Grays Harbor Shell Mitigation Project

2008 Annual Dungeness Crab Production and Live Oyster Habitat Evaluation

FINAL REPORT
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E. P. Visser

Perkins Point Consulting
Potsdam, NY

Executive Summary

Crab production for summer 2008 of 1.3 $\pm$ 0.6 million J4 juvenile production units was good, particularly relative to 2007 poor performance due to limited larval supply. Total cumulative production of mitigation efforts over the 19 year project history is now up to 28.5 $\pm$ 6.8 million Dungeness crabs. Megalopal influx into Grays Harbor was late during summer 2008 and peak crab densities were not detected until July. Three of the shell plots yielded 77% of the annual total J4 production this summer, the newest two 2006 plots: East and West, and the 2003 Up plot. Best was the 2006 West plot which on 23% of total shell area produced 38% of the annual total number of juvenile crabs this summer.

Results of the live oyster plot experiment remain questionable as wide error bars due to low sample size and inherent variability of biological population data make differences indistinguishable after three summers. Continued monitoring will shed light and hopefully resolve this question in the next couple of summers. While live oyster plots show slightly higher percent shell cover than do plots without live oysters, these differences are not statistically different. Crab utilization of the two plot groups is similar with the exception of the months of peak settlement (June in 2006 and July in 2008). Extremely low crab abundance in 2007 did not exhibit a peak settlement period. In 2006 crabs settled in greater numbers in the experimental plots with live oysters, and in 2008 peak numbers were on the control plots without live oysters. In both cases the other three sampling months showed similar crab abundances. No recommendation can yet be made about planting live oysters on a large scale to improve shell longevity, but continued monitoring is necessary and fits within the context of typical mitigation sampling regime.

Shell placement is currently planned for 2010 and will most likely be crucial by then. The 1995 Island habitat is the highest priority placement location based on field data to date, but summer 2009 sampling efforts will confirm this and determine a second priority location.

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1. Scope and Objectives

The dual aims of summer 2008 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 our 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, placement now occurs every third year (2000, 2003, 2006). Budget constraints precluded 2009 shell placement, but 2010 has been targeted for habitat construction. Total cumulative crab production attributable to mitigation efforts to date (1990-2008) is almost 28.5 million (± 6.8 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* were collected in South Channel excavation samples during summer 2008. 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 limiting factor on 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). Their survival is limited by temperatures outside the 4-24 degrees C range, long periods of desiccation and dinoflagellate blooms, but spawning 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 who 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 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 ≤ 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.

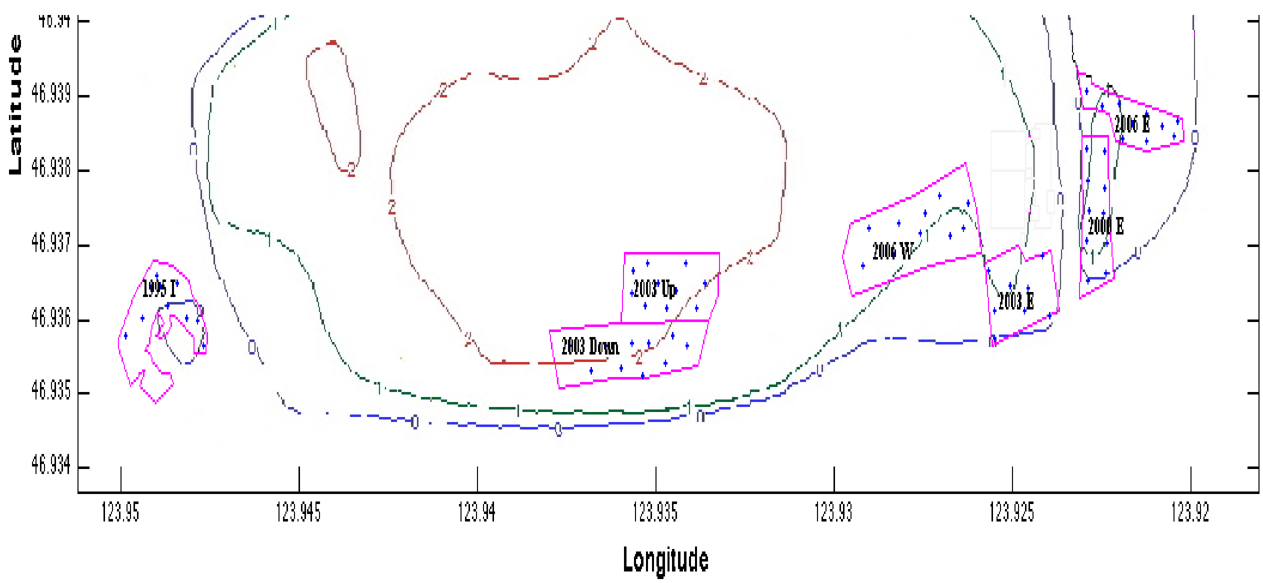

Figure 2. Map of South Channel shell mitigation site and plots sampled in summer 2008, showing tidal elevation contours and shell plot boundaries.

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 2008 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 2008 at South Channel crab mitigation sites. The initial May tide was for field site preparation, and each month's sampling was completed in three field days.

Date	Low tide time	Low tide height (ft)
May 6	8:20AM	-2.7
May 7	9:08	-2.8
May 8	9:57	-2.5
May 9	10:48	-1.9
June 4	8:05	-3.2
June 5	8:53	-3.1
June 6	9:41	-2.7
July 3	7:50	-3.0
July 4	8:37	-2.9
July 5	9:22	-2.5
August 1	7:31	-2.3
August 2	8:15	-2.1
August 3	8:56	-1.7

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. For *Hemigrapsus oregonensis*, gender and ovigery status for females was also recorded.

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.

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

2008 (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 effectively 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 2008 data, due to later timing of larval settlement, which peaked in mid June and did not show a precipitous decline after initial settlement. 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 old or new mortality rate values from past years, depending on the age of the plot with poor curve fit.

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 spat 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 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 2008 Production

The South Channel shell mitigation plots yielded almost 1.3 million (± 0.60 million) J4 production units during summer 2008. Of this total, 0.76 million + 0.32 million or 57.4% was contributed by the most recently constructed habitat, 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 three plots constructed in 2003 contributed 0.46 + 0.21 million J4 production units, which represents 34.8% of the annual total (Figure 5, Table 2). Habitat constructed in 2000 contributed 0.06 +0.04 million or 4.3% of the annual total, while 1995 habitat contributed 0.04 + 0.03 million or 3.3% of total annual production.

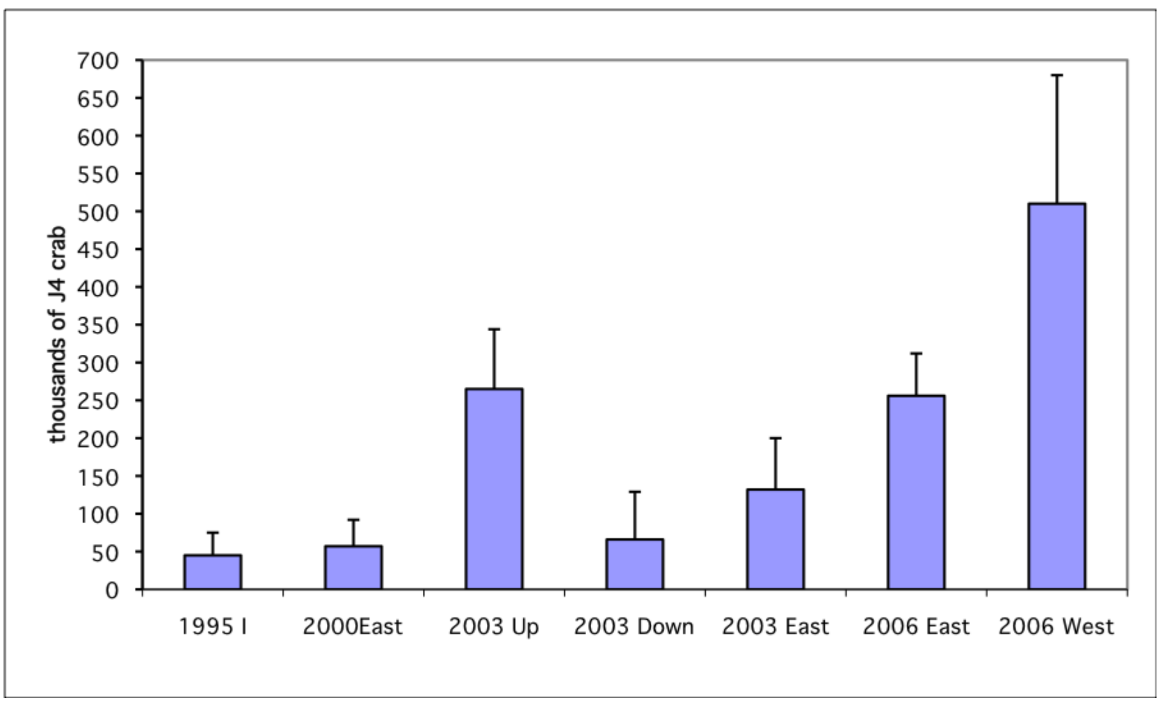

Figure 5. Summed annual production over the four month sampling period during summer 2008 for each of the eight plots sampled.

Table 2. Monthly J4 Dungeness Production by plot for 2007 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	7	0	0	0.0218	19051	50	34	0	44516	30980
	June	5	0	0	0.0218	19051	48	29	0	(0)	
	July	43	8	7.9	0.0218	19051	55	36	39173		
	August	5	1	3.2	0.0218	19051	60	39	5342		
2000EAST	May	4	0	0	0.0218	13695	20	19	0	57479	40249
	June	2	0	0	0.0218	13695	31	25	0	(0)	
	July	53	14	26	0.0218	13695	35	31	31722		
	August	21	9	8.8	0.0218	13695	45	33	25757		
2003UP	May	5	0	0	0.0218	20145	44	15	0	264990	87878
	June	3	0	0	0.0218	20145	45	17	0	(0)	
	July	124	38	26	0.0218	20145	43	14	153843		
	August	66	27	24	0.0218	20145	44	12	111147		
2003DOWN	May	0	0	0	0.0218	25422	19	18	0	66241	52742
	June	3	1	3.2	0.0218	25422	16	16	1875	(2599)	
	July	107	24	19	0.0218	25422	18	17	51137		
	August	32	5	7.1	0.0218	25422	18	17	10630		
2003EAST	May	2	0	0	0.0218	16126	31	25	0	131583	64965
	June	0	0	0	0.0218	16126	32	26	0	(20086)	
	July	139	28	19	0.0218	16126	29	21	62010		
	August	51	24	19	0.0218	16126	27	22	49487		
2006EAST	May	5	0	0	0.0218	12004	57	9	0	256286	77434
	June	3	0	0	0.0218	12004	65	12	0	(5021)	
	July	98	48	35	0.0218	12004	73	9	195329		
	August	35	13	21	0.0218	12004	77	7	55936		
2006WEST	May	3	0	0	0.0218	32603	41	23	0	509701	246728
	June	2	0	0	0.0218	32603	45	24	0	(19065)	
	July	106	39	48	0.0218	32603	48	27	282515		
	August	71	28	32	0.0218	32603	49	24	208121		
										1330796	600977

Early settlement played a relatively insignificant role this year. Dungeness crabs first detected in the 2008 samples beyond the J2 instar age/sie category contributed 46,771 J4 Dungeness crab production units to the annual total crab production. This minor contribution (3.5% of the total) contrasts strongly with 2004 when early settlement contributed 63% of annual production. Settlement during the 2008 season was late, occurring almost exclusively in late June and early July, and yet did not show a sharp peak. Vital to the issue of relative contribution of early settlement, megalopae arrived after the first sampling session, resulting in no contribution to annual production from sampling efforts in May. Thus few crabs escaped being detected by the initial sampling date and early settlers comprised an insignificant portion of the annual total. The 3.5% contribution from early settlement was from individuals that settled immediately after the June tide series, progressing through two molt intervals and being already J3s by the July sampling session, thus our sampling scheme missed them as J2 input for the growth model. June typically shows the greatest percentage of annual crab productivity, but this year not. May efforts detected no juvenile crabs utilizing the shell habitat and June sampling efforts contributed only 0.1% of summer production due to very late crab settlement. By the July sampling period, crabs had entered the estuary and sampling efforts in July contributed 862,500 J4 crabs or 64.8% of summer productivity. August typically produces only 2-7% of annual crab production, but for 2008 summer, August sampling yielded 35.0% of the total. As juvenile crabs are beginning to emigrate to subtidal habitat by August, having outgrown the most vulnerable phase of their life history and most stringent habitat requirements, August generally yields low productivity, but the lateness of settlement this year translated into smaller size classes by the August sampling date and continued use of the shell refuge habitat. Another consideration is that 2008 tides fell at the very beginning of each month, when intertidal conditions still more resemble summer than autumn. While many years show 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 continued recommendation to drop later August sampling dates in light of cost:benefit ratio of conducting field efforts at diminishing production return remains despite high percent contribution of 2008 August sampling efforts.

Average production per unit of refuge area for summer 2008 was 5.35 crabs per square meter of habitat (Figure 6). This is a typical production rate for old shell habitat corrected for area; greater than 8 years and less than 6 years when old shell habitat has been sampled. The patchy shell placement, particularly on the west end of the 2006 West plot did not translate into poor per meter squared production as the 2006 West plot yielded 8.1 crabs/m2 while the 2006 East plot yielded 7.3 crabs/m2 during summer 2008. This year showed a significant improvement over 2007 production per meter squared (Figure 6), and total production was almost 4.8 times that of last year even though shell habitat was another year older and no new habitat was placed. All plots showed similar trends in production rates, with 2008 numbers mirroring 2006 production rates and 2007 markedly lower for all four shell habitats sampled (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 while the most plausible explanation of 2008 relatively high production rates is attributable larval supply, we cannot eliminate the effects of early post-settlement survival.

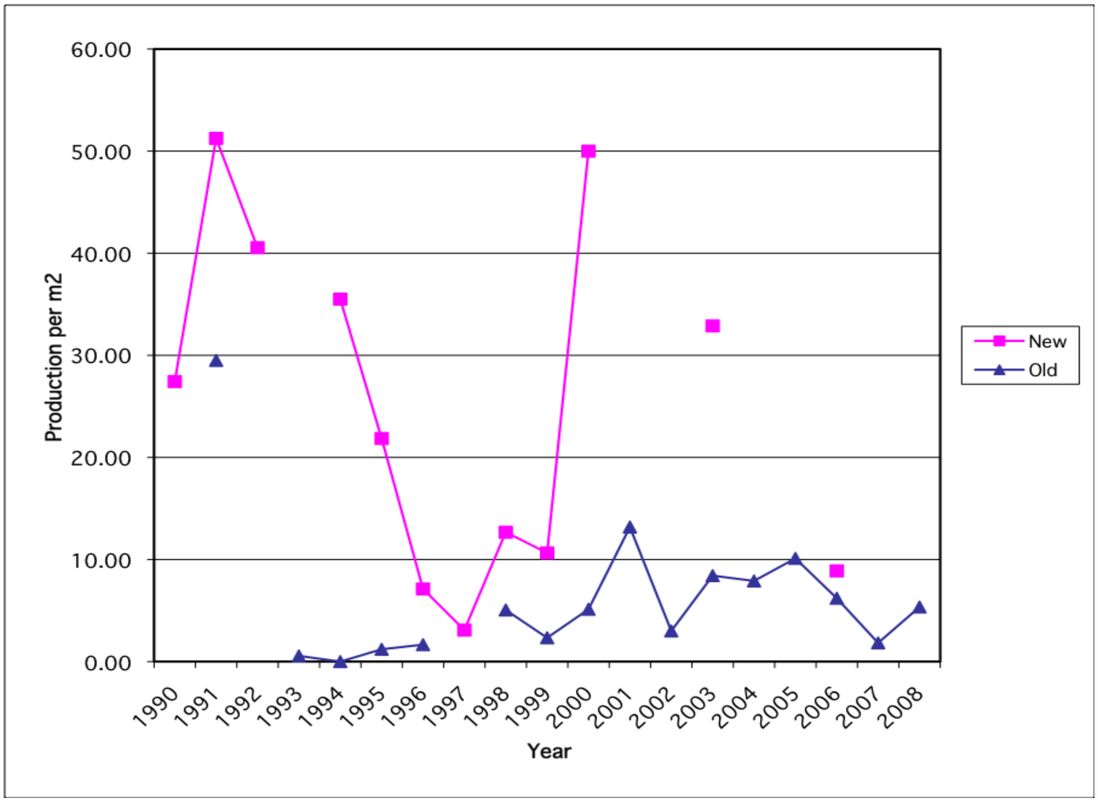

Figure 6. Total production for all years since initiation of mitigation efforts, showing contribution of new and old shell. Note high production of 'old' 1990 shell sampled in 1991, and relatively low productivity of 'new' 1996, 1997, and 2006 shell habitat.

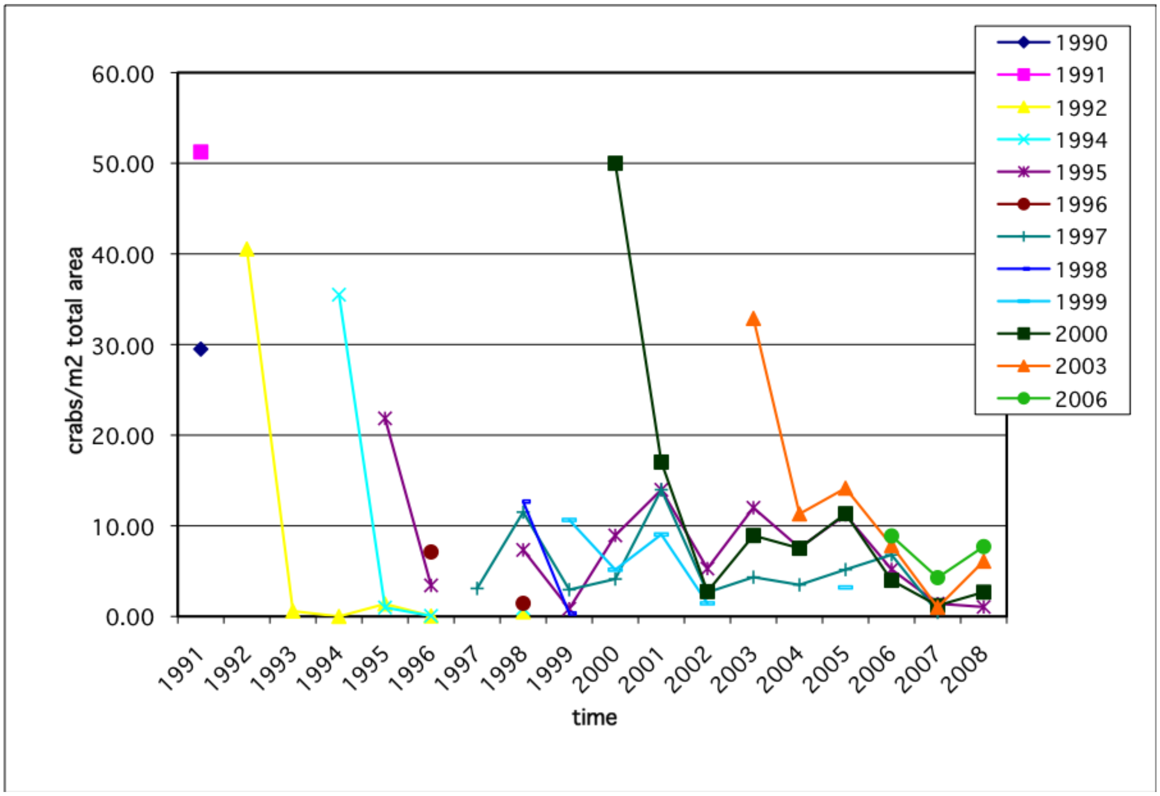

Figure 7. Historical production of J4 Dungeness crab per square meter of shell mitigation habitat created, separated by habitat. For example, the orange triangles show the average production rate of the three shell plots constructed in 2003 and sampled four consecutive years in 2003, 2004, 2005, and 2006.

Within year variation between plots shows the four plot groupings by age (2006, 2003, 2000, and 1995 shell) comprising respectively 32%, 44%, 10% and 14% of total area, ordered by increasing age. When scaled in this way for area, 2006 shell produced 57% of annual total on 32% of the total area sampled. Shell habitat constructed in 2003 likewise contributed 35% of crab productivity on 44% of total area sampled during 2008 field efforts. Both of the older plots included performed more poorly, the 1995 habitat producing 3% of juvenile crabs on 14% of the total area, and 2000 shell habitat producing 4% on 10% of the area included in sampling scheme.

4.2 Cumulative Production

Total estimated production of juvenile Dungeness crab from shell mitigation habitat is 28.5 ± 6.8 million crabs as of the end of the 2008 sampling season. The 1.33 million crab produced in summer 2008 is 1.5 times the average yield for old shell over the 19 year project history (Figure 13), but due to the high interannual variability, 2008 ranked 12/19 overall and 4/7 of years when no new shell habitat was placed.

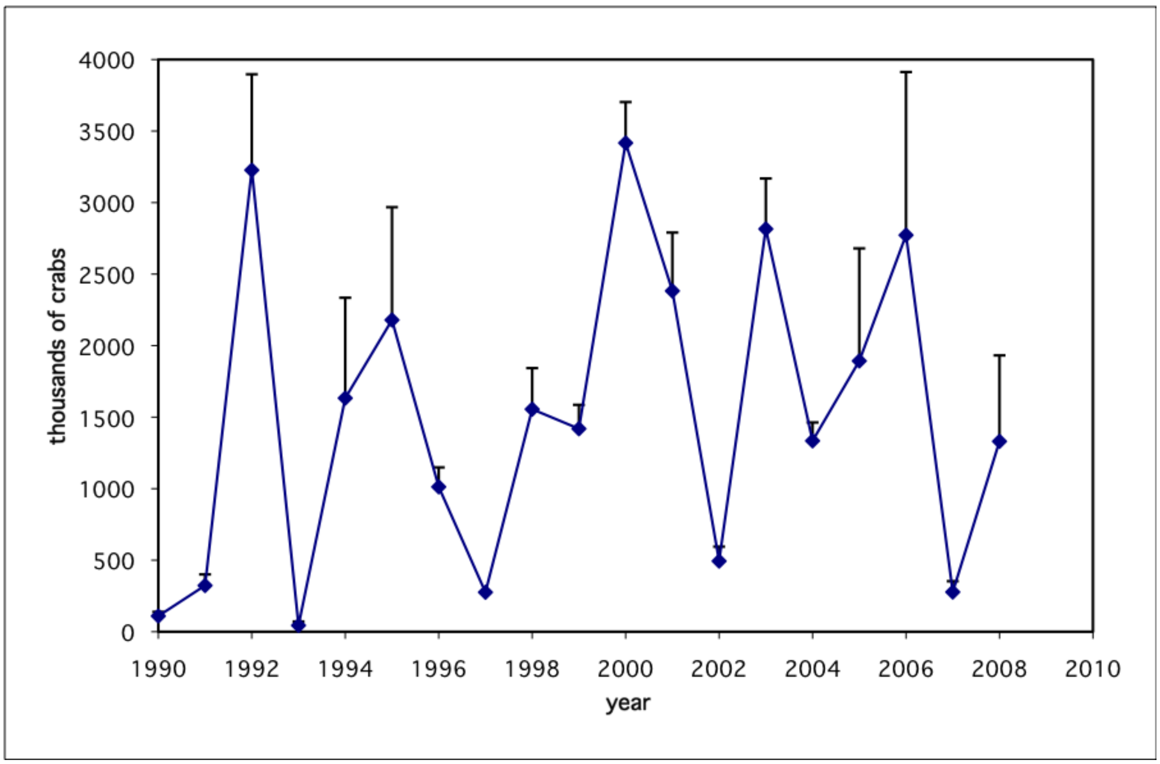

Figure 8. Historical annual yields of J4 juvenile Dungeness crabs by sampling season. Note that all plots sampled within the year are summed in this graph so that data are by year of sampling rather than the shell habitat constructed in a given year.

Of the total 28.5 million crabs produced to date (Table 3), 54% comes from the 12 plots constructed in their initial year (12 plot•years, or about 450 excavation samples) and 46% from all plots summed over all subsequent years sampled (112 plot•years, or over 6800 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	1,330,796	1,330,796	600,977
Total	**15,397,650**	**13,098,356**	**28,496,004**	**6,764,964**

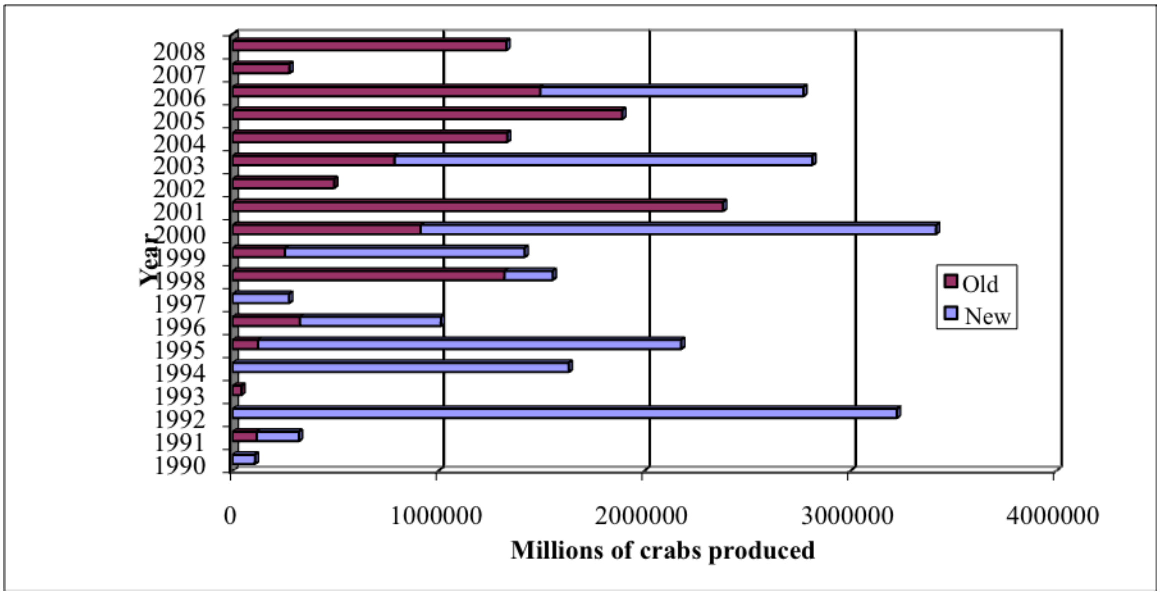

Figure 9. Historical production yields by year of sampling, separated into contribution of new and old shell habitat. No new shell habitat was created in 1993, 2001, 2002, 2004, or 2005 so there are no colored portions of the bars for these years. Likewise, old shell was not sampled in 1992 or 1994, 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 most plots show typical trends of increasing size and decreasing numbers following settlement, although with settlement this year occurring so late, the crabs are smaller by the end of the sampling season than typical (Figures 10-16). Poor oceanic conditions and associated slower developmental rates before immigration into the estuary could have been responsible for the later settlement of crab larvae in summer 2008. The sampling dates this year were very early each month, but the timing of tides alone doesn't explain the month later than average settlement. The two 2006 plots (Figures 15 and 16) stand out due to the size distribution of juvenile Dungeness crab instars utilizing these habitats in July compared to the other 4 plots (Figures 10, 11, 13 and 14), particularly the 2006 East plot with over half the crabs already molted to the J2 instar stage. Although these are the two most newly constructed plots, higher shell cover does not explain the difference in development or settlement preference since there are two other shell plots with comparable shell coverage: the 1995 and 2003 Up plots. Perhaps these are more preferable sites and the earliest recruits settle there first, with later recruits avoiding occupied habitat. All 2003 and 2006 shell plots showed similarly high crab densities in July (98-140 crabs/m^2), while the older two plots had peak densities of only 43-53 crabs/m^2. Again, the difference in crab utilization is not due to observable differences in habitat quality as the 1995 plot had the second highest percent shell coverage of all plots sampled in 2008. The shell plot data exhibited rather protracted Dungeness crab settlement, as all plots show significant numbers of the earliest instars (J1s) still migrating into the estuary in August. Two plots (2000 East and 2006 East) show low densities of J1s present already in early June, which is historically more typical timing for settlement (Figures 11 and 15), but most plots evidence no newly settled crabs until the July sampling tide.

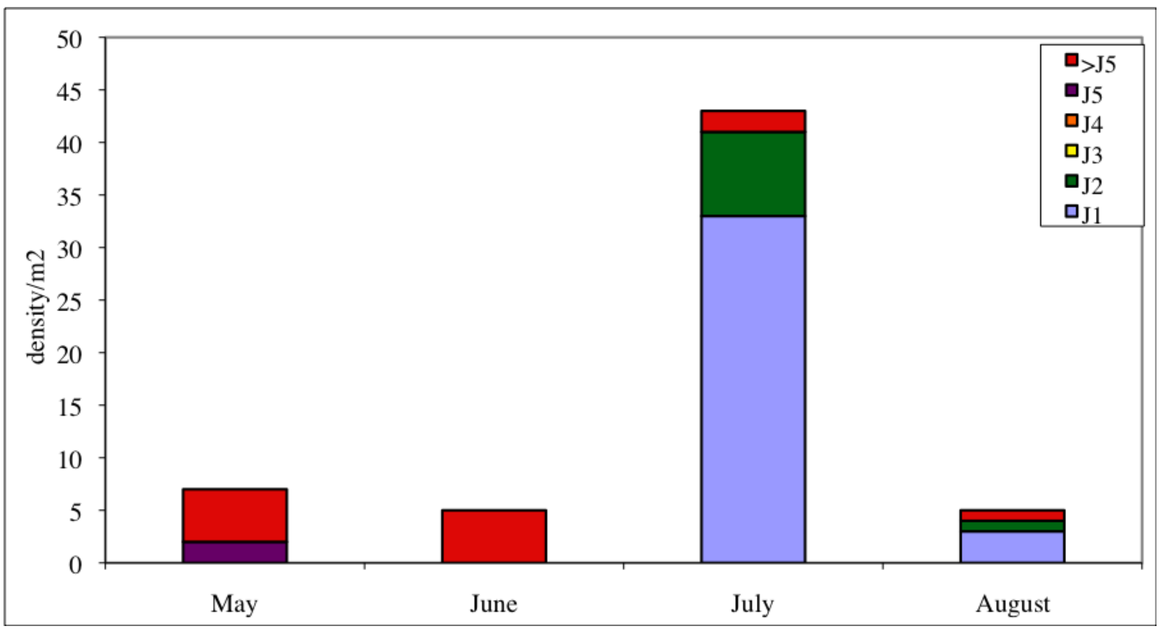

Figure 10. Summer 2008 crab data from 1995 Island plot: abundance compared to shell cover and instar size composition.

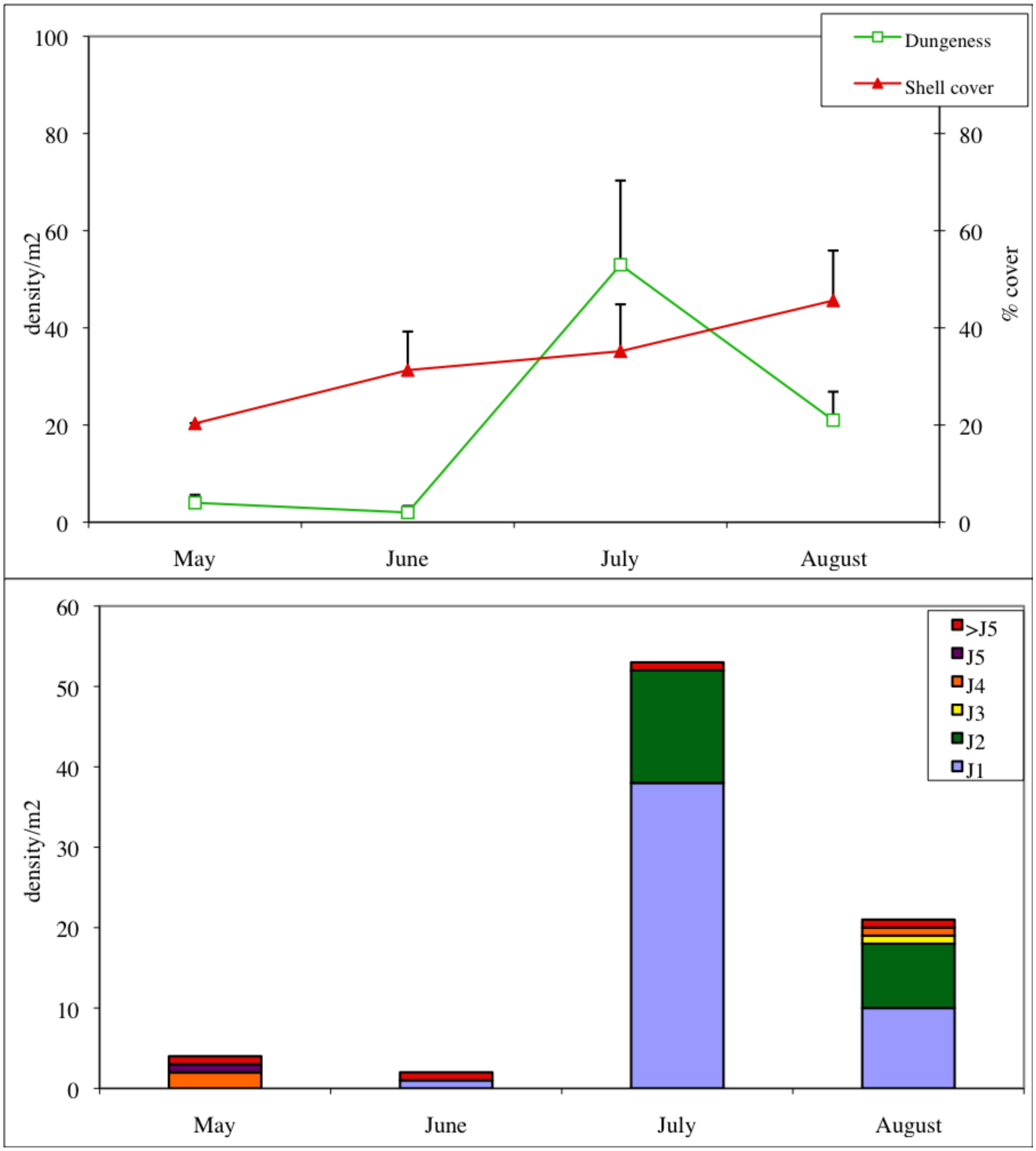

Figure 11. Summer 2008 crab data for 2000 East plot: abundance compared to shell cover and instar size composition.

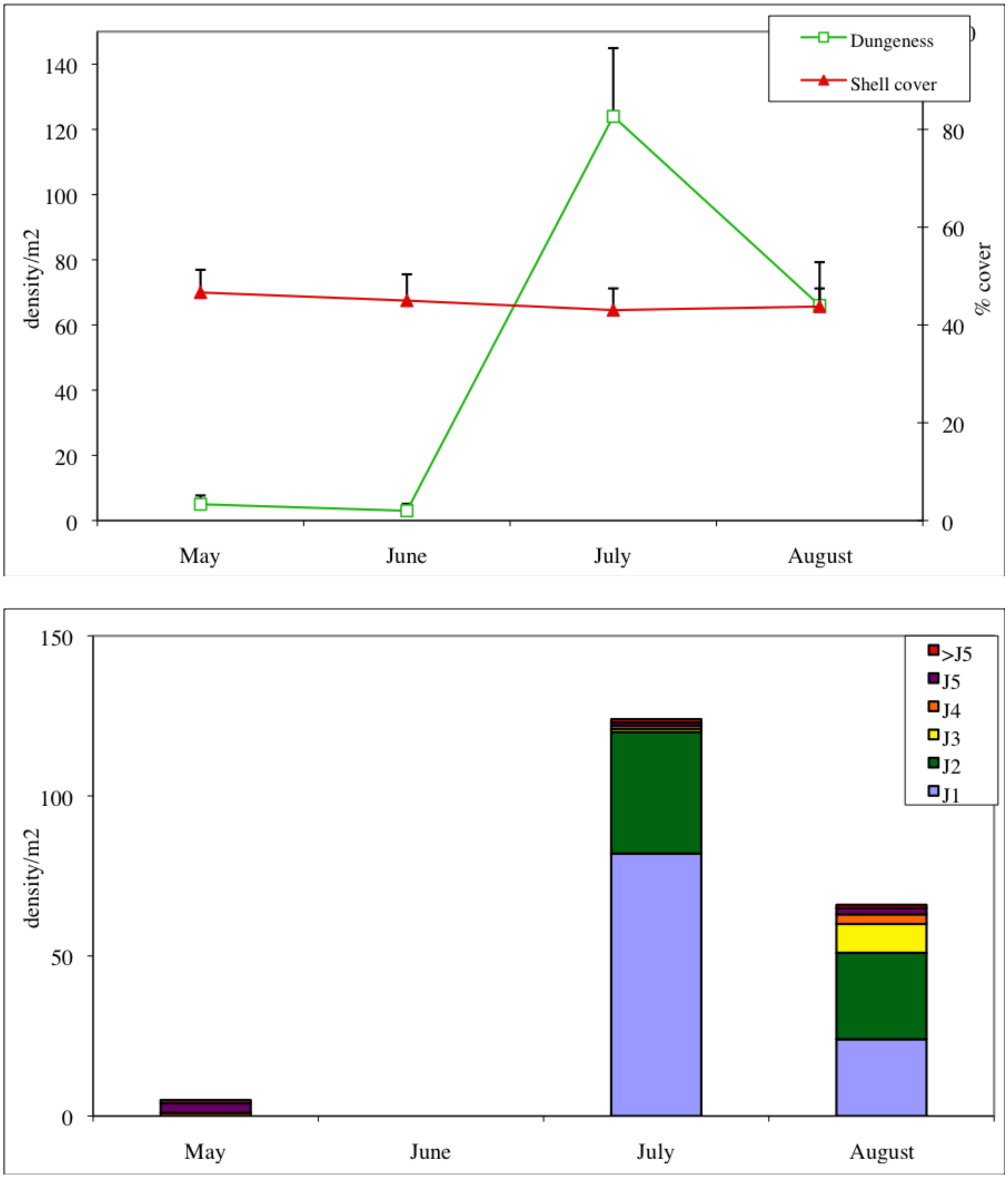

Figure 12. Summer 2008 crab data from 2003 Up plot: abundance compared to shell cover and instar size composition.

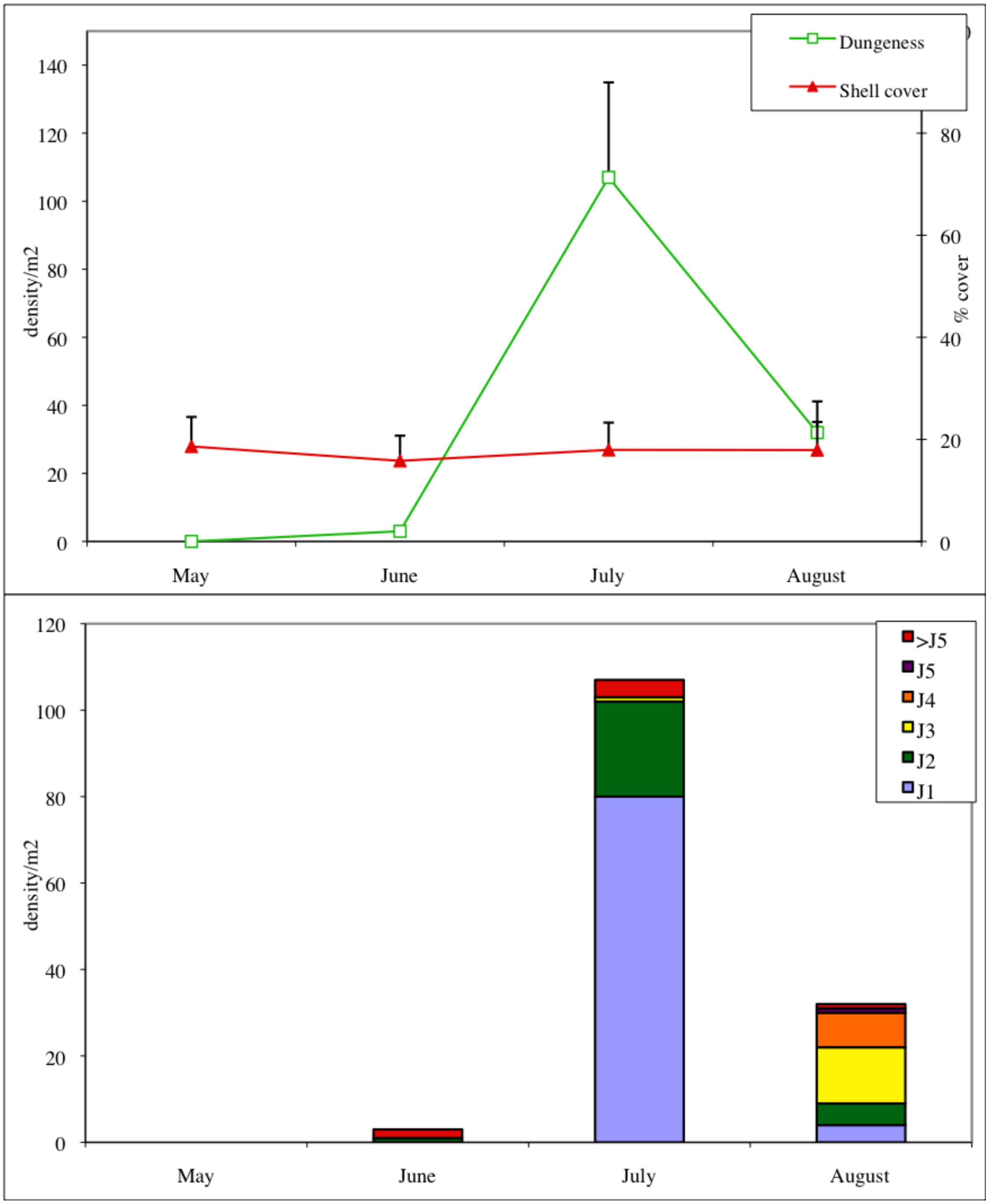

Figure 13. Summer 2008 crab data from 2003 Down plot: abundance compared to shell cover and instar size composition.

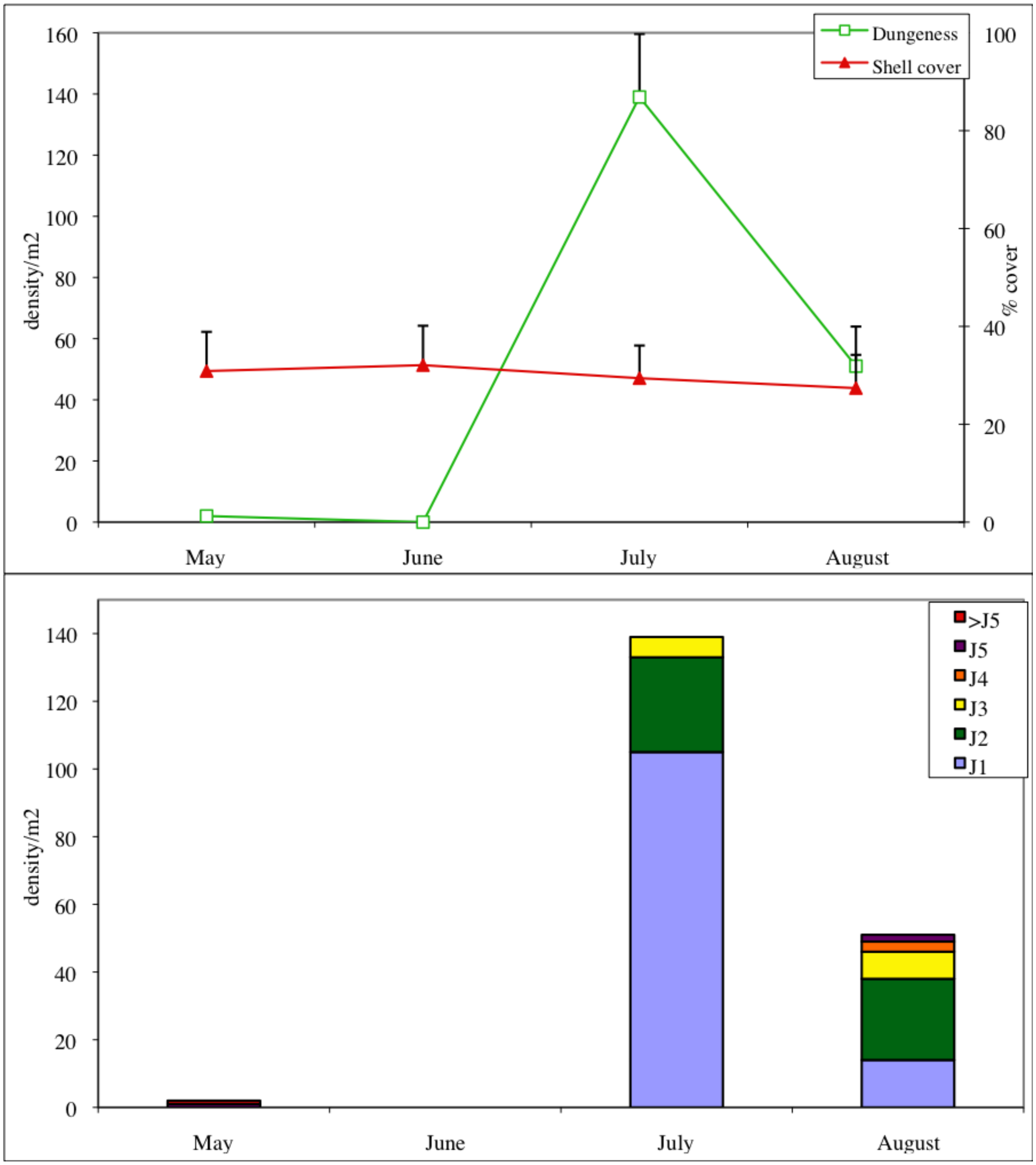

Figure 14. Summer 2008 crab data from 2003 East plot: abundance compared to shell cover and instar size composition.

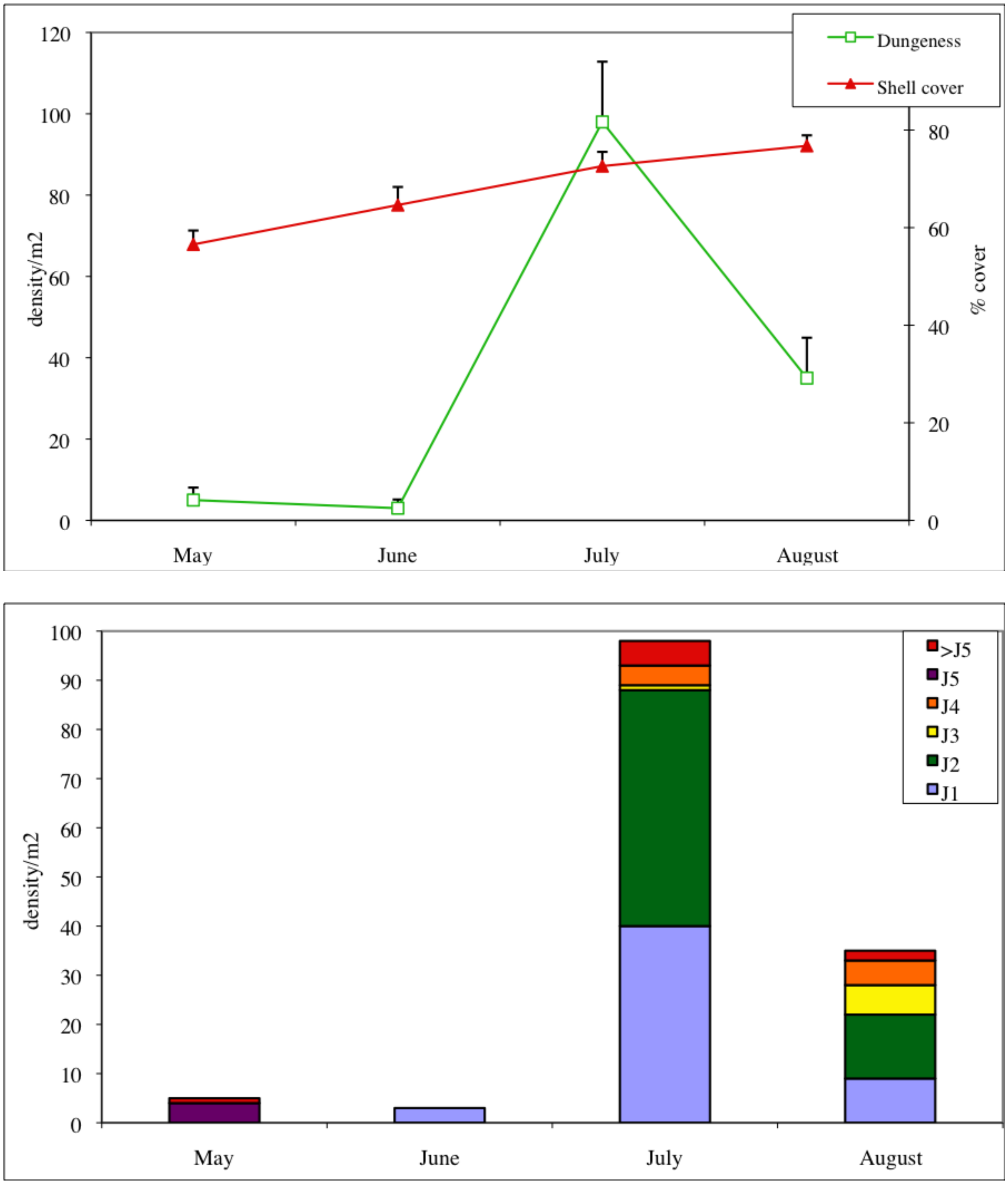

Figure 15. Summer 2008 crab data from 2006 East plot: abundance compared to shell cover and instar size composition.

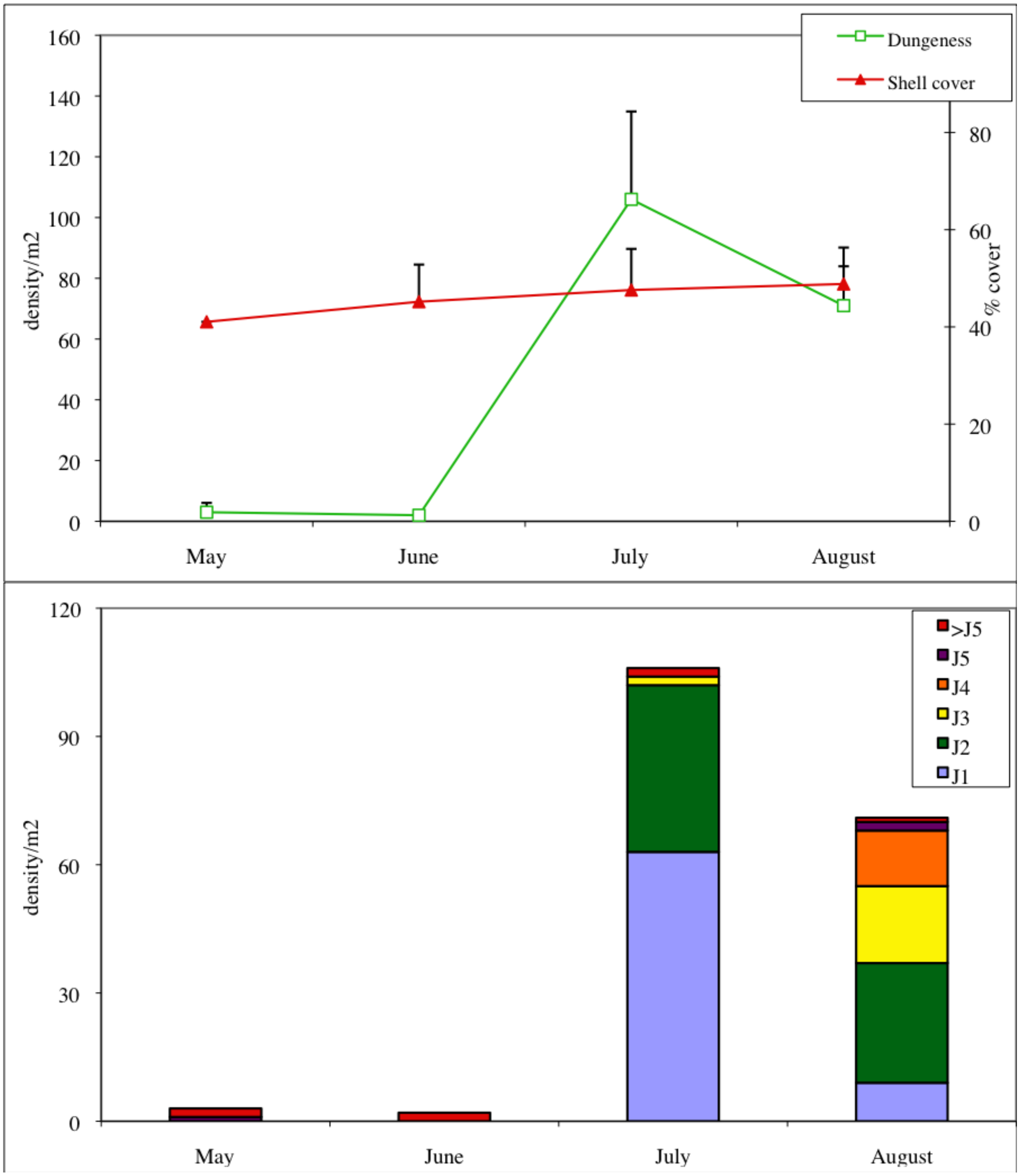

Figure 16. Summer 2008 crab data from 2006 West plot: abundance compared to shell cover and instar size composition.

4.4 Mortality

Mortality rates computed from 2008 data resulted in none of the r^2 values for the exponential curve fits being significant. With only two months (July and August) of crab density data to work with due to the late settlement of crab megalopae into the estuary, this is not surprising. Average mortality rate data from historical data was used 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, the 2006 West plot showed the least decline in crab density from July to August, suggesting highest quality refuge habitat.

Table 4. Mortality rates and corresponding survival rates realized by new and old shell habitat from 1990 through 2008.

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	0.0278	38
2007			.0218	48
2008			.0218	48
Avg	0.0189	52	0.0222	47
SD	0.0041	7	0.0067	11

4.5 Shell and Eelgrass Cover

Shell cover relationships for all shell plots over summer 2008 were flat, with slight gains in shell cover occurring over the course of the four month sampling (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 the overlay strategy for shell placement. Percent shell cover increased on the 2000 East and 2006 East plots over the 2008 summer sampling period, likely 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 and 2000 East plots (Figure 17). 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.

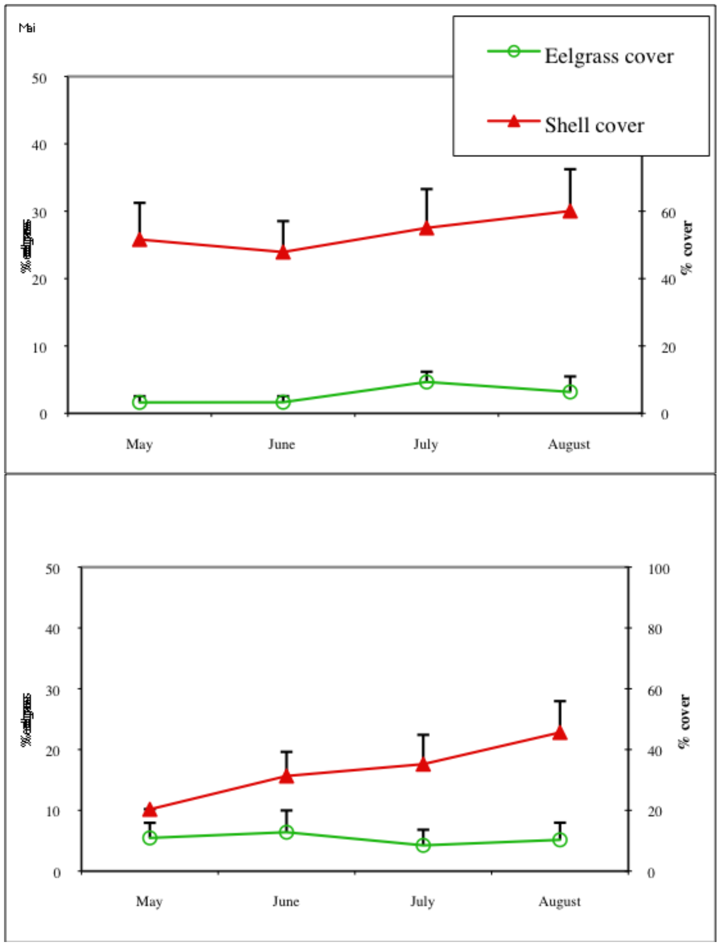

Figure 17. Oyster shell and eelgrass percent cover for the oldest two plots sampled during summer 2008: 1995 Island and 2000 East.

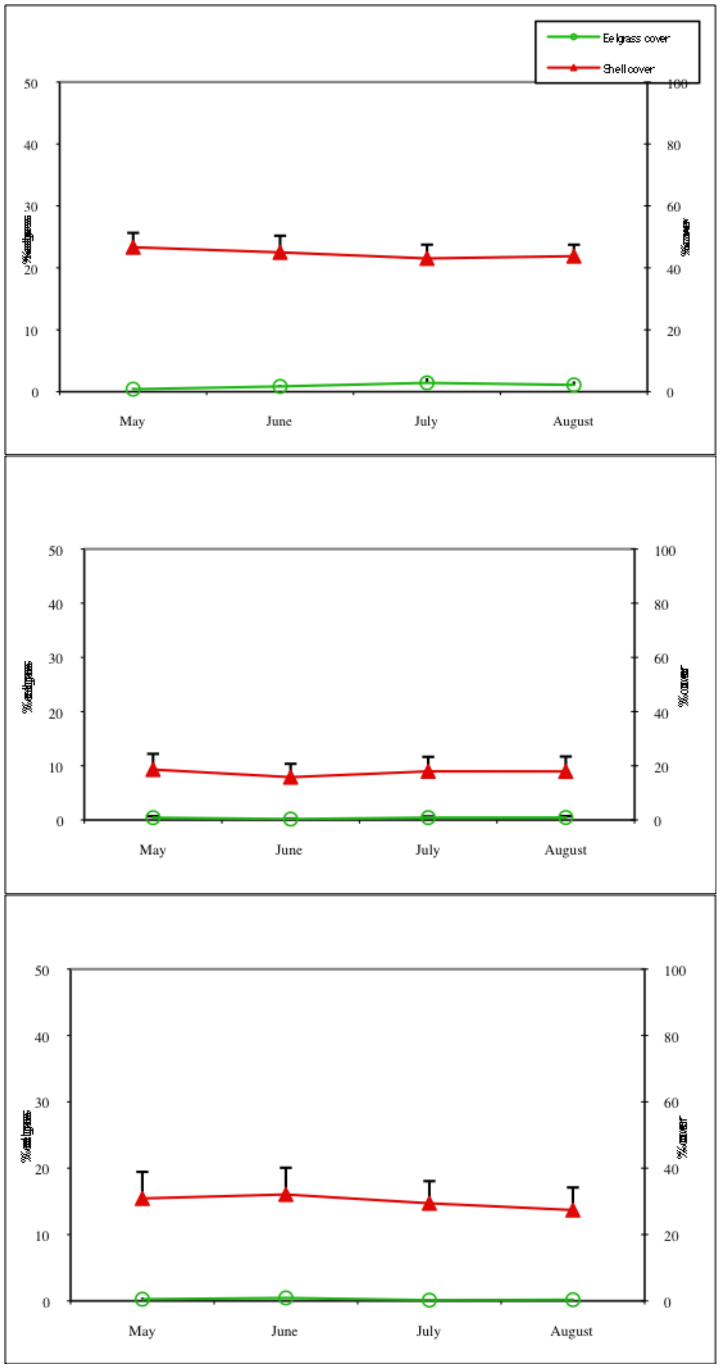

Figure 18. Oyster shell and eelgrass percent cover during summer 2008 for the three 2003 plots: 2003 Up, Down, and East plots.

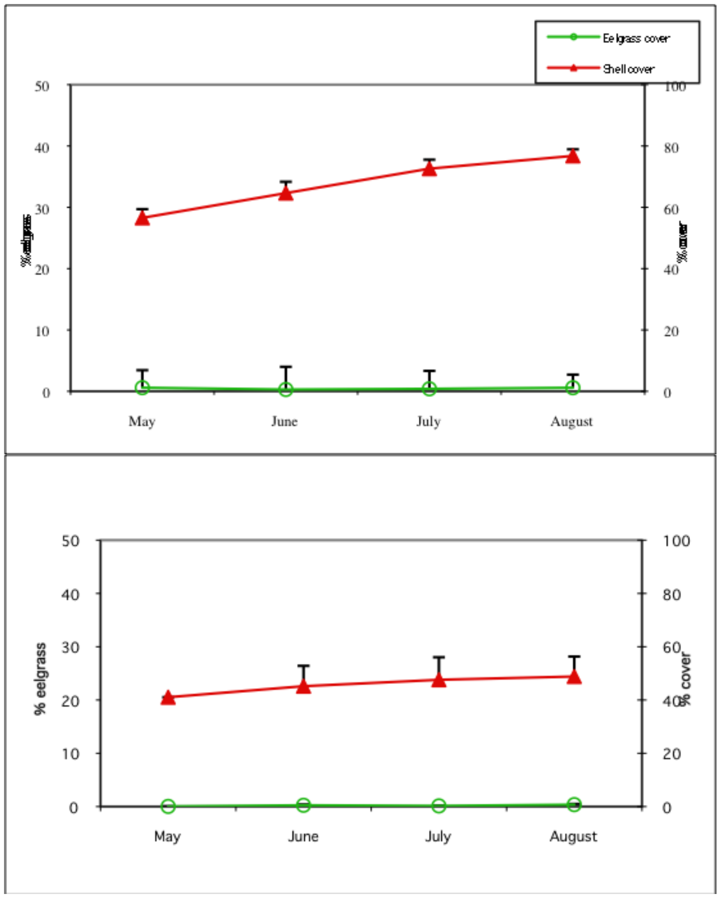

Figure 19. Oyster shell and eelgrass percent cover during summer 2008 for the two newest plots: 2006 East and 2006 West.

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 (Figure 20). 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 patchiness with sections of live and inert shells (Figure 21).

Figure 20. Live oyster specimen taken from experimental subplot on 2003 Up habitat.

Figure 21. Live oyster habitat in July 2008, showing patchiness of live and inert shell within an experimental subplot on 2003 Up shell habitat.

Percent shell cover differences between the five 2003 Up subplots planted with live oysters and the five without live oyster spat were within one standard deviation of the mean, although trends are still in the direction of greater shell cover on the live oyster plots (Figure 22). 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 and thus create a more sustainable refuge for juvenile crab.

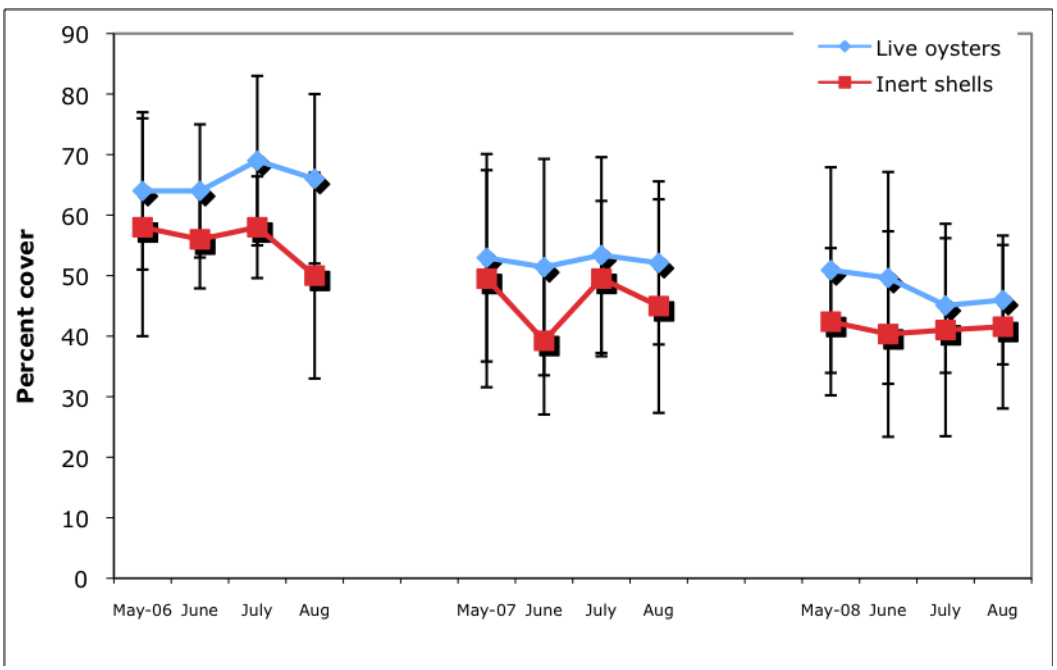

Figure 22. Percent shell cover of subplots with and without planted oyster spat over summers 2006-2008. Live oysters were planted on subplots 1,4,5,6, and 9 and subplots 2,3,7,8,and 10 were left as controls.

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 23). Clearly it is still too early to determine the functionality of these live oyster plots as effective juvenile crab refuge habitat, but in their third year, they are not significantly different from control plots.

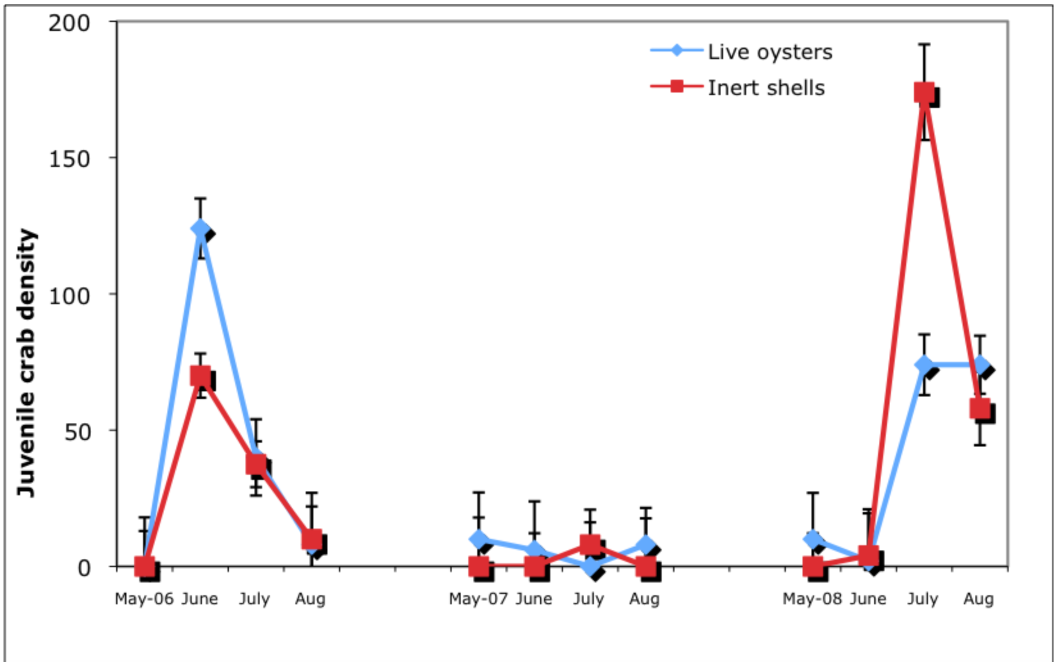

Figure 23. Juvenile Dungeness crab densities over summers 2006-2008 on experiemental plots with and without live oysters.

5. Summary and Conclusions

The 2008 summer production yield of 1.33 ± 0.6 million juvenile Dungeness crab was in the top third production for old shell habitat over the 19 year project history since mitigation efforts began in 1990 and cumulative production has now reached 28.5 ± 6.8 million crabs. The three highest yields were from the 2006 West, 2003 Up, and 2006 East plots. The summed production from these three plots comprised 77% of the 2008 annual total. On a square meter of habitat created basis, 2008 productivity was 5.35 crabs/m^2, which is slightly lower than the overall average of 6.3 crabs/m^2 but good considering the age of the shell habitat.

Shell cover remained fairly constant on all plots over summer 2008, although increased slightly on the 2000 Up and 2006 East plots over the four month sampling period. Both of these plots are located on the eastern most end of the mitigation site where the banks are steepest and apparently experienced sediment scour from hydrodynamic events occurring during the field season. The other plots with more level field topography showed flat shell cover relationships this year. The three highest producing shell mitigation plots were among the four plots with highest shell cover (42-77%) over the mud surface. The anomaly was the 1995 Island plot with shell cover in the 48-60% range, which produced only 3% of juvenile crabs. While shell cover is a major factor in productivity, it has not been the dominant factor in recent years, when larval supply seems to be more variable.

Megalopal influx into Grays Harbor was late in 2008 and peak crab densities did not occur until July. Oceanic conditions were poor as many species exhibited declines during 2008 and larval development may have been delayed as a result, causing later timing of estuarine arrival. August sampling showed the highest historical percent contribution to the annual total production for 2008 sampling, but the combination of extreme tides being at the very beginning of each month and the late arrival of megalopae explains this. In light of tight budget constraints and historical settlement patterns, the recommendation to drop the August sampling date for 2009 remains. Our longterm data set will enable estimates to be made for production during the last month of summer 2009 based on size frequency data and abundance over the May-July period.

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 third 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 shell cover in the field 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. Curiously, while 2006 showed increased crab usage on the experimental live oyster plots, 2008 abundance showed greater juvenile crabs on the control plots without live oysters during peak density in July. Crab density data for 2007 was extremely low and there were no differences between the groups. 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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