

Figure 14. Summer 2011 crab data from 2003 Down plot: abundance compared with shell cover and instar size composition.

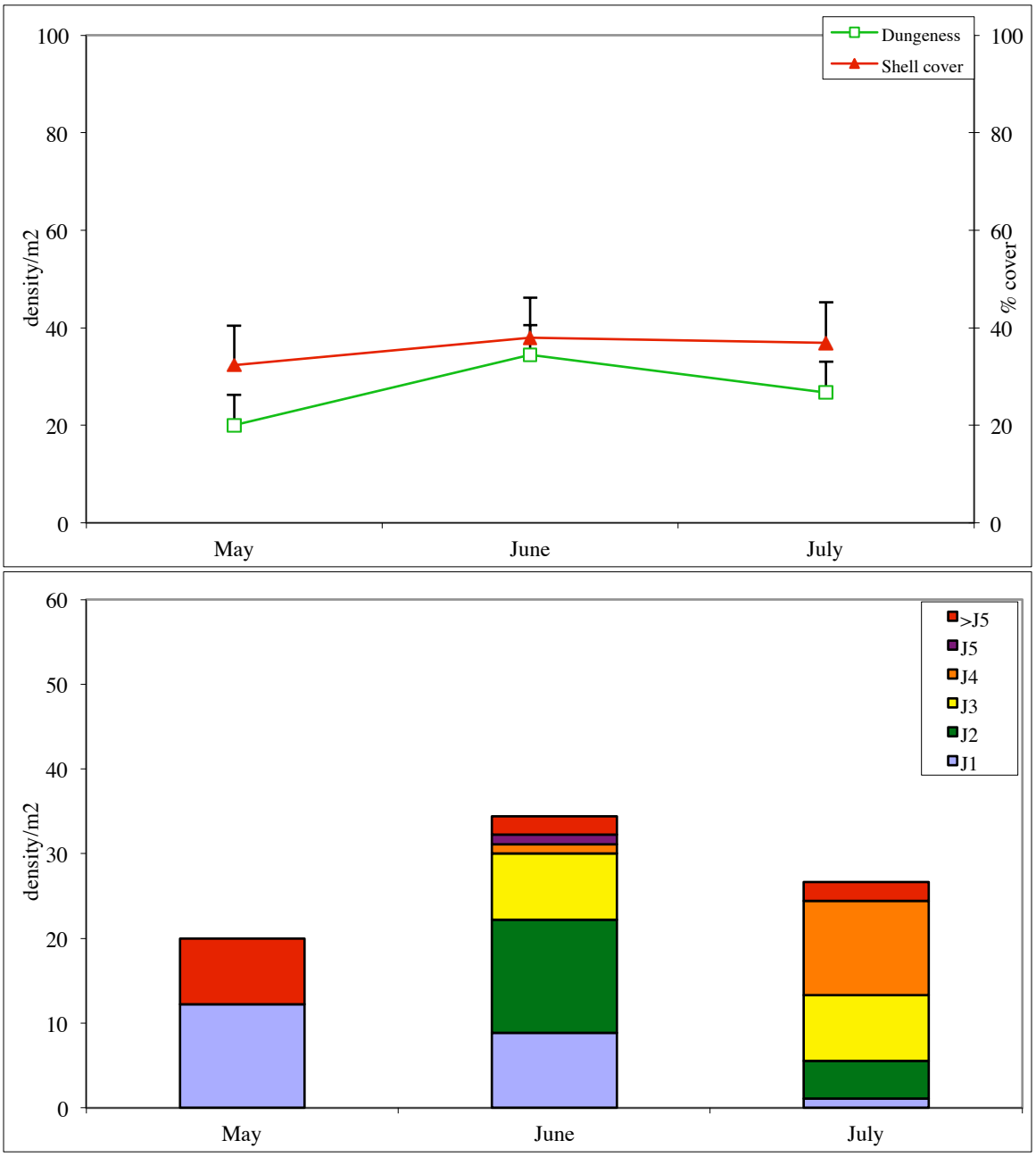

Figure 15. Summer 2011 crab data from 2003 East plot: abundance compared with shell cover and instar size composition.

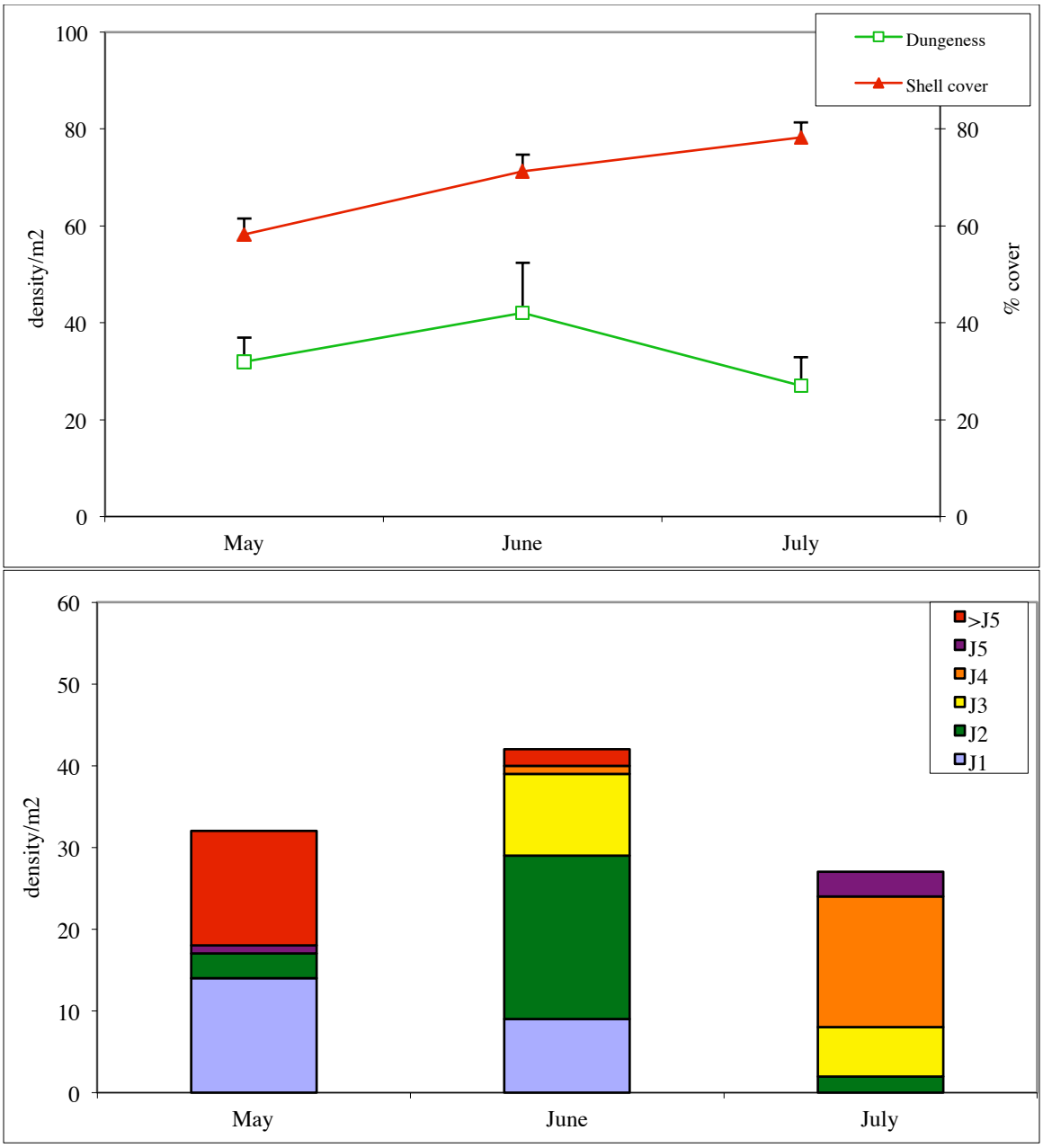

Figure 16. Summer 2011 crab data from 2006 East plot: abundance compared with shell cover and instar size composition.

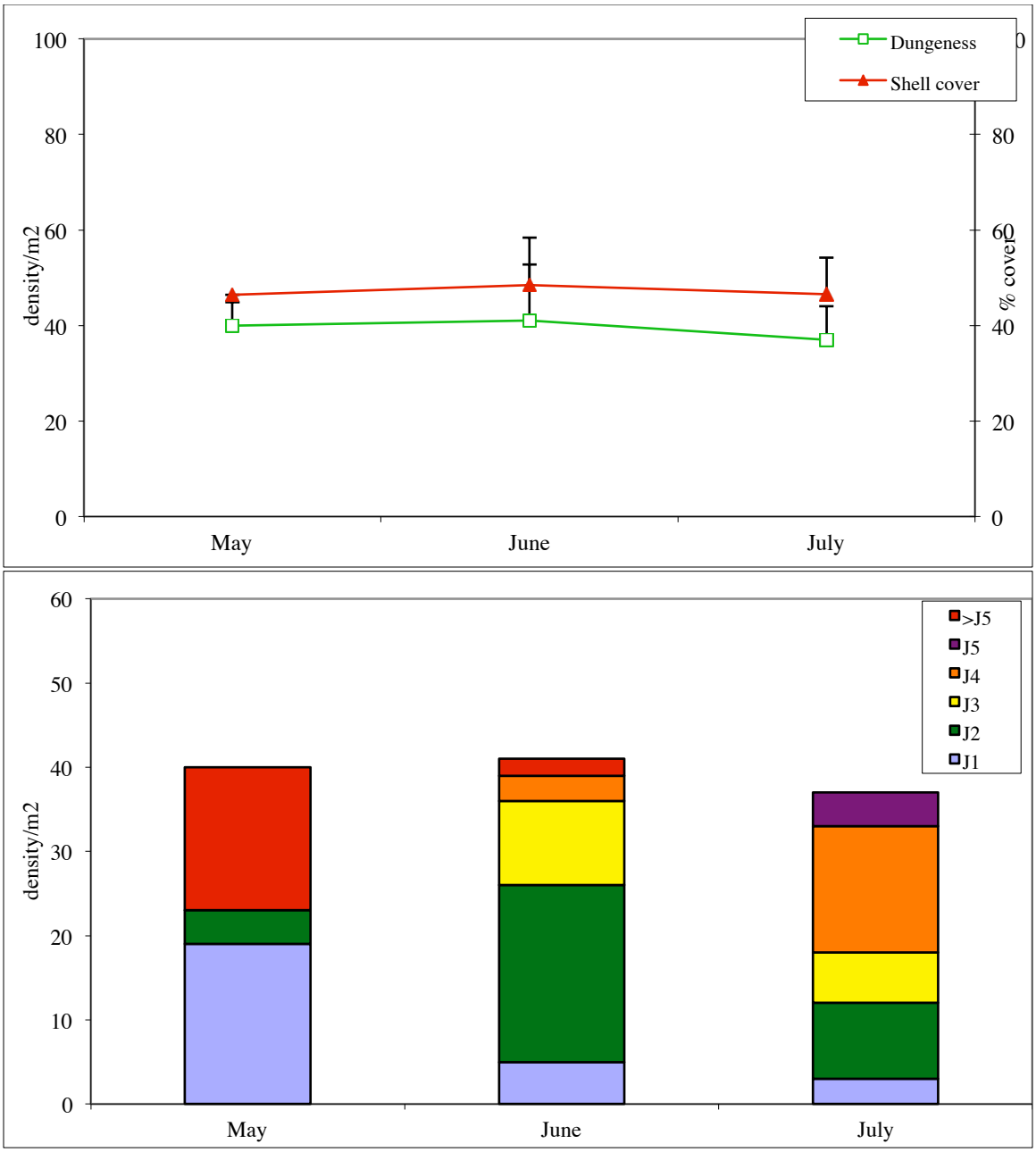

Figure 17. Summer 2011 crab data from 2006 West plot: abundance compared with shell cover and instar size composition.

4.4 Mortality

Mortality rates computed from 2011 data resulted in no significant r^2 values for the exponential curve fits on crab density data. With only three months (May - July) of crab density data to work with and sampling dates missing peak settlement event this is not surprising. Average mortality rate data from historical data was used for all 2011 computations instead of plot specific mortality rates, since we did not have valid estimates of different survival rates for juvenile crabs from separate plots (Table 4). While there were not enough degrees of freedom to statistically differentiate the mortality rates, crab abundances showed increases in midsummer 2011 indicating low mortality, extended settlement or recruitment period and most likely higher than average survival on intertidal mitigation habitat. With 22 years of crab abundance and survival data, there is a wide confidence interval around average survival rates.

Table 4. Mortality rates and corresponding survival rates realized by new and old shell habitat from 1990 through 2011.

YEAR	New Shell	% survival	Old Shell	% survival
1990	0.0195	51	N/A	
1991	0.0276	38	0.0216	47
1992	0.0179	53		
1993			0.0216	47
1994	0.0187	52	0.0216	47
1995	0.0136	62	0.0248	42
1996	0.0123	65	0.0096	71
1997	0.0158	58	0.0187	52
1998	0.0208	48	0.0343	30
1999	0.0168	56	0.0226	45
2000	0.0216	47	0.0197	50
2001			0.0321	33
2002			0.0098	71
2003	0.0220	46	0.0289	36
2004			0.018	53
2005			0.0233	44
2006	0.0200	50	0.0264	40
2007			.0137	62
2008			.0218	48
2009			.0044	86
2010			.0217	47
2011			.0217	47
Avg	0.0189	52	0.0217	47
SD	0.0041	7	0.0077	14

4.5 Shell and Eelgrass Cover

Shell cover relationships for all shell plots over summer 2011 continued to be flat, with some increases evident over the summer. This relationship indicates fairly stabilized habitat, little change in eelgrass coverage (Figures 18-20). Utilization of the overlay strategy for shell placement has improved habitat longevity and slowed sinkage of mitigation habitat. This shell placement strategy improves cost effectiveness of field efforts dramatically since the most expensive component of the project is shell placement. The only plot that showed deviation from a flat percent shell cover relationship over the 2011 summer was the 2006 East plot, which had lower shell cover in May and continually increased shell coverage values as the summer progressed. The 1995 Island plot continues to provide functional refuge habitat despite its 16-year age. Whether due local differences in hydrodynamics, sediment stability parameters such as abundance of burrowing shrimp, storm scour, or other factors, the 1995 Island has exhibited the greatest longevity of any shell plot since the mitigation project began. Eelgrass cover continues to remain relatively constant and uncorrelated with shell cover on the scale we are measuring. The only plot where eelgrass cover was significant was the 2000 East plot, but the 2006 West plot shows increased prevalence compared to past years (Figures 18, 19, and 20). Eelgrass prevalence has decreased slightly on some plots in recent years, but no long-term trends are evident in eelgrass bed coverage of the mitigation area.

Eelgrass cover continues to be very low on sample plots and show no correlation with shell cover. Since shell habitat was intentionally placed to avoid dense patches of eelgrass and plot boundaries are occasionally adjusted to reflect lost shell habitat, eelgrass cover data is not a true measure of overall eelgrass coverage on South Channel mitigation site, but only of eelgrass coverage within subplots sampled for Dungeness crab each month.

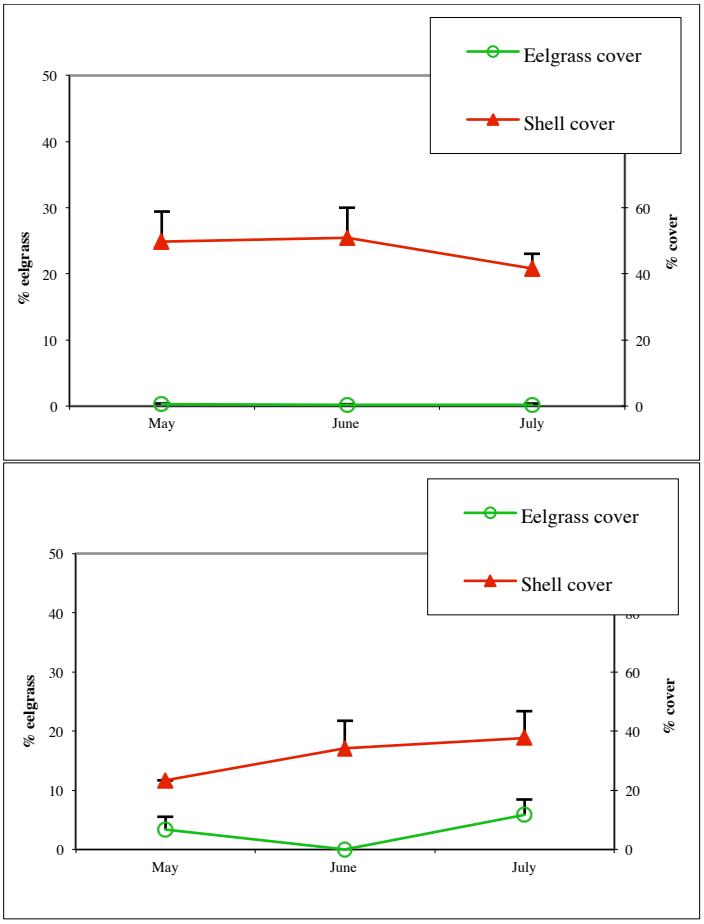

Figure 18. Oyster shell and eelgrass percent cover for the 1995 Island and 2000 East plots during summer 2011.

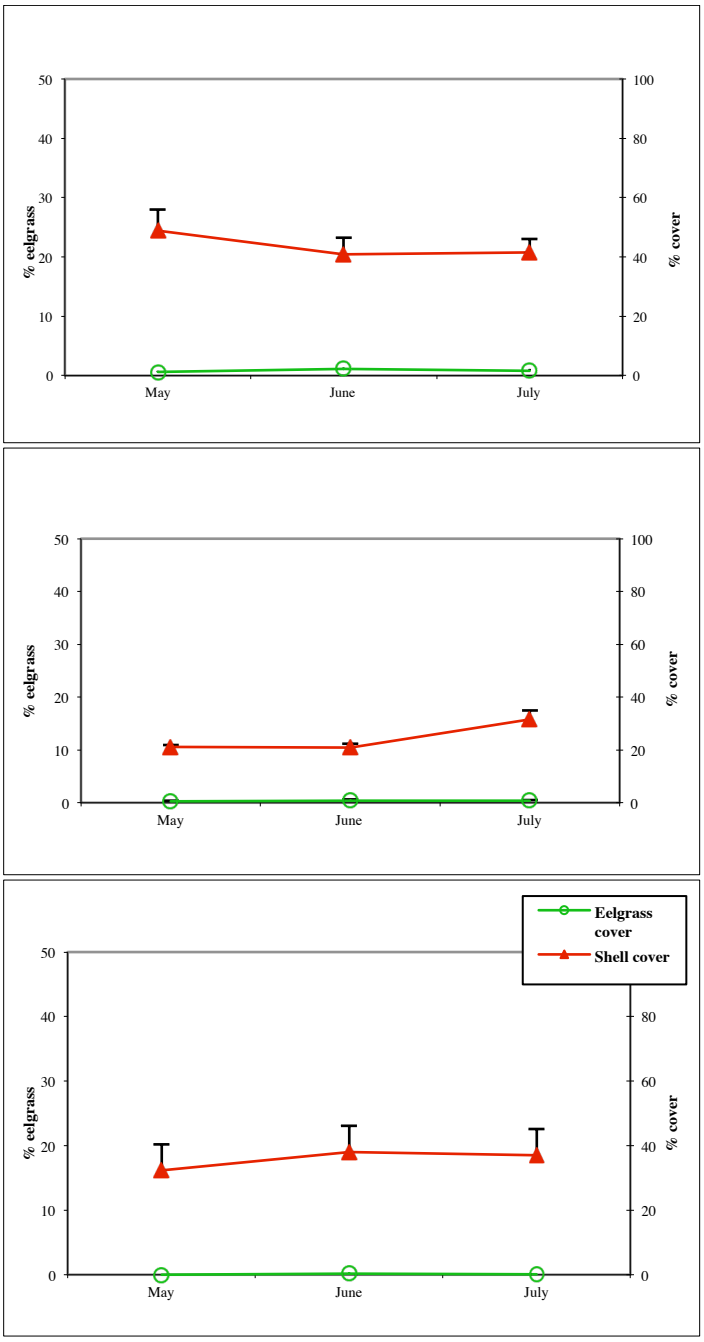

Figure 19. Oyster shell and eelgrass percent cover during summer 2011 for the 2003 Up, 2003 Down, and 2003 East plots.

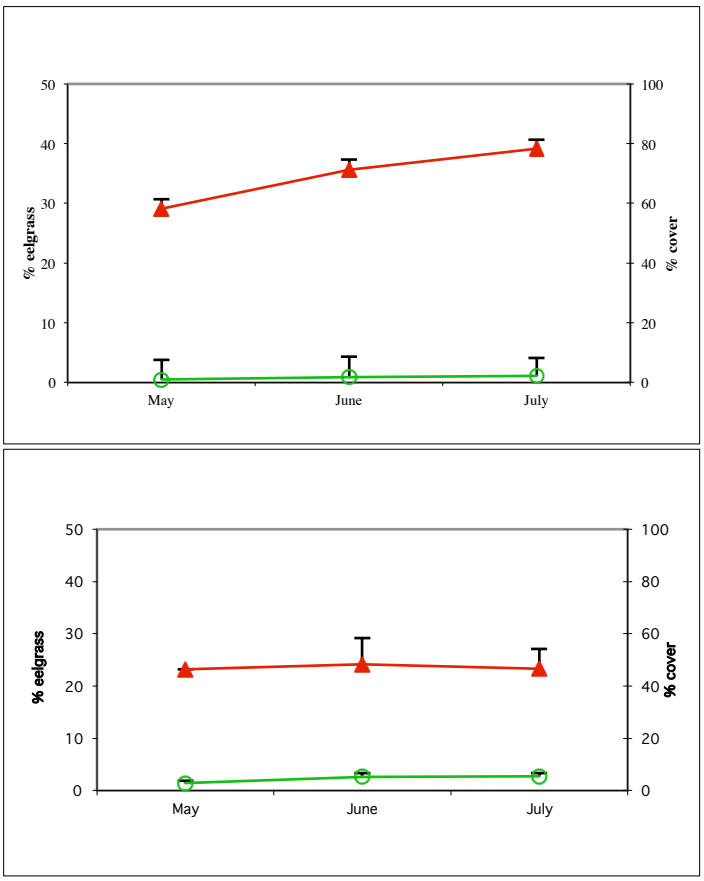

Figure 20. Oyster shell and eelgrass percent cover during summer 2011 for 2006 East and 2006 West plots.

4.6 Live Oyster Habitat

Oyster spat were planted in early spring 2006 and continue to thrive on the South Channel shell mitigation plots. Survival has been high, with mortality rates leveling off and oysters showing less evidence of crowding and competition than was initially anticipated. Instead of overcrowding and differential growth rates leading to mortality, the clusters have broken up in the field and individual oysters or smaller clusters continuing to survive on the mudflat. Live oyster habitat exhibits a three dimensionality

and although oyster spat were originally evenly distributed within each experimental subplot, most of the experimental subplots have developed a patchy distribution with sections of live and inert shells rather than uniform distribution. Many oyster shells have become distributed outside the boundaries of original placement.

Although greater shell cover is positively correlated with presence of live oysters. percent shell cover differences between the five 2003 Up subplots planted with live oysters and the five without live oysters are still within one standard deviation of the mean and thus are not statistically separable (Figure 21). With only five replicates and high field variability, differences are still indistinguishable even though mean substrate coverage of areas with live and inert oysters are deviating. The wide range of shell coverage inherent within even high quality mitigation habitat in the field requires greater statistical power that five replicate subplots will allow. Shell cover data for subplots with and without live oysters will continue to be compared in order to determine if live oysters increase habitat longevity over a longer period of time and thus create a more sustainable refuge for juvenile crab.

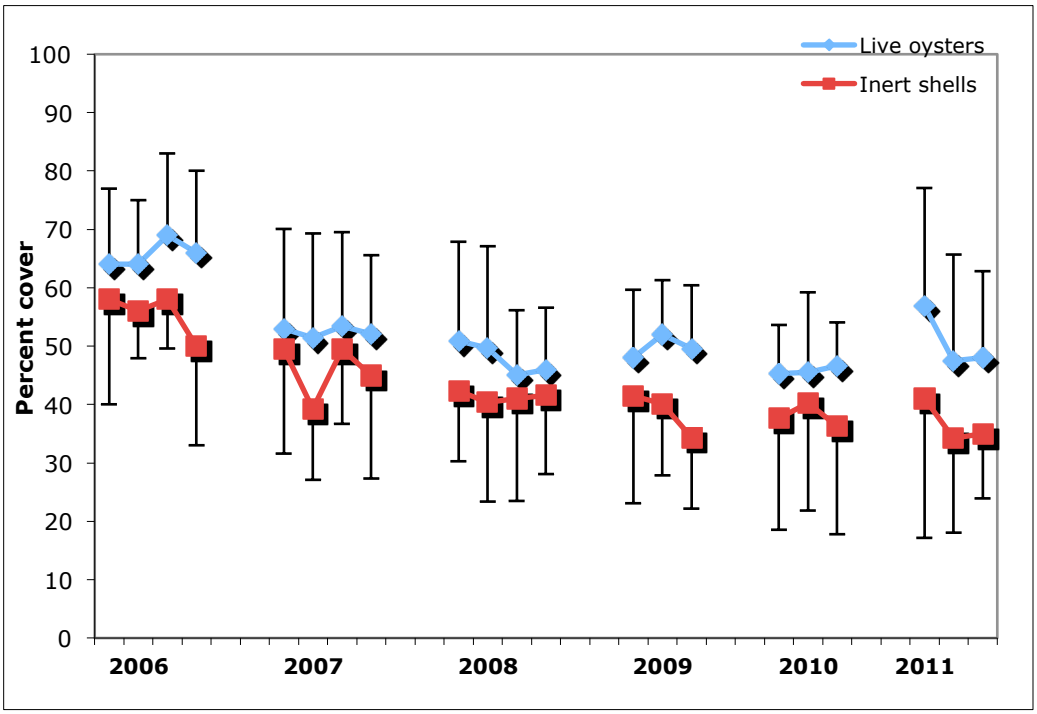

Figure 21. Percent shell cover of subplots with and without planted oyster spat over summers 2006-2011. Live oysters were planted on subplots 1,4,5,6, and 9 and subplots 2,3,7,8,and 10 were left as controls.

Crab utilization of experimental subplots exhibits a less consistent pattern than does shell cover data, with crab densities overlapping early in the summer. By the end of each summer, however, crab utilization of live oyster habitat is greater than inert oyster shell habitat, and these differences are significant for August 2011. Crab densities on both experimental and control plots show equally timed peak larval settlement, and similar decline patterns. In 2006, juvenile crab densities at peak density were greater on the experimental live oyster shell plots, while in 2008 peak densities were much greater on the control plots (Figure 22). Peak densities often represent only initial settlement patterns, though, and not a measure of stable population of crabs making use of refuge space for safety and growth through a vulnerable life history stage. The only sampling period where crab utilization numbers differed significantly between live and inert shell habitat was August, but this pattern has emerged in both of the last two sampling years. Although clearly more monitoring is required, improved functionality of these live oyster plots as effective juvenile crab refuge habitat seems to be finally emerging. Experimental and control plots are clearly distinguishable visually, and the three dimensionality of the habitat may improve survival rates as well as provide additional surface area for epibenthic forage for the juvenile crabs. It may be that the scale involved with the experimental subplots is too small to detect differences and that settling crabs are responding to a larger stimulus and do not differentiate between differences in microhabitat on the scale of our experiment. In other words, the quality habitat cue from the live oyster structure could translate into higher settlement rates on both live and control subplots, increasing crab utilization of both treatment groups, thereby enhancing mitigation success but masking differences between experimental groups. Continued comparisons between the two habitats will help tease apart these effects.

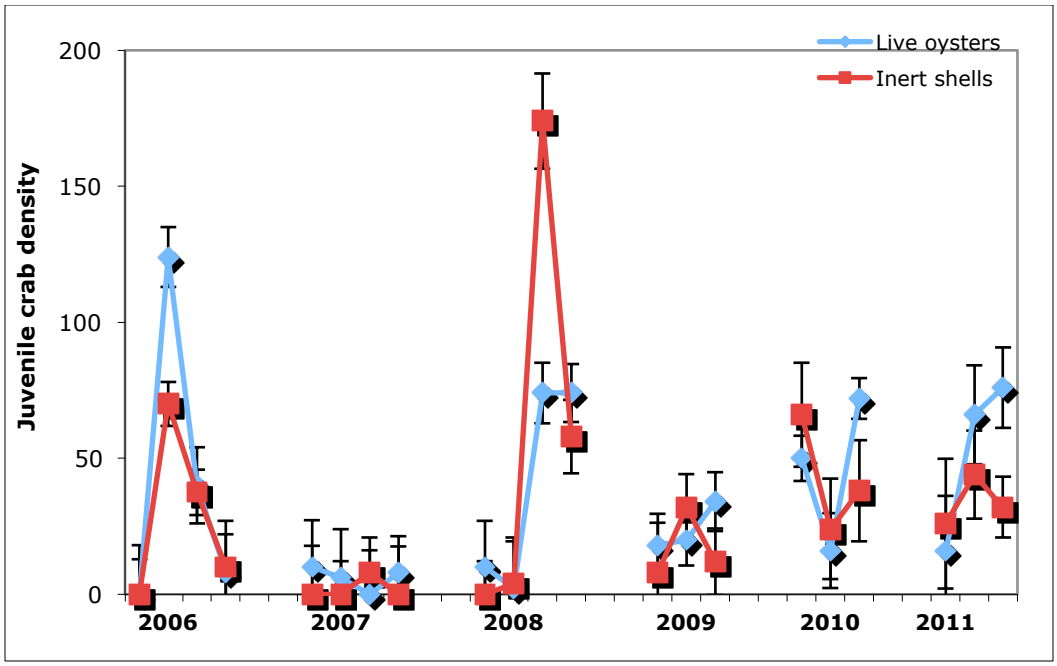

Figure 22. Juvenile Dungeness crab densities over summers 2006-2011 on experimental plots with and without live oysters.

5. Summary and Conclusions

About 1 million J4 crabs were produced by all shell plots sampled this year. The 2011 summer production yield of 1.04 ± 0.35 million juvenile Dungeness crab was about the average production for old shell habitat over the 22 year project history since mitigation efforts began in 1990 and cumulative production has now reached 31.3 ± 7.6 million crabs. The highest yield was from the 2006 West plot, which yielded 0.34 ± 0.12 million J4 Dungeness crab, or 33% of the 2011 total. The 2003 Up and 2006 East mitigation plots yielded between .15 and .19 million crabs, while 1995 Island and 2000 East plots produced 0.11 and 0.12 million crabs respectively, on 12% and 10% of the total shell area evaluated during 2011 summer. On a square meter of habitat created basis, 2011 productivity was 5.9 crabs/m^2. This is about average as far as production rates for old shell habitat since refuge space competition with *Hemigrapsus oregonensis*

ceased to be a major factor on mitigation habitat utilization by juvenile Dungeness crab in 1998, and significantly below the original target mitigation goal of 10 crabs/ m^2.

Shell cover remained fairly constant on all plots over summer 2010, although increased slightly over the summer on the 2006 East plot. Unlike 2009 when shell cover was strongly correlated with crab habitat utilization, there was no correlation between plot productivity and percent shell cover during 2011 or 2010 summer sampling periods. Shell cover has not been the major factor in determining productivity in recent years when larval supply has been variable, and the necessity of adjustment of plot boundaries due to loss of shell habitat has widened the range of plot sizes. Less than 6650 m^2 of functional shell habitat remains on the 2003 Down plot, for example.

Influx of megalopae into Grays Harbor during 2011 season occurred over a lengthened period, from before initial sampling in May throughout June and July and therefore abundance functions were fairly flat between May and July, lacking the precipitous decline that is seen when peak settlement coincides with initial sampling efforts. In light of tight budget constraints and historical settlement patterns, the decision made in 2009 to drop the August sampling trip was repeated for 2010 and 2011 seasons. Although this strategy has been indicated for balancing projected production results and cost of data collection, this decision is not recommended for the 2012 field sampling strategy due to a couple of factors. Firstly, the timing of low tides during summer 2012, at the very beginning of each month, means that juvenile crab habitat utilization will likely extend through the early August low tide, increasing production yields from collections in August. Secondly, after three years of basing annual estimations upon a shortened data series, and computing plot survival using historical average mortality rates, it is important to get updated plot specific mortality rates. With the long term data set we have available for this project, it is a unique opportunity to recognize changes that may be occurring in the population and Grays Harbor environment.

The live oyster spat experiment initiated in late March 2006 on the 2003 Up mitigation plot continues to be monitored. Survival and growth remain strong after five years of intertidal growth of these oysters and crabs are utilizing the habitat. Differences in percent shell cover remaining on the mud surface between plots with and without live oysters still overlap statistically due to the wide variation in percent shell cover values on

the intertidal shell plots and low sample size (n=5) resulting in low statistical power of detection. Juvenile crab densities on the experimental versus control plots are similar with the exception of the time period of peak settlement, but significantly more crabs utilize live oyster subplots in August compared to subplots with only inert oysters. This trend by the end of the summer is evident over the past two years. Quality of refuge habitat appears to be diverging and continued monitoring will determine whether these differences continue. If so, live oyster spat placement shows promise as a long term habitat creation strategy to maximize refuge longevity and commensurate juvenile crab production while simultaneously minimizing expense of habitat creation by dramatically spacing out timing of placement events.

With the upcoming channel deepening slated to occur in the next three to four years in North Channel of Grays Harbor, agency and crab fisherman interest in mitigation efforts is likely to be renewed. The ultimate goal of crab mitigation efforts is to keep pace or exceed estimates of impact on the estuarine population of Dungeness crab. The magnitude of this impact is estimated using the Dredge Impact Model, which takes into account volume, timing, and location of material removed, as well as population parameters such as size distribution and abundance of Dungeness crab in each dredged location. Our estimates of impact on crab populations are based on crab density data that is in some cases 30 years old. Although our population scale estimates will always be subject to some question as they involve extrapolating numbers from the past onto present dredging activities, we cannot hope to place much confidence in such projections over three decades, especially when most scientists have come to believe that we are in a period of more rapid environmental change than typical. The most recent of our crab density data is from 1996-1999, constituting population estimates which are 12-15 years old, and the rest of our dataset is based on trawl surveys conducted from 1983-1986, or 26-29 year old population values. Project planning and budgeting of shell mitigation project should certainly include trawl surveys to update our crab abundance density estimates. Getting these numbers before dredging project gets scaled up for deepening will increase credibility of impact estimates dramatically. The detailed sampling involved with quantification of credits to the crab population on the mitigation side of the crab accounting equation is not remotely matched with level of confidence possible with

population data from three decades ago. Recommendations for continued work in Grays Harbor include shell placement when budget allows, but a series of trawl surveys to update our knowledge of population status, particularly of 1+ crab within the estuary. Crabs trawls will be considerably less expensive than large-scale shell placement and should take precedence in forming future project goals. These data would allow the connection to be made between young of the year on mitigation plots and catch statistics for 3-4 year old crab, which heretofore have been too variable to correlate. The multi-year time gap between size classes of population data (young of year in mitigation samples and legal adults from catch statistics) in addition to the wide fluctuations inherent in adult crab catch data (sometimes orders of magnitude different from year to year) makes it difficult to translate dredging impact and production to the actual population effect. Updated trawl surveys similar to those being planned for summer 2012 in Willapa Bay would add confidence and corrections to the Dredge Impact Model which is still using crab data from the 1980s for many locations, as well as enabling us to get a midpoint for 1+ crab population data within the estuary.

The goal of the habitat mitigation project has been to compensate for dredging losses to the Dungeness crab population in Grays Harbor and to bring the impact to zero net loss. Comparisons between crab production data and dredge entrainment values gives the crab accounting estimates which enable progress toward this target to be assessed. Grays Harbor dredge volumes are available for all years since mitigation efforts began except 1997 (Figure 23). Running dredge volume, location, gear and timing values through the updated dredge impact model (DIM) gives annual estimates of total loss to the local Dungeness crab population within the estuary. Since crab abundance and size frequency distribution vary by location and season, and crab survival percentages vary depending on age class as well as dredging gear used, there is no simple relationship between dredge volume and population impact.

Year	Dredge Volume (mcy)
1990	8.5
1991	2.2
1992	3.4
1993	2.2
1994	2.0
1995	1.6
1996	2.2
1997	
1998	2.2
1999	2.2
2000	2.2
2001	1.2
2002	1.9
2003	2.1
2004	2.5
2005	2.1
2006	1.7
2007	1.6
2008	1.5
2009	1.9
2010	1.5
2011	1.2

Figure 23. Total dredge volume (million cubic yards) in Grays Harbor estuary by year.

The Dredge Impact Model computes number of crabs lost to the population based on dredge volume parameters and historic crab abundance and size distribution data. Total estimated loss of crabs to the natural population is diminished when measures are taken to reduce impact to the population, primarily by using the less efficient but less devastating (to crabs) clamshell dredge instead of the hopper dredge. These values are shown as credits (Figure 24). Loss minus credit gives the annual estimate of impact to the population from dredging activities in that year. Juvenile Dungeness crab production estimates were adjusted for natural mortality and converted to numbers of adult crab. The difference between these supplements to the population and annual impact is shown as net impact for each year. Cumulative impact is the running total of crab accounting, shown in red when impact was greater than production and in black when production surpassed dredging impact. The bottom line as of Spring 2012 is that based on the best dredging data we were able to obtain, the major impact of the 1990 widening and

deepening project, as well as impact of regular maintenance dredging to upkeep the larger channel has been compensated for by production of additional juvenile crabs on the shell mitigation plots.

Year	Loss	Credit	Impact	Adult 2+ Production	Net Impact	Cumulative Effect
1990	0	0	156750	1810	-154940	-154940
1991	54973	0	56457	5329	-51128	-206068
1992	60497	4758	56017	53245	-2772	-208840
1993	35758	21200	14558	730	-13828	-222669
1994	18624	0	24230	26945	2715	-219954
1995	7179	3358	8557	35957	27400	-192553
1996	15275	30019	-14744	16709	31453	-161100
1997	3611	1867	1744	4550	2806	-158295
1998	15066	11133	3933	25667	21734	-136561
1999	20100	26067	-5967	23413	29380	-107181
2000	28353	17975	11042	56379	45337	-61844
2001	18808	3339	29128	39311	10183	-51661
2002	31001	5023	32134	8147	-23987	-75647
2003	16774	10931	6445	46459	40014	-35633
2004	23849	11500	12349	22018	9669	-25964
2005	31403	8701	23474	31234	7761	-18203
2006	18589	5621	17092	45746	28654	**10451**
2007	18589	5621	17131	4578	-12553	-2102
2008	23657	11526	14096	21958	7862	**5760**
2009	32612	13533	19079	14133	-4946	**814**
2010	16427	6927	9500	15337	5837	**6651**
2011	24128	4550	19578	17226	-2352	**4299**
2012						
2013						
2014						

Figure 24. Dredging impact and comparison with production estimates, showing running total of cumulative dredging versus mitigation effect. All units are in numbers of adult crabs.

Channel deepening, planned to be undertaken in the next few years, will impose a much larger impact on the population than annual maintenance dredging and likely put the crab impact:production ratio back in the red. Since the Dredge Impact Model still relies on 1983-1986 population abundance and size class data for population impact estimates, and data from 1996-1999 trawl surveys for the outer reaches, Westport Bar to South Reach, updating crab trawl data within the estuary, especially in the inner estuary from Crossover Reach to Aberdeen would be timely and give more accurate and updated impact estimates. With many climate and ocean condition variables changing and the widespread recognition of their effect on biological populations, using 30 year old density data to estimate the impact of planned and ongoing activities on the current population requires some pretty shaky assumptions.

6. Literature Cited

Armstrong, D. A., M. Fernandez, and E. Visser. 1995. Estimated production of 0+ Dungeness crab (*Cancer magister*) in intertidal shell mitigation habitat, Grays Harbor estuary, 1990 to 1994. Final Report to the Seattle District, U.S. Army Corps of Engineers, Seattle, Washington.

Armstrong, D. A., O. O. Iribarne, P. A. Dinnel, K. A. McGraw, A. Shaffer, R. Palacios, M. Fernandez, K. L. Feldman, and G. Williams. 1992. Mitigation of Dungeness crab, *Cancer magister,* losses due to dredging by development of intertidal shell habitat: pilot studies during 1991. FRI-UW-9205, University of Washington, Seattle, 36 p.

Armstrong, D.A., C. Rooper, and D. Gunderson. 2003. Estuarine production of juvenile Dungeness crab *(Cancer magister)* and contribution to the Oregon-Washington coastal fishery. Estuaries 26:1174-1188.

Armstrong, D.A., K.A. McGraw, P.A. Dinnel, R.M. Thom, and O. Iribarne. 1991. Construction dredging impacts on Dungeness crab, *Cancer magister*, in Grays Harbor, Washington and mitigation of losses by development of intertidal shell habitat. Final Report for Seattle District, U.S. Army Corps of Engineers by the School of Fisheries, Univ. Washington, Seattle, WA. FRI-UW-9110:63 p.

Armstrong, D.A., T.C. Wainwright, J. Orensanz, P.A. Dinnel, and B.R. Dumbauld. 1987. Model of dredging impact on Dungeness crab in Grays Harbor, Washington. Final report for Batelle Laboratories and Seattle District, U.S. Army Corps of Engineers by the School of Fisheries, Univ. Washington, Seattle WA. FRI-UW-8702:167 p.

Banks, J. and P.A. Dinnel, P. A. 2000. Settlement behavior of Dungeness crab (*Cancer magister* Dana, 1852) megalopae in the presence of the shore crab, *Hemigrapsus* (Decapoda, Brachyura). Crustaceana 73(2):223-234.

Bayne, B.L. 2002. A physiological comparison between pacific oysters *Crassostrea gigas* and sydney rock oysters *Saccostrea glomerata*: food, feeding and growth in a shared estuarine habitat. *Marine Ecology Progress Series* 232:163-178.

Chavez-Villalba, J, J.C. Cochard, M. Le Pennec, J. Barret, M. Enriquez-Ciaz, and C. Caceres-Martinez. 2003. Effects of temperature and feeding regimes on gametogenesis and larval production in the oyster Crassostrea gigas. *Journal of Shellfish Research* 22(3):721-731.

Coleman, N. 1996. Potential for the establishment of wild populations and biological risk assessment of the introduction of Pacific oysters into Victoria. Marine and Freshwater Resources Institute, Department of Natural Resources and Environment, Victoria 40 pp.

Dinnel, P. A. 1996. Historical perspective of the Grays Harbor crab mitigation project. Final report to David Evans and Associates and the Seattle District, U.S. Army Corps of Engineers, Seattle, Washington. 50 p.

Dumbauld, B. R., D. A. Armstrong, and T. L. McDonald. 1993. Use of oyster shell to enhance intertidal habitat and mitigate loss of Dungeness crab (*Cancer magister*) caused by dredging. Canadian Journal of Fisheries and Aquatic Sciences 50: 381-390.

Dumbauld, B. R., E. P. Visser, D. A. Armstrong, L. Cole-Warner, K. L. Feldman, and B. E. Kauffman. 2000. Use of oyster shell to create habitat for juvenile Dungeness crab in Washington coastal estuaries: status and prospects. Journal of Shellfish Research 19(1):379-386.

Eggleston, D.B. and D.A. Armstrong. 1995. Pre- and post-settlement determinants of estuarine Dungeness crab recruitment. Ecol. Monographs 65(2):193-216.

Emmett, R.L., S.L. Stone, S.A. Hinton, and M.E. Monaco. 1991. Distribution and Abundance of Fishes and Invertebrates in West Coast Estuaries, Volume II: Species Life History Summaries. ELMR Rep. No. 8 NOAA/NOS Strategic Environmental Assessments Division, Rockville, MD.

Fabioux, C., A. Huvet, P. Le Souchu, M. Le Pennec, and S. Pouvreau. 2005. Temperature and photoperiod drive *Crassostrea gigas* reproductive internal clock. *Aquaculture* **250**:458-470.

Fernandez, M., D.A. Armstrong, and O. Iribarne. 1993. Habitat selection by young-of-the-year Dungeness crab, *Cancer magister*, and predation risk in intertidal habitats. Mar. Ecol. Prog. Series 92:171-177.

Gouletquer, P., N. Devauchelle, J. Barret, and G. Salaun. 1997. Natural reproduction cycle of the Japanese oyster *Crassostrea gigas*. La Reproduction Naturelle et Controlee des Bivalves Cultives en France, Nantes (France), 14-15 Nov 1995, IFREMER, France.

Gunderson, D.R., D.A. Armstrong, Y. Shi, and R. A. McConnaughey. 1990. Patterns of estuarine use by juvenile English sole (Parophrys vetulus) and Dungeness crab (*Cancer magister*). Estuaries 13:59-71.

Gutermuth, F.B. and D.A. Armstrong 1989. Temperature dependent metabolic response of juvenile Dungeness crab *Cancer magister* Dana: Ecological implications for estuarine and coastal populations. J. Exp. Mar. Biol. Ecol. 126:135-144.

Holsman, K.K., P.S. McDonald, D. A. Armstrong. 2006. Intertidal migration and habitat use by subadult Dungeness crab *Cancer magister* in a NE Pacific estuary. Mar. Ecol. Prog. Ser. 308:183-195.

Luckenbach, M.W., F.X. O'Beirn, and J. Taylor. 1999. An introduction to culturing oysters in Virginia, School of Marine Science, Virginia Institute of Marine Science, College of William and Mary. 24 pp.

Mann, R., Burreson, E.M., Baker, P.K. (1991). The decline of the Virginia oyster fishery in Chesapeake Bay: considerations for the introduction of a non-endemic species, *Crassostrea gigas* (Thunberg, 1793). *Journal of Shellfish Research* **10**(2):379-388.

Matthiessen, G.C. 2001. Oyster Culture. Fishing News Books, Blackwell Science Ltd., Oxford.

McGraw, K.A., L.L. Conquest, J.O. Waller, P.A. Dinnel, and D.A. Armstrong. 1988. Entrainment of Dungeness crabs, *Cancer magister* Dana, by hopper dredge in Grays Harbor, WA. J. Shell fish Res. 10(1):305.

Palacios, R. 1994. Individual growth and dynamics of living and extinct soft shell clam (*Mya arenaria*) populations in Grays Harbor (Washington), and ecological interactions with Dungeness crab (*Cancer magister*). PhD. Dissertation, School of Fisheries, Univ. Washington, Seattle, WA.

Pauley, G.B., B. Van Der Raay, and D. Troutt. 1988. Species Profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest)--Pacific oyster. U.S. Fish and Wildl. Serv. Biol. Rep. 82(11.85). U.S. Army Corps of Engineers, TR EL-82.4. 28pp.

Port of Grays Harbor Tide Tables. Reference Point, Terminal #1, Port of Grays Harbor. 111 South Wooding P.O. Box 660 Aberdeen, WA 98520.

Quayle, D.B. 1988. Pacific Oyster Culture in British Columbia: Bulletin 169. Fisheries Research Board of Canada, 196, Ottawa, Canada. 192pp.

Shatkin, G., S.E. Shumway, and R. Hawes. 1997. Considerations regarding the possible introduction of the Pacific oyster (*Crassostrea gigas*) to the Gulf of Maine: a review of global experience. *Journal of Shellfish Research* 16(2):463-477.

Visser, E. P. 2004. Grays Harbor Shell Mitigation Project: 2002 Annual Crab Production Report. Final Report to the Seattle District, U.S. Army Corps of Engineers, Seattle WA. 43pp.

Visser, E. P., and D. A. Armstrong. 1998. Grays Harbor Shell Mitigation Project Status Report: *Cancer magister* and *Hemigrapsus oregonensis* densities, modified production model, and production estimates for summer 1998. Final Report to the Army Corps of Engineers, Seattle District Office, Seattle WA. 27 pp.

Visser, E. P., P.S. McDonald and D. A. Armstrong. 2004. The impact of yellow shore crabs, *Hemigrapsus oregonensis*, on early benthic phase Dungeness crab, *Cancer magister,* in intertidal oyster shell mitigation habitat. Estuaries 27(4):699-715.

Visser, E.P. 1997. Competition, cannibalism, and prey limitation: Factors compromising the effectiveness of shell habitat mitigation for early benthic phase *Cancer magister* in Grays Harbor, WA. PhD. Dissertation, Univ. Washington, Seattle, WA. 116 p.

Wainwright, T. C., D. A. Armstrong, P. A. Dinnel, J. M. Orensanz and K. A. McGraw. 1992. Predicting effects of dredging on a crab population: An equivalent adult loss approach. Fishery Bulletin U.S. 90: 171-182.

Wainwright, T.C. and D.A. Armstrong. 1993. Growth patterns in the Dungeness crab (*Cancer magister* Dana): Synthesis of data and comparison of models. J. Crustacean Biol. 13(1): 36-50.