Grays Harbor Shell Mitigation Project

2009 Annual Dungeness Crab Production

REPORT
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Executive Summary

Crab production for summer 2009 of 0.68 ± 0.23 million J4 juvenile Dungeness crab production units was below the average annual production on old shell habitat of 0.81 million J4s. Total cumulative production of mitigation efforts over the 20-year project history is now up to 29.2 ± 6.9 million Dungeness crabs. Peak megalopal influx into Grays Harbor was before May 2009 sampling efforts commenced and thus crab densities were relatively flat over the shortened sampling period of three months. Early settlers accounted for 26% of annual production. The two 2006 plots yielded 0.33 million J4s, accounting for 49.5% of the total 2009 production.

While live oyster plots show slightly higher percent shell cover than do plots without live oysters, these differences are not statistically separable due to low sample size and inherent variability of biological population data. Efficacy of the live oyster seeding experiment thus remains questionable after the fourth sampling season. Continued monitoring will hopefully resolve this question, but sample size may be too low to expect a definitive answer. Crab utilization of the plots with and without live oysters remains indistinguishable and thus no recommendation can yet be made about live oysters as a strategy to enhance habitat longevity. Continued monitoring is necessary and fits within the context of standard annual mitigation sampling regime.

Shell placement planned for 2010 has been deferred due to budget constraints. This will be the longest stretch without new habitat construction since the inception of the mitigation project. When shell placement becomes feasible, the 1995 Island habitat is the highest priority location based on field data to date, with the 2000 East plot as a second priority location.

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1. Scope and Objectives

The dual aims of summer 2009 field efforts were again to estimate juvenile Dungeness crab production and to monitor progress of live oyster habitat with enhanced longevity and increased crab productivity per unit area as the long-term goal. Production of juvenile Dungeness crab from the intertidal mitigation plots in South Channel of Grays Harbor was estimated by conducting the excavation sampling scheme practiced in previous years. Monthly densities and size composition of 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 estimates for each functioning plot for the summer. Output of the model is J4 juvenile Dungeness crabs produced by mitigation plots each month over the summer intertidal phase of their early life history.

The duration of time oyster shell refuge habitat remains on the surface of the mudflat is a limiting factor for productivity of mitigation plots, with generally one or more years of high yield before percent shell cover decreases, requiring labor and cost intensive construction of new shell habitat to maintain juvenile crab production. Thus the experimental attempt to increase shell longevity was initiated by seeding existing empty shell habitat with 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 continues to be monitored with respect to habitat for juvenile crabs. Growth 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 U.S. 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 a head. 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, 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 "replace" crabs lost to the 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 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 (1990-2009) is 29.2 million ($\pm$ 6.9 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 generally 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 key habitat during this critical period 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 seemed to play the major role in the interaction between the populations in intertidal habitats (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 no *H. oregonensis* have been collected in South Channel excavation samples in

several years. Insufficient 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 productivity is still greatest on new shell, production per square meter on shell mitigation plots $\geq$ 1 year post-construction is much greater than before 1998, and habitat longevity questions are coming to the fore 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 is to conduct rigorous sampling to accurately assess the number of juvenile Dungeness crabs being produced by the current habitat, to optimize areas for shell placement and to monitor growth of live oysters on the 2003 Up mitigation plot as an experimental strategy for extended shell 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 is limited to temperatures within the 4-24 degrees C range as well as limited periods of desiccation or exposure to dinoflagellate blooms, their spawning success is particularly dependent on water temperature (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 standard sampling protocol used in past years continues to be followed in order to obtain juvenile *Cancer magister* and any 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 2008 summer field efforts. Then four monthly sampling series were conducted during the spring tide series early each month beginning in May. The seven plots sampled during 2008 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 they were initially constructed. 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 $\leq$ 20% shell retention on top of the mud surface before larval settlement did not remain in the sampling set for sampling efforts. Although these scantly covered plots may be contributing to juvenile crab production, their contribution relative to plots with greater habitat quality and refuge area does not merit the manpower investment to quantify their minor addition.

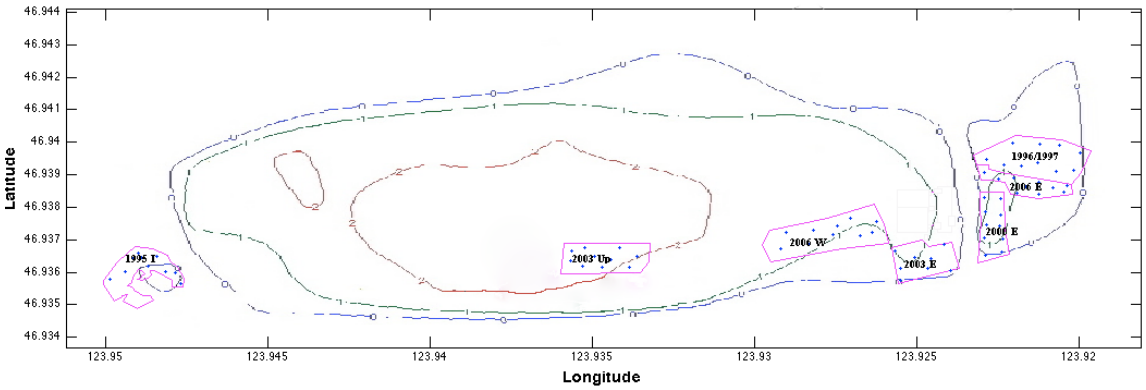

Figure 2. Map of South Channel shell mitigation site and plots sampled in summer 2009 showing tidal elevation contours and shell plot boundaries.

A sampling crew consisting of 7-8 excavation samplers and 2-4 additional shell estimators was taken to the shell mitigation plots by personnel aboard the US Army Corps of Engineers ship 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. Ten replicate excavation samples were taken monthly from each of the seven plots sampled in 2009 to obtain monthly crab density and size composition data for each plot.

Table 1. Sampling dates, approximate times, and estimated tidal heights during data collection during summer 2009 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 25	8:22AM	-2.8
May 26	9:09	-2.9
May 27	9:57	-2.6
May 28	10:46	-2.1
June 23	8:06	-3.1
June 24	8:53	-3.1
June 25	9:39	-2.7
July 22	7:47	-2.8
July 23	8:32	-2.7

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 seven plots by average percent shell cover for the individual plot. These percent shell cover estimates were taken by 4 to 6 observers visually studying each of ten fixed and marked subplots (20m x 20m) throughout each of the seven mitigation plots sampled in 2009 (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 40-60 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 (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. On plots where eelgrass beds flourish, shell placement

is therefore intentionally patchy. Percent cover estimates for eelgrass were added to the mitigation sampling scheme in recent years so that trends in eelgrass coverage can be tracked. Eelgrass distribution and abundance may be correlated with enhanced sediment stability as a result of shell placement.

Eelgrass supports much lower densities of crabs than does shell habitat, and because it 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 long term dataset from mitigation efforts combined with fishery data and 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 choice of first sampling date and whether it coincides with the major 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 are much more stable relative to that of J1s and therefore J2 density works best as an input 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 plot-specific mortality function computed for that plot, 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. The mortality rates for each plot are computed each year 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, but this was not necessary for 2009 data, due to timing of larval settlement, which peaked in before May sampling efforts and 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.

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

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

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

Differences in crab usage and shell cover 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. Status of live oysters on each of the 5 test plots was monitored monthly by collecting 30 parent shells from each subplot and counting all surviving spat on each shell and measuring a sample of six spat, the largest, smallest and 4 other representative individuals. Due to fragility of oyster matrix and necessity of returning them intact to the experimental plots, oysters were measured in the field and returned immediately to the plots. Whenever detectable, orientation was maintained when replacing parent shells, so that top and bottom surfaces retained their position. Quality of habitat over time will be 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 2009 Production

The South Channel shell mitigation plots yielded 0.67 million (± 0.23 million) J4 production units during summer 2009. Of this total, 0.33 million ± 0.08 million or 49% was contributed by the two 2006 plots. Since both of these plots were overlaid over previous plots they were expected to experience enhanced sediment stability and thus long term productivity relative to plots without underlying shell. The two plots constructed in 2003 contributed 0.16 ± 0.06 million J4 production units, which represents 24% of the 2009 annual total (Figure 5, Table 2). Habitat constructed in 2000 contributed 0.05 ± 0.02 million or 7% of the annual total, while the 1996/97 habitat contributed 0.03 ± 0.02 million J4s and the 1995 habitat contributed 0.10 ± 0.06 million or 15% of total annual production.

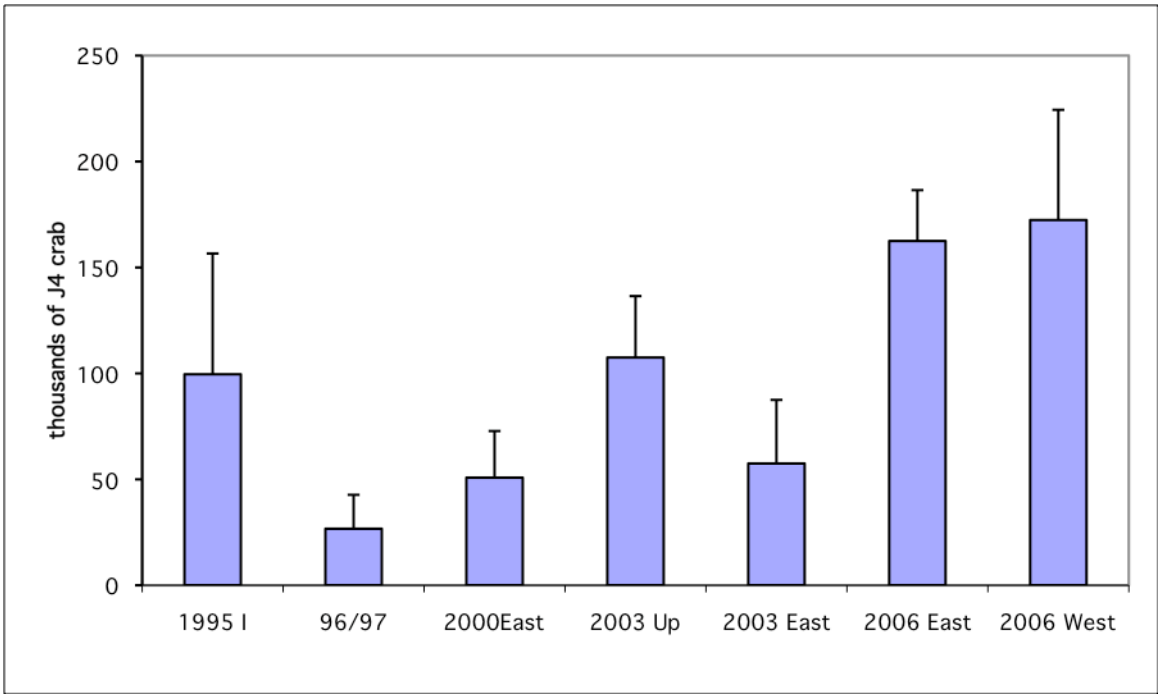

Figure 5. Summed annual production over the three-month sampling period during summer 2009 for each of the seven plots sampled this season.

Table 2. Monthly J4 Dungeness Production by plot for 2009 sampling season.

Plot	Month	Total crab density	J2 instars	st.dev.	Mortality	Plot size (m2)	Shell cover %	st.dev. %	Production	Annual prod (early set.)	st.dev.
1995 I	May	15	2	4	0.0052	19051	44	31	13974	99589	57235
	June	14	7	13	0. 0052	19051	54	37	59767	(9226)	
	July	11	2	4	0. 0052	19051	52	38	16623		
1996/1997	May	5	0	0	0.0219	30003	12	25	0	26614	16451
	June	11	6	8	0.0219	30003	18	17	15460	(7157)	
	July	5	1	3	0.0219	30003	29	25	3996		
2000EAST	May	30	4	9	0.0219	13695	29	25	7436	50587	21985
	June	9	6	7	0.0219	13695	44	33	16774	(11648)	
	July	17	7	13	0.0219	13695	33	26	14729		
2003UP	May	13	0	0	0.0219	20145	45	15	0	107053	28503
	June	26	12	13	0.0219	20145	46	12	51686	(23929)	
	July	23	8	11	0.0219	20145	42	13	31437		
2003EAST	May	16	0	0	0.0219	16126	34	25	0	57203	30103
	June	18	12	10	0.0219	16126	39	27	34931	(8086)	
	July	8	5	13	0.0219	16126	38	29	14186		
2006EAST	May	25	0	0	0.0037	12004	69	7	0	162473	23588
	June	22	10	6	0.0037	12004	85	5	89508	(47332)	
	July	20	3	5	0.0037	12004	81	8	25634		
2006WEST	May	30	0	0	0.0219	32603	44	23	0	171754	52068
	June	15	8	11	0.0219	32603	57	29	68956	(71829)	
	July	17	4	7	0.0219	32603	51	29	30969		
										675273	229934

Early settlement played a significant role in 2009 production. Dungeness crabs first detected in the 2009 samples beyond the J2 instar age/size category contributed 1.79 million J4 Dungeness crab production units to the annual total crab production. This contribution comprises 26.5% of the total and contrasts strongly with 2008 when contribution of early settlement was essentially negligible. Most of larval settlement during the 2009 season occurred before May sampling efforts, did not show a sharp peak, but was protracted throughout the summer. June typically shows the greatest percentage of annual crab productivity, and 2009 was no exception. May efforts contributed only 3.2% of the annual total. June sampling efforts contributed 516,300 juvenile crabs utilizing the shell habitat, which was 76.5% of summer production, of which 34.7% or 179, 200 were early settlers. The July sampling data contributed 137,600 juvenile crabs utilizing shell mitigation habitat or 20.4% 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 summer 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, as in 2009, the probability of negligible August contribution is higher. While many years show protracted or a late settlement pulse in July or early August, the contribution of these 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 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.

Average production per unit of refuge area for summer 2009 was 10.14 crabs per square meter of habitat (Figure 6). This is greater than the typical production rate of 6.5 for old shell habitat corrected for area; the third highest old shell production rate since mitigation efforts began 20 years ago. The patchy shell placement, particularly on the west end of the 2006 West plot did not translate into poor per meter squared production

since the 2006 plots yielded 12.5 crabs/m^2 while the 2003 plots averaged 5.3 crabs/m^2 during summer 2009. This year showed doubled production per meter squared over 2008 rates (Figure 6), even though total production was about half of 2008 yield. This is remarkable since no new shell habitat was created. All plots showed similar trends in production rates, with 2009 numbers mirroring typical patterns with the exception of the 2006 habitat, which was dramatically higher than typical old shell production rate (Figure 7). 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 eliminate the effects of early post-settlement survival.

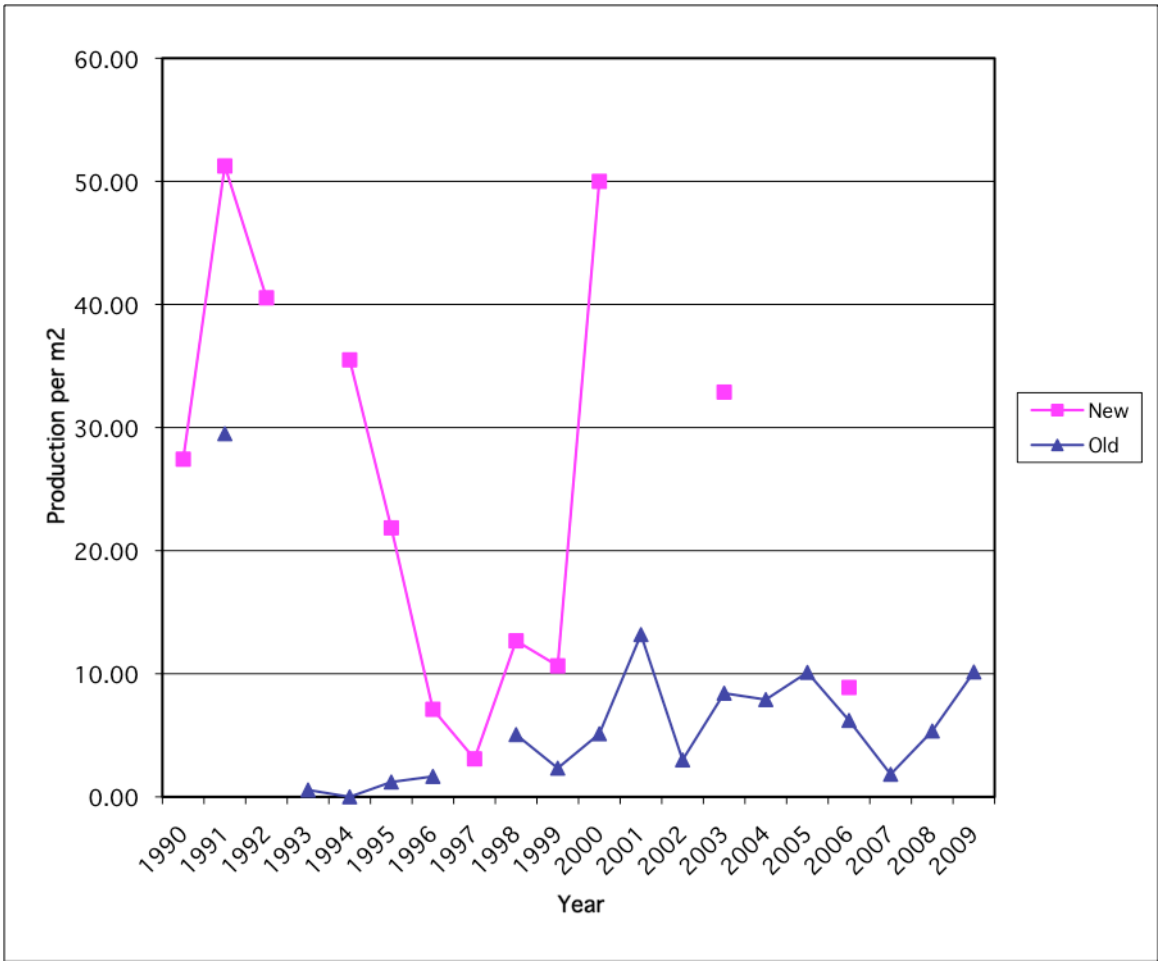

Figure 6. Total production for all years since initiation of mitigation efforts, showing contribution of new and old shell. Note high production of 'old' 1990 shell sampled in 1991, and relatively low productivity of 'new' 1996, 1997, and 2006 shell habitat.

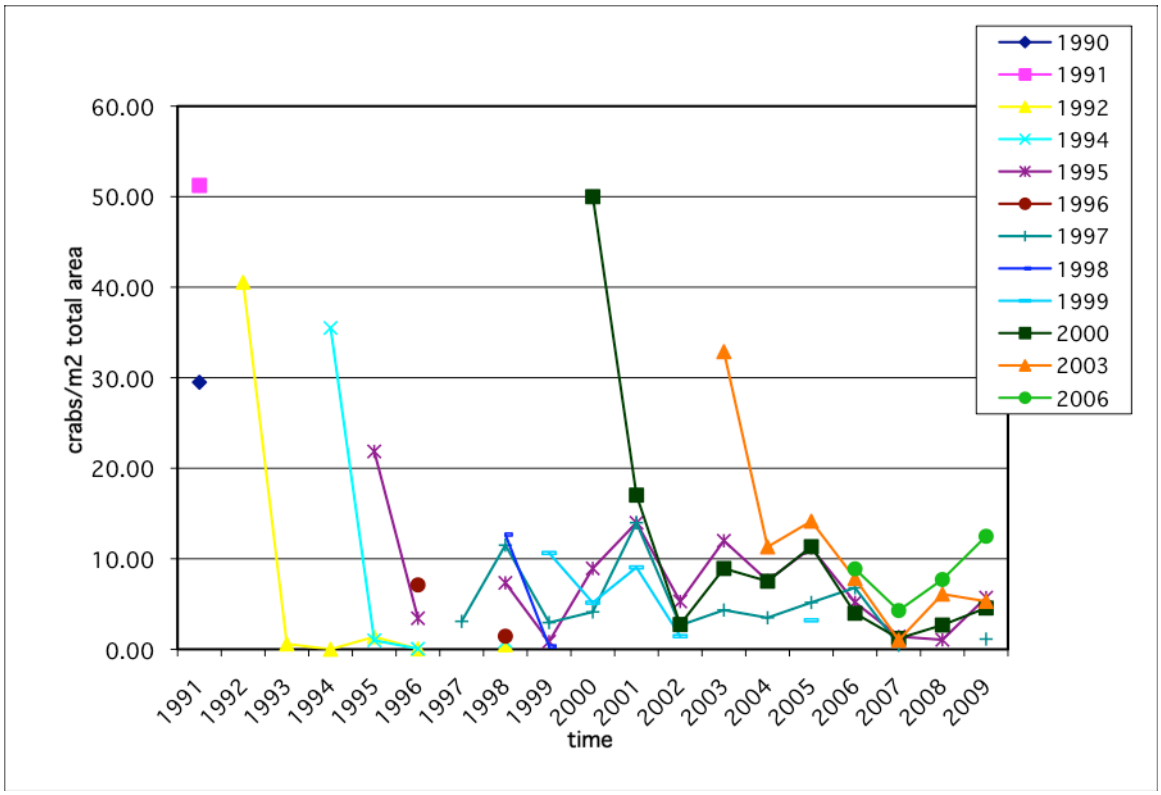

Figure 7. Historical production of J4 Dungeness crab per square meter of shell mitigation habitat created, separated by habitat. For example, the orange triangles show the average production rate of the three shell plots constructed in 2003 and sampled seven consecutive years 2003 - 2009.

Within year variation between plots shows the four plot groupings by age (2006, 2003, 2000, 1996/97 and 1995 shell) comprising respectively 31%, 25%, 20%, 21% and 13% of total area, ordered by increasing age. When scaled in this way for area, 2006 shell produced 49% of annual total on 31% of the total area sampled. Shell habitat constructed in 2003 likewise contributed 24% of crab productivity on 25% of total area sampled during 2009 field efforts. Two of the three of the older plots performed poorly, the 2000 shell producing 7% of total on 20% of total area and the 1996/97 plat producing 4% of crab production on 21% of the total shell area. 1995 habitat continues to provide good refuge, producing 15% of juvenile crabs on 13% of the total area.

4.2 Cumulative Production

Total estimated production of juvenile Dungeness crab from shell mitigation habitat is 29.2 ± 6.9 million crabs as of the end of the 2009 sampling season. The 0.68 million crab produced in summer 2009 is below the 0.81 million average yield for old shell over the 20 year project history (Figure 8), and half the average total annual production. 2009 ranked 14/20 overall and 5/8 of years when no new shell habitat was placed.

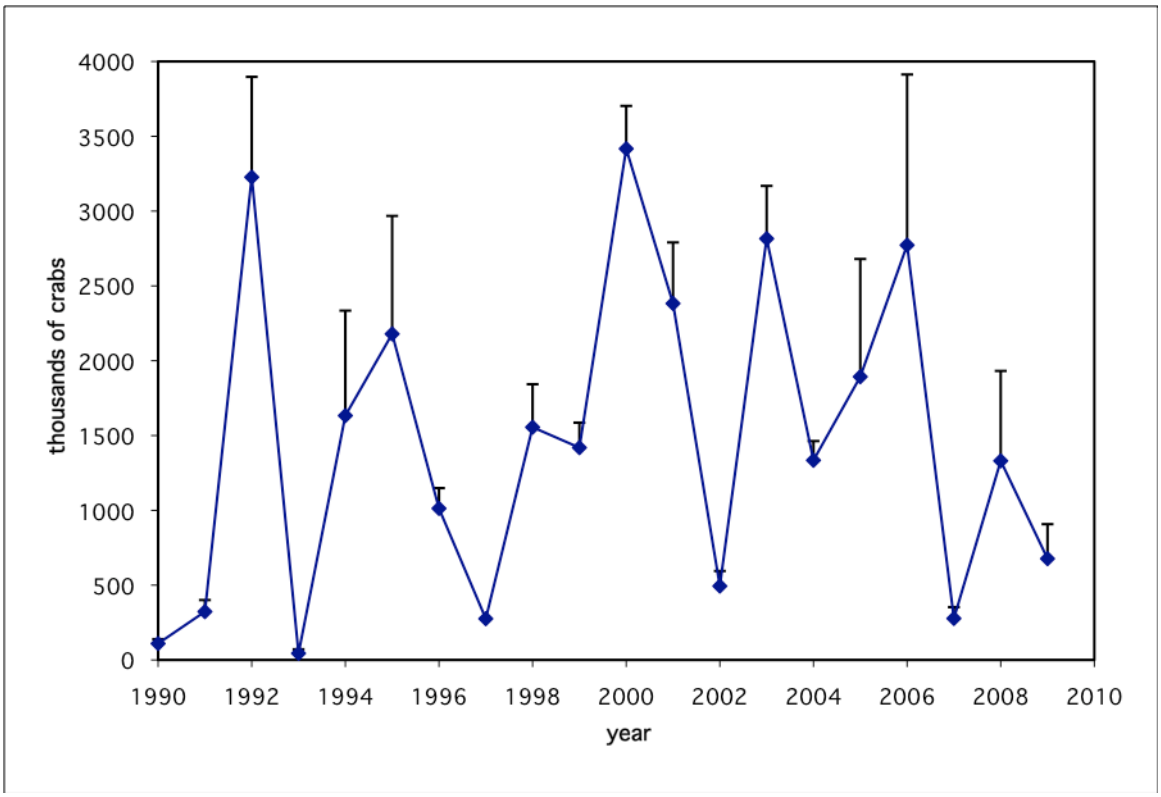

Figure 8. Historical annual yields of J4 juvenile Dungeness crabs by sampling season. Note that all plots sampled within the year are summed in this graph so that data are by year of sampling rather than the shell habitat constructed in a given year.

Of the total 29.2 million crabs produced to date (Table 3), 52.7% comes from the 12 plots constructed in their initial year (12 plot•years, or about 450 excavation samples) and 47% from all plots summed over all subsequent years sampled (119 plot•years, or

over 7000 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 9).

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	1,389,057	1,389,057	495,393
2009	N/A	675,273	675,273	229,934
Total	**15,397,650**	**13,831,891**	**29,229,539**	**6,889,313**

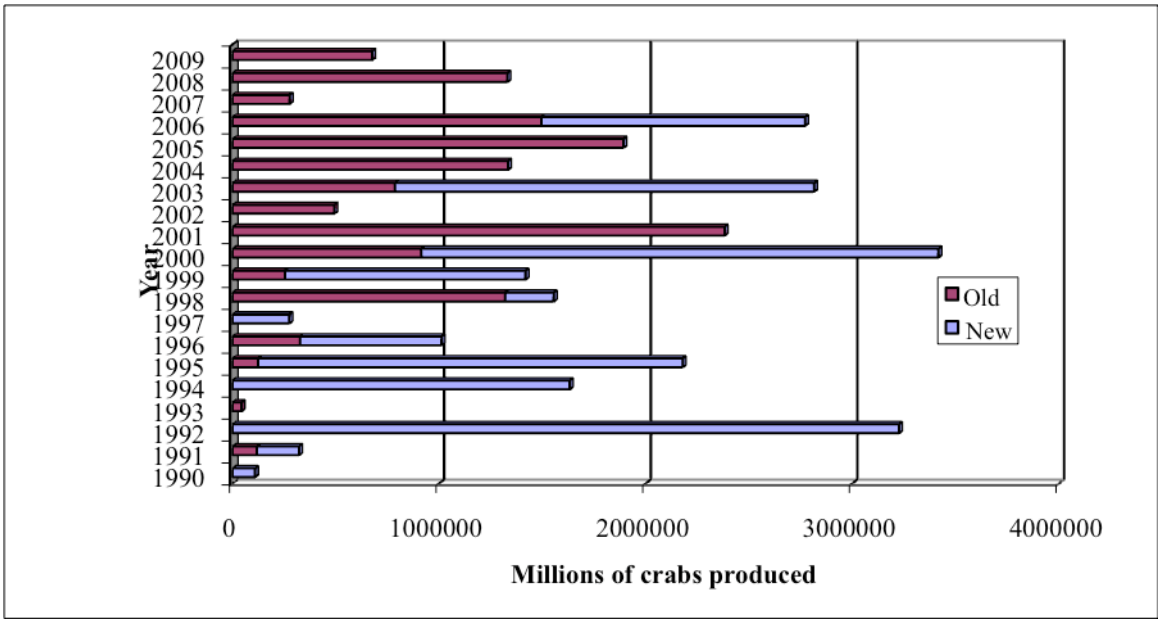

Figure 9. Historical production yields by year of sampling, separated into contribution of new and old shell habitat. No new shell habitat was created in 1993, 2001, 2002, 2004, 2005, or 2007-2009 so there are no blue colored portions of the bars for these years. Likewise, old shell was not sampled in 1992, 1994 or 1997 thus contribution of old shell cannot be quantified for these years.

4.3 Crab Density and Instar Composition

Crab density and instar composition data from all plots sampled in 2009 show classic trends of increasing size and decreasing numbers following settlement (Figures 10-16). Crabs remaining on the plots from late 2008 settlement, or recolonization can be seen in May samples on each of the seven plots. The top section of all May bars and the top two sections of the May bars on 1995 and 2006 West instar composition graphs show crabs greater than 20 mm carapace width (Figures 10-16) that could not have settled in spring 2009 and grown to that size by May 26th. Three plots show these large crabs still on the plots in June samples, the 1995, 1996/97, and 2006 East plots (Figures 10, 11, and, 15). High abundances of larger crabs in the samples from 1996/1997 plot may have contributed to poor productivity of this habitat for young of the year. An elevated mortality function would have confirmed this, but it was necessary to use the average rate due to poor significance of curve fit.

The two newest shell mitigation plots were the most productive and demonstrated the highest shell coverage (Figures 15 and 16). Percent shell coverage was a good indicator of productivity for 2009 data, with the 1995 plot and the 2003 Up plots ranking second highest in both factors, the 2000 East and 2003 East plots coming in next, and the 1996/1997 plot lowest in both factors, 20% shell cover and 4% total production.

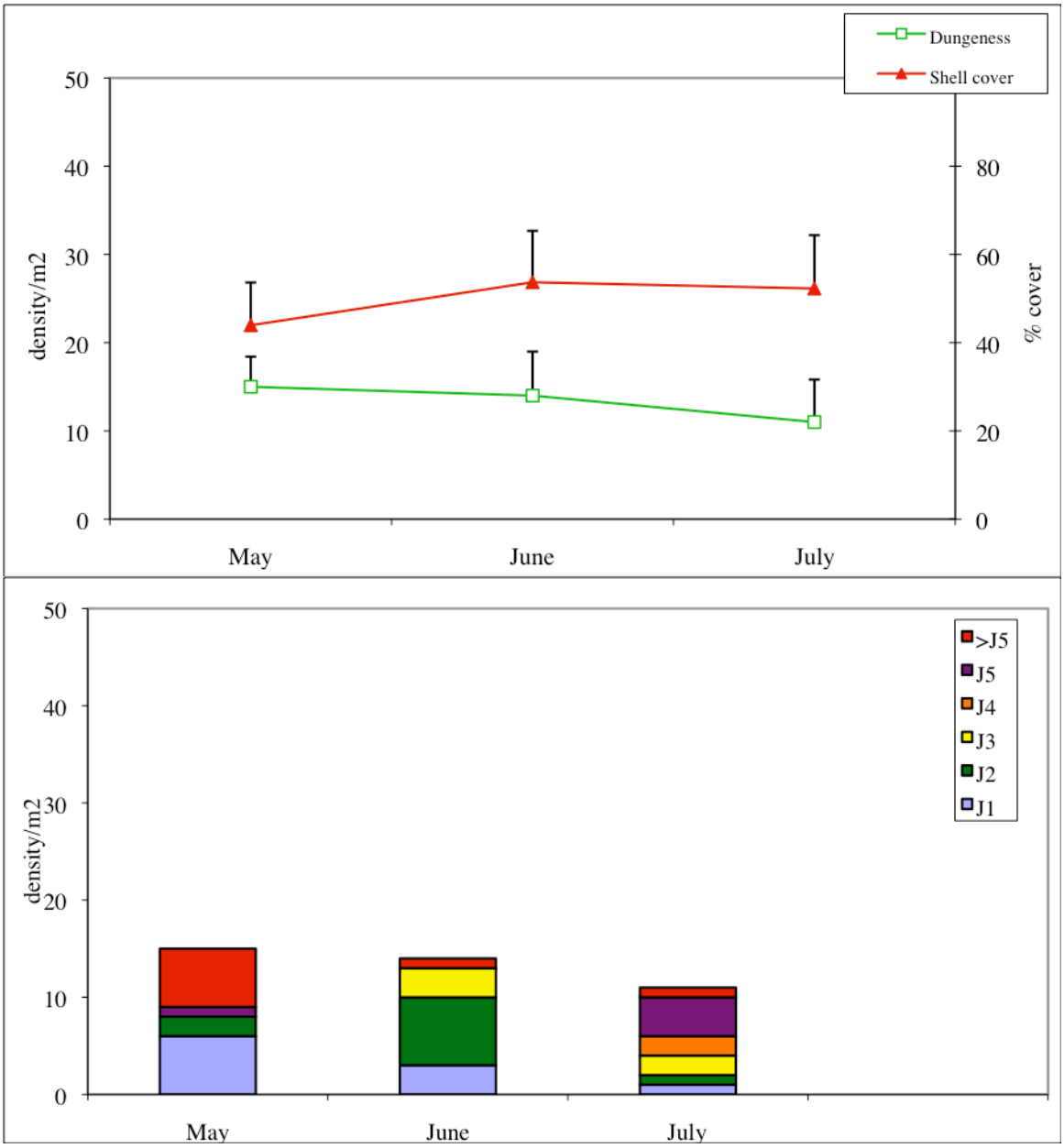

Figure 10. Summer 2009 crab data from 1995 Island plot: abundance compared with shell cover and instar size composition.

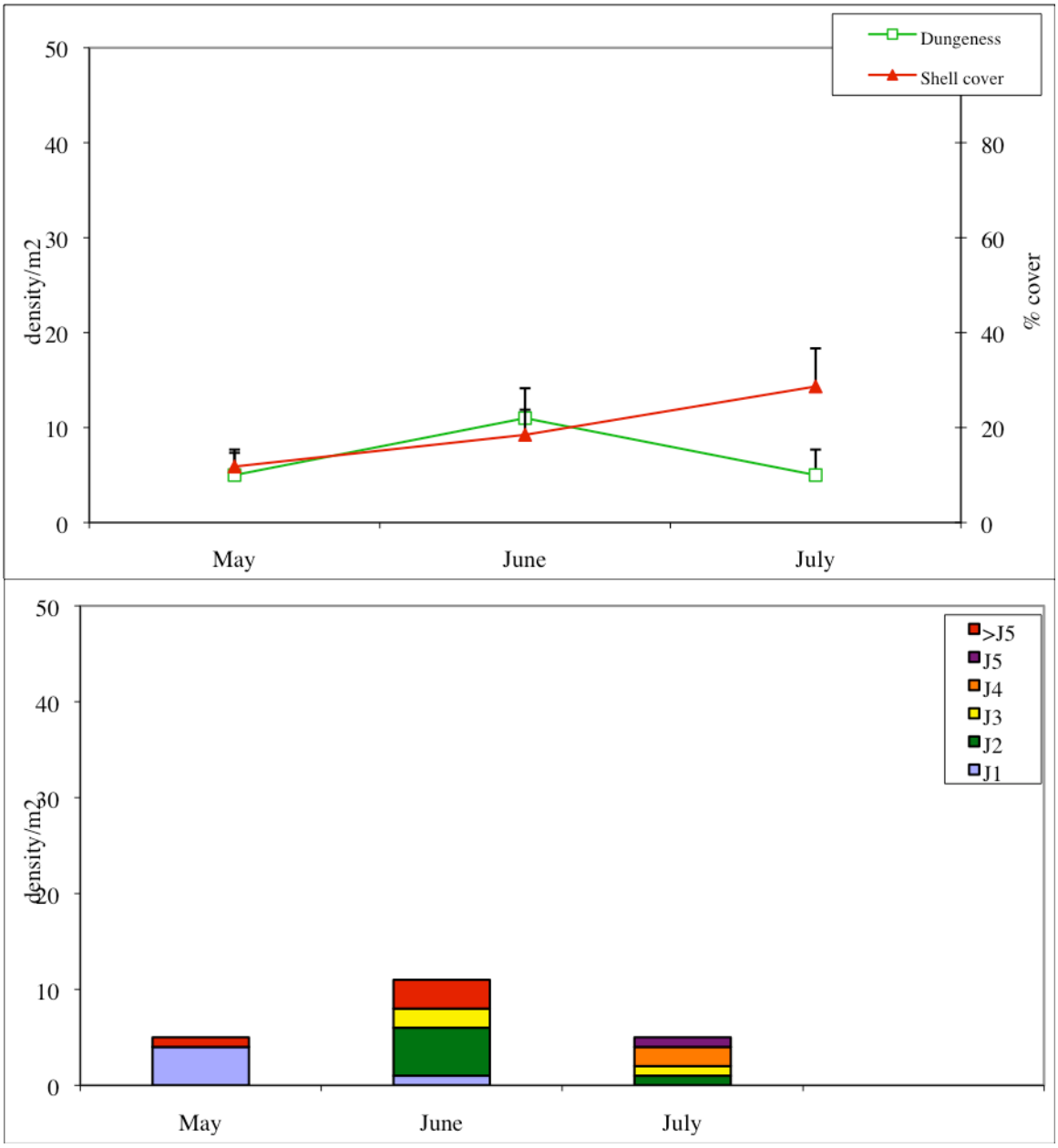

Figure 11. Summer 2009 crab data for 1996/1997 plot: abundance compared with shell cover and instar size composition.

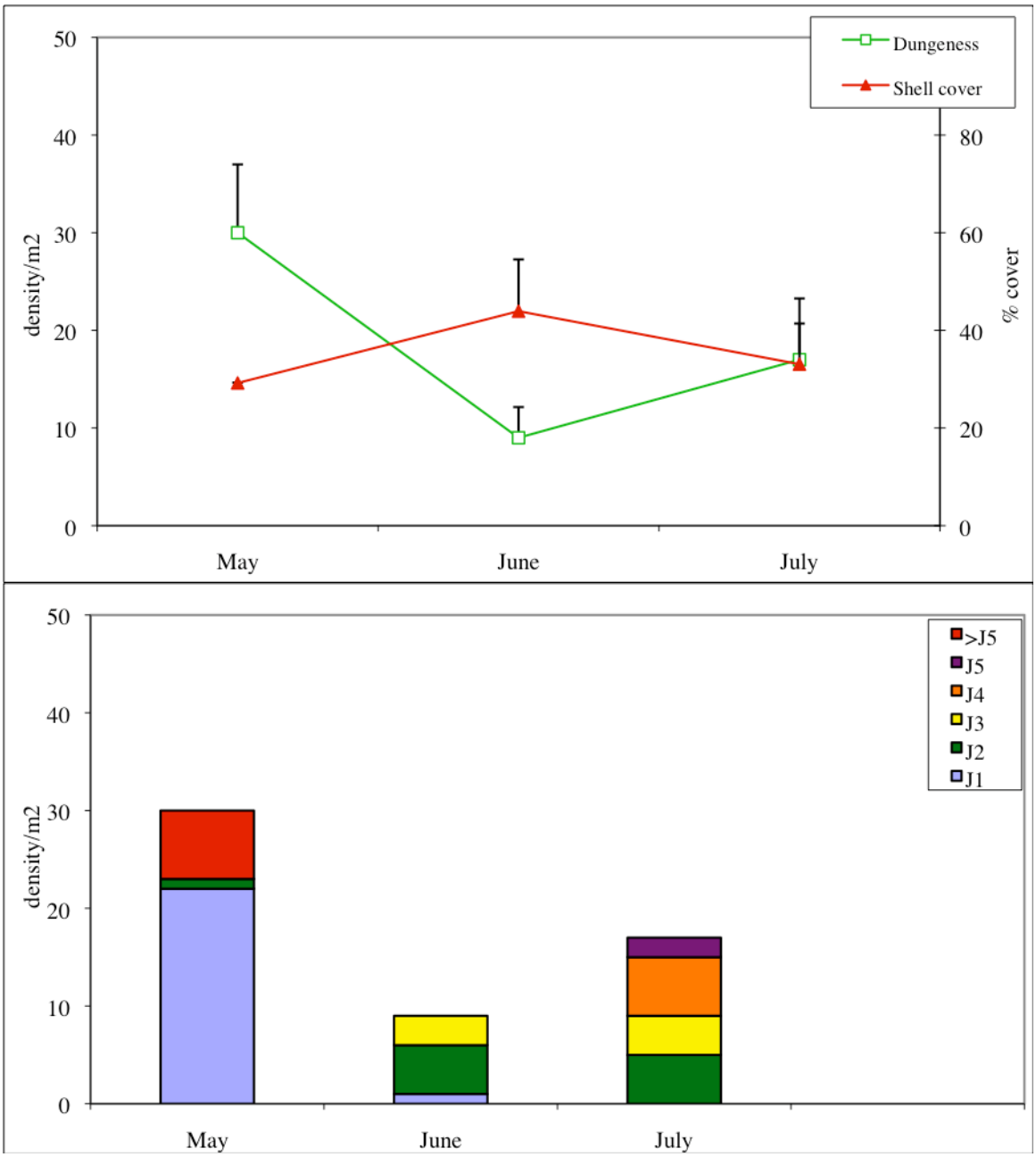

Figure 12. Summer 2009 crab data from 2000 East plot: abundance compared with shell cover and instar size composition.

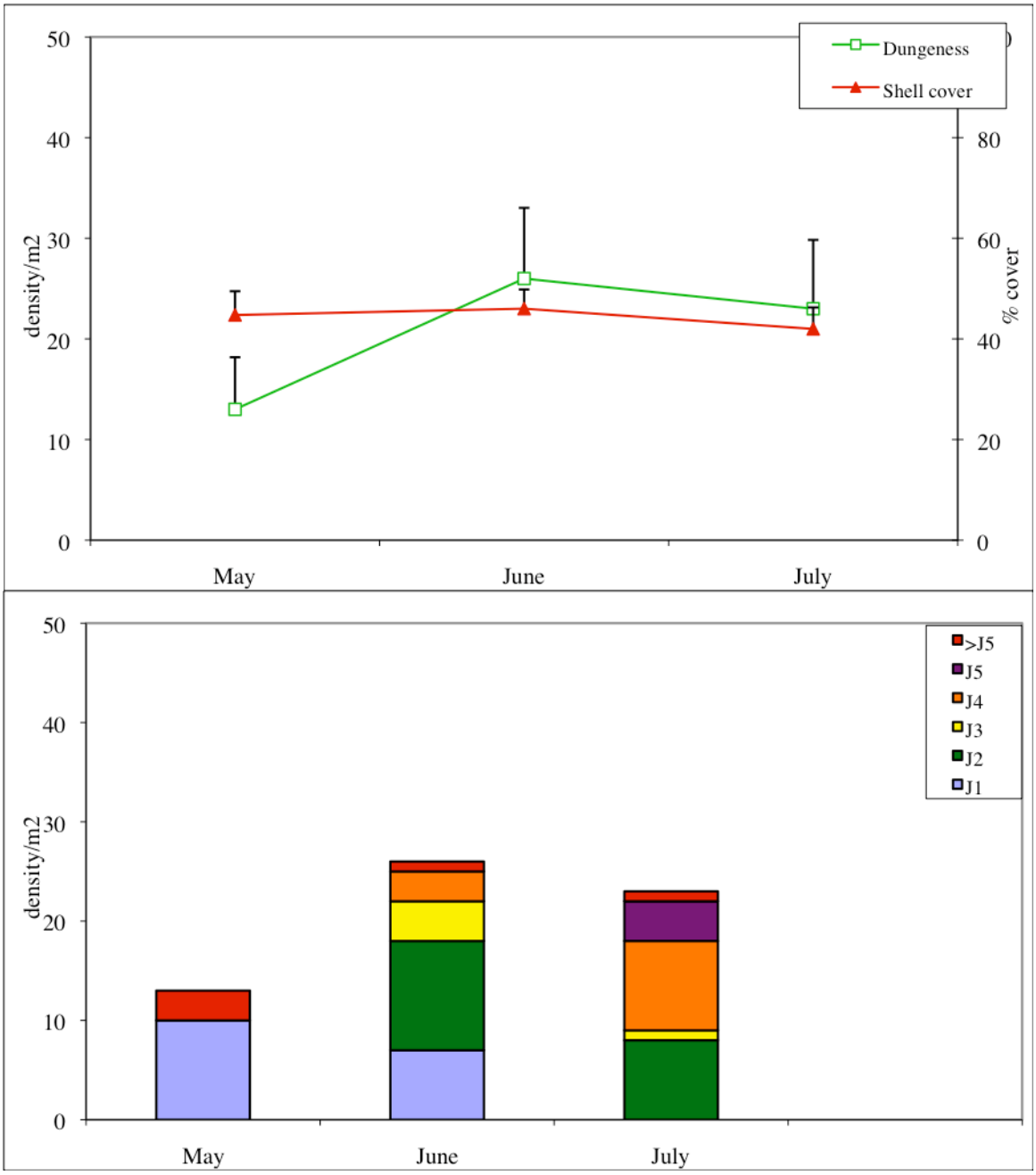

Figure 13. Summer 2009 crab data from 2003 Up plot: abundance compared with shell cover and instar size composition.

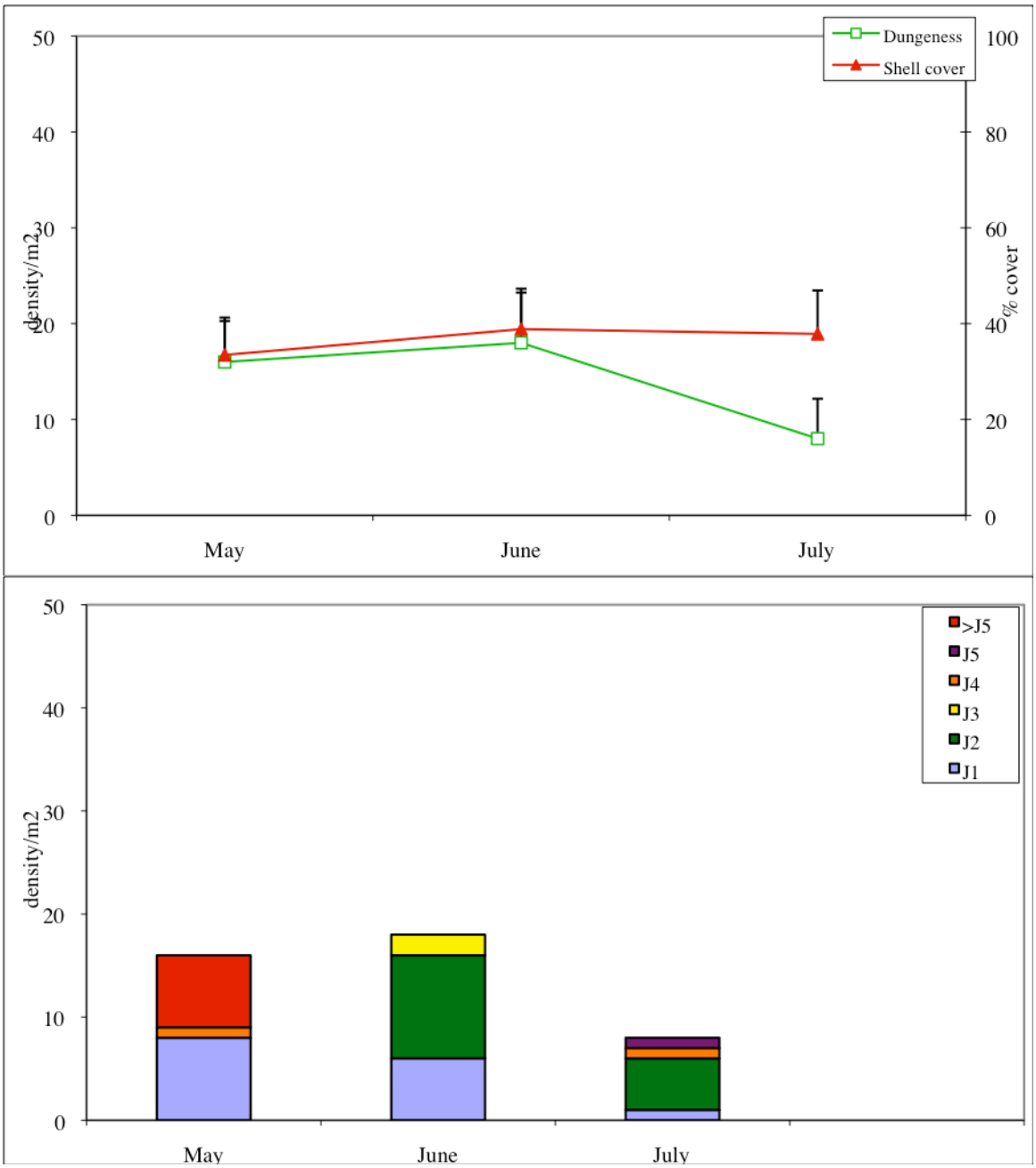

Figure 14. Summer 2009 crab data from 2003 East plot: abundance compared with shell cover and instar size composition.

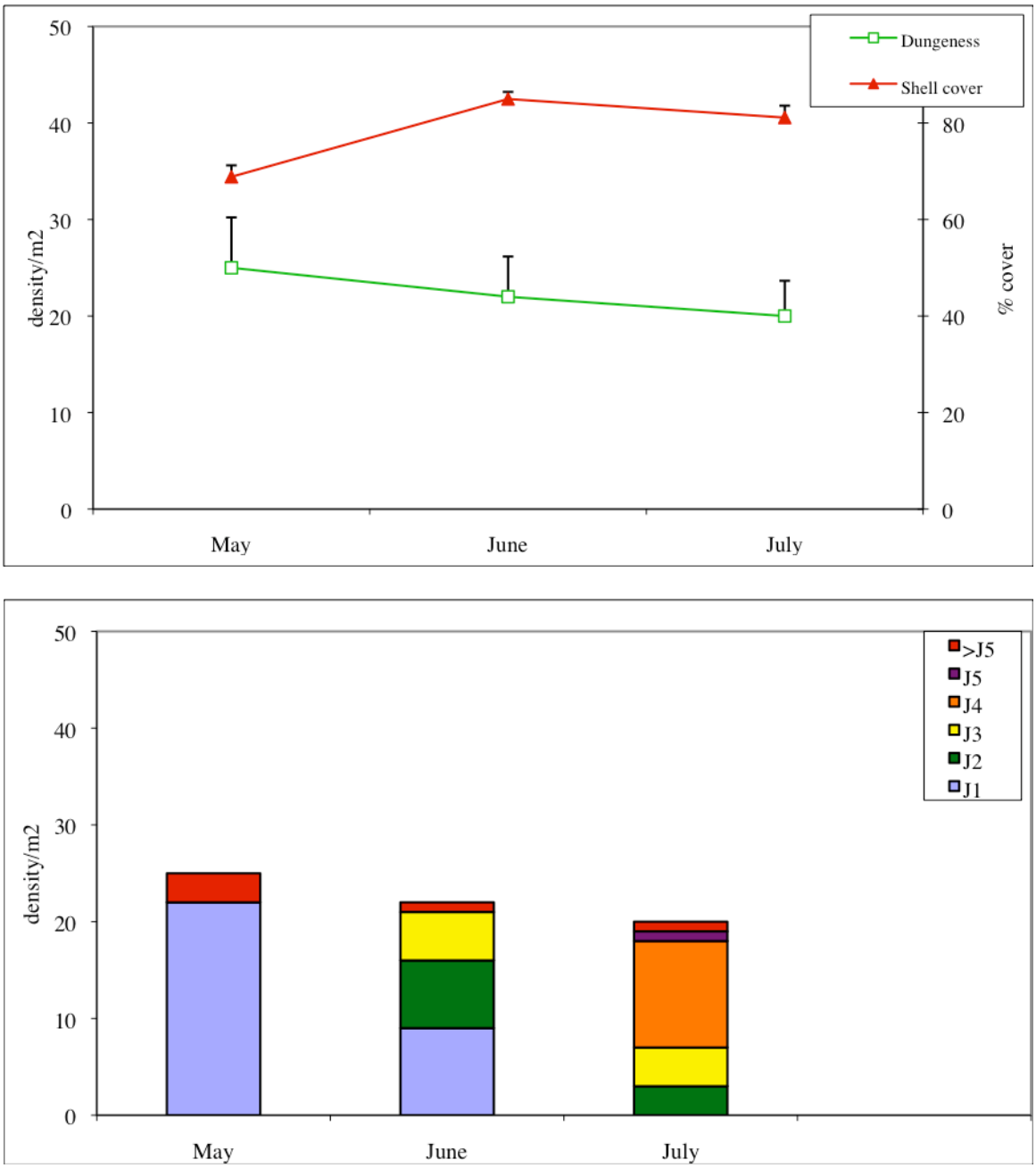

Figure 15. Summer 2009 crab data from 2006 East plot: abundance compared with shell cover and instar size composition.

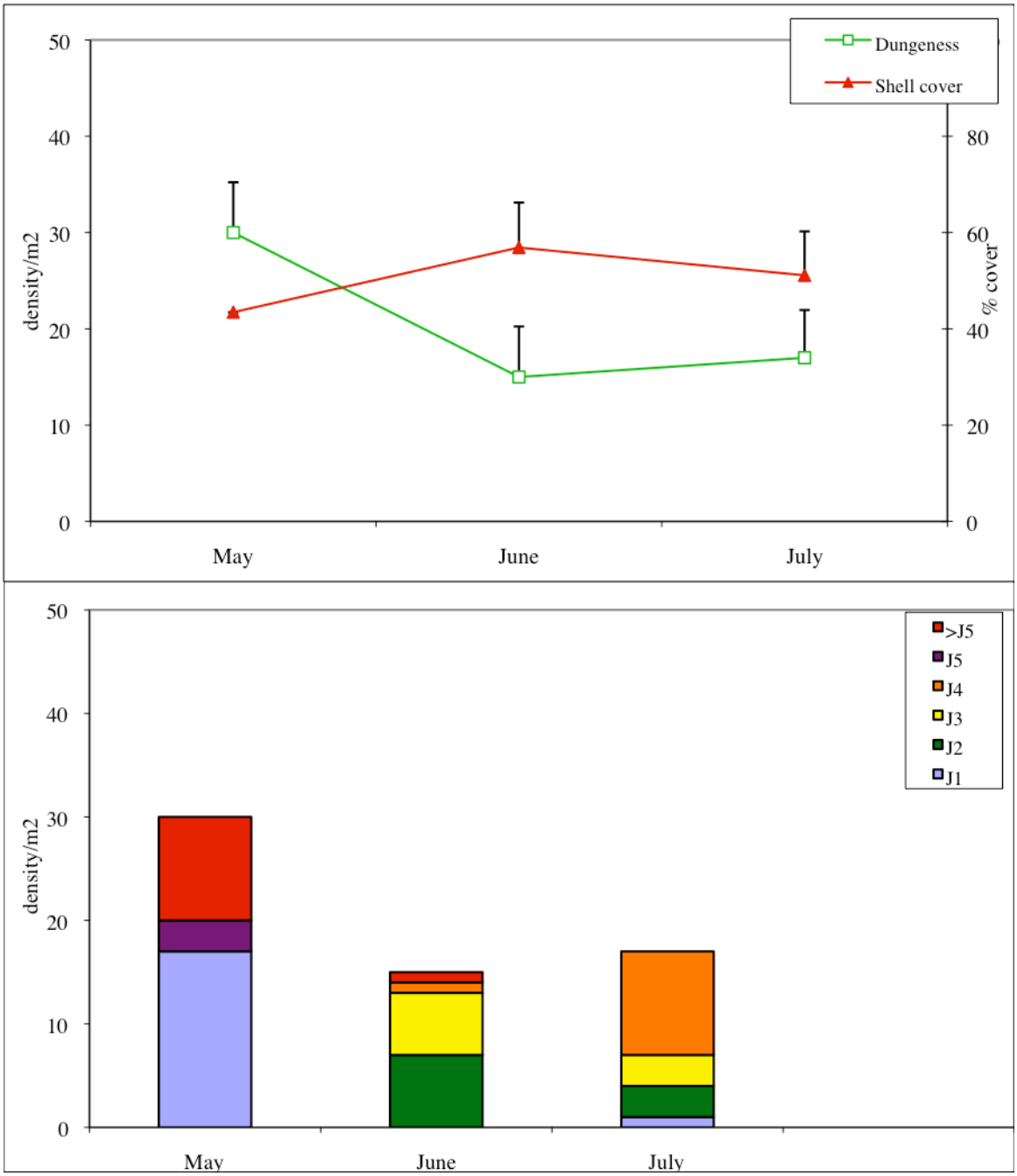

Figure 16. Summer 2009 crab data from 2006 West plot: abundance compared with shell cover and instar size composition.

4.4 Mortality

Mortality rates computed from 2009 data resulted in only two of the r^2 values for the exponential curve fits being significant. 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 except the 1995 Island and 2006 East plots instead of plot specific rates, since there was not ample justification for applying different survival rates to crab density data from each of the seven plots. While there were not enough degrees of freedom to statistically differentiate the mortality rates, crab abundances were fairly flat over summer 2009 indicating low mortality and higher than average survival on mitigation habitat.

Table 4. Mortality rates and corresponding survival rates realized by new and old shell habitat from 1990 through 2009.

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
Avg	0.0189	52	0.0217	48
SD	0.0041	7	0.0077	14

4.5 Shell and Eelgrass Cover

Shell cover relationships for all shell plots over summer 2009 were flat as well, indicating stabilized habitat (Figures 17-19). Utilization of the overlay strategy for shell placement has improved habitat longevity, and slowed sinkage of mitigation habitat is certainly a benefit of this shell placement strategy. Percent shell cover increased slightly on the 1996/1997 and 2006 East plots over the 2009 summer sampling period, possibly due to storm scour on the eastern most end of the shell mitigation site. These plots have relatively steep banks and must be affected differently than the other shell plots by proximate estuarine hydrodynamics. Eelgrass cover continues to remain relatively constant and be uncorrelated with shell cover on the scale we are measuring. The only three plots where eelgrass cover was above 1% were the 1995 Island, 1996/1997 and 2000 East plots (Figures 17 and 18). Eelgrass prevalence has decreased slightly on some plots in recent years, but no longterm trends are evident in eelgrass bed coverage of the mitigation area.

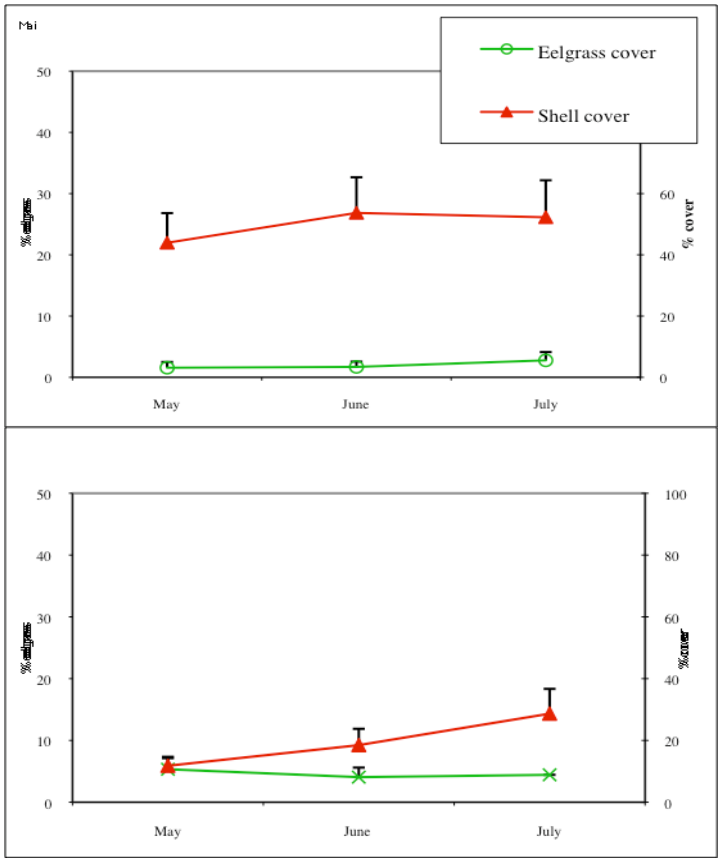

Figure 17. Oyster shell and eelgrass percent cover for the oldest two plots sampled during summer 2009: 1995 Island and 1996/1997.

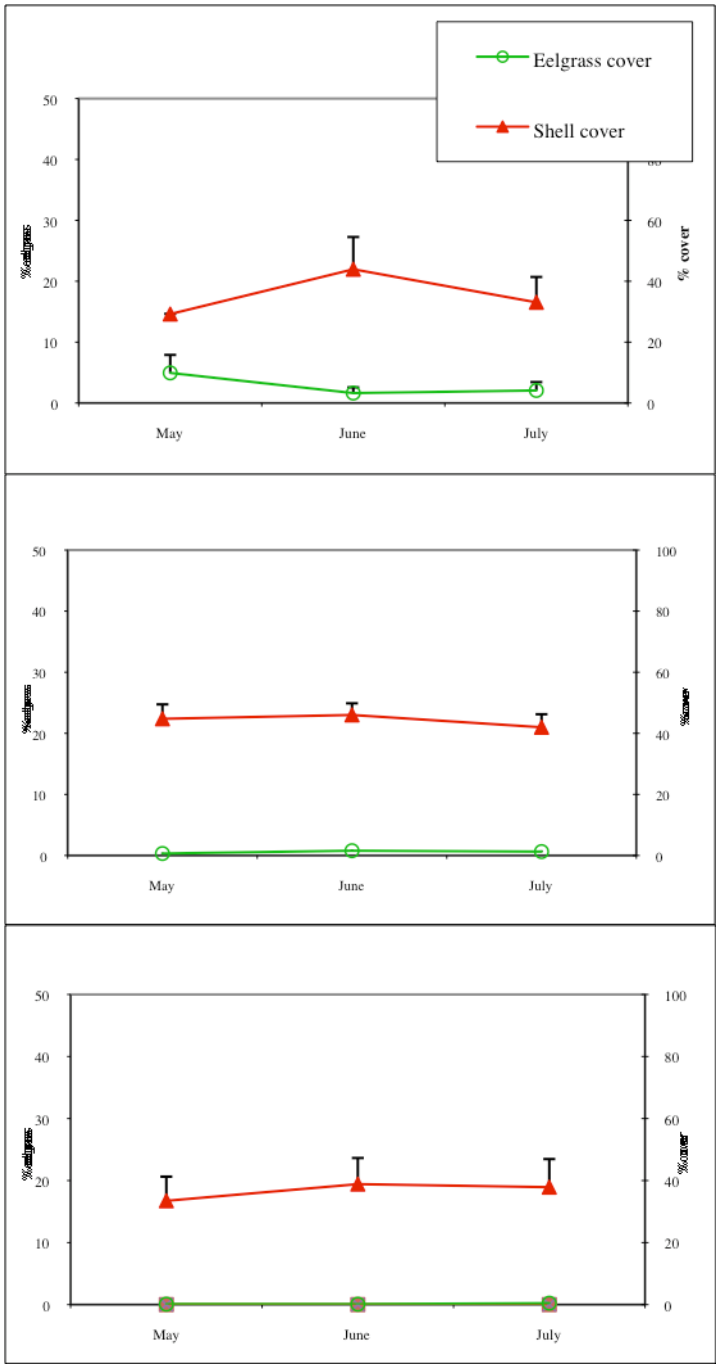

Figure 18. Oyster shell and eelgrass percent cover during summer 2009 for the 2000 East, 2003 Up, and 2003East plots.

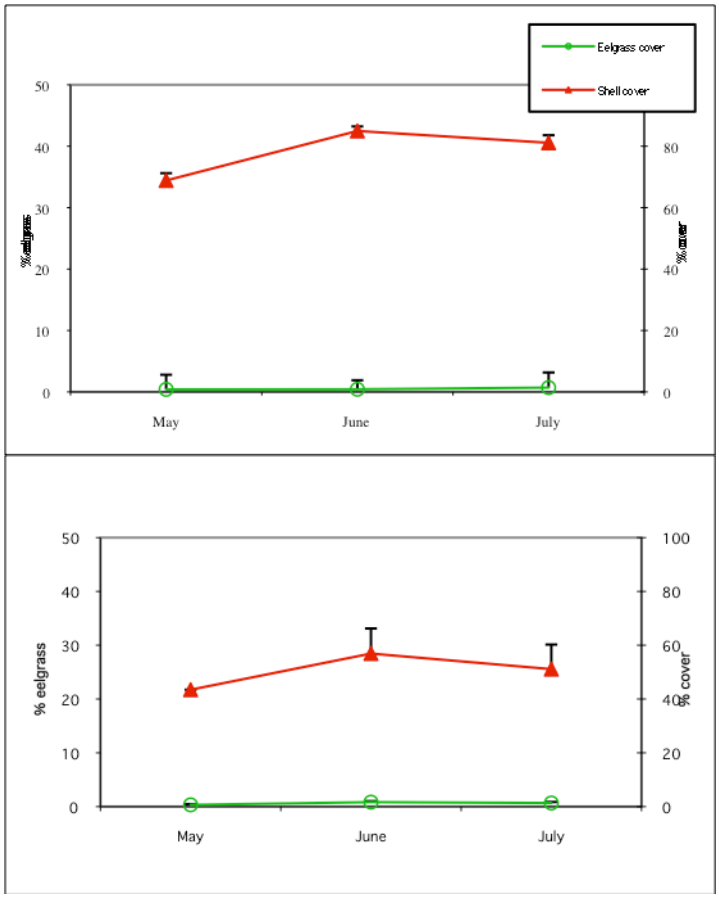

Figure 19. Oyster shell and eelgrass percent cover during summer 2009 for the two newest plots: 2006 East and 2006 West.

4.6 Live Oyster Habitat

Oyster spat planted in early spring 2006 have thrived on the South Channel shell mitigation plots. They are surviving well and showing less evidence of crowding and competition than was anticipated. Instead of overcrowding and differential growth rates leading to mortality, the clusters are breaking up in the field and individual oysters or smaller clusters continue to survive on the mudflat. Live oyster habitat is developing a three dimensionality and although oyster spat were originally evenly distributed within each experimental subplot, several of the plots have developed a patchy distribution with sections of live and inert shells.

Although greater shell cover correlates 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 were within one standard deviation of the mean (Figure 20). With only five replicates and high field variability, differences are as yet indistinguishable. 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 time and thus create a more sustainable refuge for juvenile crab.

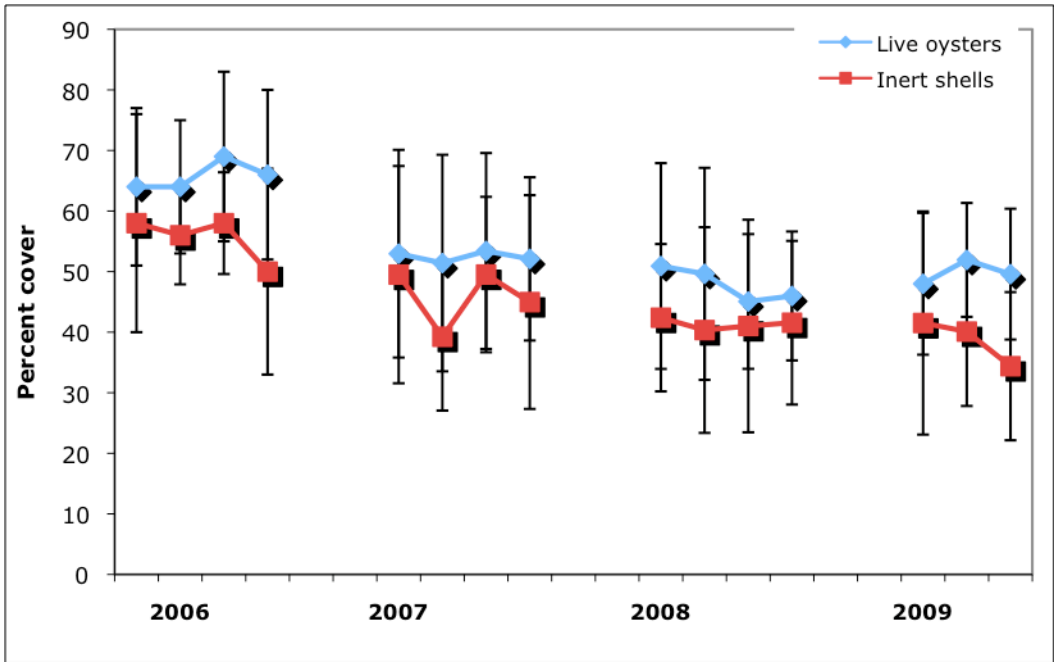

Figure 20. Percent shell cover of subplots with and without planted oyster spat over summers 2006-2009. Live oysters were planted on subplots 1,4,5,6, and 9 and subplots 2,3,7,8,and 10 were left as controls.

Crab utilization of experimental subplots shows less of a pattern than does shell cover data. 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 21). Crab utilization patterns during summer 2009 are more erratic and do not indicate any differences between

experimental and control groups. Clearly it is still too early to determine the functionality of these live oyster plots as effective juvenile crab refuge habitat, but in their fourth year there are no different from control plots.

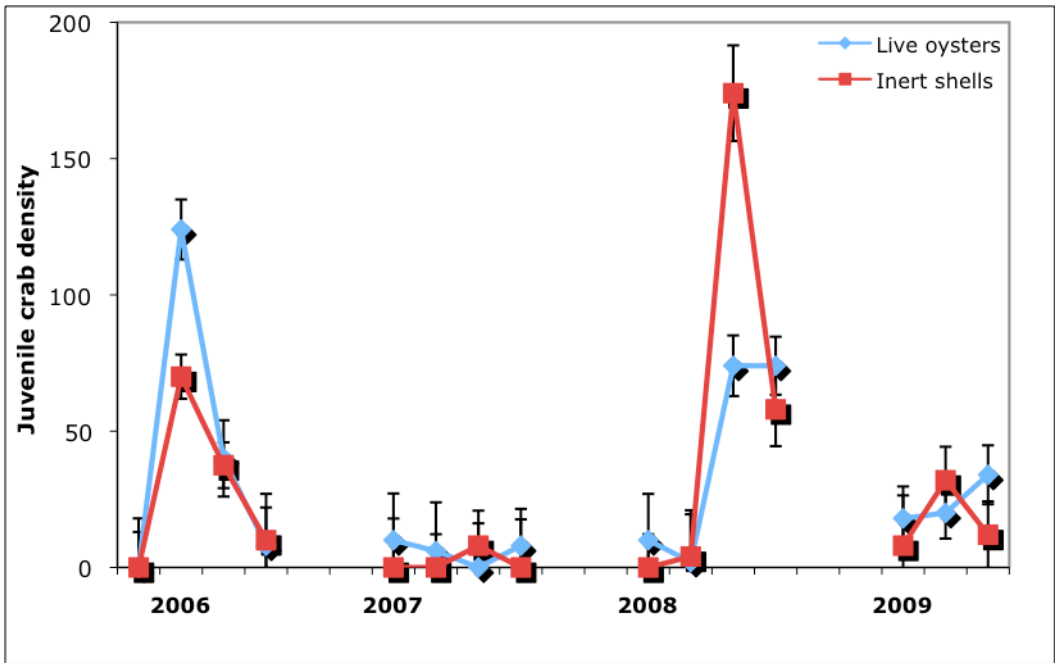

Figure 21. Juvenile Dungeness crab densities over summers 2006-2009 on experimental plots with and without live oysters.

5. Summary and Conclusions

The 2009 summer production yield of 0.68 ± 0.23 million juvenile Dungeness crab was below the average production for old shell habitat over the 20 year project history since mitigation efforts began in 1990 and cumulative production has now reached 29.2 ± 6.9 million crabs. The four highest yields were from the 2006 West, 2006 East, 2003 Up, and 1995 Island plots. The summed production from these four plots comprised 80% of the 2009 annual total crab production and 0.54 million J4 Dungeness crab. On a square meter of habitat created basis, 2009 productivity was 10.14 crabs/m^2, which is the third highest production rate on old shell habitat in 20 years, and consistent with the original

target mitigation goal of 10 crabs/ m^2.

Shell cover remained fairly constant on all plots over summer 2009, although increased slightly over the summer on the eastern most end of the mitigation area. The four highest producing shell mitigation plots were the four plots with highest shell cover (42-85%) over the mud surface. While shell cover has not been the major factor in determining productivity in recent years when larval supply has been variable, shell cover was strongly correlated with crab habitat utilization in 2009.

Megalopal influx into Grays Harbor was before May sampling events and abundance functions were fairly flat between May and July. In light of tight budget constraints and historical settlement patterns, the decision was made to drop the August sampling date for 2009. In balancing projected production results and cost of data collection, this recommendation continues for 2010 sampling strategy.

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 in the fourth year of field growth and crabs are utilizing the habitat. Differences in percent shell cover remaining on the mud surface are still indistinguishable between plots with and without live oysters due to the variation in field shell cover values and low sample size. Juvenile crab densities on the experimental versus control plots are similar with the exception of the time period of peak settlement. Crab density data for 2009 were relatively low and peak settlement was before field efforts commenced. Continued comparison between live and inert oyster habitat will help determine if this strategy should be used in the future to increase habitat longevity and improved crab production.

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