Grays Harbor Shell Mitigation Project

2005 Annual Crab Production Report

DRAFT REPORT

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Executive Summary

2005 mitigation field efforts yielded a total of 1.97 million (± 0.76) juvenile J4 Dungeness crab production units. This fifteenth year of shell mitigation in South Channel of Grays Harbor brings the total juvenile crabs produced since the project began up to 24.2 (± 4.9) million crabs. Sampling was conducted monthly May through August, towards the end of each month. Two of the highest producing plots were recently constructed, in their third year post-construction: the 2003 Up and 2003 Down plots. The next two highest producing plots were much older: the 1995 Island, and 1996/1997 plots. These four plots produced 72% of the total 1.97 million realized for summer 2005. The 2000 Up, 2000 East, 2003 East, and 1999 Up plots contributed 24% of the total, while the 1995 Mainland and 1997 East plots together produced only 87,000 crabs, or 4% of the total.

Production per meter squared averaged 10.2 crabs /m^2 for summer 2005, which meets the original mitigation target. Mortality for summer 2005 was low, and many plots enjoyed much higher than average survival rates, particularly the 1996/1997 and 1995 Island plots. Shell cover was again a strong predictor of crab production, as well as early settlement patterns. Tidal elevation was not correlated with productivity, nor was production /m^2 or eelgrass abundance. The lack of correlation with crabs/m2 of habitat could be due to the highly variable shell cover this year and extreme patchiness of some areas.

The overlay strategy continues to be effective and is recommended for shell placement options in 2006. The 1999 Up and 1996/1997 plots are the best candidates for new shell due to their historical high production rates, their sediment stability and favorable tidal elevation. Both have exhibited loss of shell cover, with the 1999 Up plot down to an average of about 15% shell cover and the 1996/1997 plot at less than 28% overall but very patchy distribution of shell within the plot.

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Grays Harbor Shell Mitigation Project

2005 Annual Crab Production Report

I. Scope and Objective

The primary objectives for summer 2005 field efforts were 1) to assess juvenile crab usage and shell cover for mitigation plots in order to obtain production estimates, 2) to assess potential for live oyster growth on mitigation plots, and 3) to revisit PacMan mitigation site and evaluate its suitability for future shell placement. Production estimates for J4 juveniles were computed using monthly densities and size composition of early benthic phase *Cancer magister*. While data on all sizes of crab was collected, only field densities of J2 and J3 crab were used to compute J4 production by calculating and applying appropriate growth and natural mortality rates. Percent shell cover data were also collected for all plots which had a significant percentage ($\geq$ 20%) of shell as surface substrate. Shell cover serves as a measure of protective habitat for juvenile Dungeness crabs. Abundance of *Hemigrapsus oregonensis* and presence of eelgrass, both of which can influence production of juvenile Dungeness crab, were surveyed and recorded. Live oysters and the PacMan site were assessed by field site observation.

II. Background

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 (Fig. 1) 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 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. This target goal was met in 2001 and the mitigation for construction impacts completed. Mitigation for ongoing operation and maintenance impacts continues, and total crab production by the mitigation project from 1990- 2005 is over 24 million J4 juveniles.

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. 1993a, 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 J5 instar (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.

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 (Visser 1997, 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, Visser et al. 2004). 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 ≥ 1 year since construction is much greater than before 1998. 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 every few years, and to investigate strategies that might improve shell longevity such as growth of live oysters.

Figure 1. Crabs typically found in ACOE shell mitigation samples (clockwise from right: J5, J4, J3, J2, J1 Dungeness instars and megalopae. Photo on right shows large male *Hemigrapsus oregonensis*).

III. Methodology

Field protocol

The standard sampling protocol used in past years was followed to obtain juvenile *Cancer magister* and *Hemigrapsus oregonensis* 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, four sampling trips were made once monthly beginning in May 2005. The ten plots sampled during summer 2005 were the 1995 Island, 1995 Mainland, 1996/1997 Overlay, 1997 East, 1999 Up, 2000 Up, 2000 East, 2003 Up, 2003 Down, and 2003 East 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 plot which did not retain ≥ 20% of shell remaining on the surface was not sampled. These areas yield little to no production of juvenile Dungeness crab and do not merit sampling effort as there is little refuge available to the crabs, and thus extremely low juvenile densities and thus productivity.

A sampling crew consisting of 6-7 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 ten plots sampled in 2005 to obtain monthly crab density data for each plot. (Only nine replicates were possible for 1995 Mainland and 1997 East plots due to loss of shell along boundaries and consequential decreased size of plots.)

Table 1. Sampling dates, approximate times, and estimated tidal heights (based on data for Markham Point) during data collection during summer 2005 at South Channel crab mitigation sites. There were three sampling dates each month; the initial tide in May was used for field site preparation.

Date	Low tide time	Low tide height (ft)	Sunrise time	Shoalhunter departed dock
May 23	7:28AM	-2.0	5:32	5:00
May 24	8:12	-2.4	5:31	5:30
May 25	8:57	-2.6	5:30	5:30
May 26	9:44	-2.5	5:29	6:00
June 22	7:55	-2.9	5:22	5:00
June 23	8:43	-3.0	5:22	5:15
June 24	9:29	-2.9	5:22	5:45
July 21	7:38	-2.8	5:43	4:45
July 22	8:25	-2.9	5;44	5:15
July 23	9:10	-2.6	5:45	6:00
August 19	7:17	-2.3	6:19	4:45
August 20	8:02	-2.2	6:20	4:45
August 21	8:45	-1.9	6:22	5:15

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).

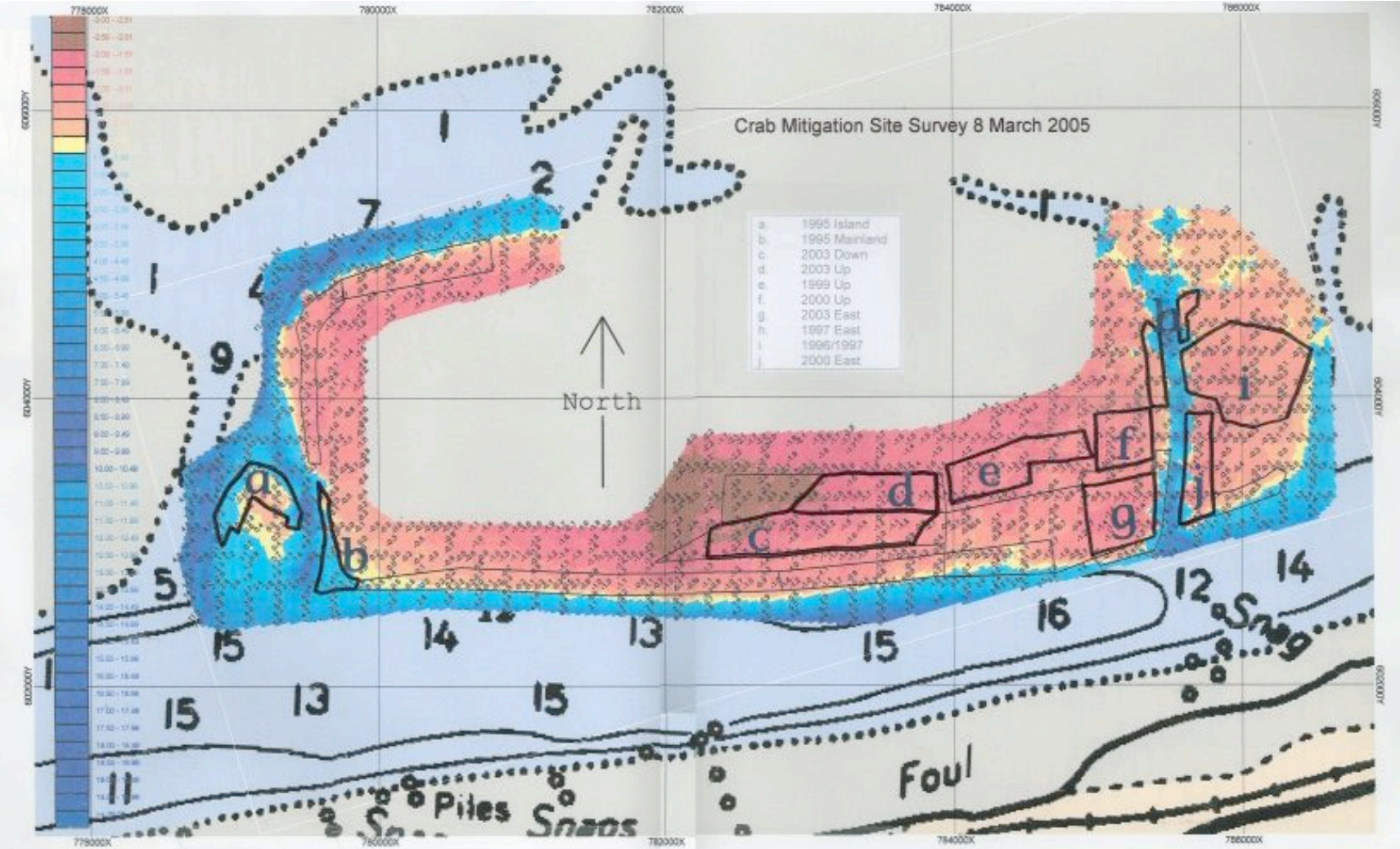

Figure 2. Map of the Army Corps of Engineers shell mitigation plots in South Channel, Grays Harbor, WA, as of March 8, 2005

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 3). All crabs retained by the screen were placed into bags to be identified to species and measured back on the ship after the tide rose. Crabs were identified to species, measured to the nearest 0.1 cm carapace width, and recorded. For *Hemigrapsus oregonensis,* gender and state of ovigery for females was also recorded.

Figure 3. Sampling procedure, showing screen with shell material from 0.1 m2 quadrat and sorting technique of rinsing and visual inspection for animals.

Estimates of amount of refuge area available within each plot were necessary in order to translate the crab density data into total number of crabs produced. Total amount of refuge space was computed by multiplying plot size by percent shell cover. These percent shell cover estimates were taken by 4 to 6 observers visually studying each of ten marked subplots (20m x 20m) throughout each of the ten plots sampled in 2005. The amount of shell remaining above the surface of the mud and therefore representing refuge space available to the juvenile crabs was recorded (Figures 4-6). Thus, the overall monthly shell cover estimate for each plot was based on 40-60 individual independent

Figure 4. Variation in shell habitat quality, showing approximately 1% and 10% coverage of mud surface.

Figure 5. Variation in shell habitat quality, showing approximately 50% coverage of mud surface.

Figure 6. Variation in shell habitat quality, showing approximately 95% coverage of mud surface.

estimates, resulting in a mean and a standard deviation as input for the production model. Only nine subplots were surveyed in the 1995 Mainland and 1997 East plots due to space constraints. Shell along the southern boundaries of these plots had completely sunk beneath the surface as of summer 2004, necessitating adjustment of plot boundaries to exclude plots with zero shell cover. Since crab production computations are based on average crab density and shell cover multiplied over total plot area, these changes required adjusting the total plot area to reflect the lost usable crab habitat as well.

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 (Figure 7). 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. Investigation of eelgrass distribution and abundance is underway 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. The conceptual basis of the mitigation project considers production estimates from shell plot sites as extra crabs produced in Grays Harbor as a direct result of the artificial habitat created by mitigation efforts, and the inherent assumption that this production is directly 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. We are building a dataset with enough timeframe to address some of these questions about if the apparent trends are consistent with shell coverage.

Figure 7. Field site perspective, showing patchiness of habitat and proximity of shell and eelgrass habitats and some live oysters.

Data analysis

Data from the field notebooks were entered 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. 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. 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), but this was not necessary for 2005 data, due to timing of larval settlement and timing of spring tides. Multiplying the density of surviving crabs by the effective refuge area (the product of total habitat area constructed and percent shell cover) gives the number of crabs produced by each plot for each month over the summer. Thus,

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

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.

IV. Results and Discussion

2005 Production

Mitigation efforts realized 1,971,469 (± 764, 003) juvenile 4th instar Dungeness crabs for summer 2005 (Table 2). Production from the three newest plots (constructed in spring 2003: the 2003 Up, Down, and East plots) contributed 46% of this total, 0.90 million J4s (Table 3). The four highest producing plots (in order of decreasing production: 2003 Up, 2003 Down, 1995 Island, and 1996/1997 plots) yielded about 72% of the total for the summer, 1.4 million J4s (Figure 9). These four plots yielded 0.30 – 0.49 million crabs each, for 25%, 16%, 16%, and 15% of production respectively. The 2000 Up, 2000 East, 2003 East, and 1999 Up plots produced between 0.08 and 0.15 million juvenile crabs each, which represents 4 – 8% of the annual total for each of these four plots. The 1995 Mainland and 1997 East plots together accounted for only 4% of the annual total and are prime candidates for being dropped from the sampling regime for summer 2006 efforts.

Early settlement accounted for about 21% of total production, which indicates late settlement, since sampling began in late May (the first field excavation samples were collected and processed May 24-26). The contribution of early settlement corresponds roughly to the production values, with the four highest producing plots having the four highest numbers of early settlers, the two next highest producing plots having the next two highest early settlers, etcetera, and the two lowest producing plots having the lowest numbers of early settlers. These data indicate that plot quality remains fairly consistent over the summer and that either the crabs select appropriate habitat from the beginning, or that initial colonization densities weigh heavily in the relative ranking of factors influencing total summer production. Area, shell cover, and survival rates are positively

correlated with total production, while elevation and per meter square production are very weakly correlated with total production for 2006 (Table 3).

All ten plots showed settlement of first juvenile instars in May, while 7/10 had J1 in June, 5/10 had J1 in late July, and 9/10 had J1 in late August (Figures 14-23). Seventy five percent of settlement occurred in May, and 11% in August. August typically exhibits this second settlement pulse in Grays Harbor, WA. June and July make up 9 and 5 % of annual settlement onto the mitigation plots respectively. Curiously, almost 30% of the May settlement pulse was comprised of individuals settling onto the 2003 East plot. The vast majority of total crab production, 96%, resulted from data collected in May and June, 82 and 14% respectively. July sampling efforts resulted in 3% of the annual total and August contributed only 1% of the 1.97 million total J4 crabs produced.

The top four producing plots are the same plots that yielded the four highest production values last year, as well as the top four in 2003. Plot size, and shell cover, but not tidal elevation, eelgrass cover, initial crab density, or plot age, help explain the production values realized by each plot in 2005.

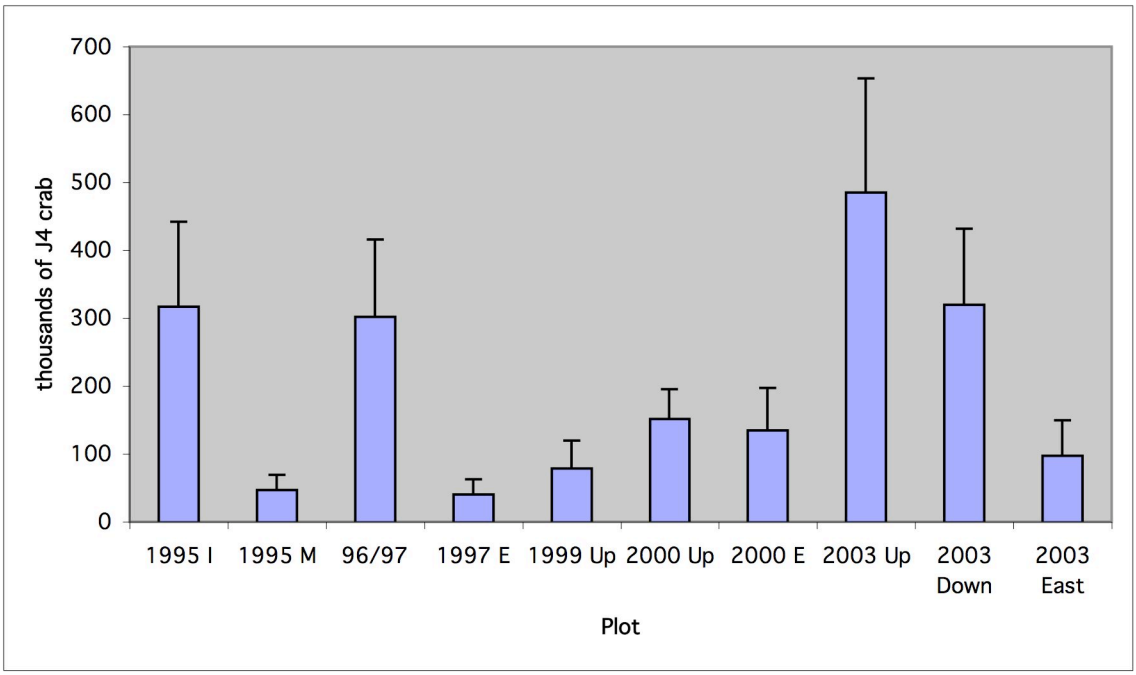

Figure 9. Annual crab production during summer 2005 by each of the ten plots sampled this season.

Table 2. Summary data for the 2005 production model; output is production of J4 instars.

Habitat	Mo	J2/m2	sd	Survival	% Shell	sd	Prod/Mo	Early	Total Prod	St. Dev.
1995 I	M	24	24	0.57	0.60	0.39	158000	66896	316718	125268
	J	11	8.8	0.57	0.66	0.40	78954			
	J	0	0	0.57	0.61	0.40	0			
	A	2	4.2	0.57	0.59	0.43	12868			
1995 M	M	47	32	0.44	0.15	0.13	22679	19248	46587	22155
	J	6	7.1	0.44	0.19	0.16	3776			
	J	0	0	0.44	0.22	0.18	0			
	A	2	4.4	0.44	0.14	0.12	884			
96/97	M	17	14	0.83	0.25	0.16	152753	106813	302249	113777
	J	3	4.8	0.83	0.29	0.16	31474			
	J	1	3.2	0.83	0.31	0.18	11210			
	A	0	0	0.83	0.26	0.17	0			
1997 E	M	36	33	0.34	0.27	0.23	23786	13638	40086	22307
	J	3	7.1	0.34	0.36	0.29	2661			
	J	0	0	0.34	0.36	0.28	0			
	A	0	0	0.34	0.34	0.26	0			
1999 Up	M	39	22	0.50	0.11	0.09	50772	19350	78286	41145
	J	3	4.8	0.50	0.12	0.07	4063			
	J	1	3.2	0.50	0.20	0.12	2237			
	A	1	3.3	0.50	0.16	0.10	1864			
2000 Up	M	30	12	0.46	0.52	0.17	99652	27748	151251	43799
	J	7	8.2	0.46	0.53	0.18	23850			
	J	0	0	0.46	0.63	0.11	0			
	A	0	0	0.46	0.56	0.17	0			
2000 E	M	28	25	0.36	0.55	0.33	75035	33382	134350	62448
	J	7	8.2	0.36	0.59	0.34	20117			
	J	2	4.2	0.36	0.60	0.35	5817			
	A	0	0	0.36	0.52	0.34	0			
2003 Up	M	62	52	0.50	0.58	0.16	361389	70788	485386	167876
	J	5	9.7	0.50	0.58	0.16	29216			
	J	4	9.7	0.50	0.60	0.16	23993			
	A	0	0	0.50	0.51	0.16	0			
2003 D	M	51	39	0.37	0.43	0.18	203361	42878	319692	112428
	J	17	18	0.37	0.44	0.20	69265			
	J	1	16	0.37	0.45	0.19	4189			
	A	0	0	0.37	0.34	0.16	0			
2003 E	M	36	33	0.37	0.27	0.21	57534	19644	96864	52799
	J	9	9.9	0.37	0.29	0.17	15414			
	J	2	4.2	0.37	0.36	0.21	4272			
	A	0	0	0.37	0.31	0.	0			
									1971469	764003

Table 3. Mitigation data for plots sampled in Summer 2005 ranked by productivity. Production/m^2 here is corrected for shell cover, so it is # crabs per unit of 100% shell cover. (Production per square meter used elsewhere in the paper is production per meter of total habitat within each plot.).

Plot	Area (m2)	Max. area	Elev. (ft > MLLW)	Prod/m2 (# J4)	Hist Prod/m2	Shell %	Surv rate	Early (mil J3)	Prod (mil J4)	% Prod
2003Up	20145	20145	1.1-3.1	41	31-71	57.75	0.50	0.07	0.49	0.25
2003D	25423	25423	0.7-2.4	29	16-50	41.50	0.37	0.04	0.32	0.16
95 I	19051	21000	-1.9-0.0	27	7-20	62.50	0.57	0.07	0.32	0.16
1996/97	42662	48944	0.1-0.9	27	11-48	27.75	0.83	0.11	0.30	0.15
2000Up	13912	13912	0.9-1.3	21	9-57	56.00	0.46	0.03	0.15	0.08
2000 E	13695	14553	0.7-1.3	18	5-53	56.50	0.36	0.03	0.13	0.07
2003 E	16126	16126	0.8-1.4	22	17-55	30.75	0.37	0.02	0.10	0.05
1999Up	22858	39920	0.8-1.6	29	17-59	15.25	0.50	0.02	0.08	0.04
1995M	7479	73000	-1.7-0.0	42	10-22	17.50	0.44	0.02	0.05	0.02
1997 E	7224	23050	-0.5-0.8	20	3-52	28.00	0.34	0.01	0.04	0.02
Sum								**0.42**	**1.97**	

Cumulative production values

Total production of juvenile Dungeness crab from the South Channel shell mitigation plots is over 24 million J4 individuals thus far (Table 4, Figure 10). A little over half of this production is from plots in their initial year after construction (58.4%) while the remaining 41.6% is from old plots one or more years post-construction. The same information is shown in graphical form (Figure 11) where the contribution of new and old shell to each year's production total can be compared by bar color. The relative contribution of shell older than one year post-construction increases every year. This old shell habitat remains viable juvenile Dungeness crab refuge, primarily due to the absence of competition from *Hemigrapsus oregonensis* and the consequent release from avoidance behavior (Banks and Dinnel 2000, Visser 1997). The overlay strategy for new shell placement also seems to contribute to shell longevity and habitat stability, causing habitat to function as viable refuge space several years after construction.

Table 4. 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, not 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	1,971,469	1,971,469	764,003
Total	14,120,458	10,073,292	24,193,748	4,925,021

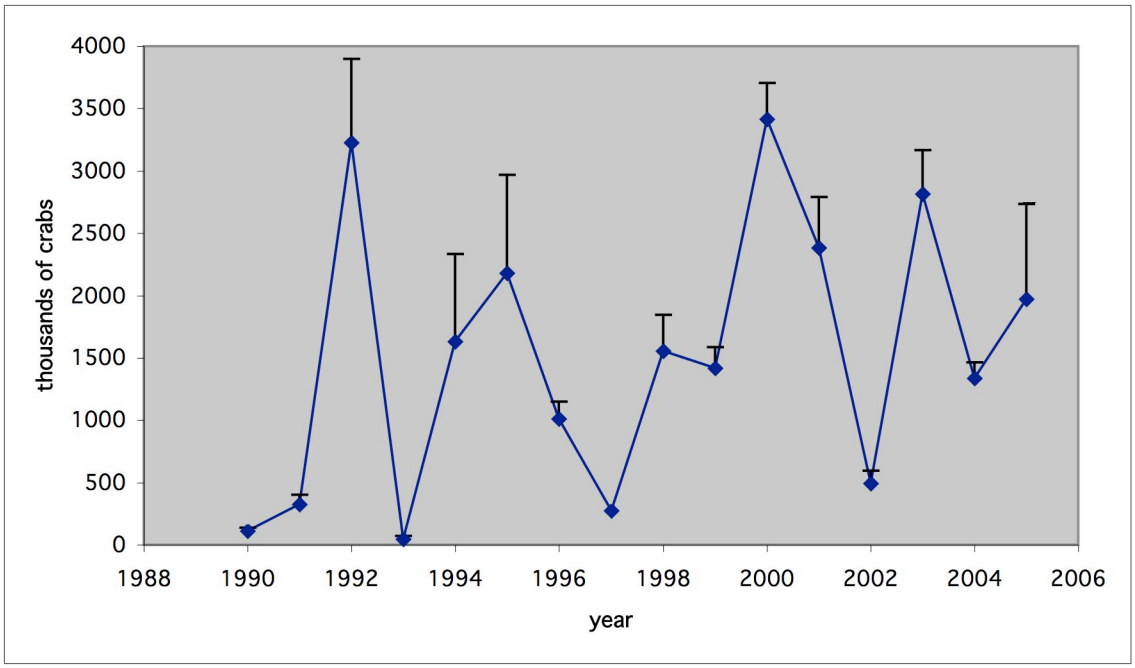

Figure 10. Annual production for all plots sampled, showing 2006 production slightly over the average annual production.

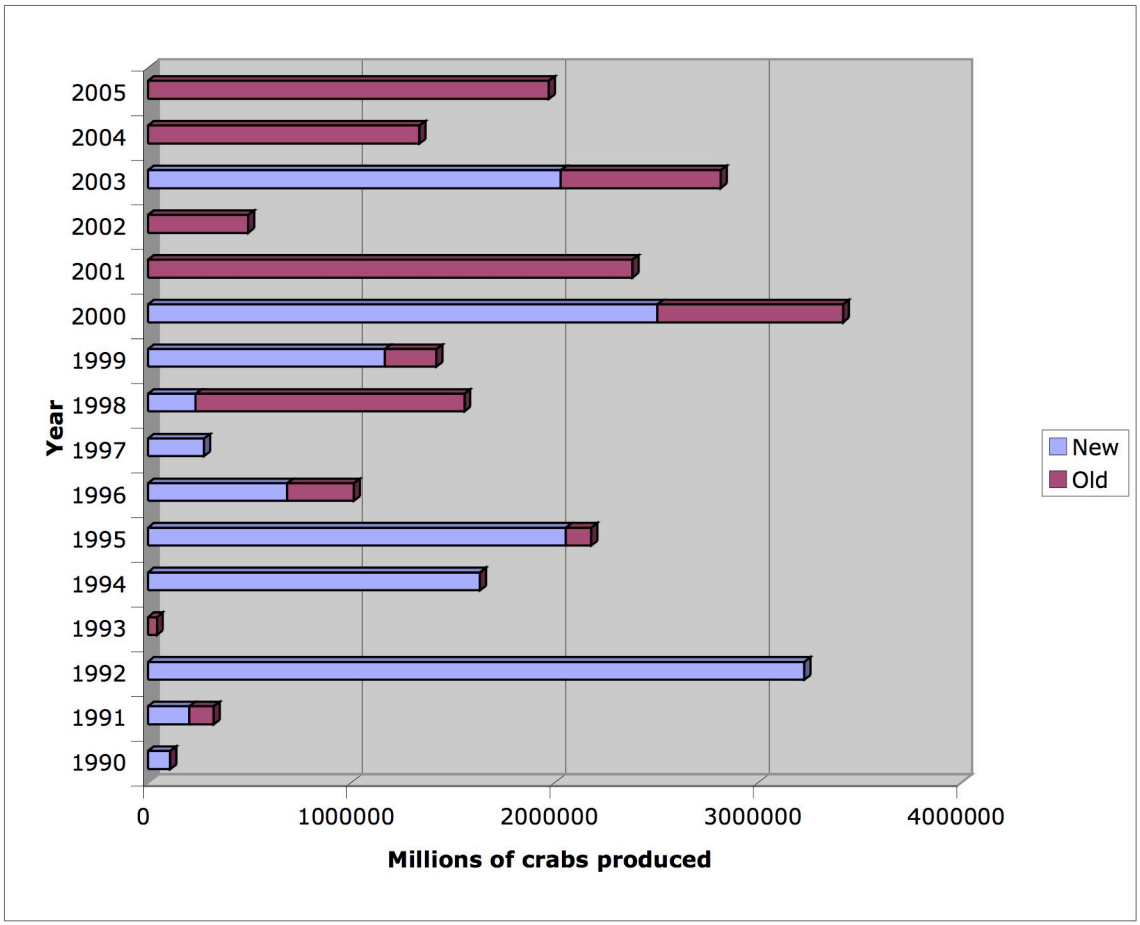

Figure 11. Cumulative production of the shell mitigation project by year. Colors show amount of each year's total attributable to shell placed in that year versus older shell placed in previous years. No new shell habitat was created in 1993, 2001, 2002 or 2004, so there are no blue portions of the bars for these years. Likewise, old shell was not sampled in 1992 or 1994 and no red portion exists for these years. Actual production of crab on ACOE mitigation plots is thus higher reported, since all plots which were in fact producing crabs were not sampled.

Average production per square meter was 10.23 crabs/m^2 during summer 2005, which is higher than the overall average of 6.8 crabs/m^2 for old shell habitat, but lower than the 26.6 crabs/m^2 average produced by new shell (Figure 12). The production per area realized for summer 2005 corresponds to the 10 crabs/m^2 targeted by original mitigation goals before the project began, and prior to the old versus new shell discrepancy. The three plots constructed in 2003 averaged 14.2 crabs/m^2, while the two 2000 plots sampled during summer 2005 averaged 10.3 crabs/m^2. At 24.1 crabs/m^2, the

2003 Up plot showed highest juvenile crabs production per unit area. The 1995 Island remains an incredibly productive habitat, yielding 16.6 crabs/m^2. The 1999 Up, 1997 East, 2003 East, 1995 Mainland, and 1996/1997 plots yielded between 3.4 and 7.1 crabs per square meter. The 2000 Up, 2000 East and 2003 Down yielded between 9.8 and 12.6 crabs/m^2.

Shell habitat since the 1998 recruitment failure of *Hemigrapsus oregonensis* has remained more productive in subsequent years after construction compared to before 1998. The only exception to this change in functionality of old shell is in 1991 before *H. oregonensis* had colonized the plots (Figures 12 & 13).

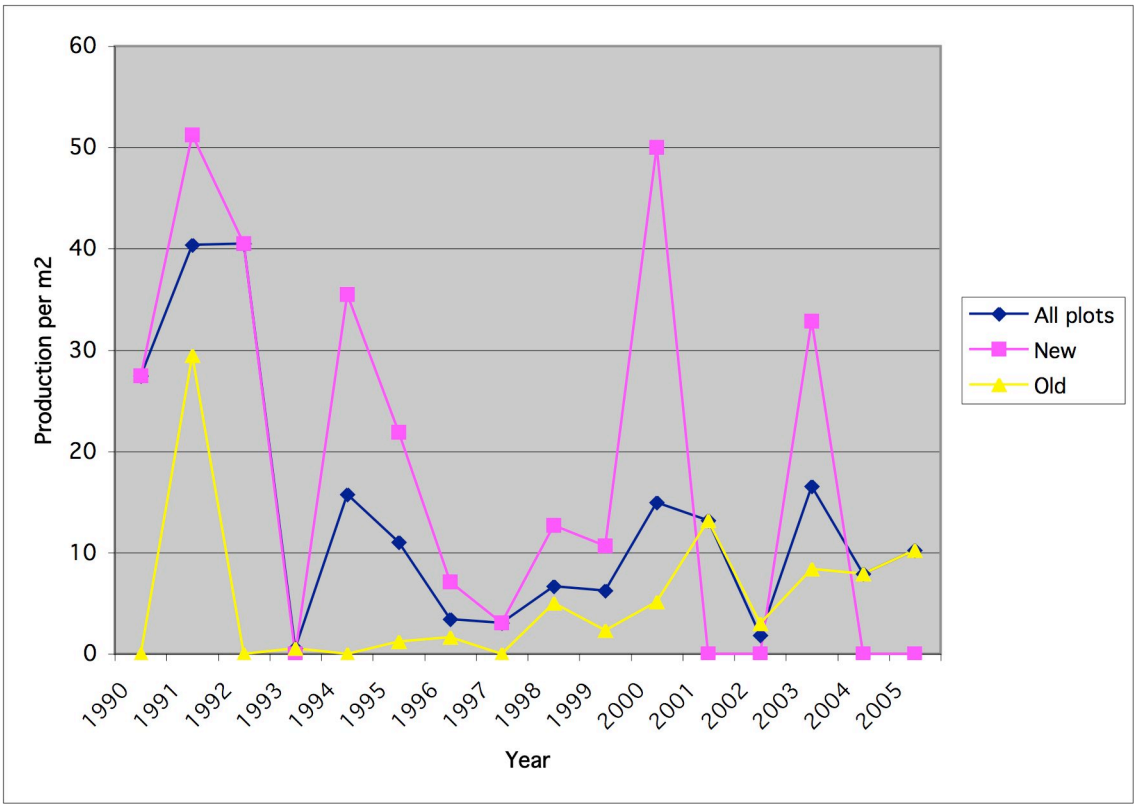

Figure 12. Average production rates (J4 crabs per m^2) for new, old, and all plots over the 15 year history of the mitigation project. Zero values indicate either no new shell placement (1993, 2001, 2002, 2004 and 2005) or no sampling effort allocated (1992 and 1997 old shell).

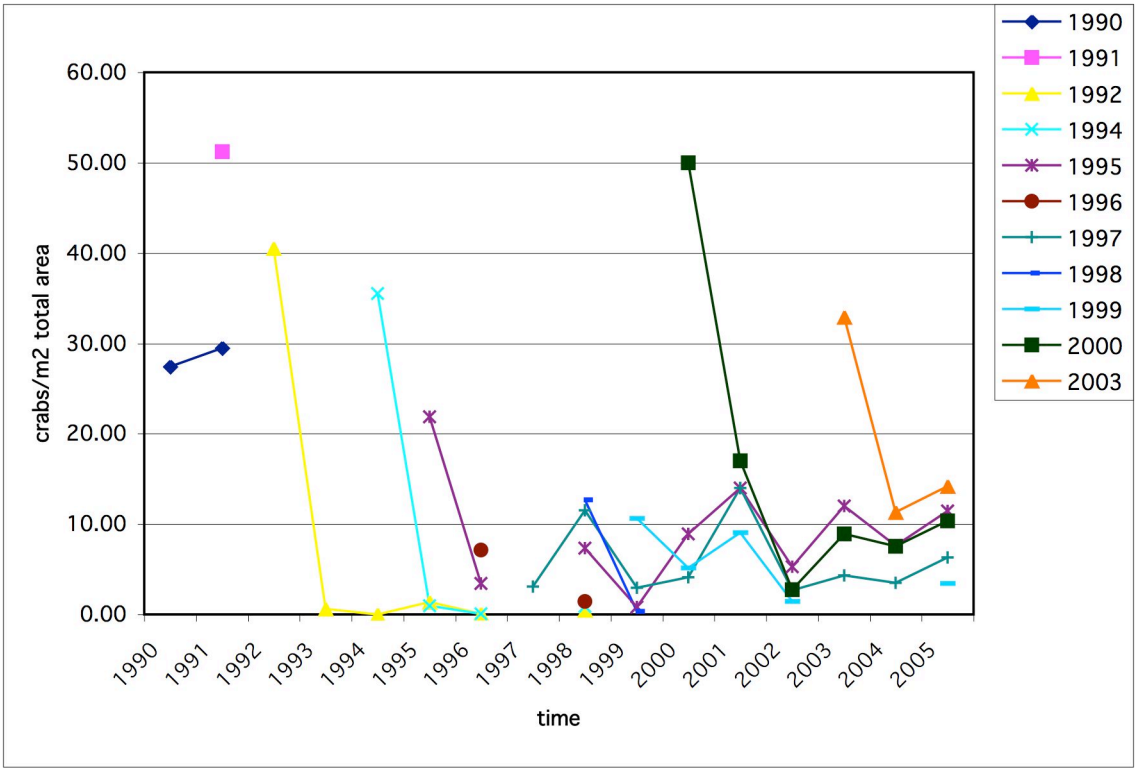

Figure 13. Plot production rate by shell plot created over time for total area of habitat constructed (not corrected for shell cover). The colors and year labels in legend represent shell plots constructed in each year, while the years across the bottom are chronological sampling dates. Thus, green squares show the 2000 shell plot sampled four times: first in 2000 as new shell, then in 2001, 2002, and 2003 as old shell.

Crab density and instar composition

Initial high densities on all plots in May, diminishing as natural mortality surpasses new settlement, set the mortality function for the juvenile crabs inhabiting each plot over the summer. The coefficient for x in the trendline equation shows the monthly mortality, hence dividing it by 30 gives daily mortality rate for each plot. Settlement peaked during the month of May, as evidenced by the abundance of J1 and J2 instars on all plots during the late May sampling period (24-26th). Crab densities ranged from above 90 crabs/m2 to under 40 crabs/m2 in May, depending on the plot (Figures 14-23). Minor settlement in June and July show several small settlement pulses before the more typical late settlement pulse in August, particularly obvious on the 1999 Up, 2000 Up, and 1995 Island plots (Figures 14, 18, and 19).

Instars can be tracked throughout the summer as they grow larger in size and diminish in abundance. J5 instars have outgrown their period of greatest vulnerability and typically begin migration to subtidal substrate at this point. Immigration of crabs smaller than J5 instar is included in the mortality function, since at this size their probability of survival outside the protected refuge area is extremely low. Sub-adult crab (1+ years old) regularly forage intertidally at high tide (Holsman et al. 2006 and Visser unpubl. data), and early benthic phase juveniles are vulnerable to cannibalism as well as predation from sculpin and other fish.

Only one *Hemigrapsus oregonensis* was collected in excavation samples during summer 2005, a female in May. Clearly, competition with this crab species is not affecting habitat use at this time and 2005 fits into the post-Hemigrapsus phase of mitigation ecology which began with a striking Hemigrapsus recruitment failure in 1998 and continues to the present.

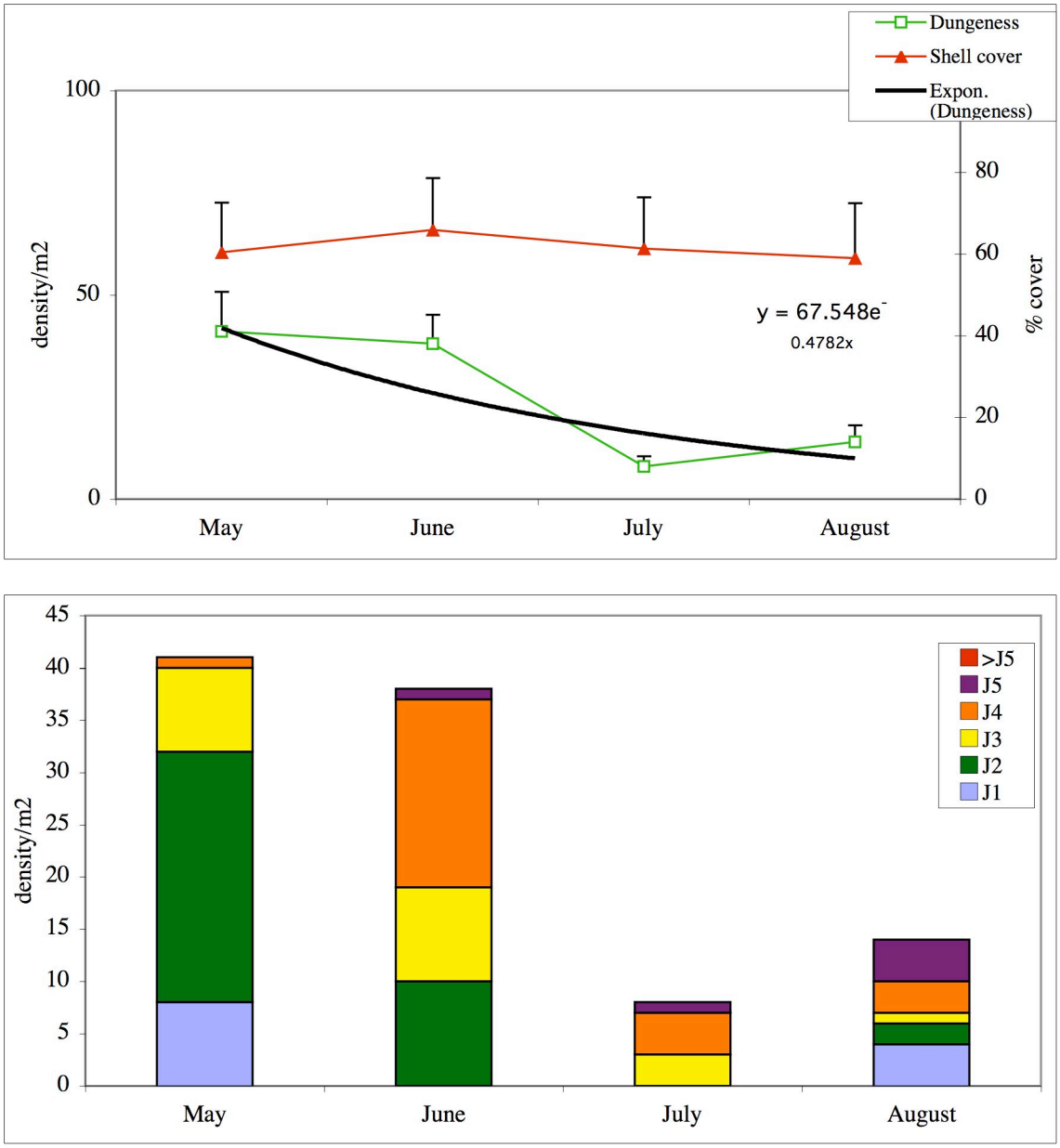

Figure 14. 1995 Island data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

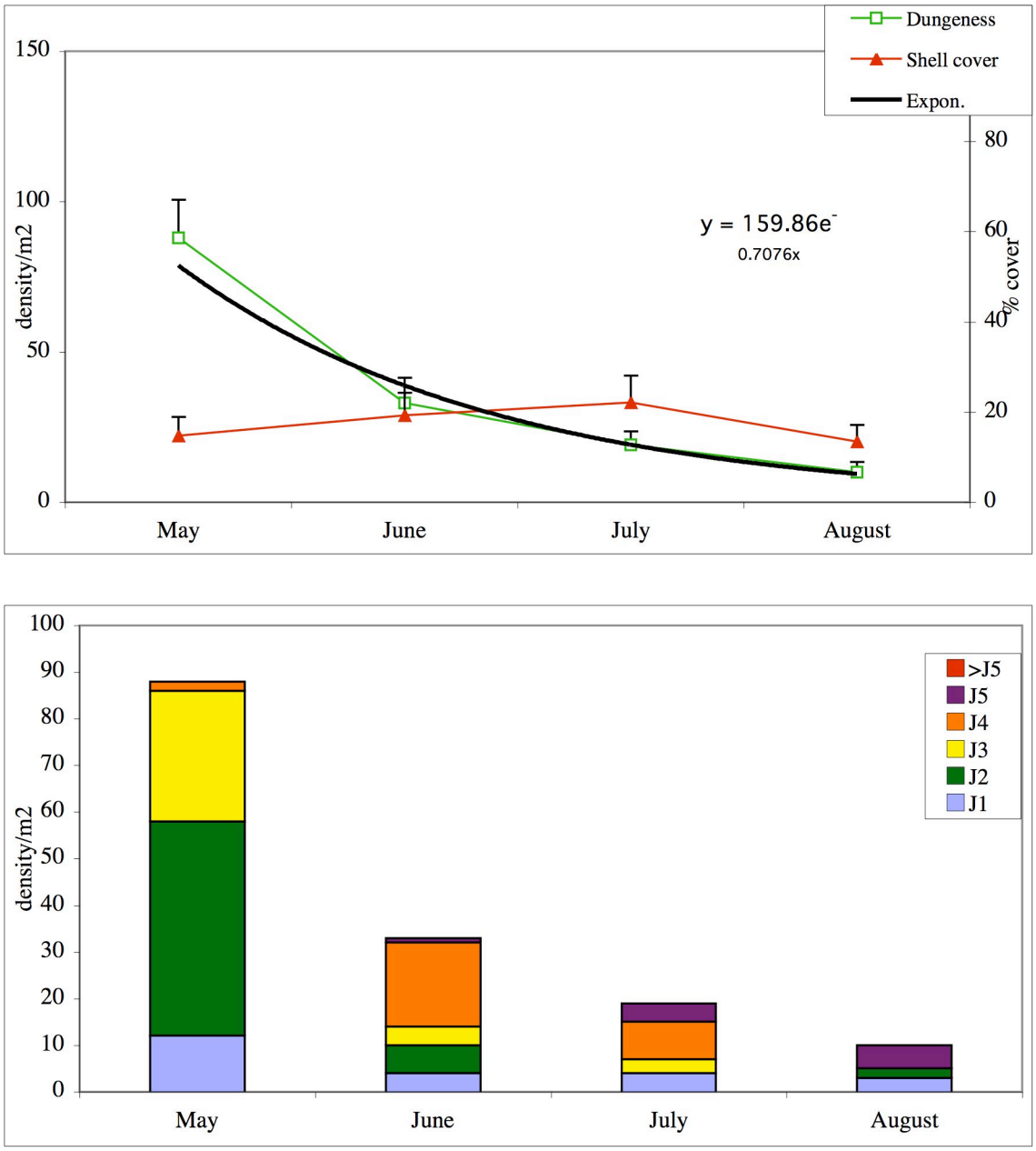

Figure 15. 1995 Mainland data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

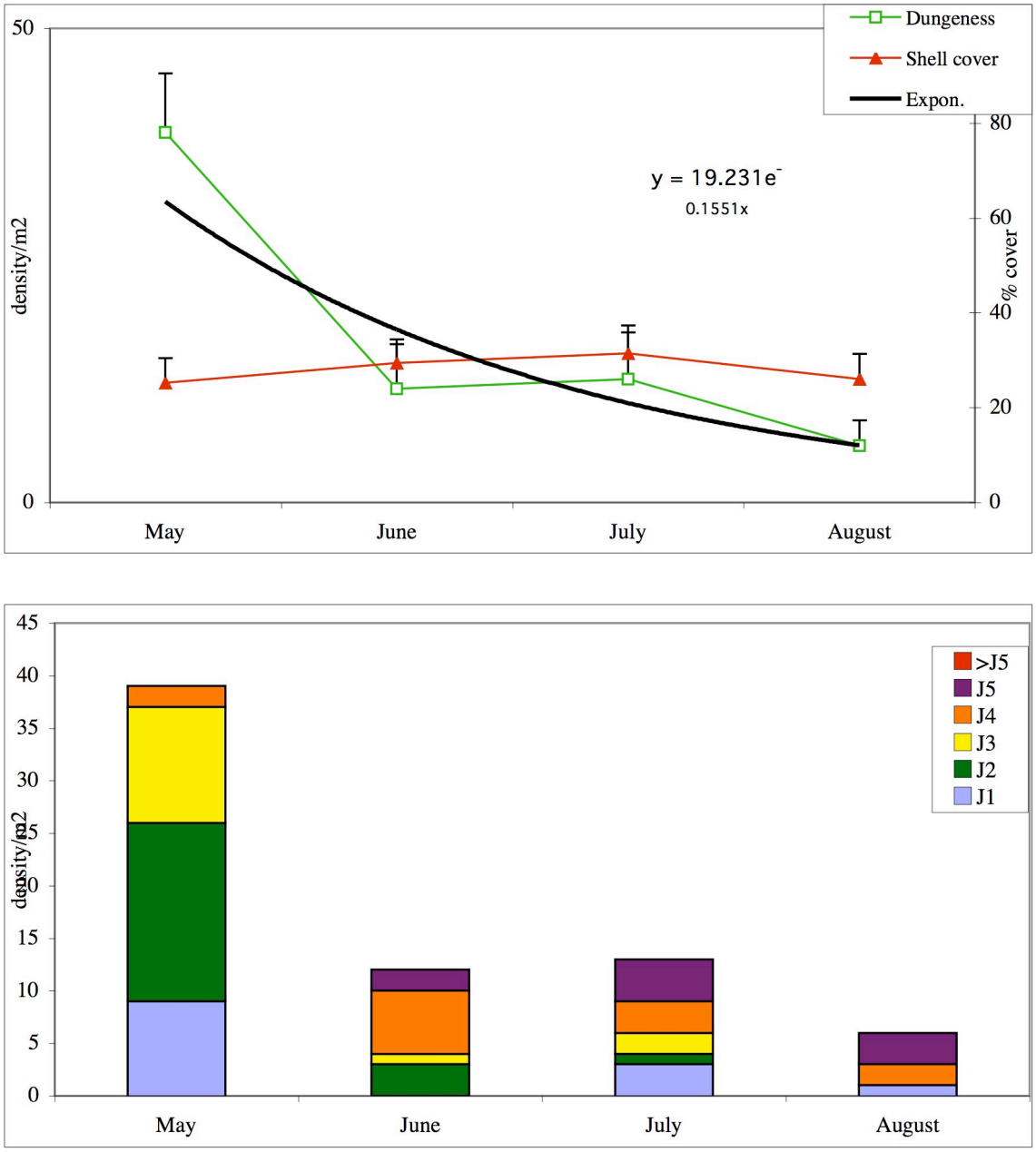

Figure 16. 1996/1997 data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

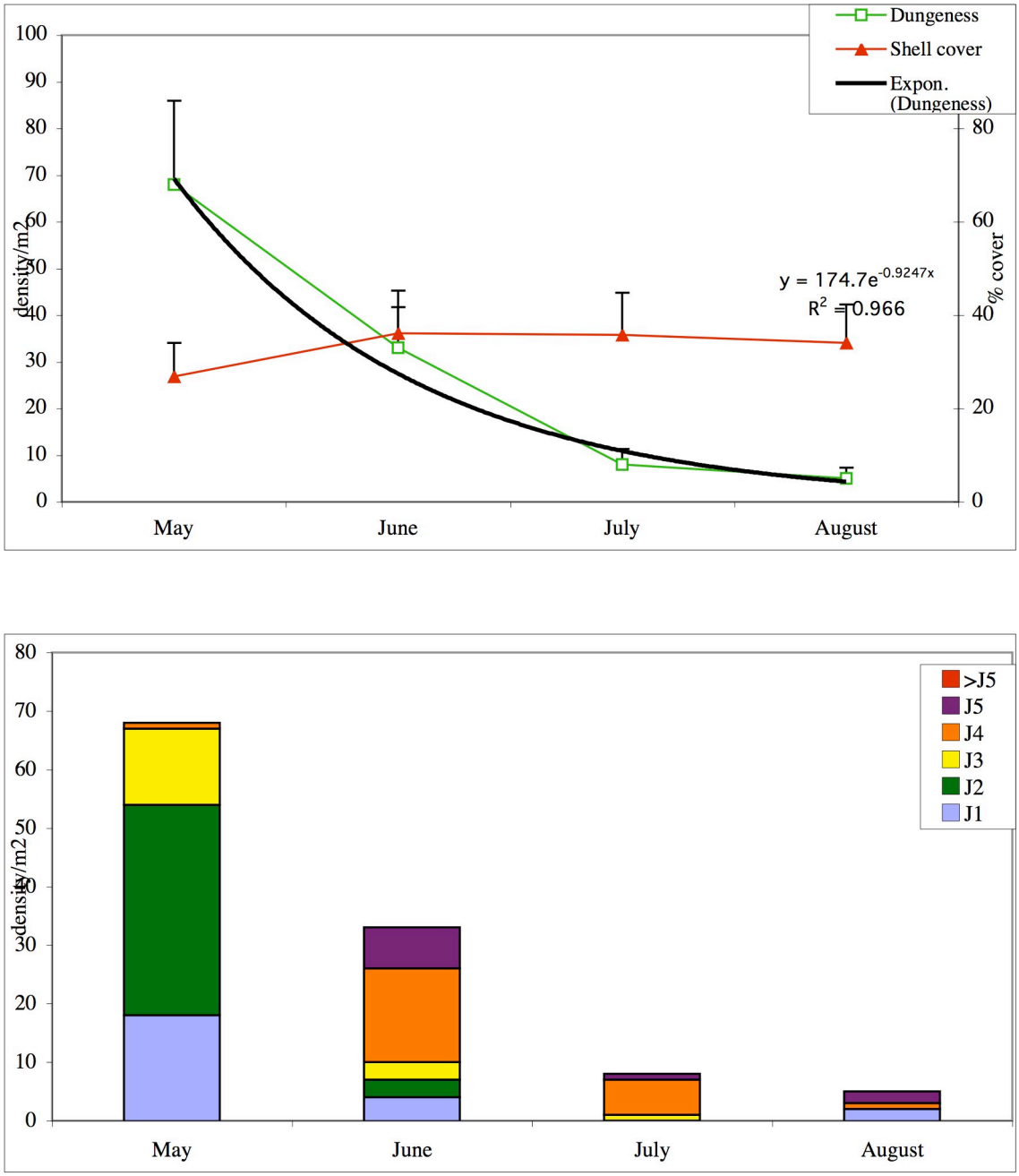

Figure 17. 1997 East data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

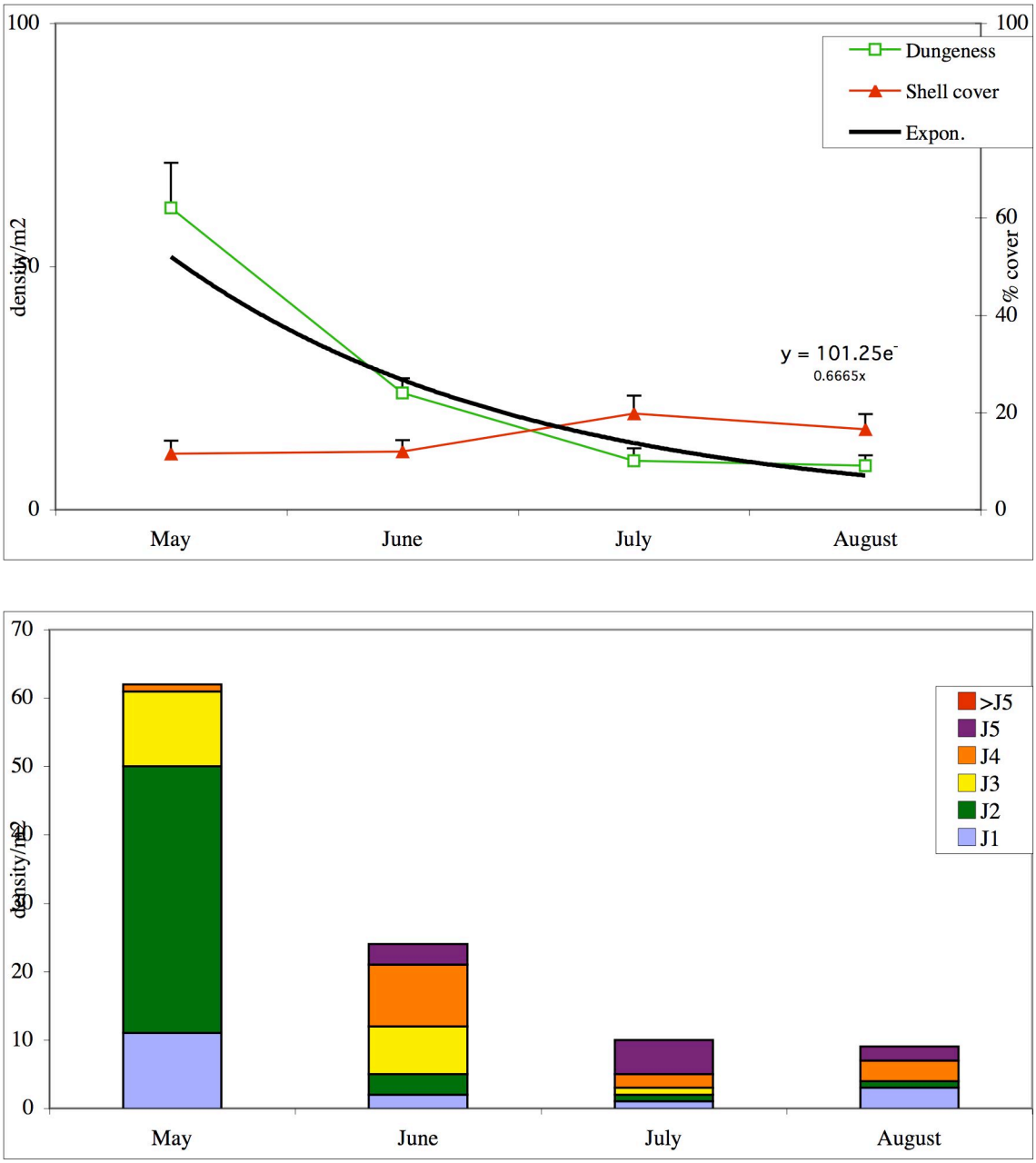

Figure 18. 1999 Up data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

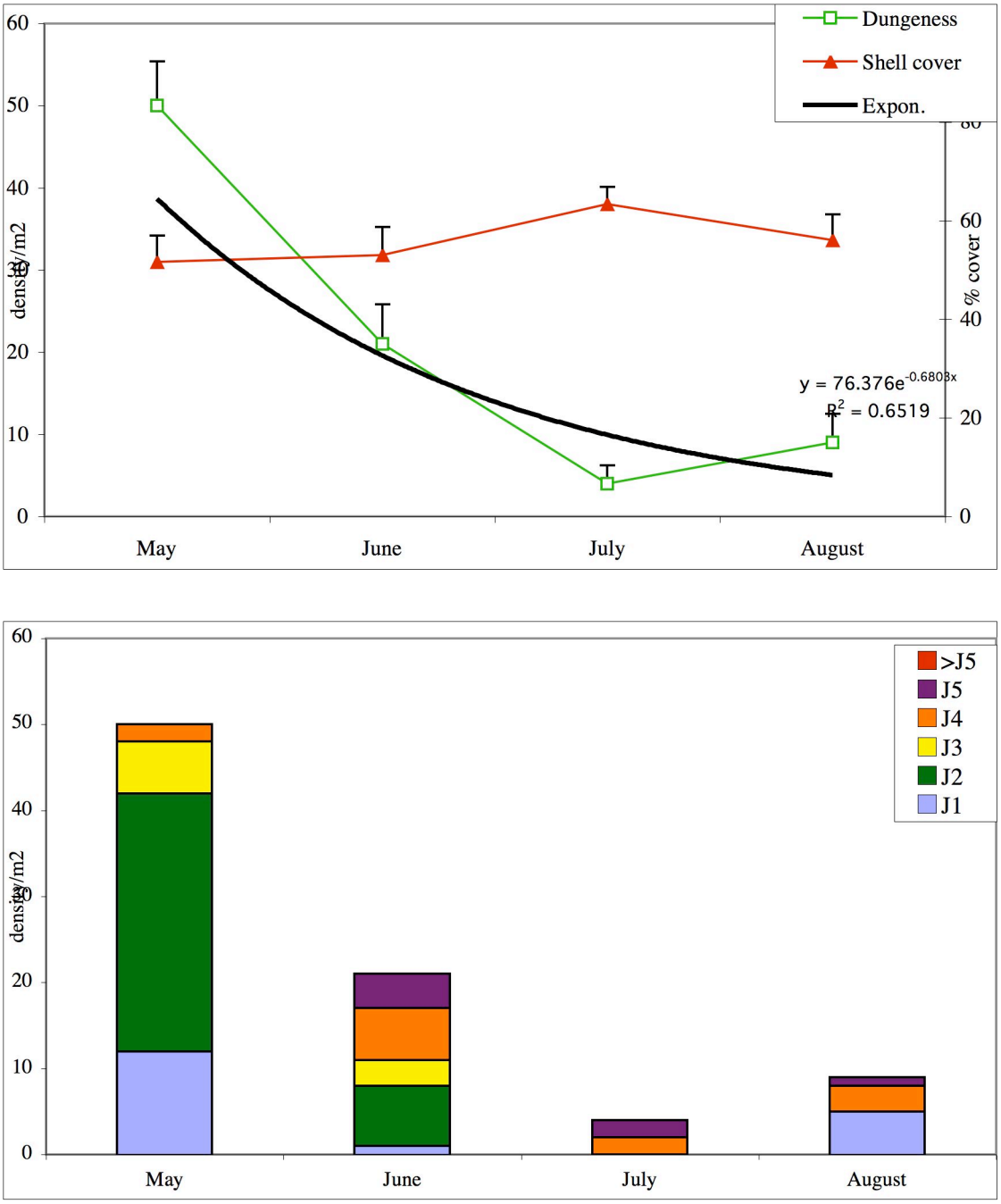

Figure 19. 2000 Up data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

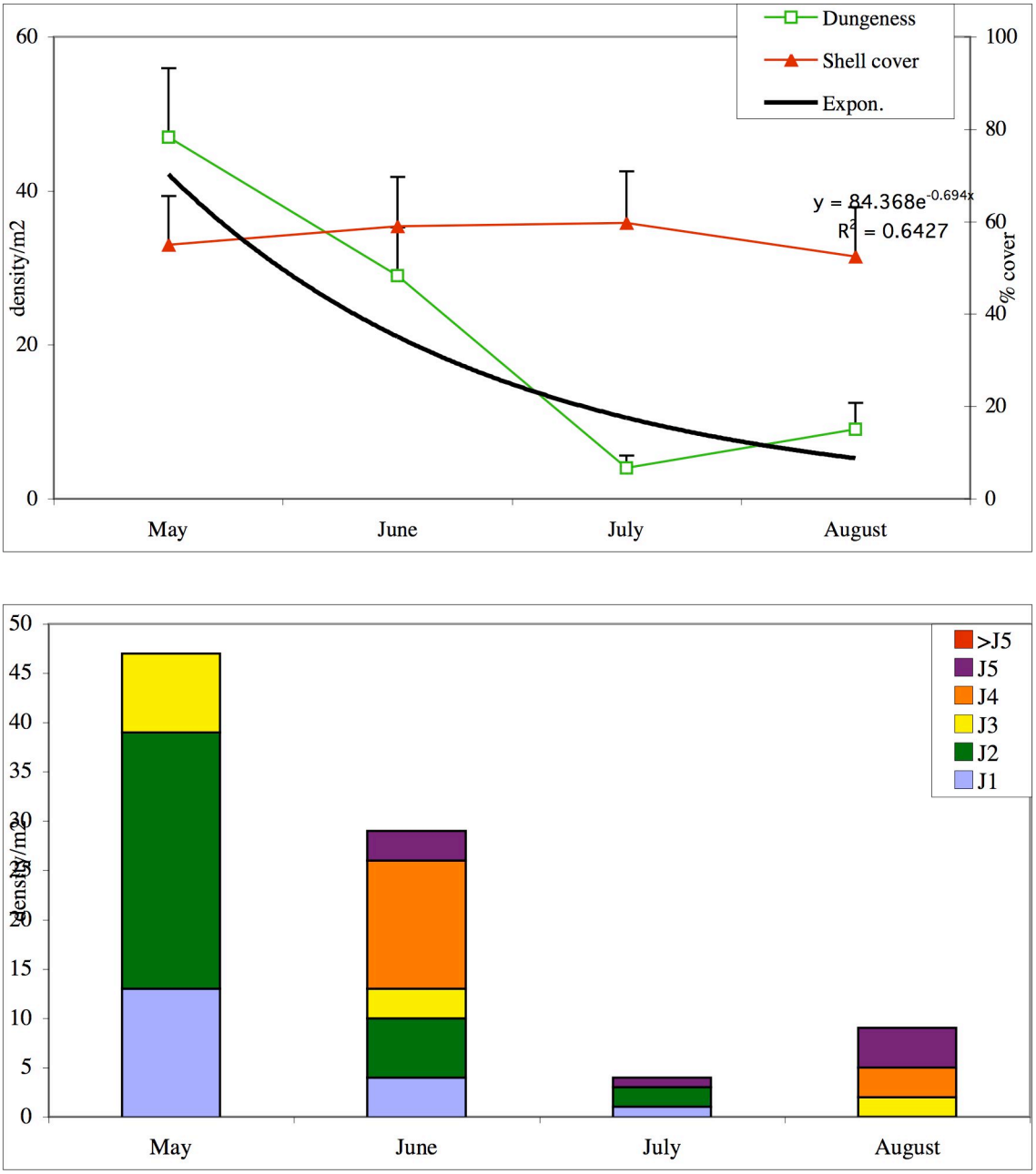

Figure 20. 2000 East data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

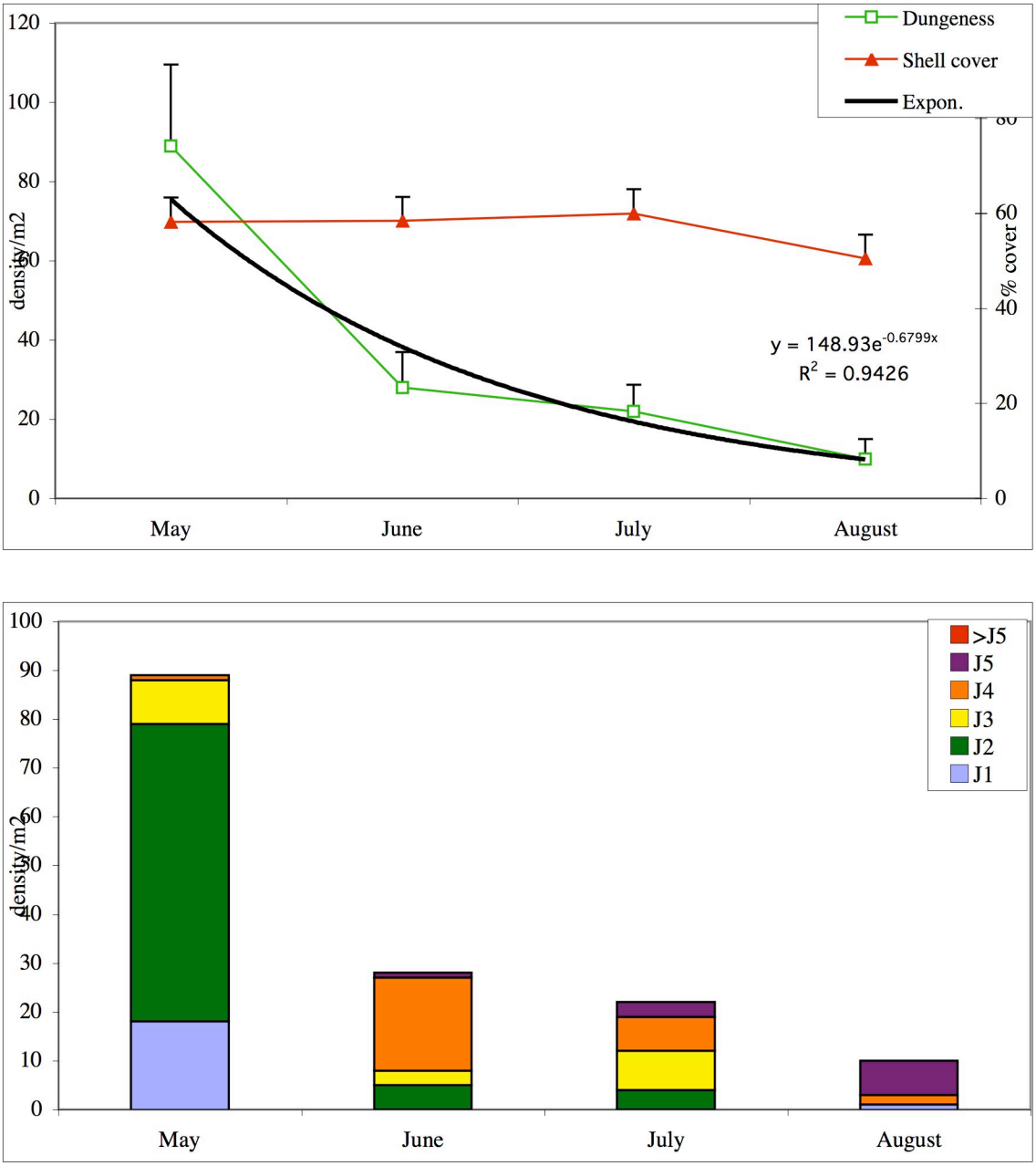

Figure 21. 2003 Up data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

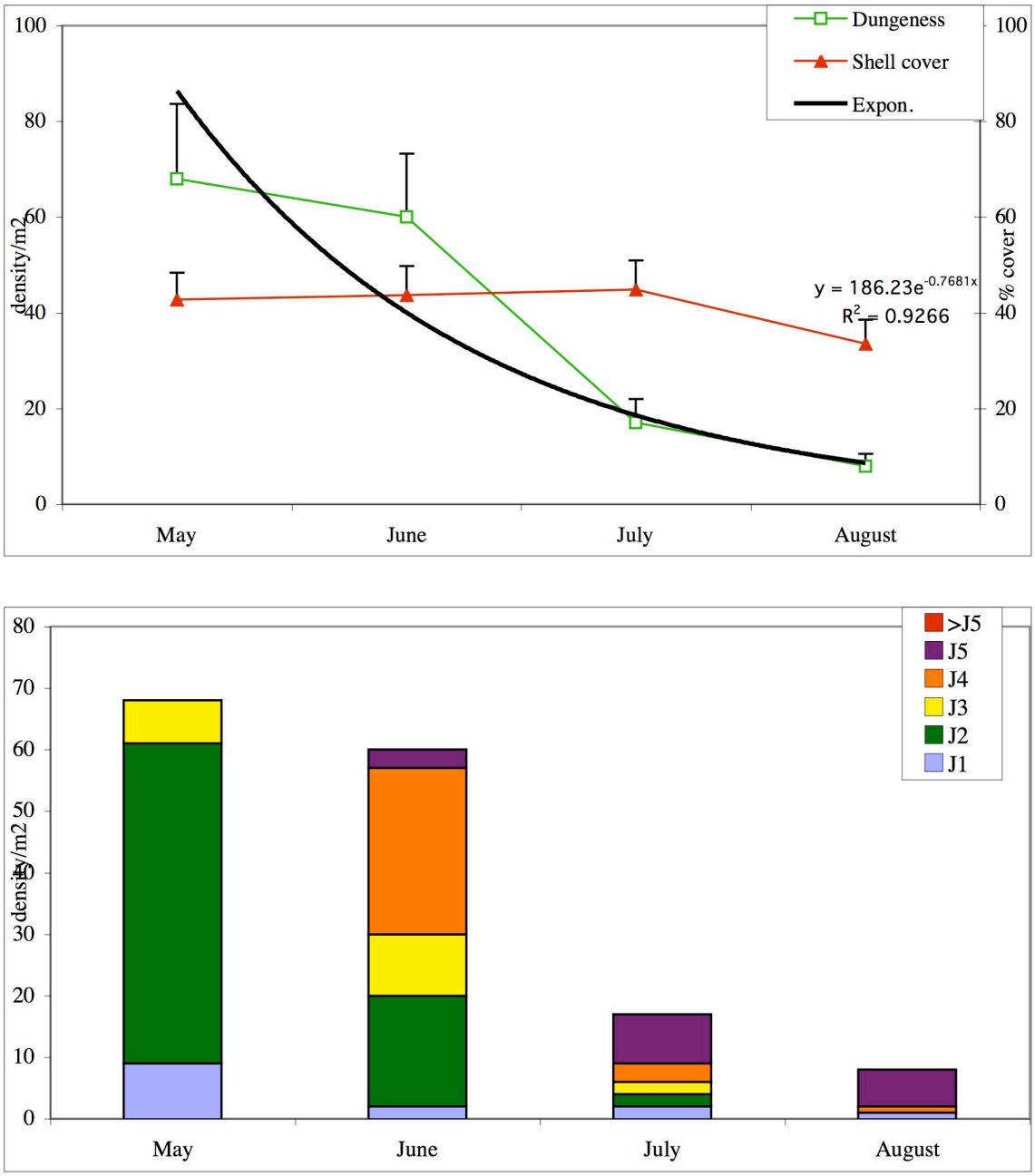

Figure 22. 2003 Down data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

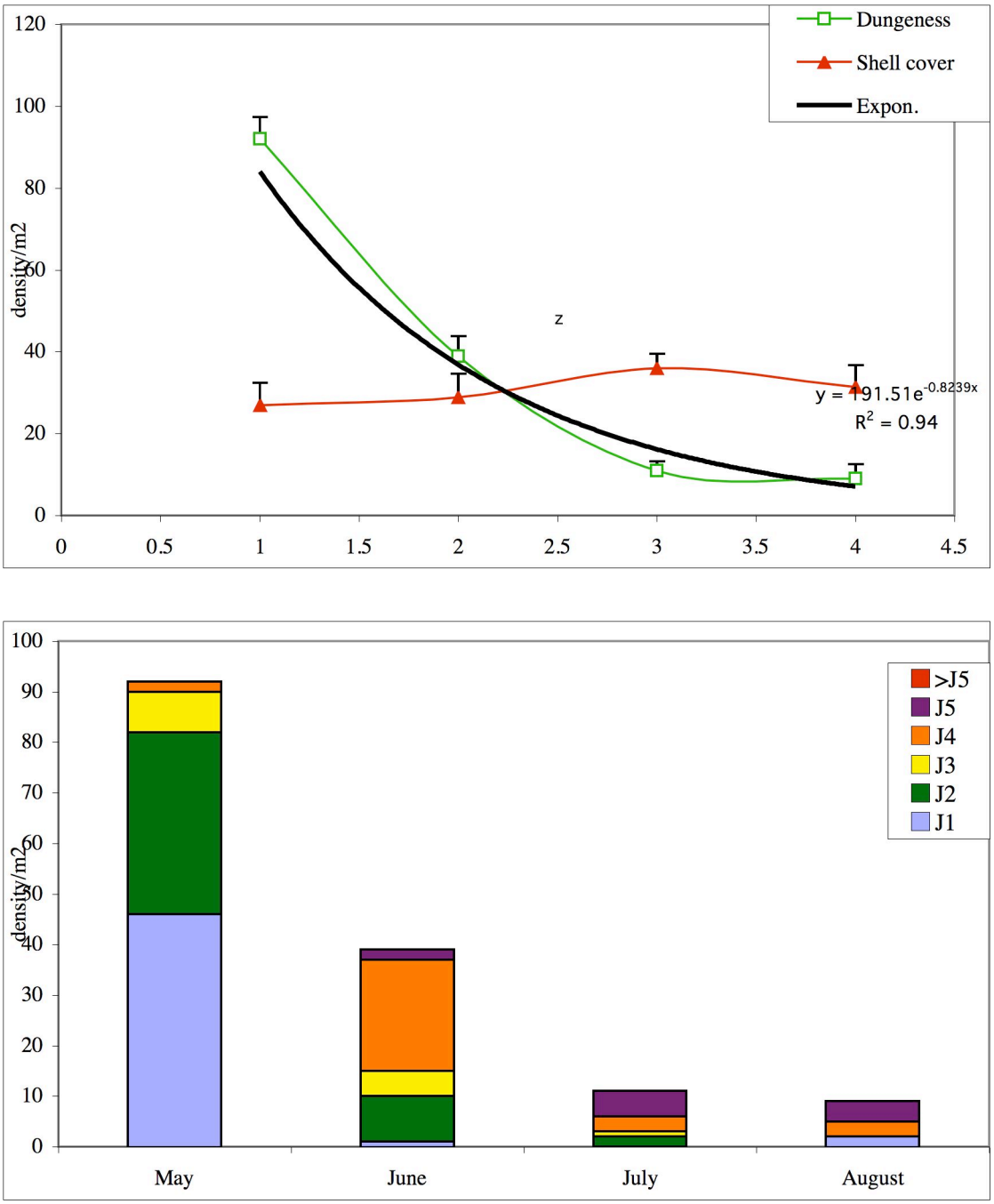

Figure 23. 2003 East data: Dungeness and *Hemigrapsus* densities (crabs per m^2), percent shell cover, and Dungeness crab instar composition for May through August 2005. Trendline is the exponential mortality function fit to juvenile Dungeness crab density curve.

Eelgrass data

Within-plot variation in eelgrass abundance is low within a given year (Figures 24-27), but between years, eelgrass densities vary (Visser 2004). During summer 2005, eelgrass densities ranged from 0 – 7% cover for all ten plots over the four month sampling period. The highest eelgrass cover values occurred on the 1996/1997 and 1999 Up plots, with the 2000 Up and 2000 East plots close behind (Figures 25-27). In contrast, 2004 data showed highest eelgrass cover data on the 1995 Island plot (which is near zero for 2005). Three out of the nine plots sampled in both years (1995 Island, 1997 East, and 2003 Down) had lower eelgrass coverage in 2005 compared to 2004. The remaining six had comparable cover both years. There is still no relationship evident between shell and eelgrass coverage within the mitigation area, although eelgrass abundance on the shell plots is patchy and nearby areas in South Channel have not been surveyed for comparison.

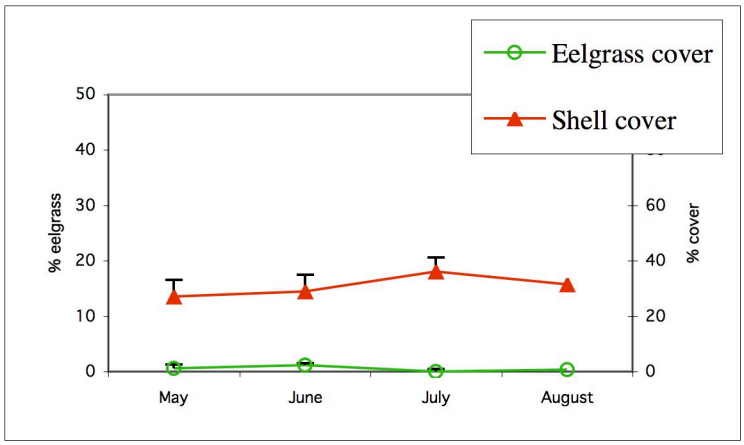

Figure 24. Eelgrass and shell cover data for the 2003 East shell plot during summer 2005.

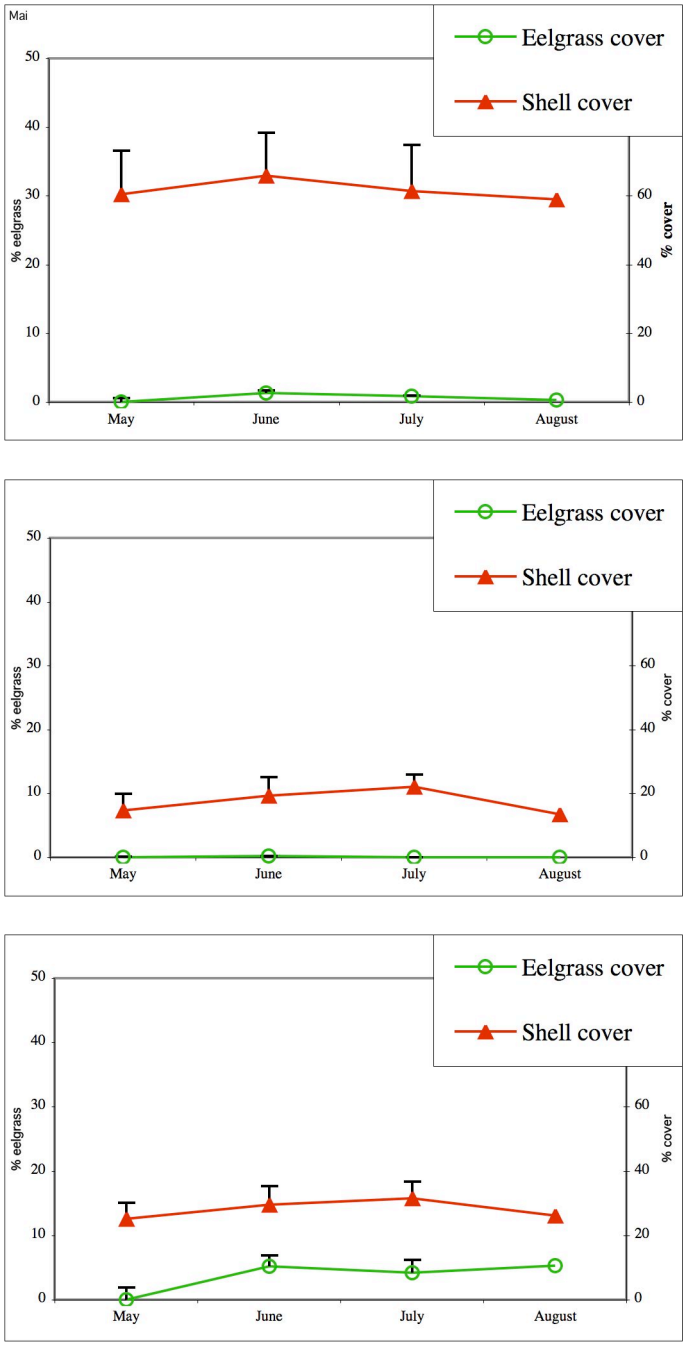

Figure 25. Eelgrass and shell cover data for the 1995 Island, Mainland and 1996/1997 shell plots during summer 2005.

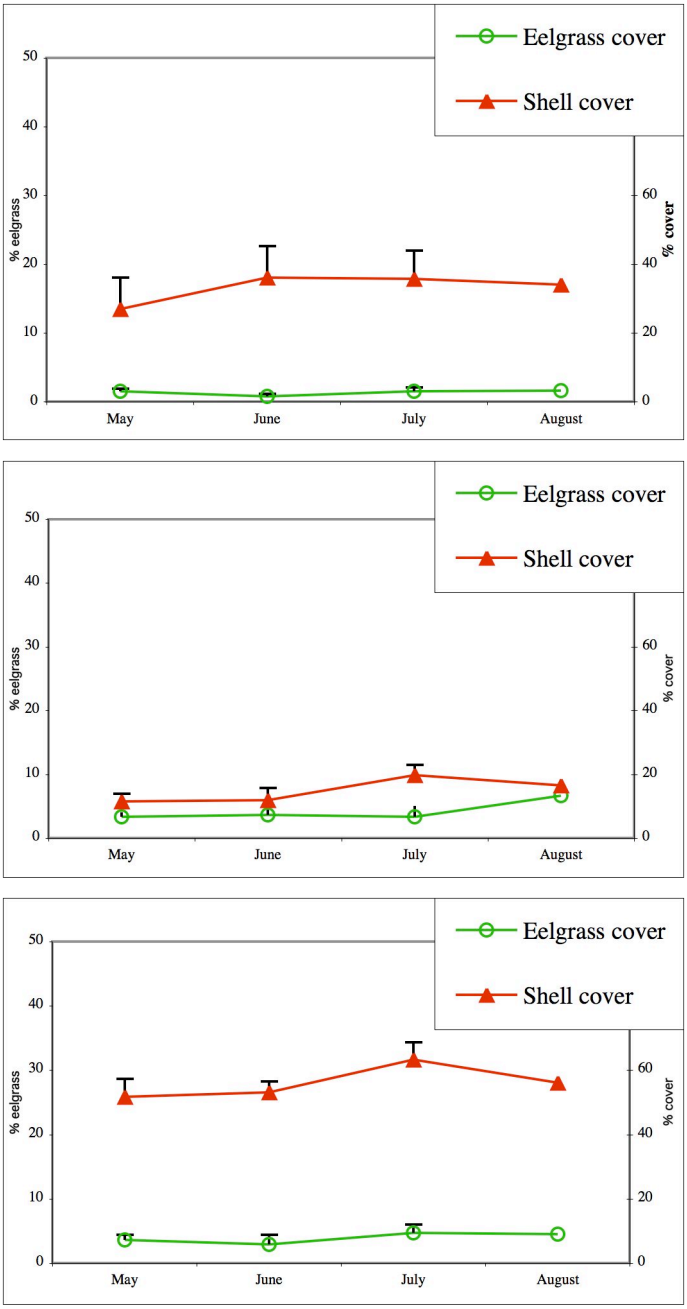

Figure 26. Eelgrass and shell cover data for the 1997 East, 1999 Up, and 2000Up, shell plots during summer 2005.

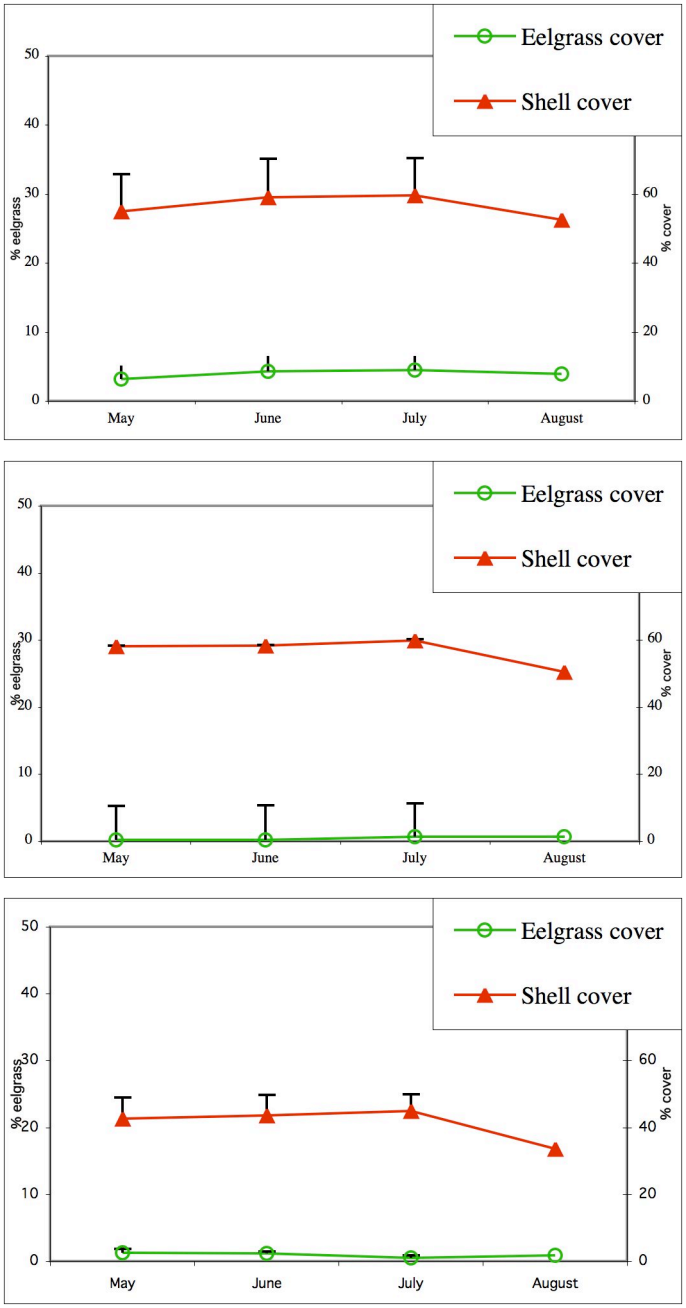

Figure 27. Eelgrass and shell cover data for the 2000 East, 2003 Up, and 2003 Down plots during summer 2005.

Mortality rates

Survival rates again were widely variable between years, and ranked mortality rates for 2005 and 2004 data had an average difference of 3.7, while comparing 2003 and 2005 data gave an average difference of 3.3. The highest survival rates were on the 1996/1997 plots, the 1995 Island, and the 1999 Up plots rather than on the newer shell as might be expected. Neither survival rate nor ranked survival correlated well with production. While new shell has the greatest variability in production, old shell shows the greatest variability in survival rates (Table 5). Although not quite as high as 2004, 2005 survival was among the highest 5 realized on old shell since mitigation efforts began in 1991.

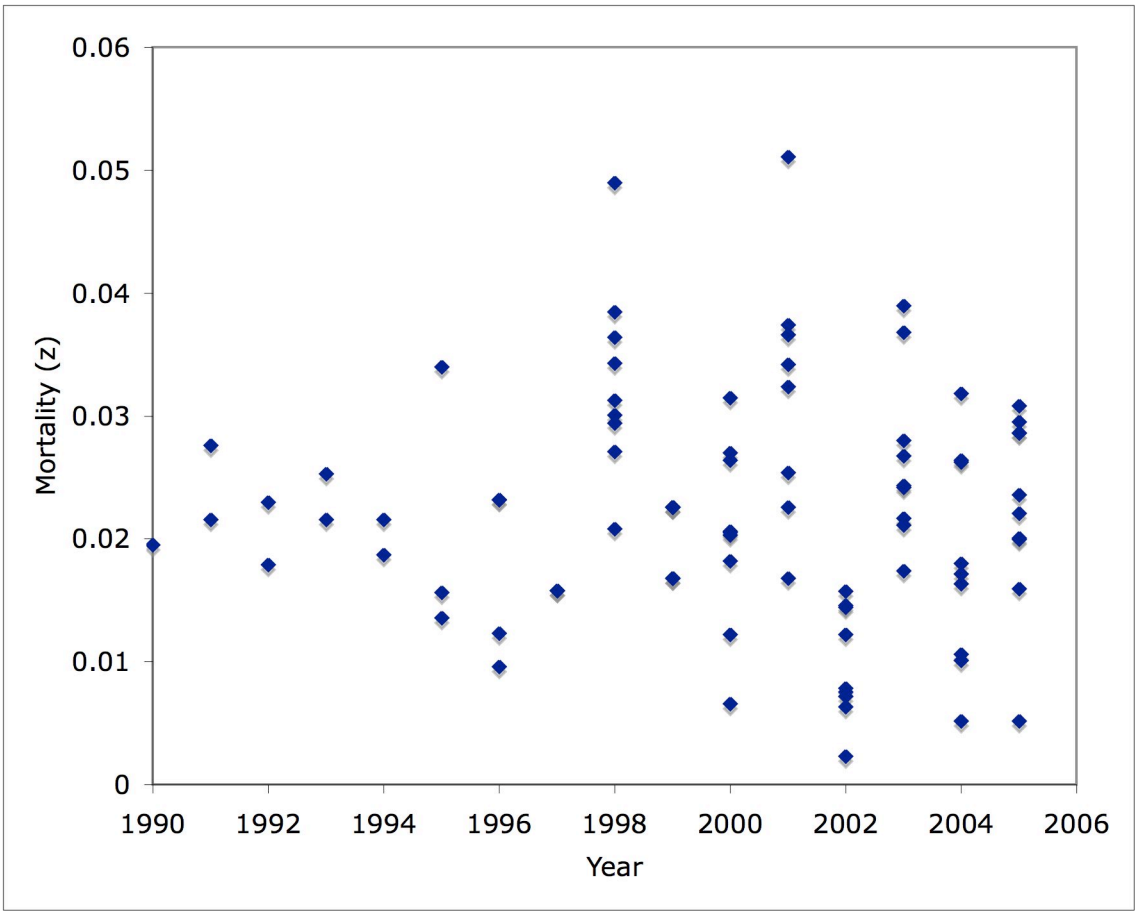

Figure 28. Mortality rates for juvenile Dungeness crab within shell plots since 1990, showing wide range from 0.002 to 0.052. 2005 data shows a typical range, but lower than average values.

Table 5. Annual mortality rates for new and old shell plots. Survival is the percent of crab juvenile J2 instars surviving through the 35 day interval to the J4 stage when exodus to subtidal areas occurs.

Year	New shell	% Survival	Old Shell	% Survival
1990	0.0195	50.54	N/A	
1991	0.0276	38.06	0.0216	46.95
1992	0.0179	53.45		
1993	N/A		0.0216	46.95
1994	0.0187	51.97	0.0216	46.95
1995	0.0136	62.13	0.0248	41.98
1996	0.0123	65.02	0.0096	71.46
1997	0.0158	57.52	0.0187	51.97
1998	0.0208	48.29	0.0343	30.10
1999	0.0168	55.54	0.0226	45.34
2000	0.0216	46.95	0.0197	50.18
2001	N/A		0.0321	32.51
2002	N/A		0.0098	70.96
2003	0.0220	46.32	0.0289	36.37
2004	N/A		0.0180	53.26
2005	N/A		0.0224	50.76
Average	0.0188	52.34	0.0219	48.36
Std dev	0.0043	7.6408	0.0073	12.49

Survival of the 0+ cohort and particularly the J4 juveniles produced by the shell mitigation plots has always remained an open question. Data from a recent field analysis of 1+ juveniles within Grays Harbor estuary (Armstrong et al. 2003) offer possible insight into the translation of these J4 production units into 1+ sub-adults a year after emigration from the shell plots. Combined trawl survey data for the three major habitat types sampled (lower main channels, lower side channels, and upper estuary sites) averaged over the June-August survey dates do not correlate with mitigation outputs from the previous years. Mitigation efforts yielded 0.3, 1.6, and 1.4 million J4 crabs in 1997, 1998, and 1999 respectively, while Armstrong et al. (2003) estimated average 1+ Dungeness crab densities at 200, 700, and 1400 crabs/hectare in Grays Harbor in 1998, 1999, and 2000. Relative contribution of mitigation-generated crabs to the whole population from all recruitment sources throughout Grays Harbor is probably minor, but

this lack of correlation is disconcerting and merits further investigation into how the J4-J5s emigrating from South Channel shell plots fit into the ecology of the estuary as a whole.

V. Summary and Conclusions

The 2003 Up plot yielded ¼ of the total annual juvenile crab production realized for all plots in 2005, 0.49 million J4 individuals. The 2003 Down, 1995 Island, and 1996/1997 plots yielded over 0.3 million each. These four plots contributed 72% of the total 1.97 million crabs produced in 2005. Only five of the 15 years since the beginning of the mitigation efforts have surpassed 2005 production values. This is notable, since in four of these five years, new shell habitat contributed the vast majority of the crabs. 2001 and 2005 sampling years stand out as striking exceptions to the generality that old shell supports diminished abundance of juvenile crabs. As of fall 2005, the cumulative production of juvenile Dungeness crabs exceeded 24 million J4 production units.

Production rate per unit refuge area met the 10 crabs/m^2 target, and exceeded the expectation for old shell habitat. Mortality rates were generally low for 2005 crabs, particularly those settling on 1996/1997, 1995 Island, 2003 Up, and 1999 Up plots. Shell cover (but not eelgrass cover) continues to correlate well with crab density and production, and remains a strong predictor of crab habitat utilization. Tidal elevation did not correlate with crab abundance, nor did per meter square production rate. The key factors contributing to the high total production for 2005 are percent shell cover, early settlement values, high survval rate, and total plot area.

No shell was visible at the former PacMan site during summer 2005. Factors which compromise the feasibility of shell placement at this site include lack of visible habitat, difficulties in navigation and the impossibility of using the Shoalhunter here, and timing issues on a given low tide given its distance from the South Channel sites.

Live oysters were noted on many of the South Channel shell plots during summer 2005. Not only the former 1994 plot where live oyster spat were planted, but also 2003 Up, 1995 Island, and 2003 Down. Experimental planting of oyster spat on an existing shell substrate seems likely to provide increased structure and three-dimensionality of refuge space, but also to increase shell longevity as oysters grow.

Shell placement recommendations for spring 2006 shell are firstly, the 1999 Up plot, which has decreased in both percent shell cover, and crab productivity but has historically produced high yields. Secondly, the 1996/1997 plot if enough shell material remains to do two new plots. Although the 1996/1997 plot had high productivity during 2005 summer, shell cover is quite low. Shell cover is the top factor predicting crab abundance, so shell placement on this plot should increase plot productivity dramically. The overlay strategy has been successful, and using former plots as basement for new shell placement is strongly recommended.

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