Grays Harbor Shell Mitigation Project

2006 Annual Dungeness Crab Production and Oyster Spat Placement

DRAFT REPORT
May 2007

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Executive Summary

Production for summer 2006 yielded 2.77 + 1.1 million fourth instar juvenile Dungeness crabs (J4). All crabs collected in 2006 samples were *Cancer magister* except one male *Hemigrapsus oregonensis* found in July, so clearly historically important interspecific competitive interactions for refuge space were not operating this year. Although total production in 2006 was among the highest total annual yield realized by mitigation efforts since 1990 (2006 ranked 4th), production values were low when analyzed on a per meter square basis. The 9 crabs/m^2 by 2006 mitigation habitat gave the third lowest performance of all 12 shell habitats in their initial year of construction, a rate which has also been met or exceeded by old shell (1 or more years post-construction) in 4 of the 18 years sampled. Since mortality rates were average for 2006 , and shell longevity on the mud surface was better than typical for newly constructed habitat, this diminished performance is most likely attributable to a drop in larval supply.

Of the 2.77 million J4 crabs produced, 1.28 million was produced by new 2006 shell and the remaining 54% from the other 7 plots sampled. The 2006 West plot yielded 0.82 million and the 2006 East plot produced 0.46 million crabs. After the two 2006 plots, the ranked order of contribution, in decreasing order of importance, was the 2003 Down plot (0.41 million crab), 1995 Island (0.24), 2003 Up (0.25), 1996/1997 (0.22), 2003 East (0.19), 2000 East (0.12), and 2000 Up plots (0.07 million crab). Old shell plots in summer 2006 exhibited average per meter square production compared to other years.

Oyster spat placement went smoothly and oyster monitoring protocol was developed and incorporated into the standard field plan. Juvenile oysters showed high survival throughout their first summer, dropping from a widely variable average of 37 spat per shell to a less variable average of 22 spat per parent shell. Growth was rapid; size of live oysters went from 7 mm at time of planting in late March to almost 40 mm in mid August, with oysters exhibiting growth of about 2.7 mm/mo between March and May and 9.2 mm/mo between May and August.. Survival and growth was consistent among the 5 subplots and no differences in percent cover were detectable between subplots with and without live oysters. Trends in the direction of increased shell cover on plots with live oysters may have been starting to develop by the end of the 2006 season.

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1. Scope and Objectives

The dual aim of summer 2006 field efforts was to estimate juvenile Dungeness crab production and to investigate increased habitat longevity with enhanced long-term productivity per unit area as a goal. Production of juvenile Dungeness crab from the intertidal mitigation plots in South Channel of Grays Harbor was estimated by conducting the usual sampling scheme. Monthly densities and size composition of crab less than ~25mm carapace width and amount of intertidal area covered with empty oyster shells serve as input for a growth model incorporating natural mortality giving production estimates for each functioning plot for the summer. Output of the model is number of individual J4 crabs produced by mitigation plots each month over the summer intertidal phase of Dungeness crab life history.

The time oyster shell refuge habitat remains on the surface of the mudflat is a limiting factor for productivity of mitigation plots, with generally a few years of high yields before percent shell cover decreases, requiring labor and cost intensive construction of new shell habitat to maintain juvenile crab production. Thus an experimental attempt to increase shell longevity was initiated by seeding habitat of empty shells with live oyster seed. Oyster shells with live spat were distributed on 5 subplots of the 2003 Up plot in late March and survival and growth of these live oysters was monitored throughout the season. Growth of these live oysters will hopefully compensate for sedimentation and sinkage of shells, not only helping maintain percent shell cover relative to the 5 'normal' subplots without live oysters, but creating a three dimensional substrate that serves as a reef, perhaps supporting higher densities of juvenile crab.

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 attempts to avoid and minimize the impact, as well as compensation for the 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 represents 1-4% of the annual crab fishery in Grays Harbor. Construction of intertidal juvenile habitat by depositing inert 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 effort 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 time it takes for juvenile crabs to reach legal fishery size, the number of crabs required for impact compensation was reached. Thus the target goal for mitigation efforts became 9 million J4 juveniles after the initial widening and deepening project. 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 takes place every third year (2000, 2003, 2006). Total cumulative crab production attributable to mitigation efforts to date (1990- 2007) is over 26 million ($\pm$ 6 million) J4 juveniles.

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. Thus the shell mitigation concept is to provide key habitat during this initial vulnerable period in order to increase the number of >25mm carapace width individuals 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.

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 *Neotrypea pugetensis* and *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 only one *H. oregonensis* was collected in South Channel excavation samples during summer 2006. Insufficient data exists to determine whether this is a reproductive failure or a 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 in the absense 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 between 4-24 degrees C,

long periods of exposure to air 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 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 0.30mm 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, NIMPIS, 2002). 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 metres 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 75mm 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 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 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 late March and again in early May to determine which sites would be sampled and to measure boundaries, as well as map and mark the plots chosen. The newly constructed 2006 shell plots, 2006 East and 2006 West were surveyed using a GPS unit and 10 subplots were staked for consistent shell cover monitoring. Since the new 2006 East shell plot was constructed by overlaying shell material over the southern portion of the 1996/1997 plot, the boundary of the latter plot was adjusted to reflect the new division between new and old shell habitat. Thus the area of this plot became lower and three subplots (1,2, and 3) were moved north to keep the sample size of 10 subpots within the 1996/1997 plot. Then four sampling series were conducted once monthly during the spring tide series in midmonth beginning in May 2006. The nine plots sampled during summer 2006 were the 1995 Island, 1996/1997 Overlay, 2000 Up, 2000 East, 2003 Up, 2003 Down, and 2003 East 'old' shell plots as well as the two newly constructed 2006 East, and 2006 West plots (Figures 2 and 3).

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 which did not retain ≥ 20% of shell remaining on the surface by May 2006 was not sampled during this season. 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 time and manpower investment to quantify their minor addition.

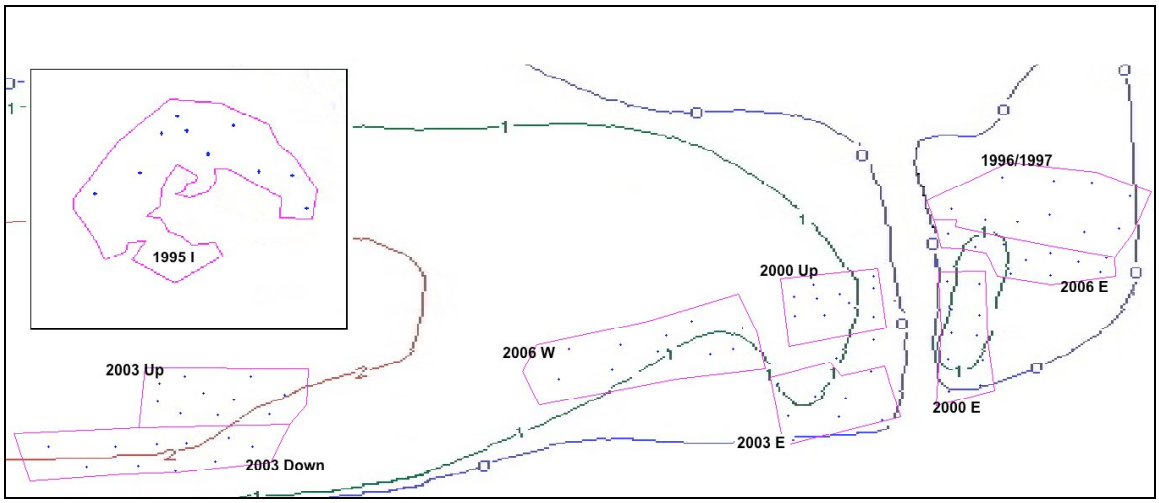


Figure 2. Map of South Channel shell mitigation site. 1995 Island is 0.84 km west of the western boundary of 2006W and magnified 1.5 times relative to the other plots to show detail.

Figure 3. Contractor depositing standard oyster shell over new 2006 plot area at high tide by maintaining course while raising net to gradually drop shell.

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 nine plots sampled in 2006 to obtain monthly crab density data for each plot.

Table 1. Sampling dates, approximate times, and estimated tidal heights (based on data for Markham Point) during data collection during summer 2006 at South Channel crab mitigation sites. There were three crab sampling dates each month; the initial tide in May was used for field site preparation, and the March tides were used for oyster spat placement.

Date	Low tide time	Low tide height (ft)
March 29	6:36	-0.2
March 30	7:23	-0.9
March 31	8:10	-1.2
May 13	7:57AM	-1.4
May 14	8:36	-1.6
May 15	9:17	-1.7
May 16	9:59	-1.6
June 12	8:18	-2.3
June 13	9:01	-2.4
June 14	9:44	-2.3
July 11	7:59	-2.5
July 12	8:43	-2.6
July 13	9:25	-2.4
August 19	7:37	-2.3
August 10	8:19	-2.3
August 11	9:01	-2.0

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 the mud down to 5 cm below the shell layer, and was sorted by hand and seived through a 3 mm mesh screen (Figure 4). 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 ship after the tide rose (Figure 5), recorded, and returned to the estuary alive. For *Hemigrapsus oregonensis,* was also recorded.

Figure 4. Collection of excavation samples in the field. Metal quadrat in the left of photo defines the 0.1 m2 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.

Figure 5. . The carapace width of each juvenile crab collected was measured and recorded aboard the Shoalhunter before crabs were returned alive to Grays Harbor estuary.

Estimates of amount of refuge area available within each plot were necessary in order to translate the crab density data (on a permeter 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 of each of the nine 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 nine plots sampled in 2006 (Figure 6). 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, resulting in a mean and a standard deviation as input for the production model.

Figure 6. Landscape view of shell mitigation plots showing patchiness of habitat and crew member doing visual estimate 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. On plots where eelgrass beds flourish, shell placement is therefore patchy. Percent cover estimates for eelgrass have been added to the mitigation sampling scheme in recent years so that trends in eelgrass coverage can be tracked. Monitoring of eelgrass distribution and abundance continues due to its possible correlation 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 do not 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, and the inherent 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 same mortality function computed for that specific 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 2006 data, due to timing of larval settlement, which peaked approximately two weeks after the initially sampled tide series. Standard curve fit protocol of r2 values were applied to these mortality rate computations and 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 values from past years.

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 at as great a

risk and begin to move to subtidal areas, making their intertidal densities a poor measurement of population abundance. 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 are less than 5 crabs • m^{-2} and generally zero in areas with no shell or eelgrass refuge, 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 Spat Placement

Parent oyster shells with live spat attached were purchased from Coast Seafoods Company, who seeded them in their hatchery during early fall 2005. These overwintered spat (Figure 7) were chosen as they would be less vulnerable to chipping and predation in the field and presumably have better survival rates. Planting was conducted in late March from homogenized stock and these parent shells were evenly distributed on 5 randomly selected subplots of the 2003 Up shell mitigation plot, which represents half of the total of the 10 subplots. Even coverage was controlled by distributing equal numbers of bags regularly thoughout each pf the 5 plots. Forty-four bags of spat were taken to each subplot for a planting density of approximately 26 shells per square meter, which is midway between standard densities practiced by oyster growers and experimental densities used in Willapa Bay (Brett Dumbauld, pers. comm.) Bags were opened and parent shells were distributed by hand evenly over 2003 Up shell surface (Figure 8).

Figure 7. Top photo shows parent shells with live spat, bagged and ready for field. Lower photo shows close up of oyster spat as of March 30, 2006.

Figure 8. Planting of live oyster spat on subplot 9 of 2003 Up. Bags were evenly spaced throughout the subplot before being opened and parent shells were then placed by hand within shell plot.

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, largest, smallest and 4 others deemed representative by crew member at time of measurement. Due to the time involved in obtaining these measurements, oysters were measured onboard the Shoalhunter, kept cool and damp overnight and returned to their plot of origin the next day. 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 2006 Production

The South Channel shell mitigation plots yielded almost 2.8 million (± 1.1 million) J4 production units during summer 2006. Of this total, 1.3 million or 46% was contributed by newly constructed habitat, 0.8 million by the larger 2006 West plot, and 0.5 million by the 2006 East plot (Figure 9, Table 2). Both of these new plots were overlaid over previous plots and should experience enhanced sediment stability relative to plots without a shell underlayer, and therefore continued long term productivity. Habitat constructed in 2003 contributed 0.84 million or 30% of the annual total, while 2000 habitat contributed 0.2 million or 7%, and the 1995 -1997 habitats contributed 0.5 million or 17% of total annual production.

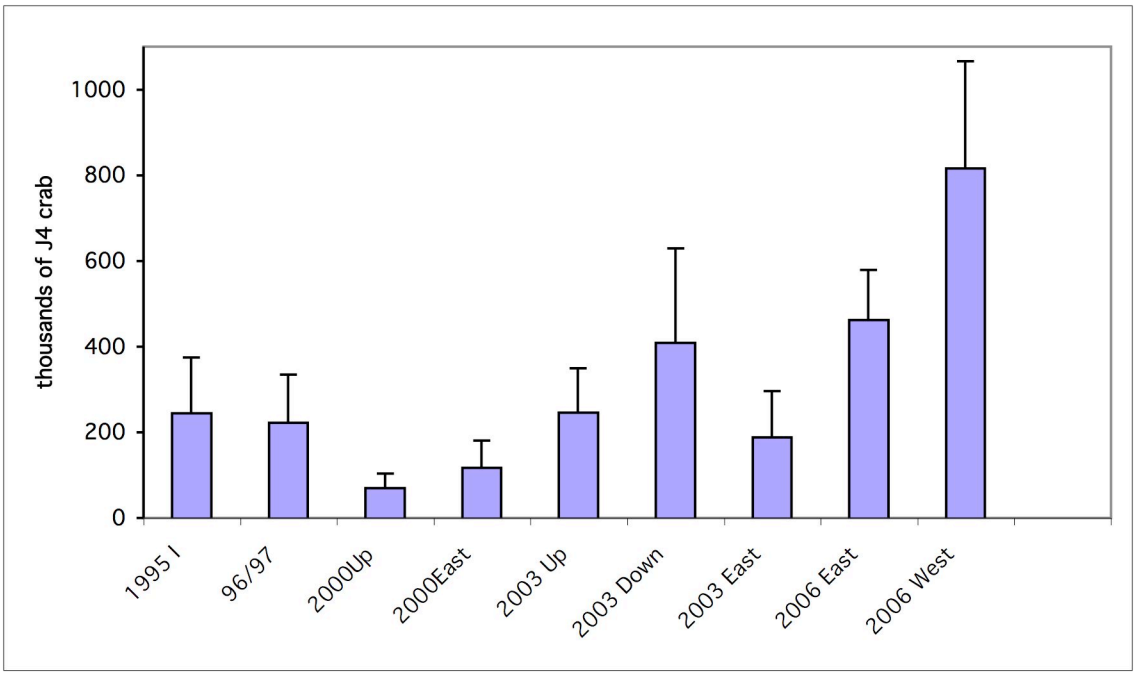


Figure 9. Summed annual production over the four month sampling period during summer 2006 for each of the nine plots sampled.

Table 2. Monthly J4 Dungeness Production by plot for 2006 sampling season.

Plot	Month	Total crab density	J2 instars	st.dev.	Mortality	Plot size (m2)	Shell cover %	st.dev. %	Production	Annual prod	st.dev.
1995 I	May	3	0	0	0.0259	19051	63.9	36.7	0	243733	130669
	June	52	38	28	0.0259	19051	61.7	38.7	180416		
	July	19	5	10	0.0259	19051	61.6	35.1	23728		
	August	11	1	3	0.0259	19051	59.6	38.2	4585		
96/97	May	0	0	0	0.0219	30003	24.2	14.9	0	222689	111325
	June	50	37	33	0.0219	30003	27.2	17.1	140400		
	July	46	16	16	0.0219	30003	27.4	15.6	61208		
	August	5	0	0	0.0219	30003	29.5	16.7	0		
2000UP	May	3	0	0	0.0219	13912	33.5	15.5	0	69205	33996
	June	29	26	26	0.0219	13912	32.5	14.7	54642		
	July	38	5	5	0.0219	13912	38.1	16.8	12300		
	August	10	1	1	0.0219	13912	35.0	16.7	2263		
2000EAST	May	1	0	0	0.0137	13695	45.6	26.7	0	116784	63955
	June	25	19	23	0.0137	13695	49.4	30.9	79549		
	July	17	4	5	0.0137	13695	52.8	31.9	17921		
	August	11	2	4	0.0137	13695	53.2	32.9	9032		
2003UP	May	0	0	0	0.0396	20145	60.8	15.1	0	245210	104857
	June	97	68	76	0.0396	20145	60.1	15.5	205757		
	July	31	8	14	0.0396	20145	63.5	17.5	25561		
	August	9	1	3	0.0396	20145	58.2	16.7	2928		
2003DOWN	May	4	0	0	0.0299	25422	40.3	21.7	0	409096	220800
	June	102	90	47	0.0299	25422	40.4	24.0	325366		
	July	45	16	24	0.0299	25422	36.1	23.0	51693		
	August	17	3	5	0.0299	25422	35.1	23.0	9404		
2003EAST	May	1	0	0	0.0229	16126	39.2	23.0	0	188584	106892
	June	67	59	46	0.0229	16126	36.6	21.0	156285		
	July	22	8	10	0.0229	16126	30.3	19.7	17547		
	August	17	7	7	0.0229	16126	29.1	20.6	14752		
2006EAST	May	6	0	0	0.0200	12004	95.7	3.3	0	461706	116811
	June	93	71	30	0.0200	12004	93.7	3.6	396476		
	July	38	9	13	0.0200	12004	93.5	3.4	50154		
	August	28	0	0	0.0200	12004	93.0	3.6	0		
2006WEST	May	1	0	0	0.0188	32603	87.4	13.0	0	815486	251121
	June	69	49	27	0.0188	32603	83.5	15.9	690783		
	July	20	4	7	0.0188	32603	81.5	16.2	55014		
	August	32	1	3	0.0188	32603	80.7	18.2	13617		
										2528760	1009756

Early settlement played a relatively insignificant role this year, 171,000 J4 production units coming from crabs collected over the J2 instar early in the sampling season. This minor contribution (6% of the total) contrasts strongly with 2004 when early settlement contributed 63% of annual production. Settlement during the 2006 season peaked sharply rather than exhibiting a protracted nature, and vital to the question of relative contribution of early settlement, peaked later than the first sampling session, resulting in no contribution to annual production from efforts in May. Thus few crabs escaped being detected by the initial sampling date. The 6% contribution from May 2006 was due to the percentage of crabs that settled immediately after the May tide series, progressing through two molt intervals and being already J3s by the June sampling session. June almost always shows the biggest productivity, this year 87% of total production was monitored in June. July sampling measured 11% and August only 2% (Figure 10). As juvenile crabs are beginning to emigrate to subtidal habitat by August as they outgrow the most vulnerable phase of their life history and most stringent habitat requirements, August always yields low productivity (6% of the total in 2002, 2% in 2003, 7% in 2004 when there was no May sampling date). 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. Biologically, it is interesting to see the data from August, but since the maximum percent contribution of sampling efforts fin August always falls within the error bars of the total estimate for the summer, it is worth discussing the cost:benefit ratio of continuing to conduct field sampling efforts in August. Ship time and personel from Seattle require internal logistical and financial shuffling on top of the ~$10K for Perkins Point Consulting expenses (it's just the draft, so I'll add…. as much as I hate to recommend this…).

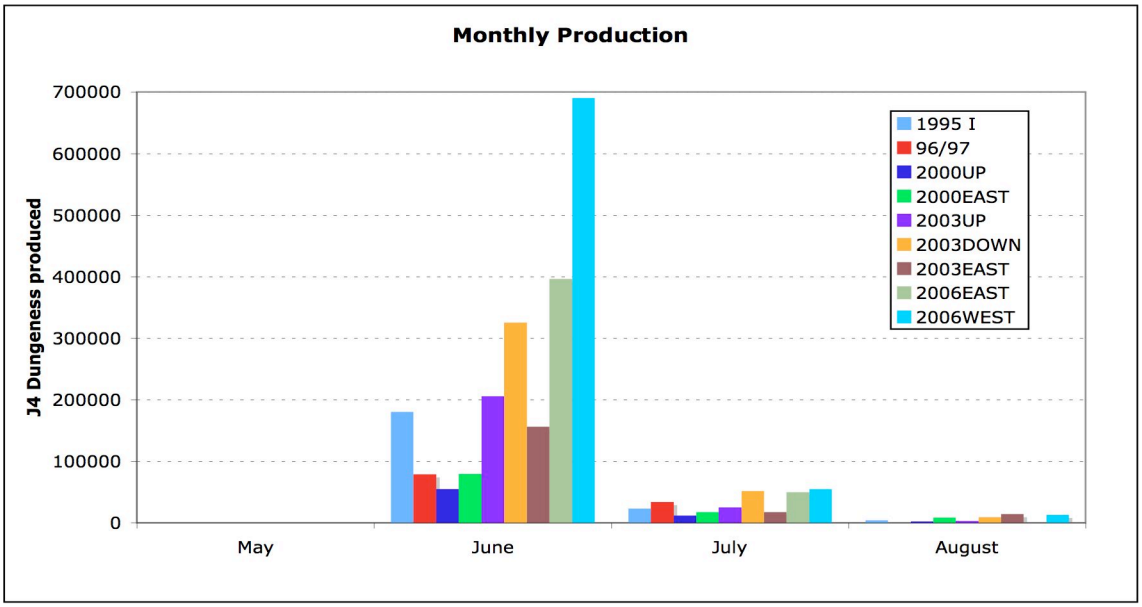


Figure 10. Production of J4 Dungeness crabs by plot each month during summer 2006. Gray and turquoise bars (last two for each month) are the newly constructed 2006 plots.

Average production per unit of refuge area for summer 2006 was 6.8 crabs per square meter of habitat overall, 9 crabs/m^2 for new habitat and 6.2 crabs/m^2 for old shell (Figure 11). This is an average production rate for old shell habitat corrected for area, but quite low compared to normal productivity of new shell plots (7-51 crabs/m^2 with an average of 26 crabs/m^2). Shell placement, especially on the west end of the 2006 West plot was patchier than usual, although shell cover was fairly constant over the summer and mortality rates were normal, so at least for the initial summer, this patchy distribution does not seem to be the cause of lower production than might have been anticipated. Other years, such as 1996 and 1997, produced less than 10 crabs/m^2 in their first year post construction, and both 1998 and 1999 were relatively low producers as new habitats, yielding 12 and 11 crabs/m^2 respectively (Figure 12). In all of these examples, unlike 2006, shell cover played a major role in low productivity. The 1996 plot had only 29% its first summer, the 1997 new shell dropped from 58 to 48 during its initial summer, and the 1998 shell went from 44 to 32 during its year of construction. As a final example, the three 1999 new shell plots dropped from an initial 85% cover to 48% during the first 4 months post-construction. The 2006 East shell dropped only from 96% cover in May to 93% cover in August and the 2006West plot dropped from 87% in May to 81% cover by August. Although our data does not include direct measures of larval supply and cannot

eliminate the effects of early post-settlement survival, diminished larval supply is the most plausible cause of the newly constructed 2006 habitats less than stellar productivity relative to other years.

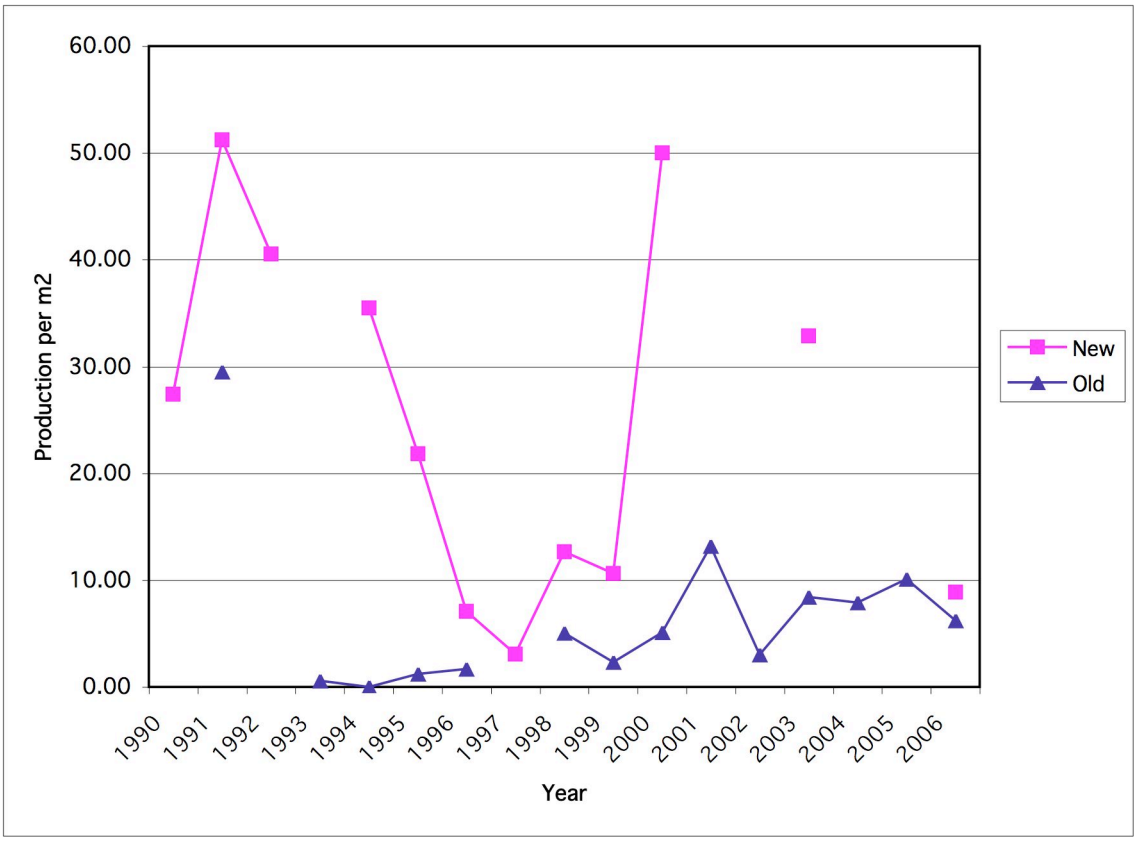


Figure 11. Total production for all years since initiation of mitigation efforts, showing contribution of new and old shell. Note high production of 'old' 1990 shell sampled in 1991, and relatively low productivity of 'new' 1996, 1997, and 2006 shell habitat.

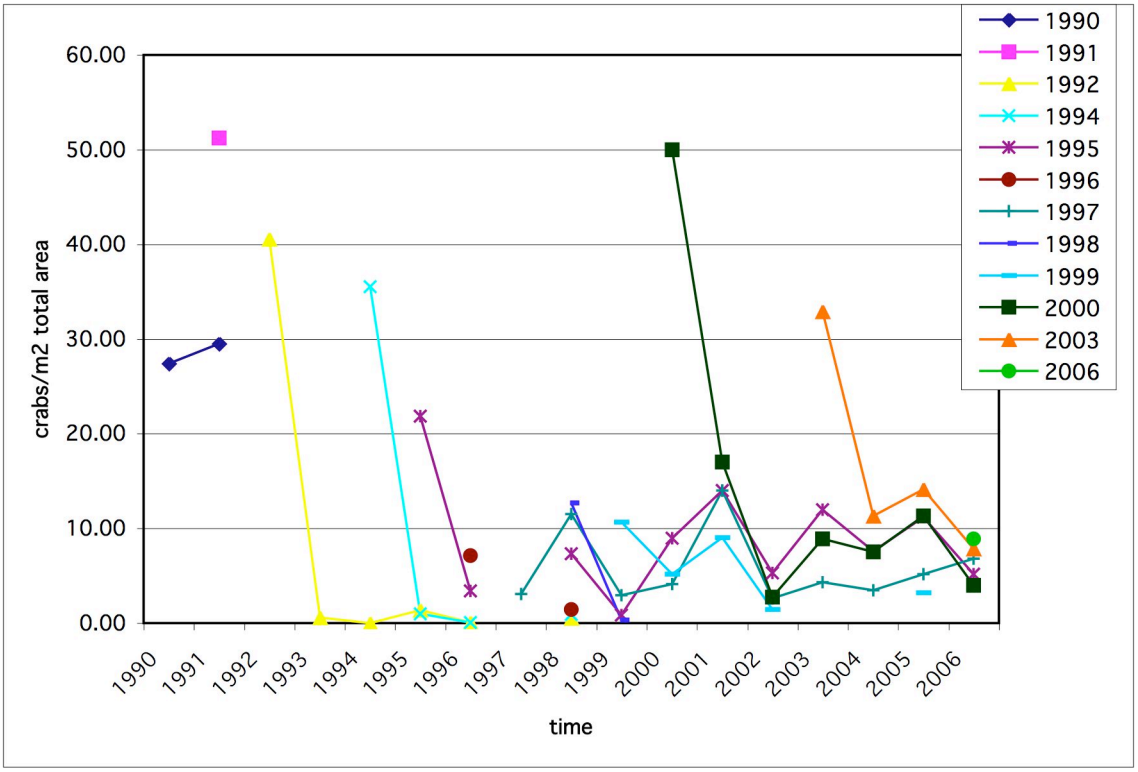


Figure 12. Historical production of J4 Dungeness crab per square meter of shell mitigation habitat created, separated by habitat. For example, the orange triangles show the average production rate of the three shell plots constructed in 2003 and sampled four consecutive years in 2003, 2004, 2005, and 2006.

Within year variation between plots shows the four plot groupings by age (2006, 2003, 2000, and 1995-1997 shell) comprising 24%, 34%, 15% and 27% respectively of total area in order of increasing age. Thus new shell constituted almost half of total 2006 production on ¼ of the total habitat, which is predictably high relative to within year variation since new habitat consistently performs well. Likewise, 2003 and 1995 Island habitats contributed to production in proportion to their relative area 30% production from about 1/3 of the total area from 2003 plots, and 9% of production from 10% of the area from 1995 Island. 1996/1997 and both of the 2000 plots are lower producing plots when corrected for area.

4.2 Cumulative Production

Total estimated production of juvenile Dungeness crab from shell mitigation habitat is 26.9 ± 6 million crabs as of the end of the 2006 sampling season. The 2.8 million crab produced in summer 2006 represents one of the six most productive in the 16 year mitigation history (Figure 13), mostly due to the large amount of shell placed and extent of area covered. 1990 for example exhibited excellent production per square meter, but was only a 4000 m^2 test plot and therefore total crabs produced were quite low.

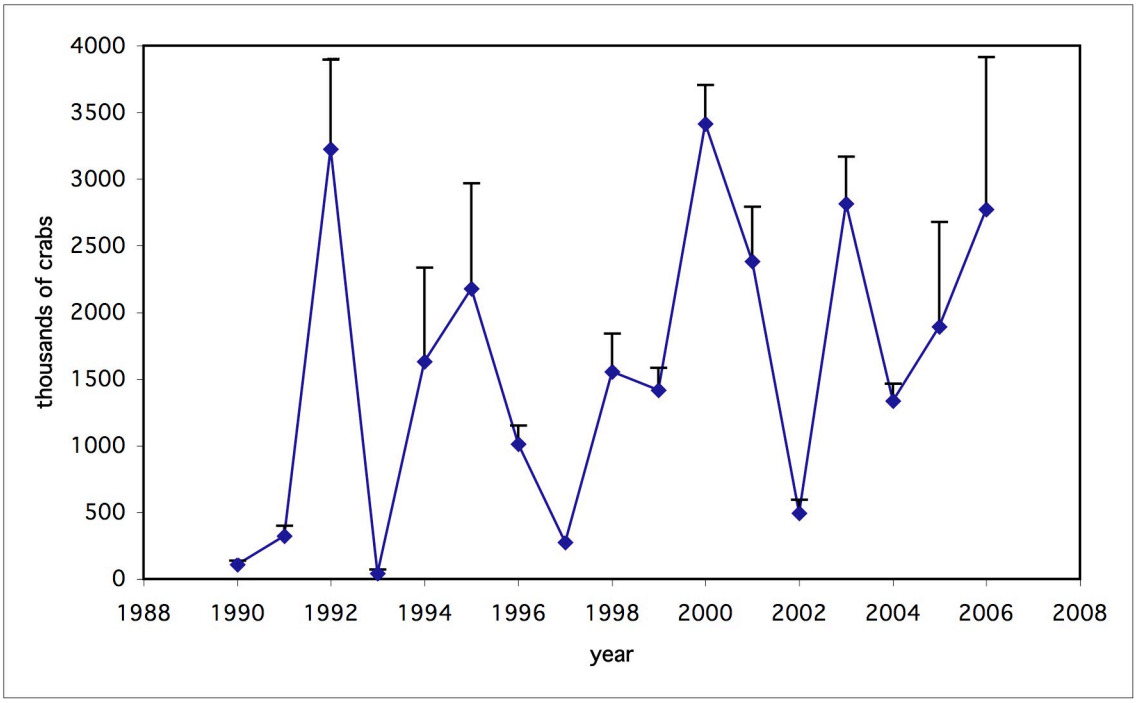


Figure 13. Historical annual yields of J4 juvenile Dungeness crabs by sampling season. Note that all plots sampled within the year are summed in this graph so that data are by year of sampling rather than the shell habitat constructed in a given year.

Of the total 26.9 million crabs produced to date (Table 3), 57% comes from the 12 plots constructed in their initial year (12 plot-•years, or about 450 excavation samples) and 43% from all plots summed over all years sampled (83 plot•years, or over 3500 samples). New shell is typically much more productive than old shell, although that difference has narrowed since interspecific competition with *Hemigrapsus oregonensis* currently does not play a role in Dungeness crab behavior and habitat usage within shell plots (Figure 14).

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
Total	15,397,650	12,497,935	26,887,740	5,301,443

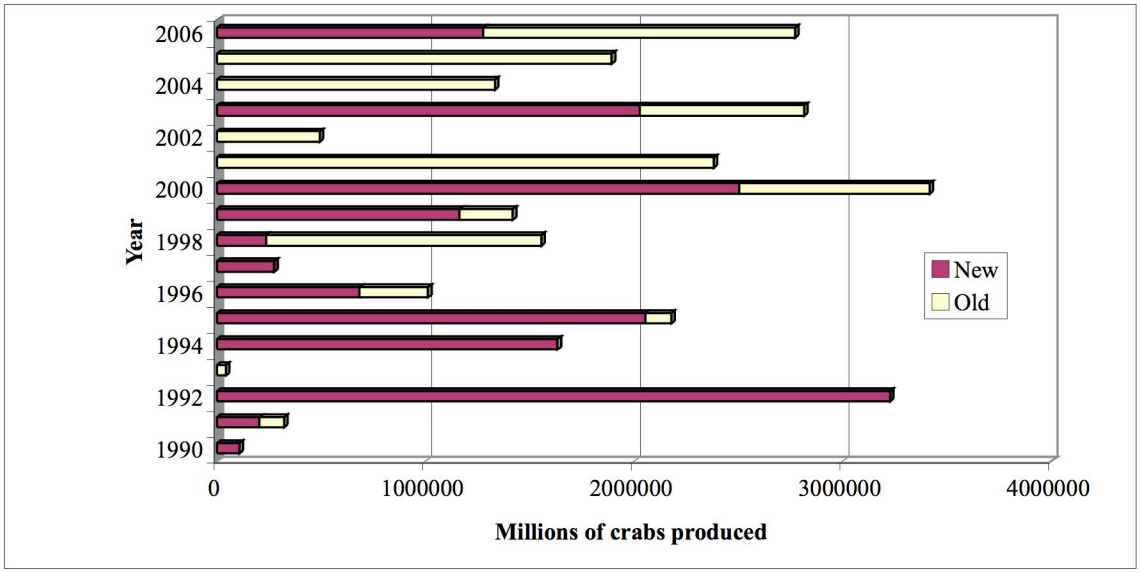


Figure 14. Historical production yields by year of sampling, separated into contribution of new and old shell habitat. No new shell habitat was created in 1993, 2001, 2002, 2004, or 2005 so there are no maroon portions of the bars for these years. Likewise, old shell was not sampled in 1992 or 1994, 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 (Figures 15-23). Two plots (1996/1997 and 2000 Up, Figures 16 and 17) show a sharp drop in crab density between July and August following higher than expected abundance for July. The 1996/1997 plot phenomenon may be partially explained by interaction with the new 2006 East plot (Figure 22), which demonstrated high abundance of J2 instars in June, which did not follow a normal natural mortality curve later in the summer. The new 2006 East plot is immediately adjacent to the 1996/1997 plot and as it is an overlay over part of the former 1996/1997 plot, is higher in elevation. Flooding tides would serve to a transport displaced juveniles from the 2006 East plot towards the 1996/1997 plot, which experienced lower initial settlement between the May and June spring tides. If this scenario occurred, competition among similar sized individuals on the new shell could result in the losers having to accept the less complex habitat (and less preferred as evidenced by settlement patterns). This seems a plausible explanation, as the apparent survival between June and July on the 1996/1997 plot (96%) is not realistic, but our data cannot confirm the theory. Likewise, proposing emigration from the 2000 Up plot which experienced a dramatic drop in crab abundance between July and August (Figure 17), onto the 2006 West plot (Figure 23) just west of the 2000 Up plot would explain the curious increase in crabs on the new 2006 West plot between July and August. This possibility, although appealing, is more of a stretch logistically as distances are greater and habitat selection by juvenile crabs would be expected to play a greater role earlier as part of the settlement process, rather than in late summer. Most of the 20 crabs/m^2 'excess' on the 2000 Up plot would have to successfully make it to the new 2006 West shell habitat to explain the results rather than random dispersal where some get lucky and find the new habitat. This precise directionality and success of emigrants is not plausible, but interplot migrations will be something to watch in the 2007 data.

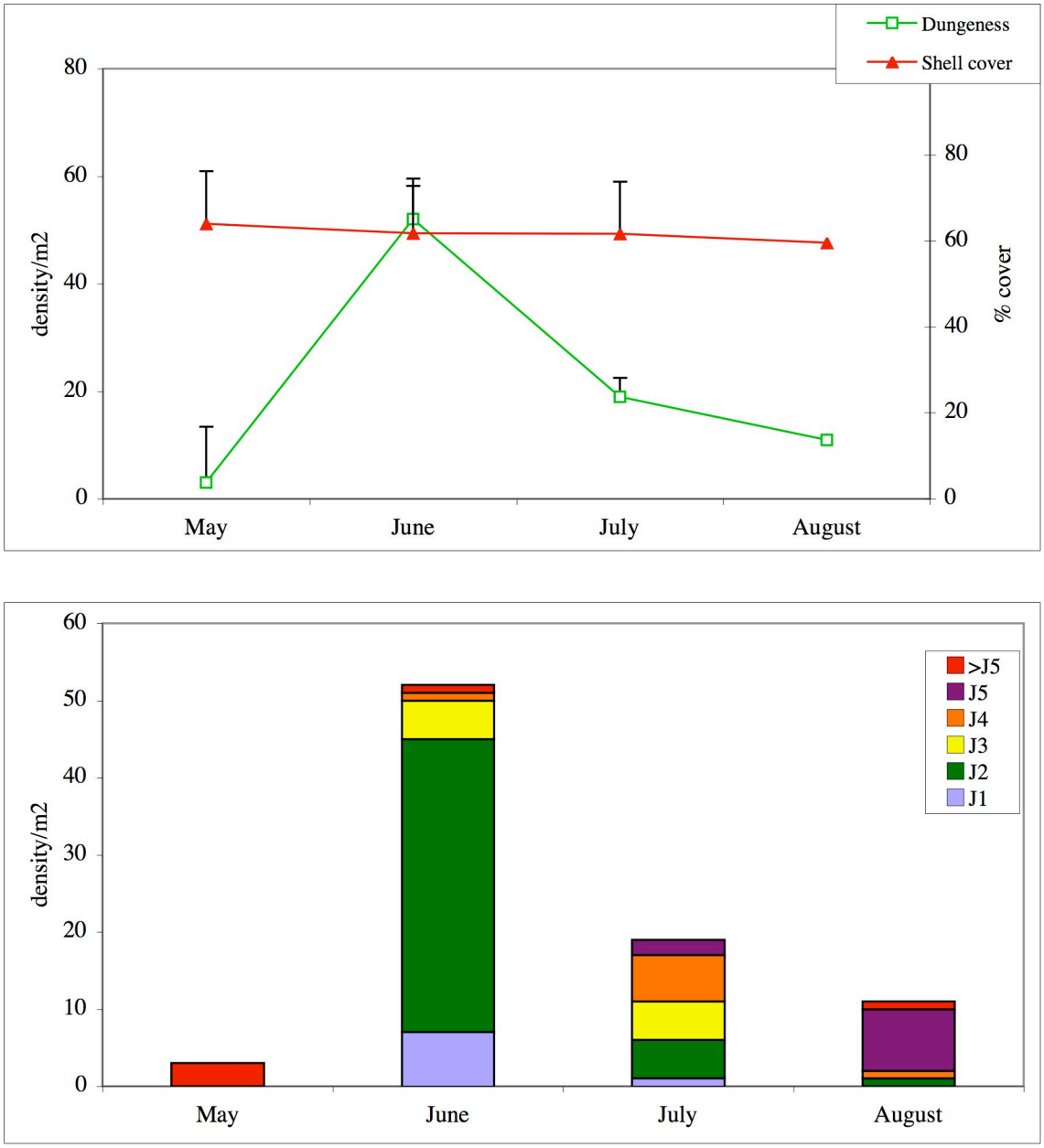


Figure 15. Summer 2006 crab data from 1995 Island plot: abundance compared to shell cover and instar size composition.

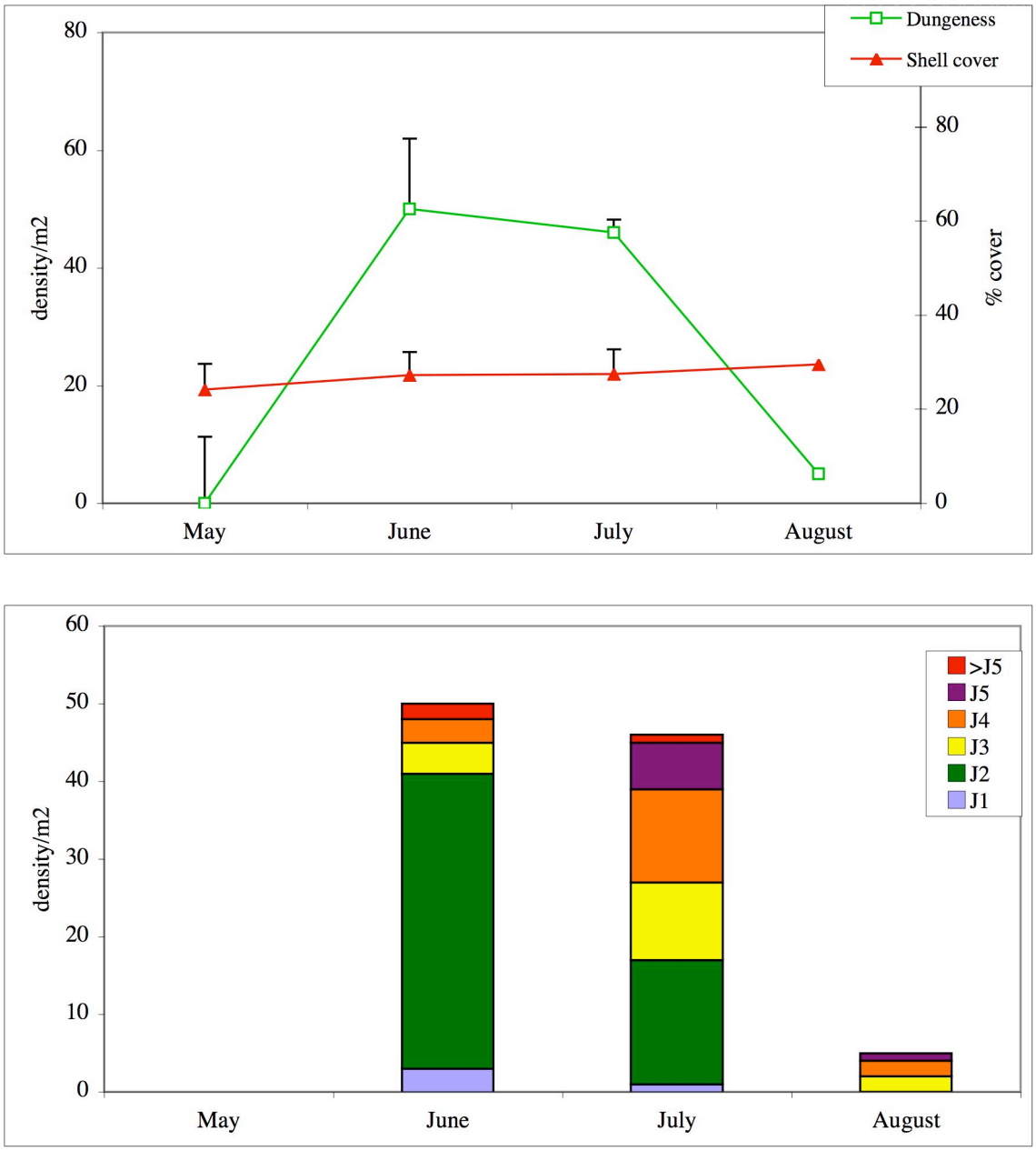


Figure 16. Summer 2006 crab data for 1996/1997 plot: abundance compared to shell cover and instar size composition.

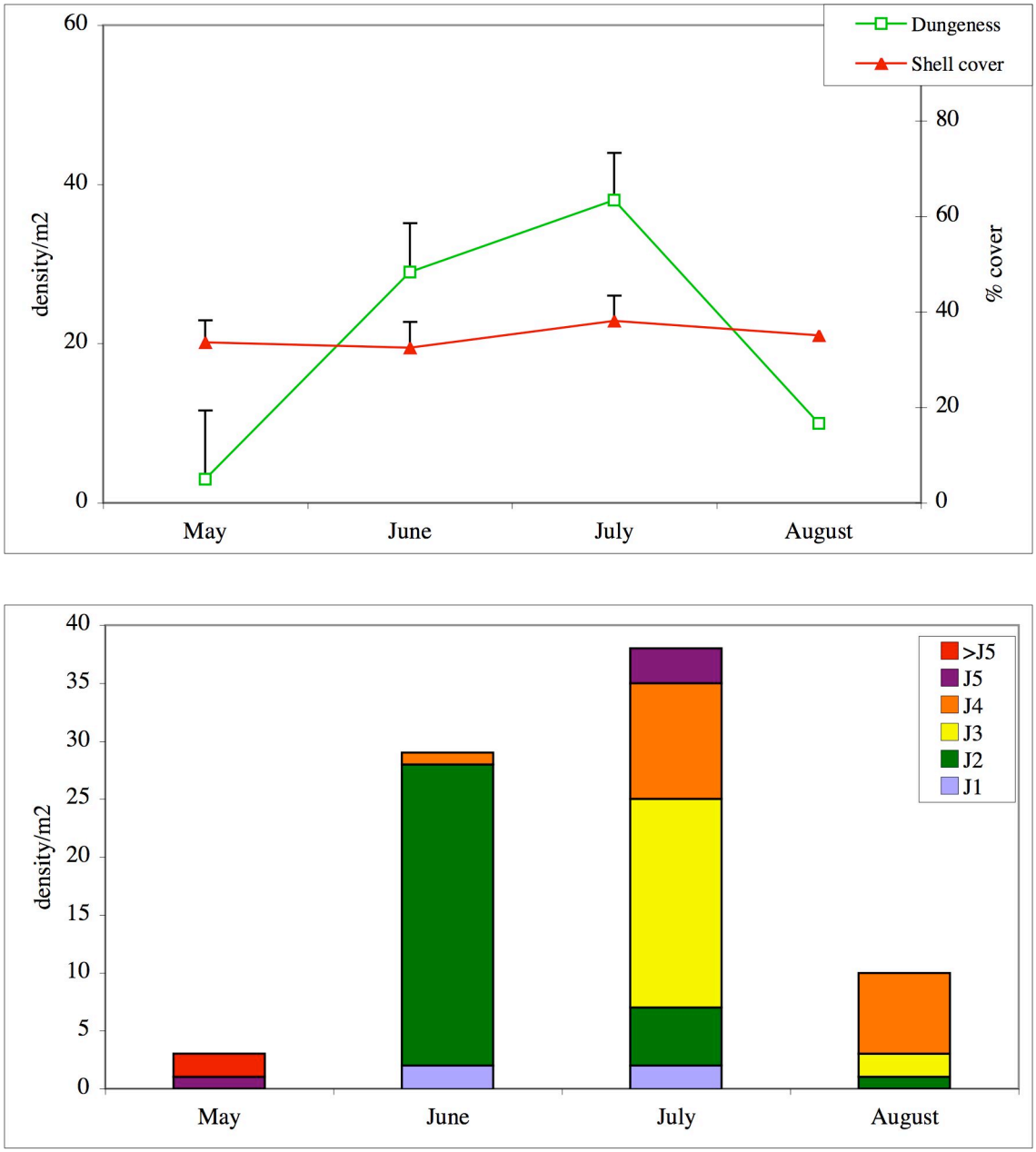


Figure 17. Summer 2006 crab data from 2000 Up plot: abundance compared to shell cover and instar size composition.

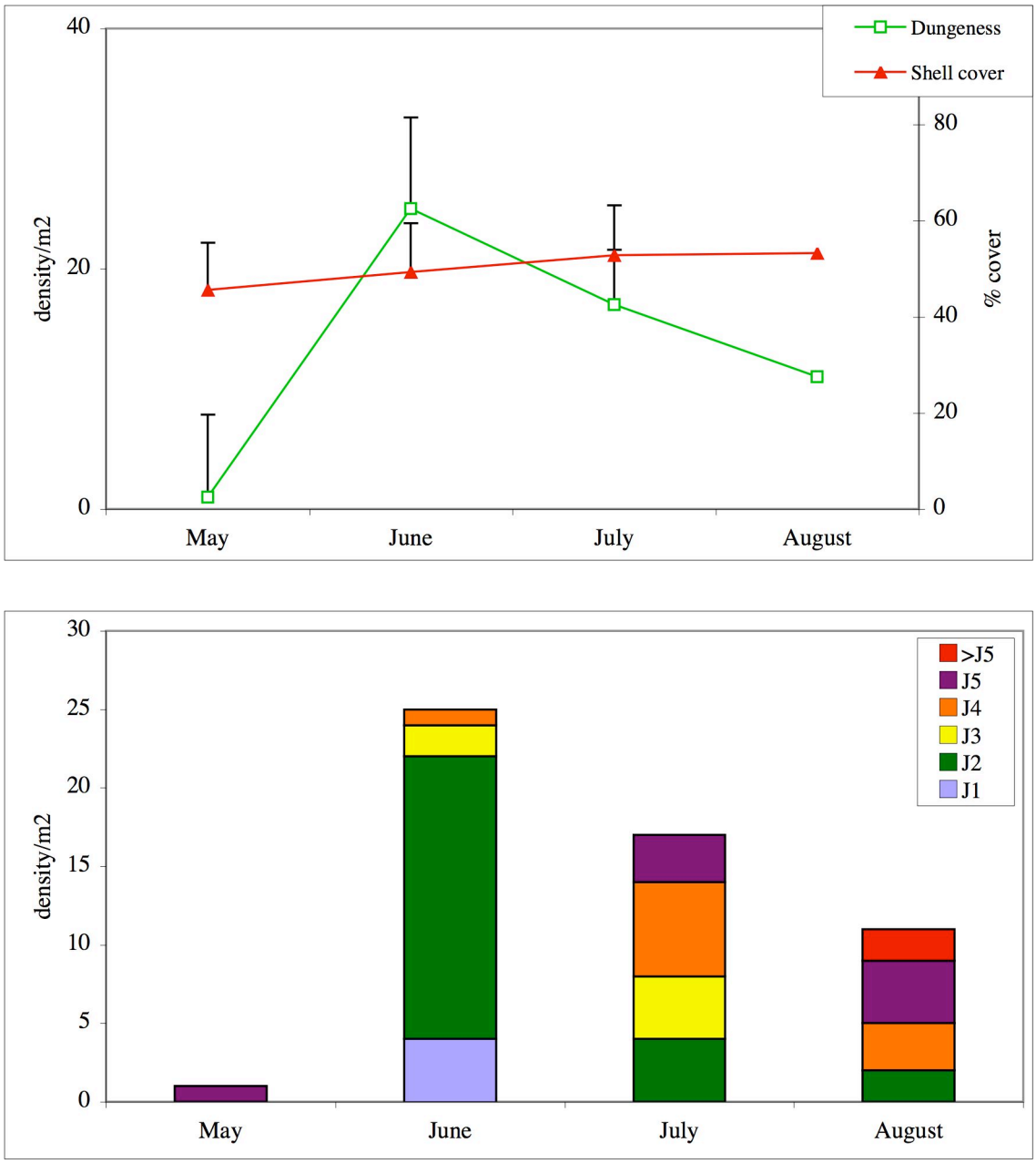
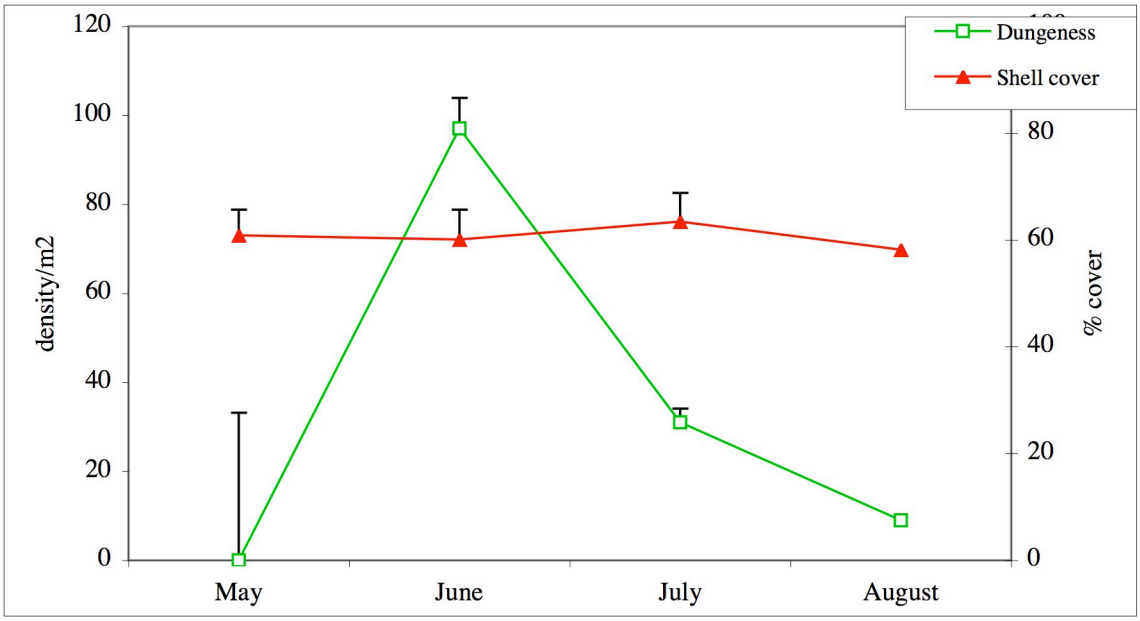


Figure 18. Summer 2006 crab data from 2000 East plot: abundance compared to shell cover and instar size composition.



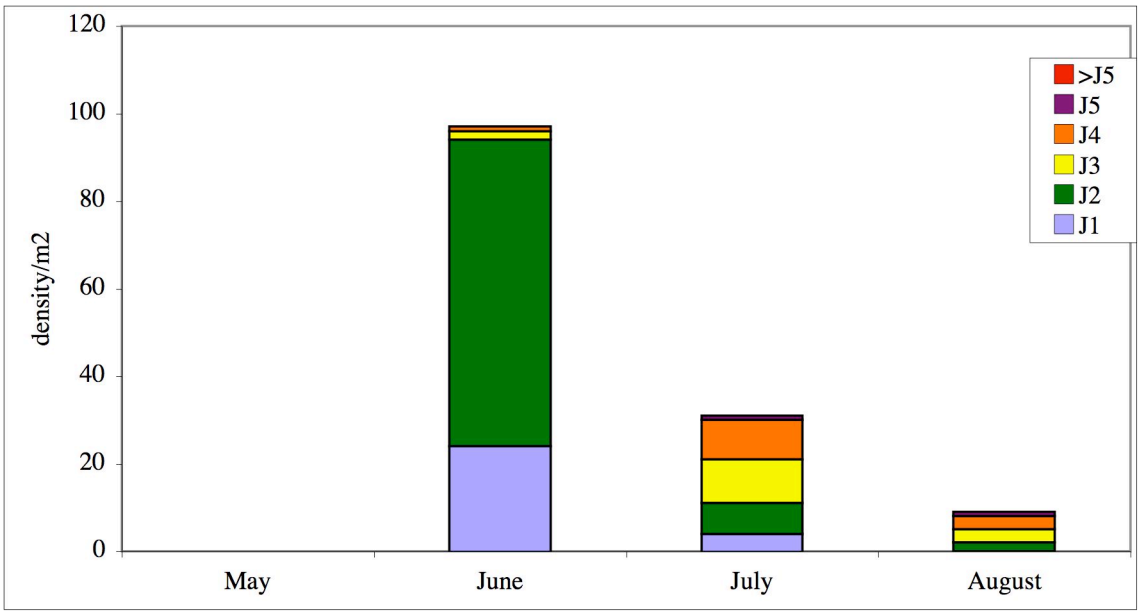
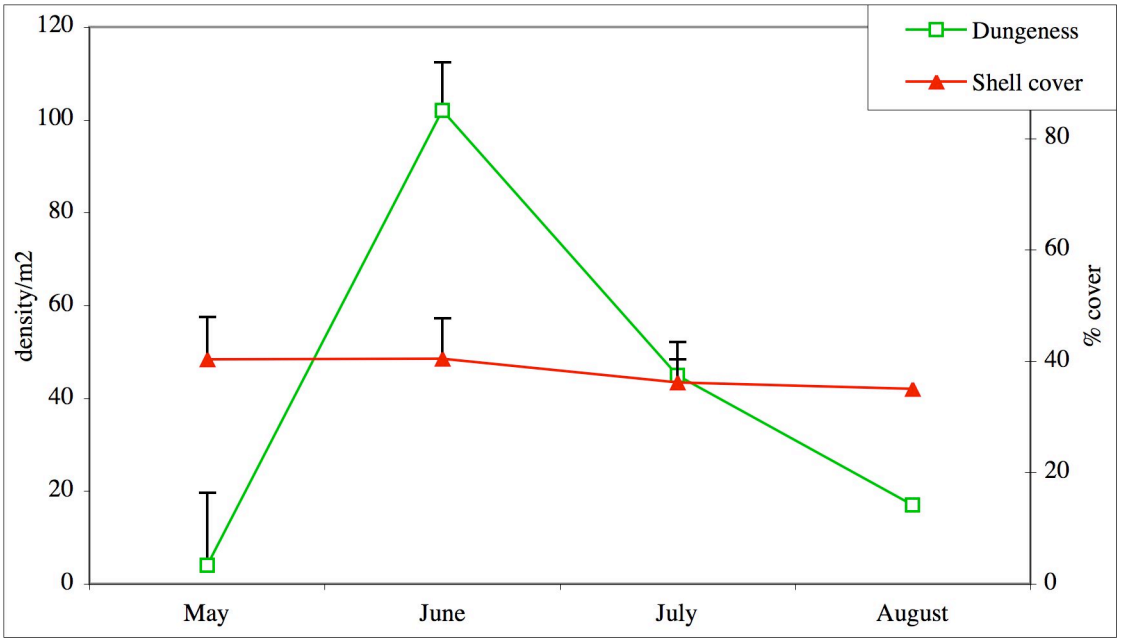


Figure 19. Summer 2006 crab data from 2003 Up plot: abundance compared to shell cover and instar size composition.



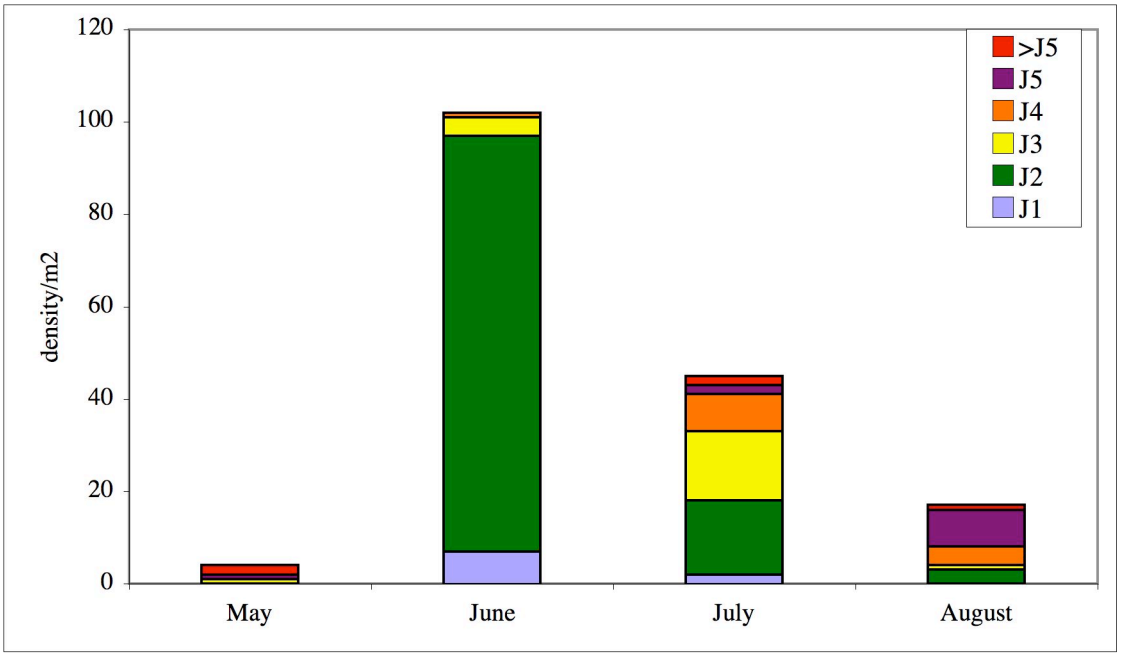


Figure 20. Summer 2006 crab data from 2003 Down plot: abundance compared to shell cover and instar size composition.

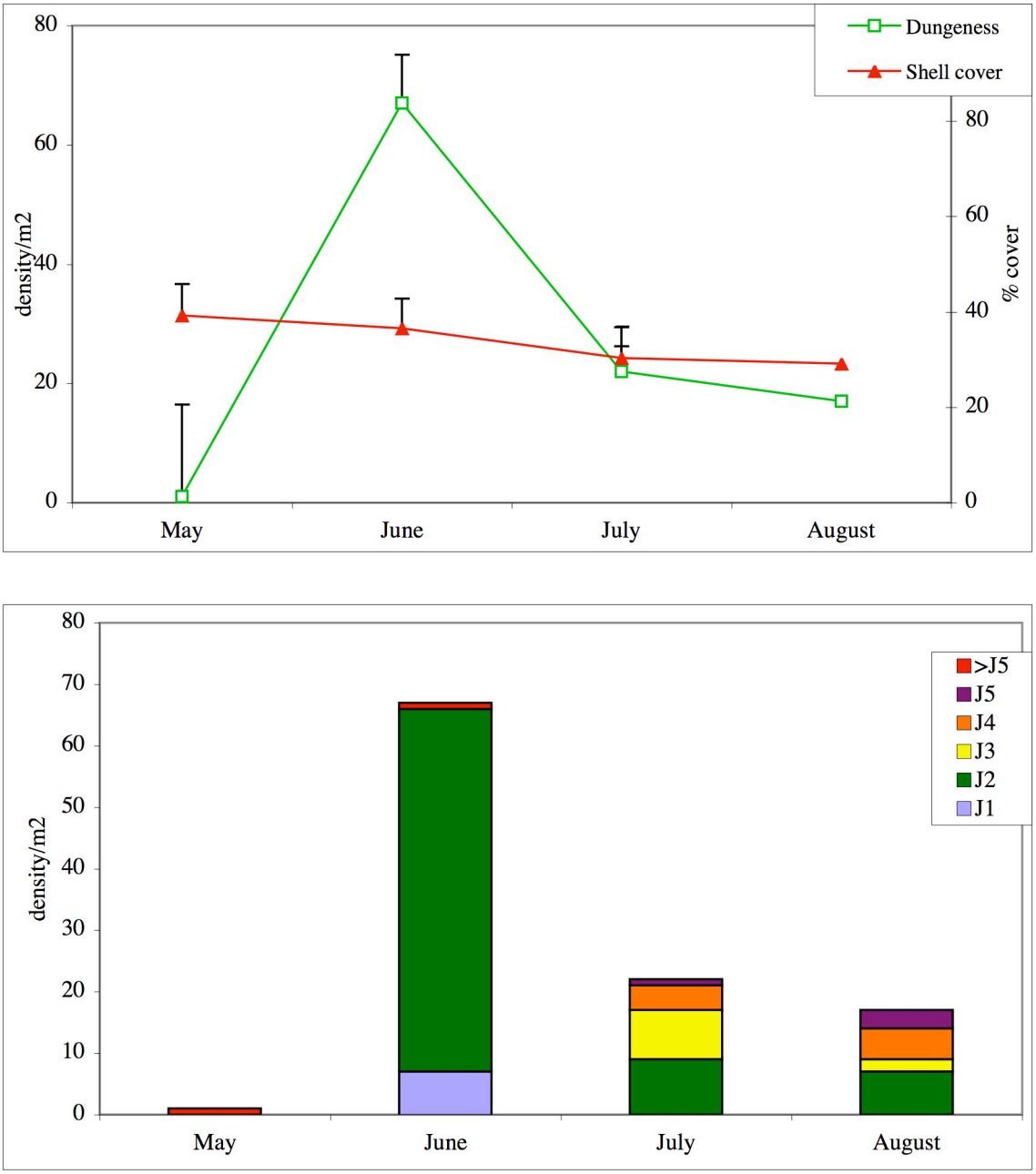


Figure 21. Summer 2006 crab data from 2003 East plot: abundance compared to shell cover and instar size composition.

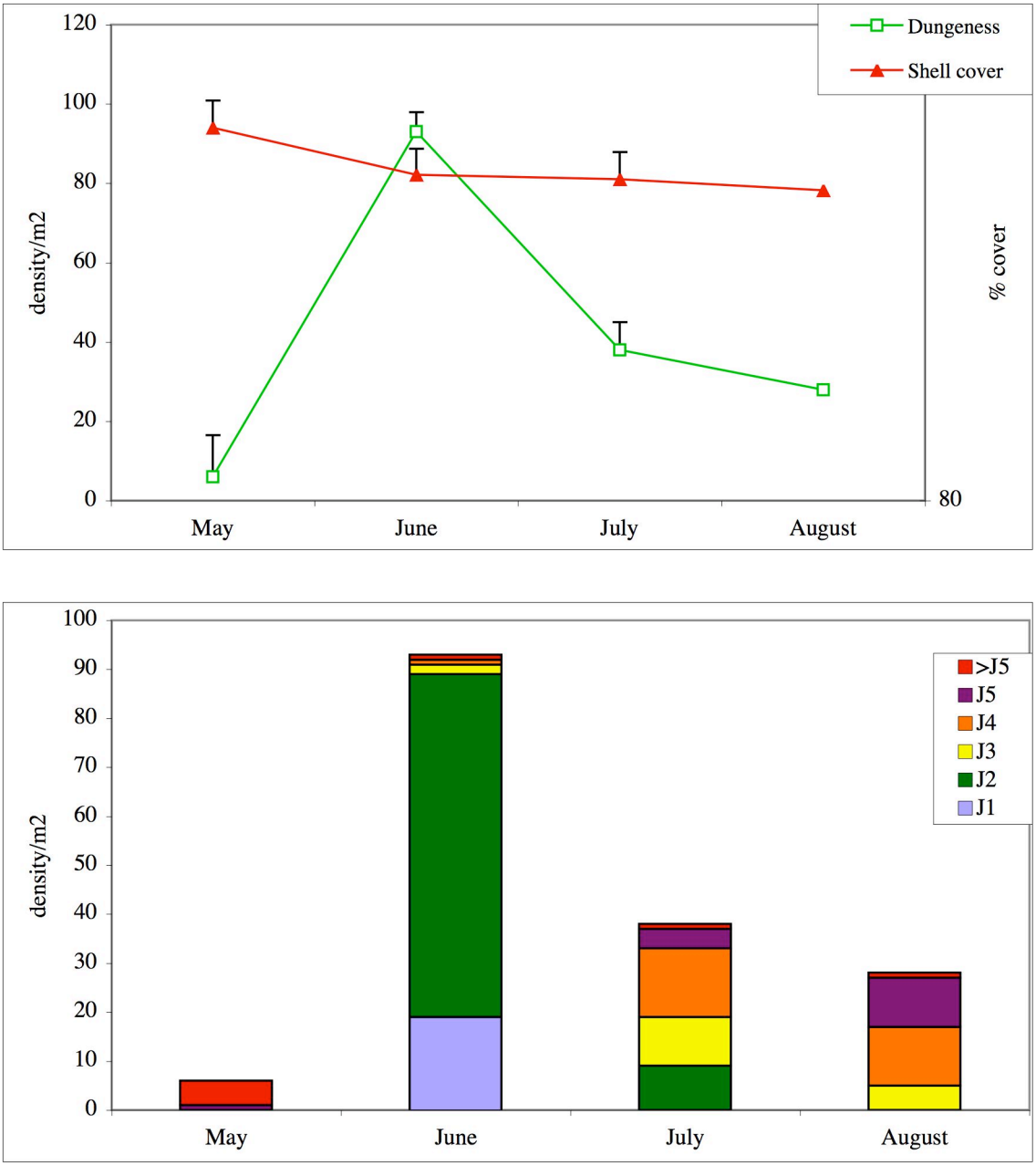


Figure 22. Summer 2006 crab data from 2006 East plot: abundance compared to shell cover and instar size composition.

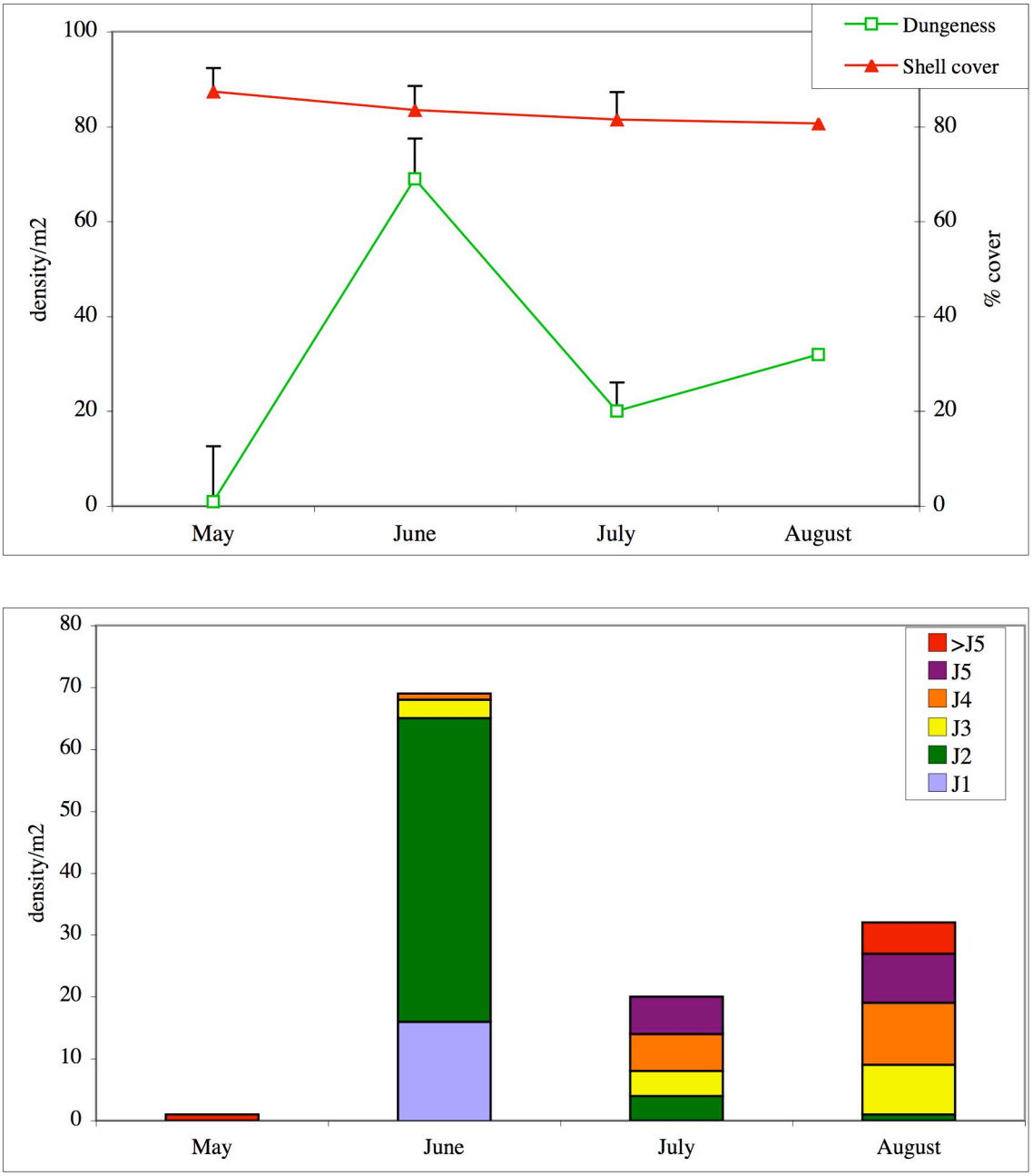


Figure 23. Summer 2006 crab data from 2006 West plot: abundance compared to shell cover and instar size composition.

4.4 Mortality

Mortality rates computed from 2006 data fall in the normal range for new shell and slightly higher than average (lower survival) for old shell habitat, fourth lowest since the project began in 1990 (Table 4). The r^2 values for the mortality function fit to crab abundance data showed poor fit for three of the plots (1996/1997, 2000 Up and 2006 West) and thus average mortalities from new and old shell in past years were used for data from these plots.

Table 4. Mortality rates and corresponding survival rates realized by new and old shell habitat from 1990 through 2006. Mortality on new shell was close to the historical average, while mortality on old shell habitat was low during summer 2006.

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
Avg	0.0189	52	0.0223	47
SD	0.0041	7	0.0070	12

4.5 Shell and Eelgrass Cover

Shell cover for all shell plots was flat, with less loss over the summer than usual for new shell (Figures 24-26). Slowed sinkage of mitigation habitat is certainly a benefit of the overlay strategy for shell placement. 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 1996/1997, 2000 Up and 2000 East plots (Figures 24 and 25).

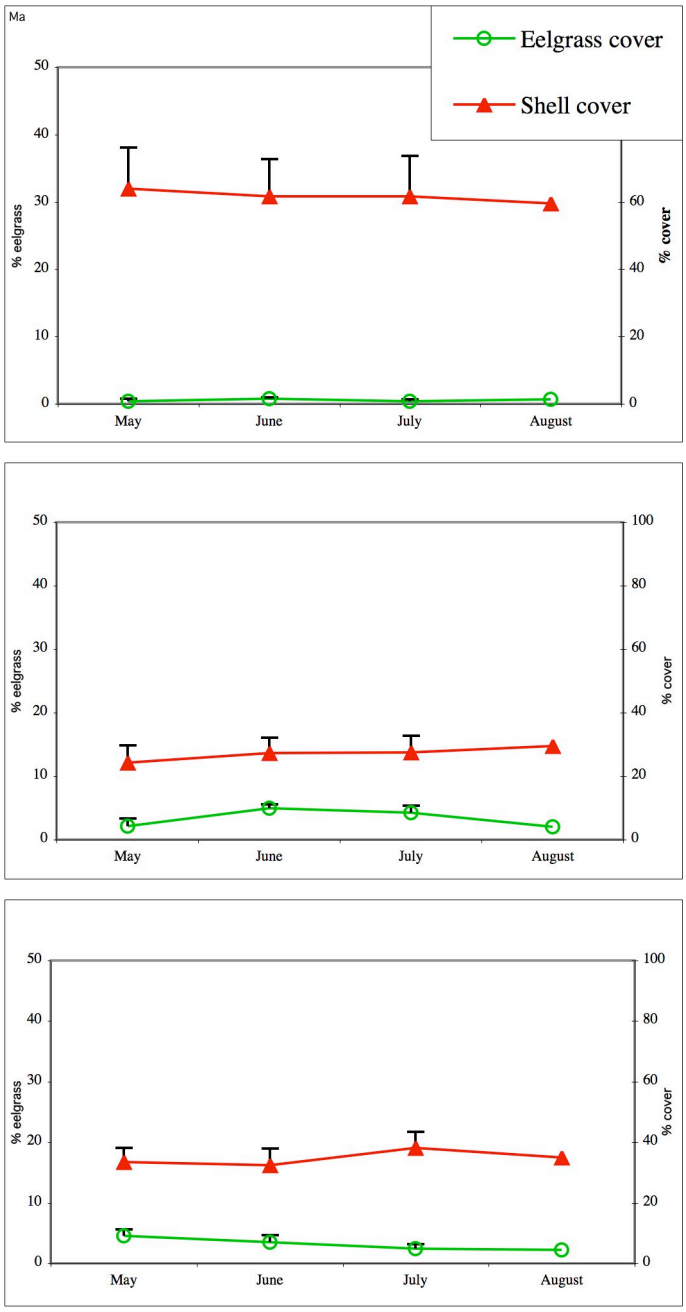


Figure 24. Oyster shell and eelgrass percent cover for the oldest three plots sampled during summer 2006: 1995 Island, 1996/1997, and 2000 Up.

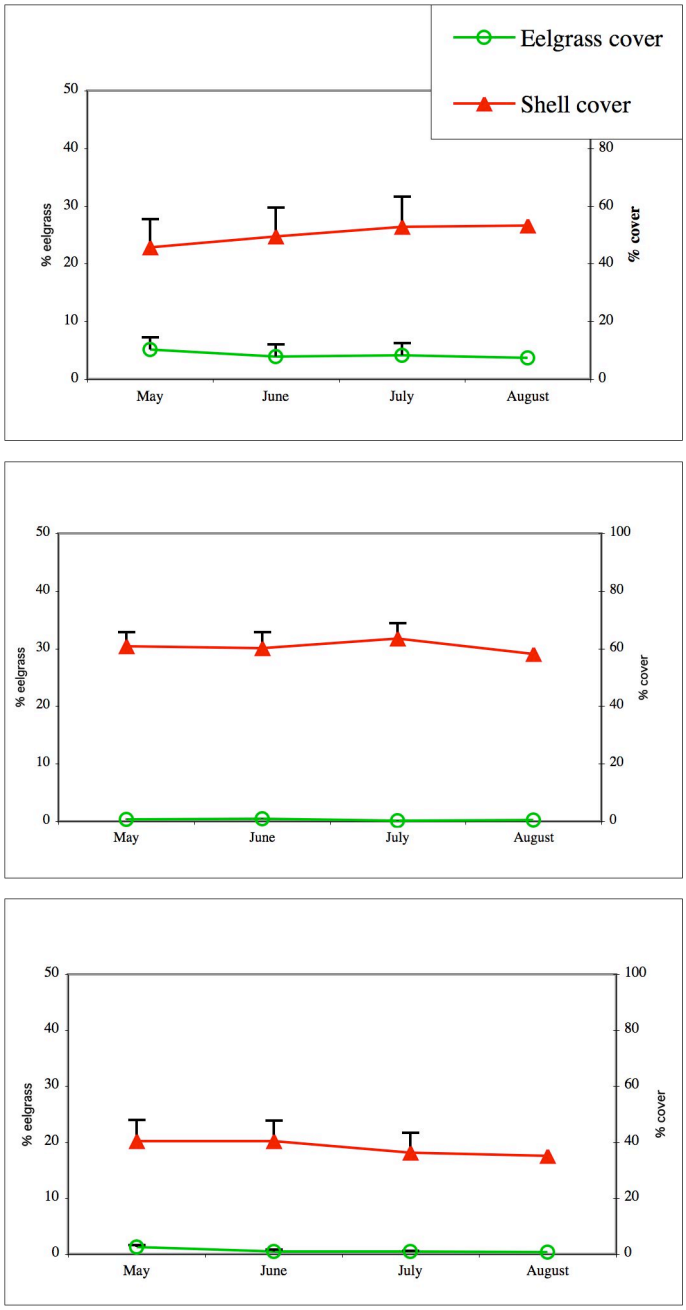


Figure 25. Oyster shell and eelgrass percent cover during summer 2006 for the 2000 East, 2003 Up, and 2003 Down plots.

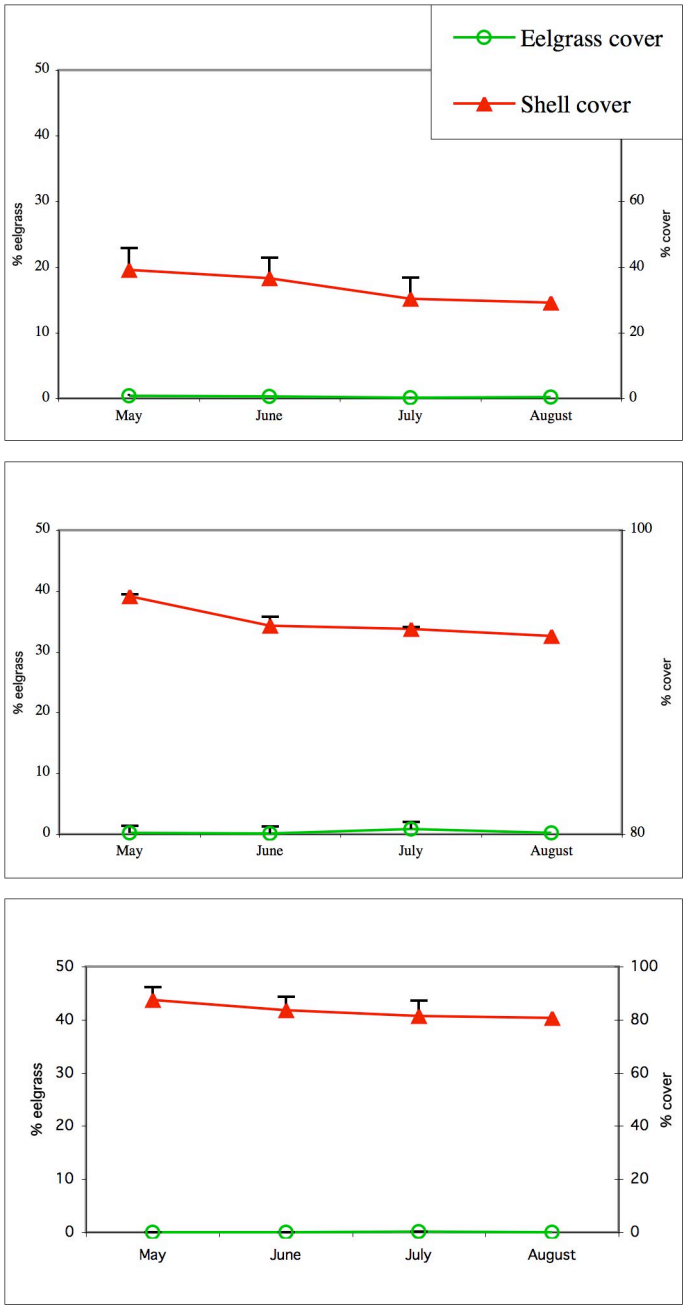


Figure 26. Oyster shell and eelgrass percent cover during summer 2006 for the three newest plots: 2003 East, 2006 East and 2006 West.

4.6 Oyster Spat Growth and Survival

Survival was measured as spat count per parent shell, which showed wide variation from less than 10 per shell to almost 100 in a few cases (Figure 27). Oysters experienced

high survival rates and strong growth patterns. There was no significant change in spat count over time during this short sampling period, since differences could not be detected given the wide variability. The average number of spat per parent shell dropped by 10-15 spat per shell, showing the low mortality. There were no detectable differences among the 5 subplots, as clearly seen from the widely overlapping error bars (standard deviations) around count of spat per parent shell (Figure 27). The data so far are from a very small window of early and rapid development and counts per shell will likely diverge as overgrowth occurs, affecting survival of those losing the space competition battle.

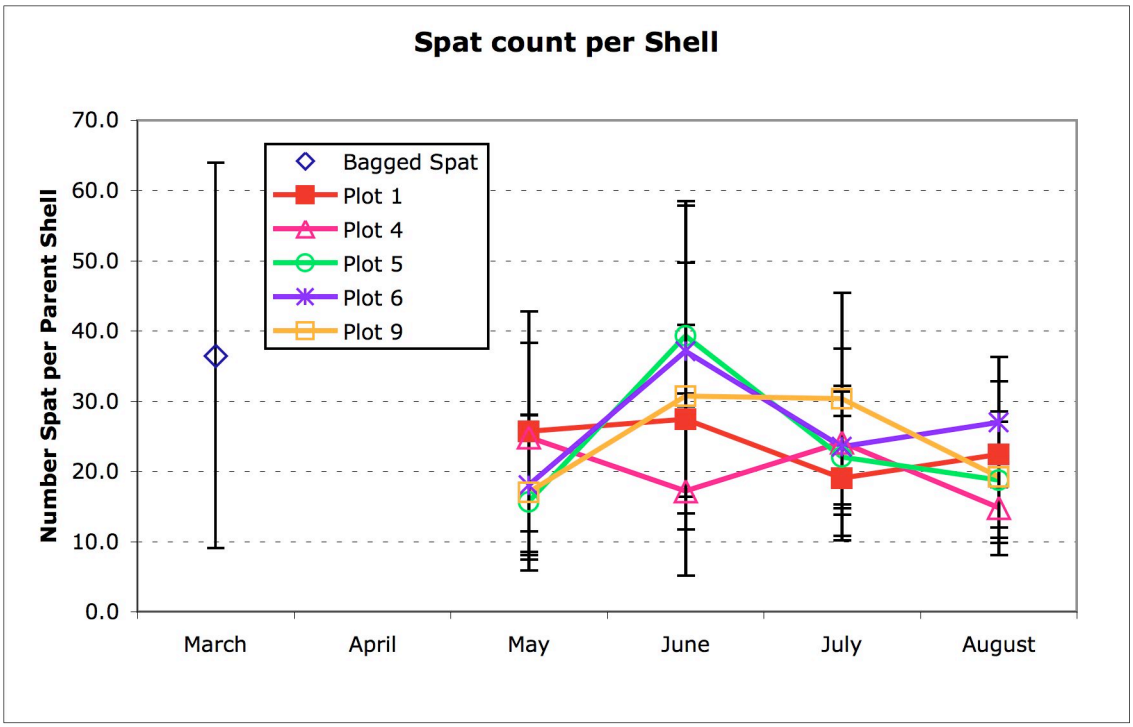


Figure 27. Mean and standard deviation of live oyster spat per parent shell during summer 2006 for the five subplots of 2003 Up where live spat was planted..

Growth was rapid and crowding was evident by August 2006 (Figure 28). Average size of live oysters went from 7mm at time of planting in late March to almost 40mm in mid August (Figure 28). Slower growth is evidenced between March and May due to lower temperatures followed by faster growth from May-August. No differences among the five plots can be seen after so short a monitoring period. Size variability as shown

visually (Figure 29) and by standard deviation about the mean (Figure 28), which increased over the course of the summer, probably due to crowding and differential quality of conditions on a given parent shell. Presumably, smaller oysters are those becoming crowded out and experiencing loss of optimal growth conditions and are expected to experience further decline as growing conditions deteriorate for the smallest juveniles. Differential mortality during the fall and winter is expected, which should decrease size variability since smaller individuals will likely suffer higher mortality rates. Standard deviation about the mean size increases over time during summer 2006, as competitive dominants optimize their own local growth conditions at the expense of the smallest ones.

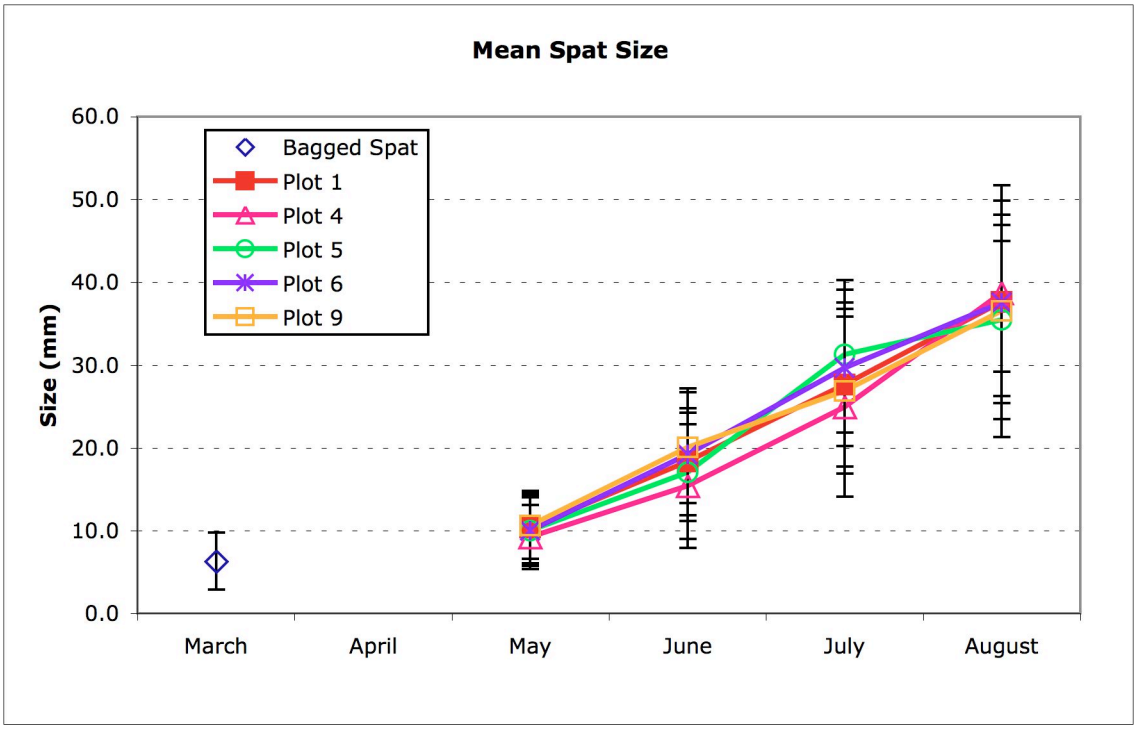


Figure 28. Mean spat size for each of the five live oyster experimental subplots within the 2003 Up habitat, showing growth over the first summer. March measurements were taken before placement in the field.

Figure 29. Live oysters in mid August 2006. Top photo shows growth variation and disadvantage to spat growing on bottom side of parent shell. Bottom shows size variation and three dimensionality of habitat starting to develop.

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 were starting to be visible by August 2006. Resulting percent shell cover between subplots with and without live oysters will continue to be compared in order to determine if live oysters increase habitat longevity by creating a more sustainable refuge for juvenile crab.

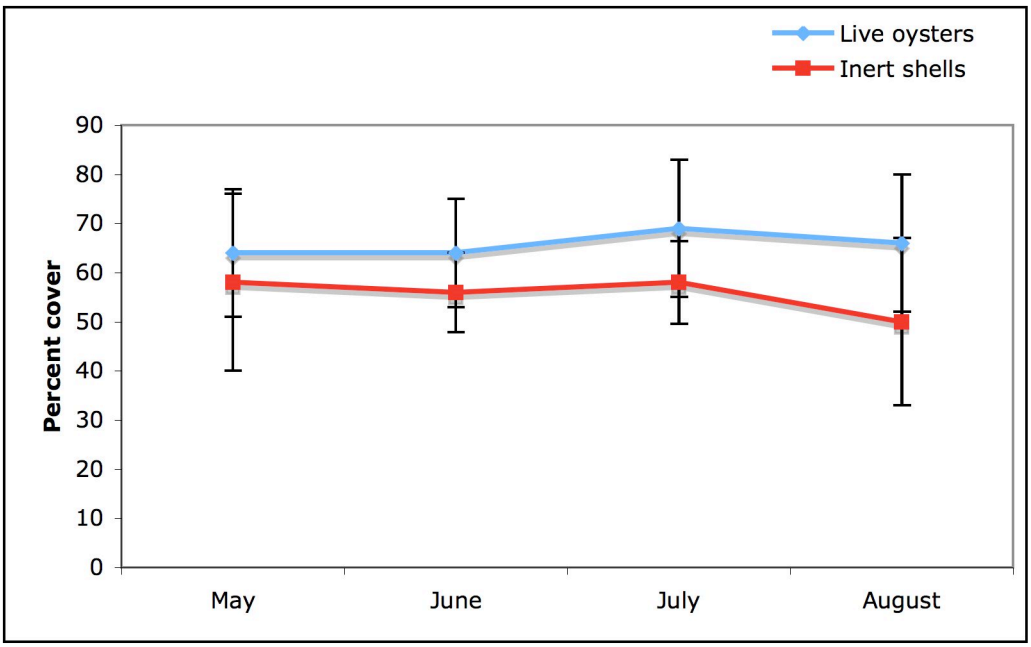


Figure 30. Percent shell cover of subplots with and without planted oyster spat over summer 2006. Live oysters were planted on subplots 1,4,5,6, and 9 and subplots 2,3,7,8,and 10 were left as controls.

5. Summary and Conclusions

The 2006 summer production yield of 2.77 + 1.1 million juvenile Dungeness crab was the fourth highest since mitigation efforts began in 1990 and cumulative production has now reached 26.9 +6 million crabs over the 18 year project history. On a square meter of habitat created basis, however, 2006 productivity was disappointingly low. While newly constructed shell habitat generally yields an average of 21 crabs/m^2, with a range of 3 -52 crabs/m^2), 2006 habitat produced only 9 crabs per square meter of habitat. The other four newly constructed plots with less than 12 crabs/m^2 yield in their first year

(1996, 1997, 1998, and 1999) all suffered from low shell longevity and their low juvenile crab production could be explained by diminished area of persisting effective crab refuge space. The 2006 habitat, by contrast, experienced very little loss of habitat and showed a relatively flat shell cover over time relationship for its first summer compared to most new shell habitats. The low yield per unit area is probably best explained by diminished larval supply to the plots, although our data cannot distinguish between early post settlement processes and true larval supply.

Of the 2.77 million crabs produced during summer 2006, 46% were from the two new 2006 shell plots. The 2006 East plot, which overlaid the southern border of the 1996/1997 plot, produced 0.82 + 0.25 million crabs and the 2006 West plot, which overlaid the former 1999 Up plot, produced 0.46 + 0.12 million J4 crabs. The three plots constructed in 2003 made up 30% of the total 2006 production, yielding 0.41 + 0.22, 0.25 + 0.10, and 0.19 + 0.11 million from 2003 Down, 2003 Up, and 2003 East plots respectively. The 1995 Island plot produced 0.24 + 0.13 million crab. The 1996/1997 plot produced 0.22 + 0.11 million crab with decreased surface area relative to past years, due to the overlay of new shell and consequent change in southern boundary of the plot. The 2000 plots produced 0.12 + 0.06 and 0.07 + 0.03 million crabs from 2000 East and 2000 Up.

The live oyster spat experiment was initiated in late March 2006 on the 2003 Up mitigation plot. Survival and growth over the first summer of growth were strong and consistent among the 5 subplots, with oysters exhibiting growth of about 2.7 mm/mo between March and May and 9.2mm/mo between May and August. Although no differences in percent cover are yet detectable between subplots planted with live oysters and those without, trends in the direction of increased shell cover appeared to be developing by August. Summer 2007 data will be much more informative as the oysters will have overwintered on the plot and may be large enough to start functioning as juvenile Dungeness crab refuge habitat. Some predation by crab on the small oyster spat took place as evidenced by chipping and shell gaping, but juvenile oyster survival rate exceeded expectations.

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