

Grays Harbor Shell Mitigation Project 2000 Report

**Cumulative mortality and production updates,
2000 Crab densities, instar composition, and shell cover**

Final Report

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Scope and Objective

The primary objective of summer 2000 sampling efforts was to obtain production estimates for the new 2000 shell mitigation plots as well as for old shell plots constructed in previous years. ('Old' refers to any plot sampled one year or more after original construction.) In order to do so, monthly densities and instar composition of juvenile Dungeness crab as well as percent shell cover data were collected for all plots which seemed likely to produce significant numbers of crab. Other factors expected to influence productivity, such as abundance and size composition of *Hemigrapsus oregonensis* and presence of eelgrass were also noted.

The production model and the data used by it to estimate productivity were checked for consistency. Mortality rates for past years from 1990 through the present were reanalyzed and all production values obtained over the past ten years were updated and corrected. Thus more accurate estimates of annual and cumulative production could be computed and the sources of this production could be analyzed.

Background and Life History

Controversy over Dungeness crab (*Cancer magister*) mortality due to dredge entrainment arose as a result of widening and deepening the shipping channel through Grays Harbor and into Aberdeen in the late 1980s (McGraw et al. 1988, Wainwright et al. 1992). Despite efforts by the U.S. Army Corps of Engineers (COE) to select gear type and plan timing of operations to minimize impacts, an estimated 26% of resident crab in the path of the hopper dredge were entrained. Mitigation was deemed necessary by state and federal agencies and thus construction of intertidal juvenile habitat was initiated in 1990 to increase survival rates during the first summer of growth (Dumbauld et al. 1993).

By 1994, South Channel was chosen as the sole location of mitigation efforts after comparisons throughout Grays Harbor estuary indicated that shell longevity was greatest there (Armstrong et al. 1991).

Dungeness crab megalopae ride flood tide currents 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), sometimes at densities exceeding 500 crabs per m² (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) and shell habitat no longer seems to be crucial refuge habitat for them.

Hemigrapsus oregonensis colonized the shell mitigation plots in later years, to the detriment of juvenile Dungeness crab production (Visser 1997). Initial years after shell plot construction tend to support high densities of *Cancer magister* whereas subsequent years tend to have much lower densities of Dungeness crab and much higher abundances of *Hemigrapsus*. While predation by gregarious *Hemigrapsus* on settling Dungeness crab megalopae is partly a factor, competitive dominance for refuge seems to play a more major role in the relationship (Visser 1997). Due to bioturbation and sediment destabilization by *Neotrypea pugetensis* and *Upogebia californiensis*, as well as colonization of the plots by *Hemigrapsus*, production of Dungeness crab on shell habitat generally declines sharply beyond the initial year of construction. The ongoing challenge of the habitat mitigation project is to locate appropriate areas for shell placement each spring and to conduct summer sampling to accurately assess the number of juvenile Dungeness crabs being produced by the created habitat.

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. After an initial trip to the habitat mitigation plots in early May to determine which sites would be sampled and to measure boundaries, map and mark those plots, sampling trips were made once monthly beginning in early June. The nine plots sampled during summer 2000 were the 1995 Island, 1996/1997 Overlay, 1997 East, 1999 Up, 1999 Down, 1999 Overlay, 2000 Up, 2000 Down, and 2000 East, which was overlaid on top of the former 96 East plot (Figure 1). 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), any plot which did not have a significant amount of shell remaining on the surface was not sampled. These areas would certainly yield little to no production of juvenile Dungeness crab and thus did not merit the manpower required to sample them.

A sampling crew consisting of 5-6 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 2000. Collection of these samples consisted of haphazardly placing a 0.1 m² 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 sieved through a 3 mm mesh screen (Figure 2). 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.

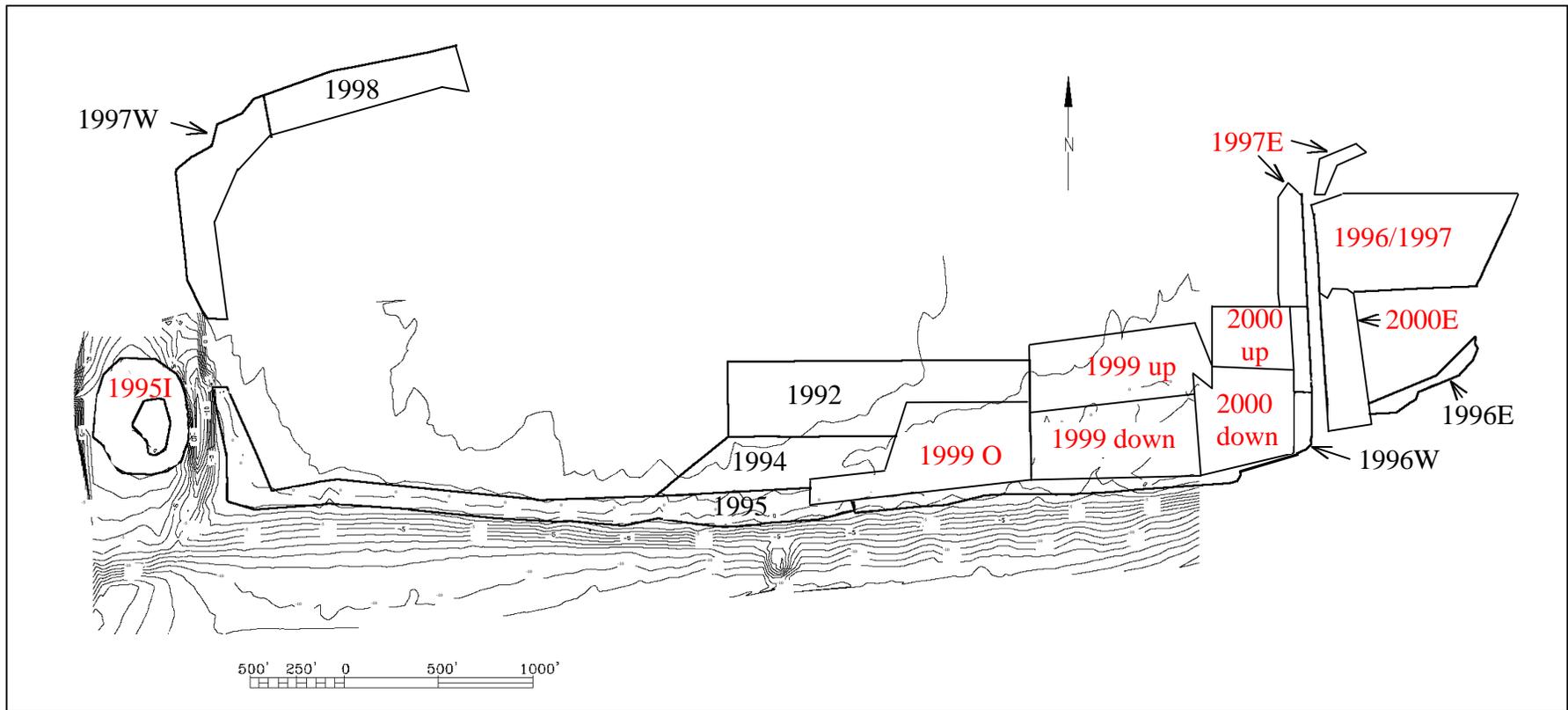


Figure 1. Map of the South Channel shell mitigation sites. Plots in color are the ones sampled during summer 2000. Access to the sites is via the channel running E-W along the bottom edge of the map.



Figure 2. Excavation sample protocol, showing quadrats used to determine 0.1 m² area, screen full of shell material and mud, and sorting of crabs using 3 mm mesh screen.

Table 1. Sampling dates, tidal heights, and times for 2000 summer data collection at South Channel shell mitigation plots.

Date	Low tide time	Low tide height
3-Jun	8:11 AM	-1.9
4-Jun	9:00	-1.9
5-Jun	9:49	-1.7
1-Jul	7:08	-1.9
2-Jul	7:58	-2.1
3-Jul	8:46	-2.1
30-Jul	6:53	-1.9
31-Jul	7:41	-2.0
1-Aug	8:27	-1.9
28-Aug	6:34	-1.6
29-Aug	7:19	-1.6
30-Aug	8:02	-1.4

Note: The times and tidal heights listed above are for Pacific Beaches. Corrections for Westport are -0:08 minutes and 0.0 feet, while corrections for Aberdeen are +0:48 minutes and +1.6 feet. Since the South Channel sites are located about halfway between these two, actual times are about +0:20 minutes and +0.8 feet. No exact corrections are available for this location.

Percent shell cover estimates were taken by visually estimating the amount of shell remaining above the surface of the mud and available for crab refuge space on each plot. Visual shell estimates were obtained by 4-6 observers on ten replicate 20m x 20m areas within each of the nine plots sampled. Thus the overall average percent shell cover for each plot during each monthly sampling period was based on 40-60 individual estimates, giving a mean and standard deviation as input for the production model.

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. 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. The J4 instar was previously agreed upon by COE and agency personnel to serve as the production unit, since by the time the crabs reach J5 instars, they are no longer at as great a risk and begin to move to subtidal areas. Thus, the computed mortality rate is applied over a 35 day interval for J2 instars and 20 days 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 crab density and instar composition, shell cover, and number of crabs produced per plot are presented and discussed.

Results and Discussion

Dungeness crab density

Juvenile *Cancer magister* density patterns were more typical during summer 2000 than the previous year. Densities were highest in early June (Table 2; Figures 3-11), except for on the 1996/1997 plot (Figure 4), where densities peaked in early July. The high settlement peaks often seen at the first sampling period were not evident in the 2000 data, most likely because the initial sampling period was in early June instead of mid-May, when Dungeness megalopae generally move into Grays Harbor estuary. Nevertheless, initial densities were much higher on the new 2000 shell mitigation plots (Figures 9-11; $x = 102.3 \text{ crabs} \cdot \text{m}^{-2}$) than on older shell plots (Figures 3-8; $x = 44.7$), suggesting that settling crabs selected the new shell plots and/or initial survival rates differed dramatically between new and old habitats. Certainly refuge space is more plentiful and more readily accessible on the new shell plots than on the old ones (Figure 12). By July crab density averaged $38.7 \cdot \text{m}^{-2}$ on old shell plots (Figures 3-8) and $66.7 \cdot \text{m}^{-2}$ on new 2000 shell (Figures 9-11).

Density curves were fairly flat over the course of the summer compared to years with high initial settlement peaks, and sloped off gradually as the summer progressed. By the last sampling period during the last few days of August (the early 'September' sampling date), Dungeness crab densities had declined to an average of $17.7 \text{ crabs} \cdot \text{m}^{-2}$ on new shell plots and $12.7 \text{ crabs} \cdot \text{m}^{-2}$ in old shell plots (Table 2). The 2000 Down plot showed a sharp decline in juvenile Dungeness crab abundance between the July and August sampling dates, apparently mostly due to poor survival of the J2 size class as they molted (Figure 10, instar composition).

Table 2. Summary densities and percent shell covers for plots sampled in 2000.

Habitat (construction year)		June (density /m2)		July (density /m2)		August (density /m2)		Sept (density /m2)	
		mean	s.e.	mean	s.e.	mean	s.e.	mean	s.e.
1995 Island	H	4.0	2.2	4.0	2.2	1.0	1.0	1.0	1.0
	D	25.0	13.0	23.0	7.5	11.0	2.8	10.0	3.9
	J2	12.0	4.4	9.0	3.8	1.0	0.9	1.0	0.9
	%	50.6	11.4	63.1	10.3	65.7	11.2	68.0	10.3
1996/1997	H	24.0	6.9	23.0	5.8	11.0	3.5	5.0	3.1
	D	25.0	6.4	56.0	11.0	21.0	6.9	9.0	4.1
	J2	19.0	6.3	8.0	2.8	3.0	2.2	2.0	1.9
	%	25.6	3.3	21.5	3.6	24.4	5.0	33.4	6.0
1997 East	H	17.0	8.0	6.0	3.4	17.0	9.4	11.0	3.8
	D	67.0	17.0	39.0	6.2	12.0	3.3	14.0	3.7
	J2	50.0	15.2	11.0	3.8	2.0	1.3	3.0	1.6
	%	33.2	6.5	37.3	7.6	36.6	7.1	36.9	8.0
1999 Up	H	2.0	1.3	2.0	1.3	1.0	1.0	0.0	0.0
	D	51.0	11.0	50.0	16.0	25.0	4.5	9.0	3.1
	J2	28.0	6.3	16.0	7.0	4.0	2.2	2.0	1.3
	%	30.4	5.0	25.5	5.3	23.9	4.9	22.5	4.4
1999 Down	H	0.0	0.0	1.0	1.0	3.0	2.1	0.0	0.0
	D	57.0	12.0	25.0	7.3	16.0	5.0	5.0	2.2
	J2	39.0	10.4	10.0	2.5	3.0	2.2	0.0	0.0
	%	9.2	2.7	6.8	2.1	8.4	2.2	6.7	2.1
1999 Overlay	H	8.0	5.1	12.0	5.9	11.0	8.2	13.0	5.0
	D	43.0	10.0	39.0	6.9	19.0	2.8	29.0	4.8
	J2	24.0	7.9	18.0	4.4	5.0	2.5	4.0	2.2
	%	19.0	4.8	11.4	5.4	16.7	6.7	15.7	6.0
2000 Up	H	0.0	0.0	2.0	1.3	0.0	0.0	0.0	0.0
	D	101.0	15.0	35.0	6.5	33.0	5.2	18.0	4.7
	J2	67.0	13.9	27.0	7.0	9.0	2.8	4.0	3.2
	%	94.4	0.8	92.0	1.3	84.1	2.4	80.7	2.7
2000 Down	H	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	D	124.0	29.0	118.0	12.0	29.0	5.5	16.0	4.3
	J2	60.0	12.6	81.0	11.1	8.0	4.7	2.0	1.3
	%	89.6	3.2	80.8	7.2	64.9	8.1	54.6	7.9
2000 East	H	3.0	1.5	1.0	1.0	1.0	1.0	0.0	0.0
	D	106.0	26.0	87.0	15.0	45.0	9.0	19.0	4.1
	J2	20.0	5.7	67.0	13.0	16.0	4.1	5.0	2.2
	%	95.4	0.8	91.2	2.2	84.2	4.0	85.5	4.0

H = *Hemigrapsus*

D = Dungeness

J2= Dungeness 2nd instars

% = percent oyster shell

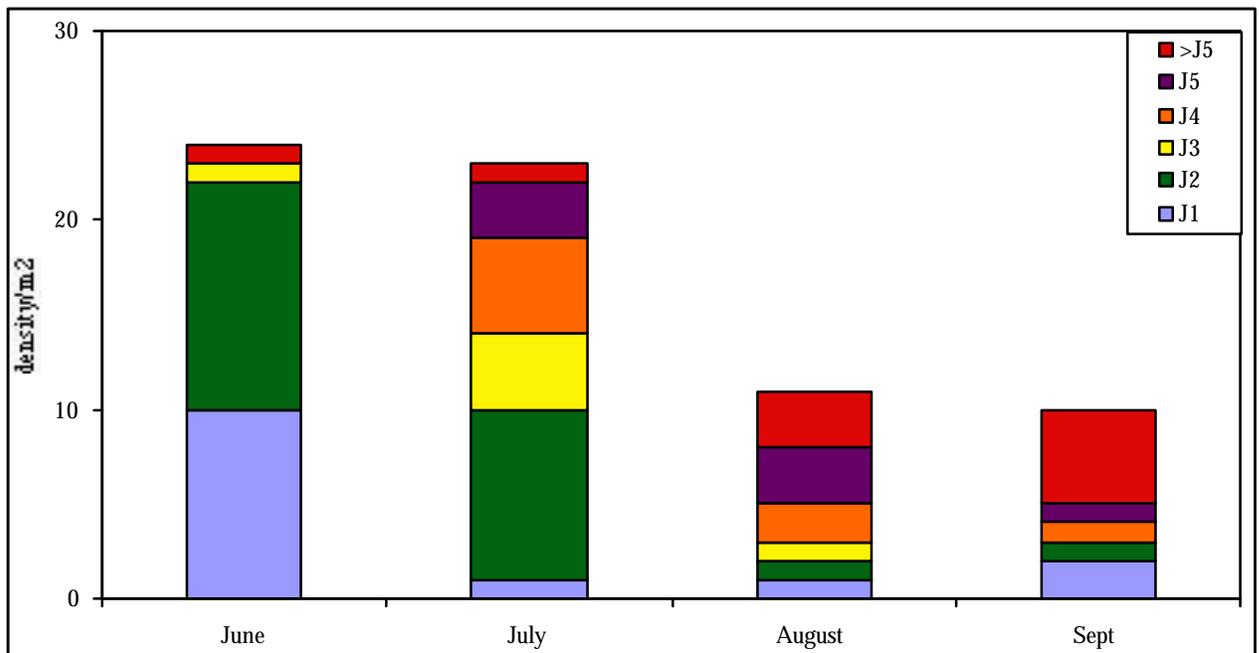
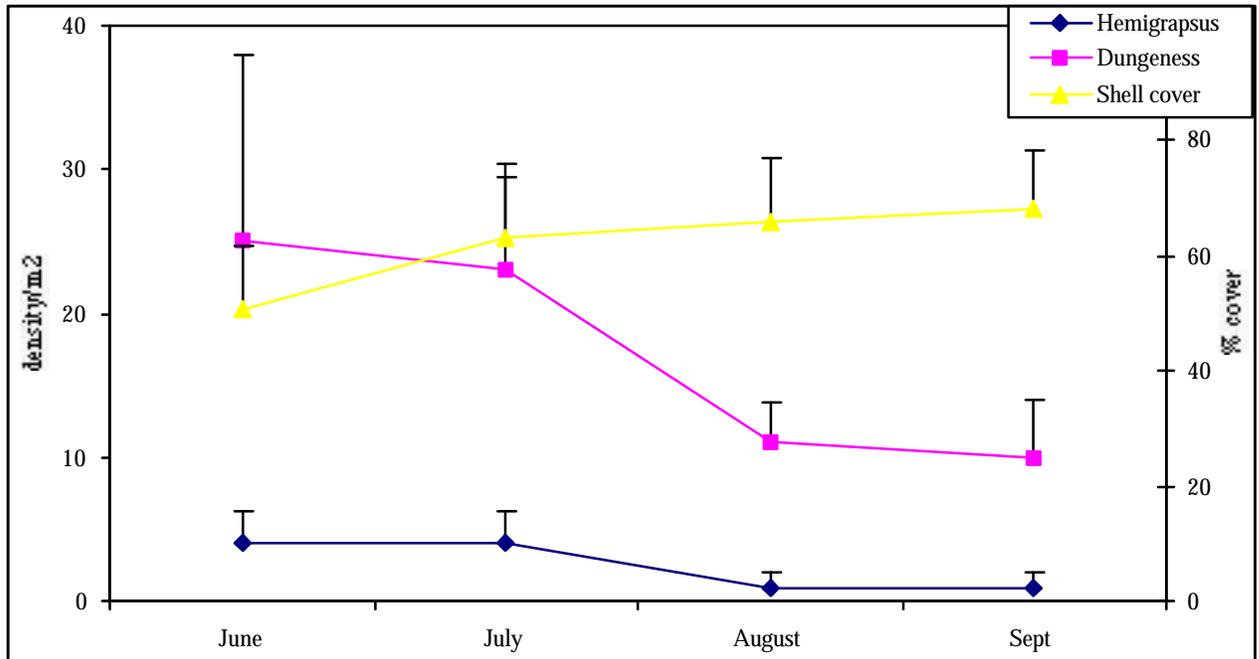


Figure 3. 1995 Island plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

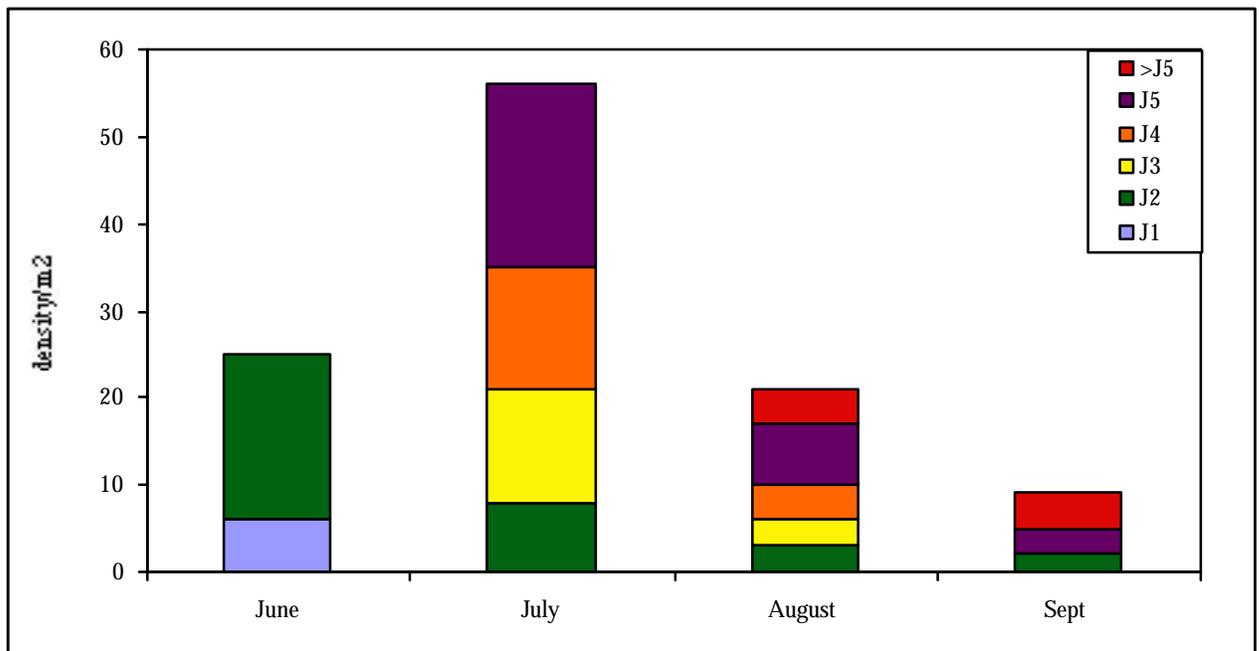
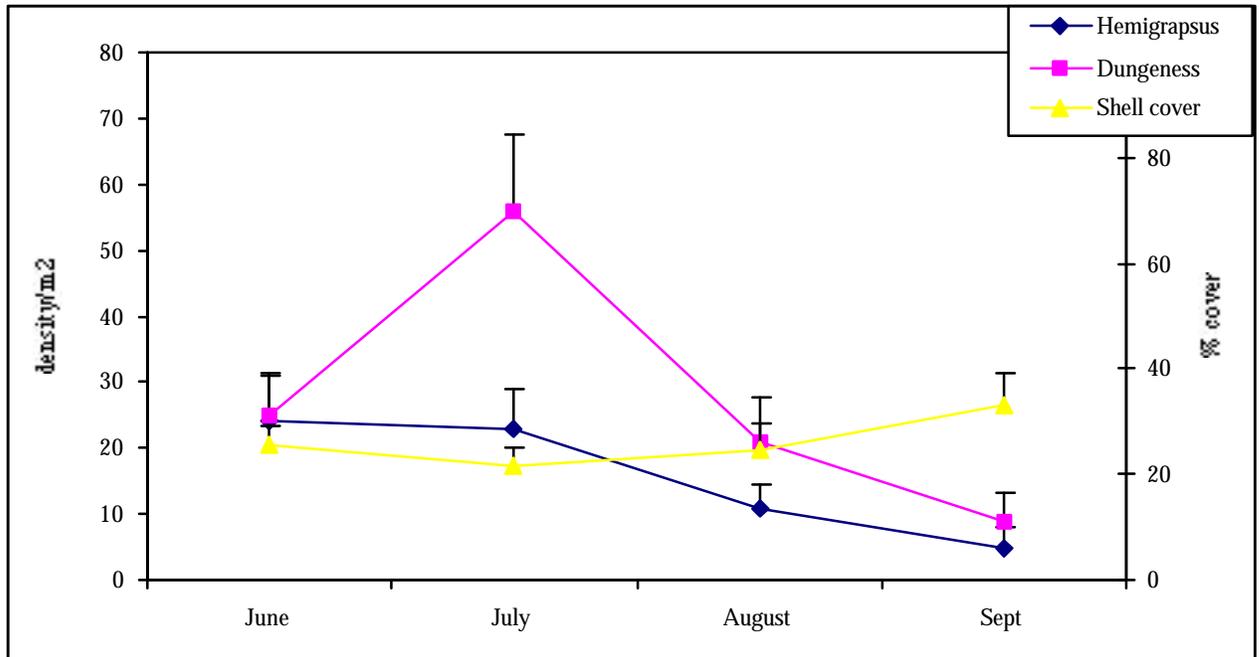


Figure 4. 1996/1997 plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

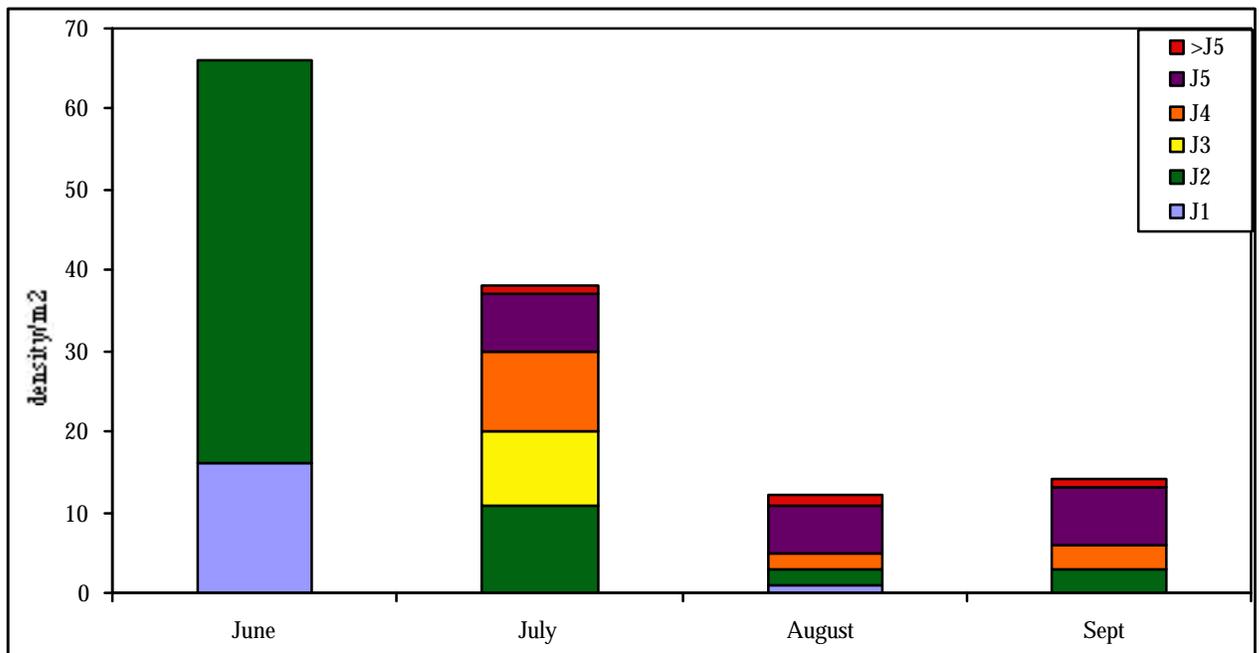
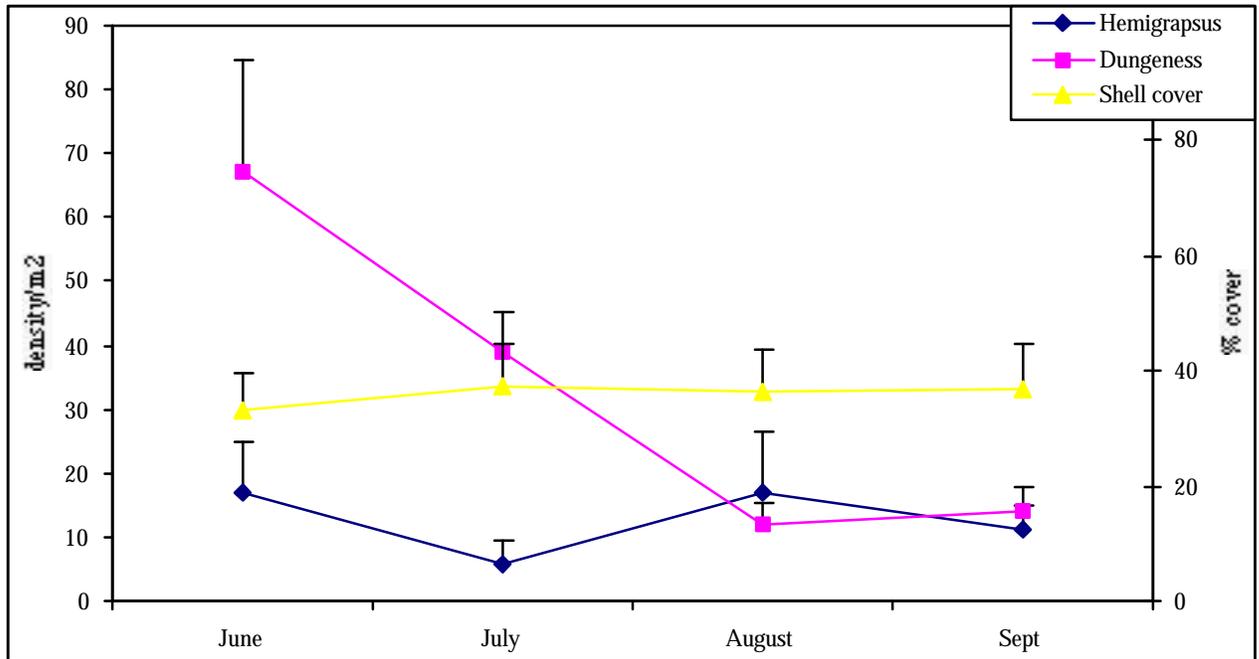


Figure 5. 1997 East plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

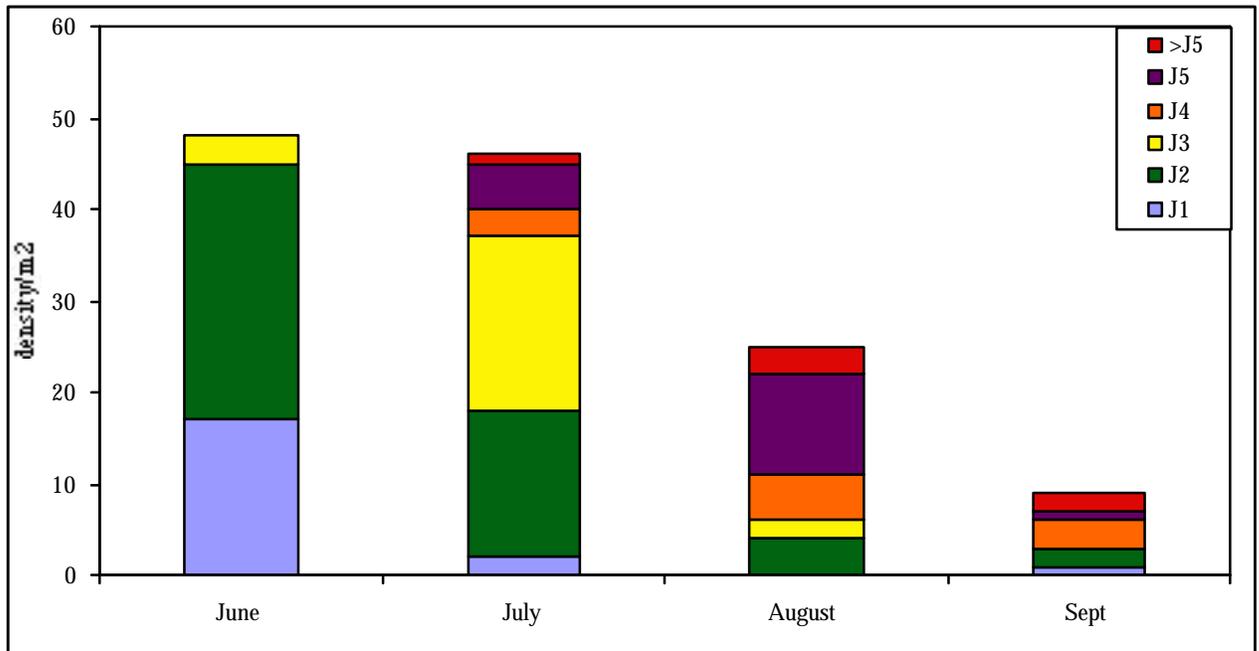
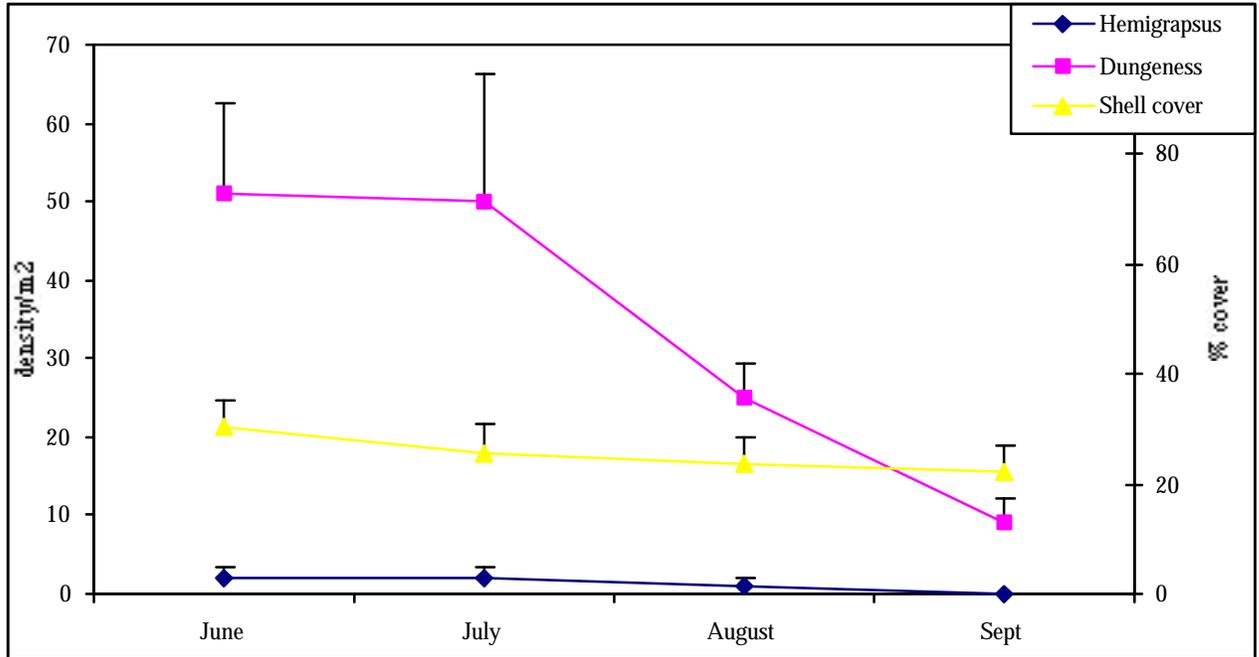


Figure 6. 1999 Up plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

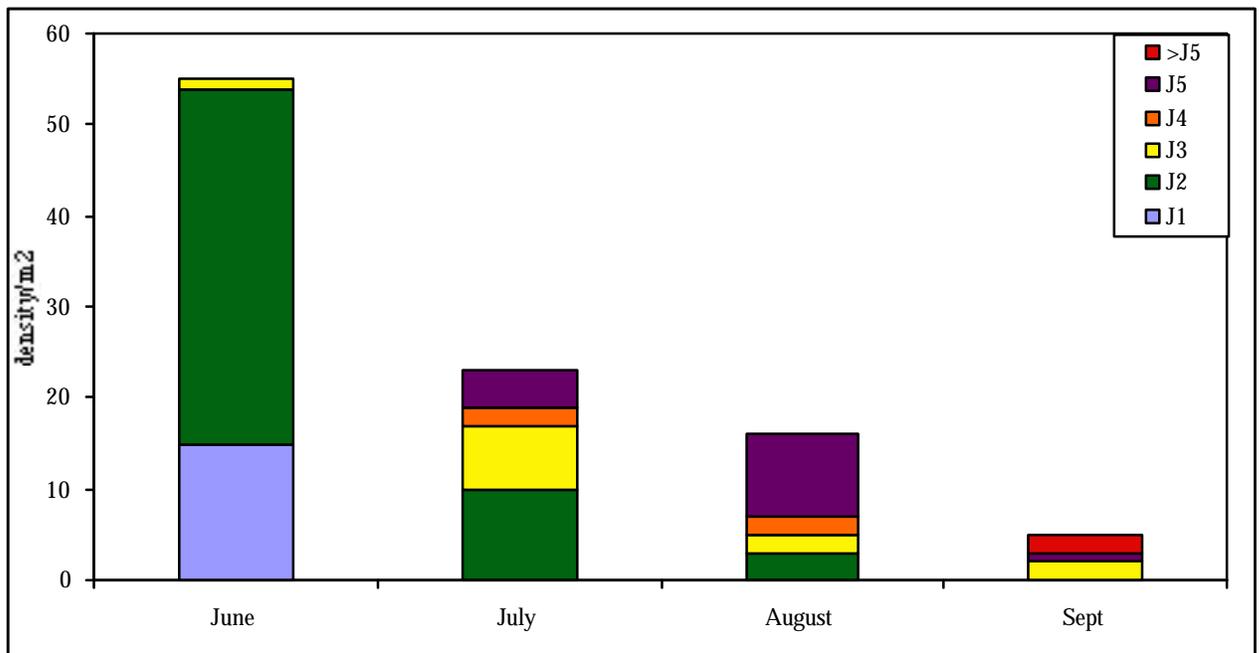
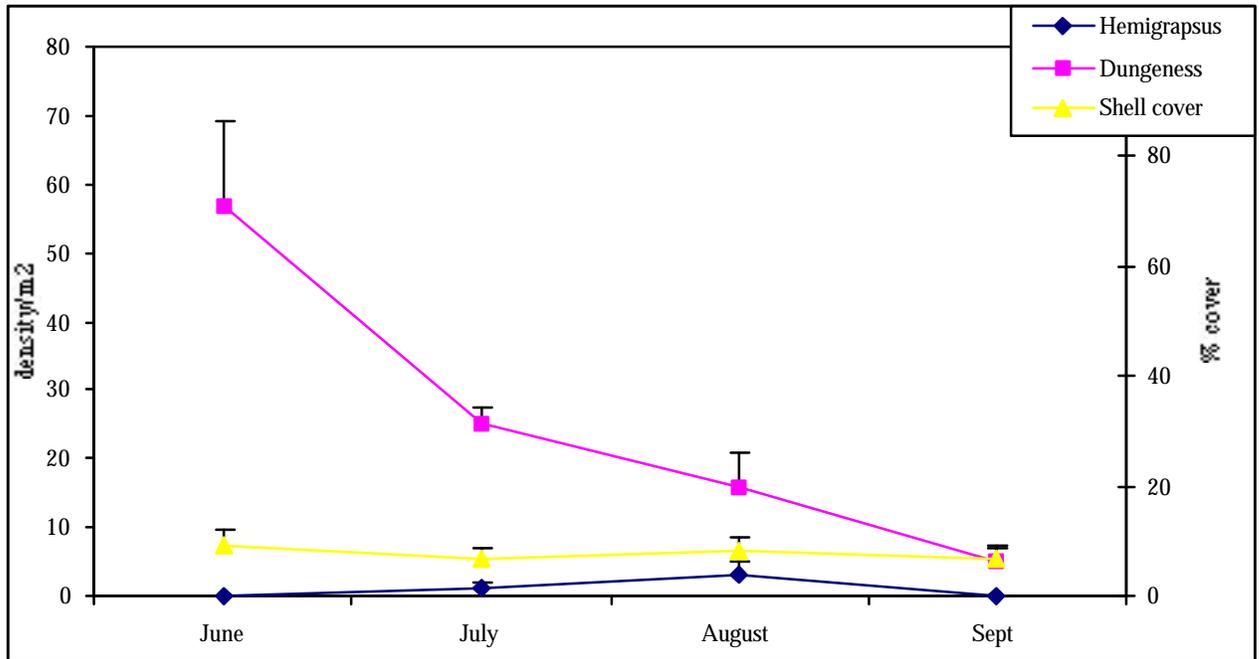


Figure 7. 1999 Down plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

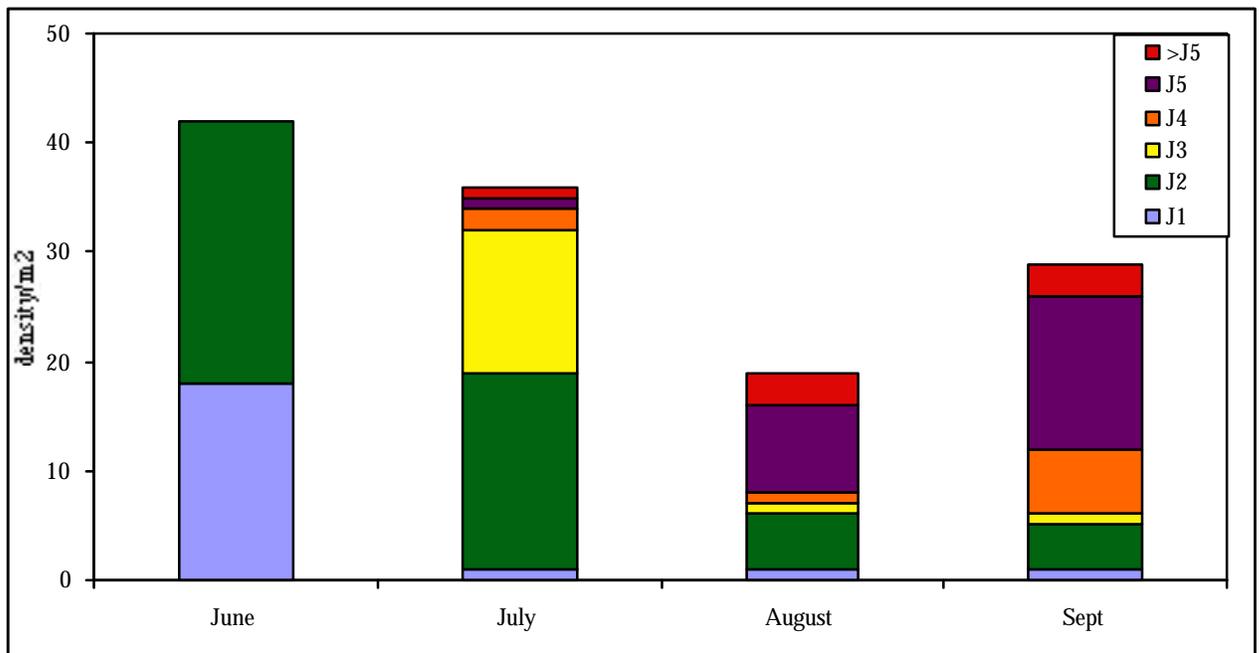
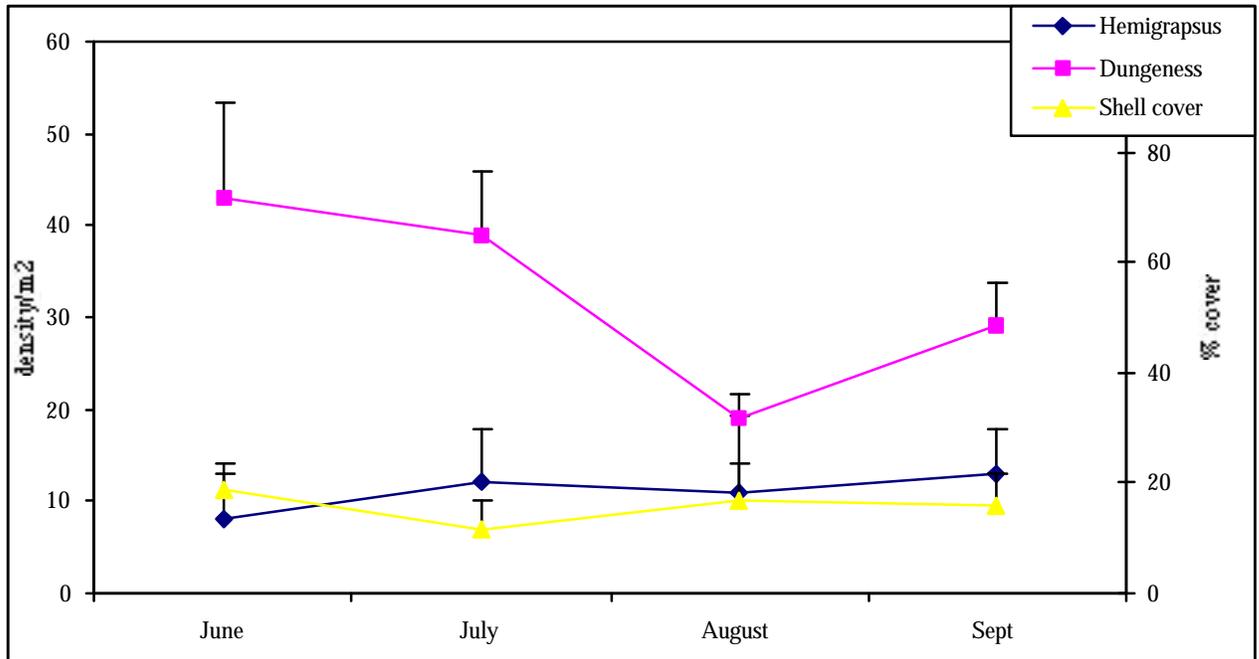


Figure 8. 1999 Overlay plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

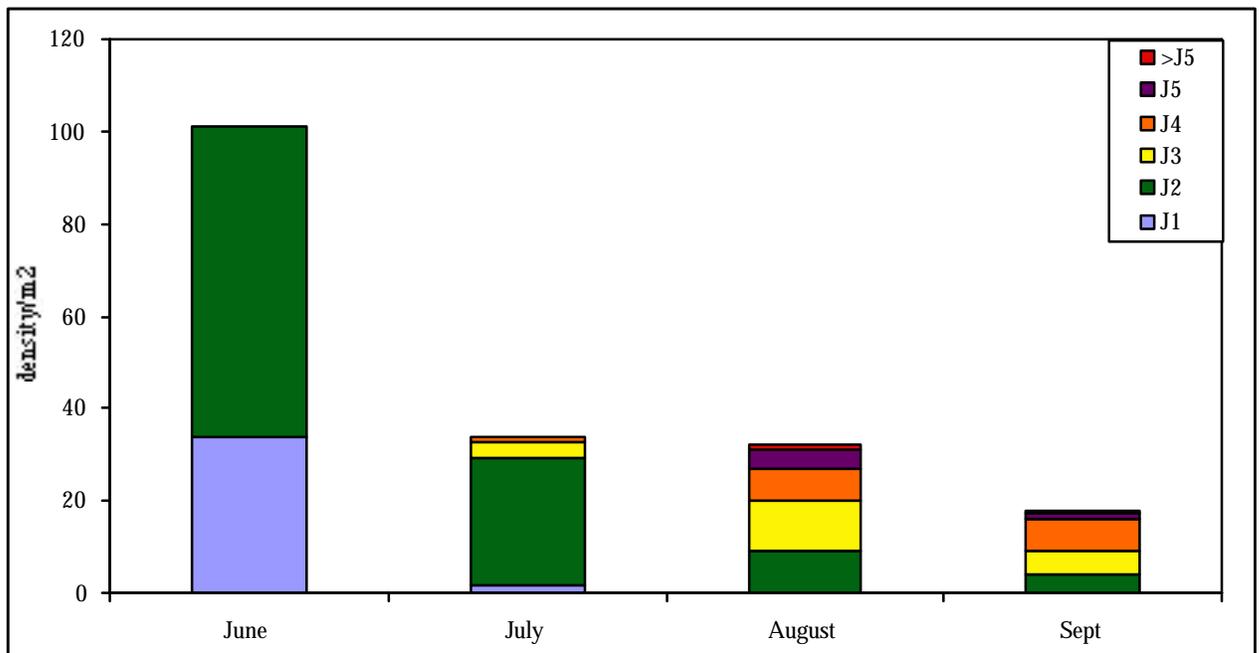
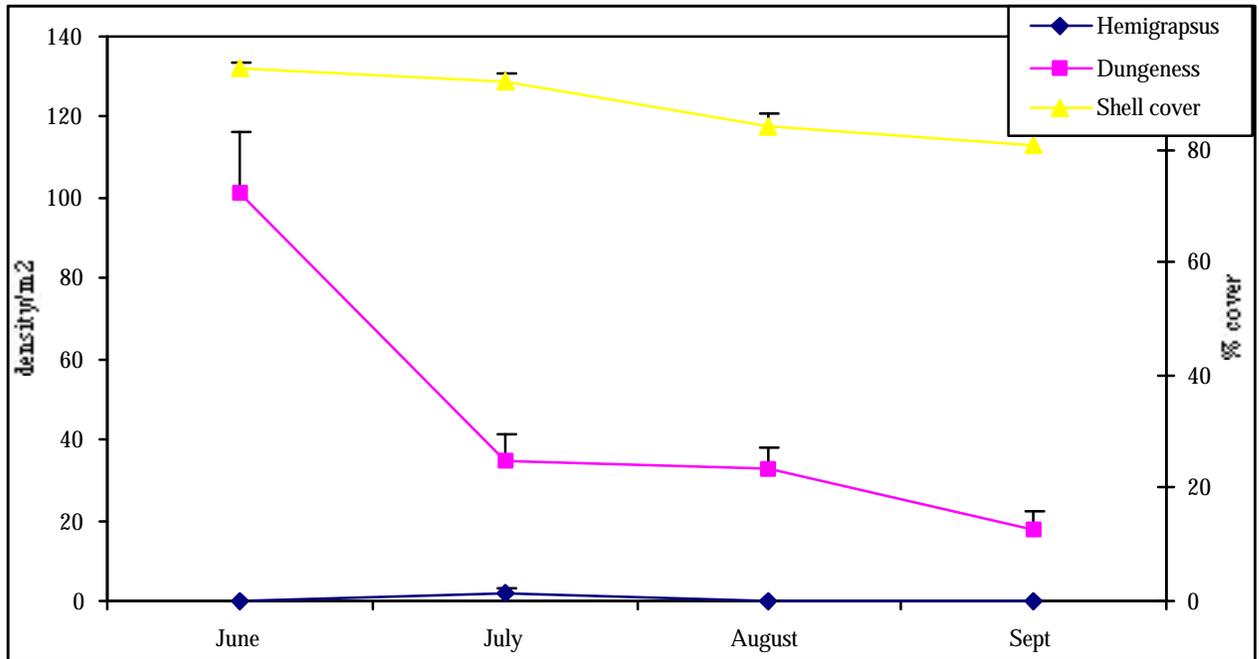


Figure 9. 2000 Up plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

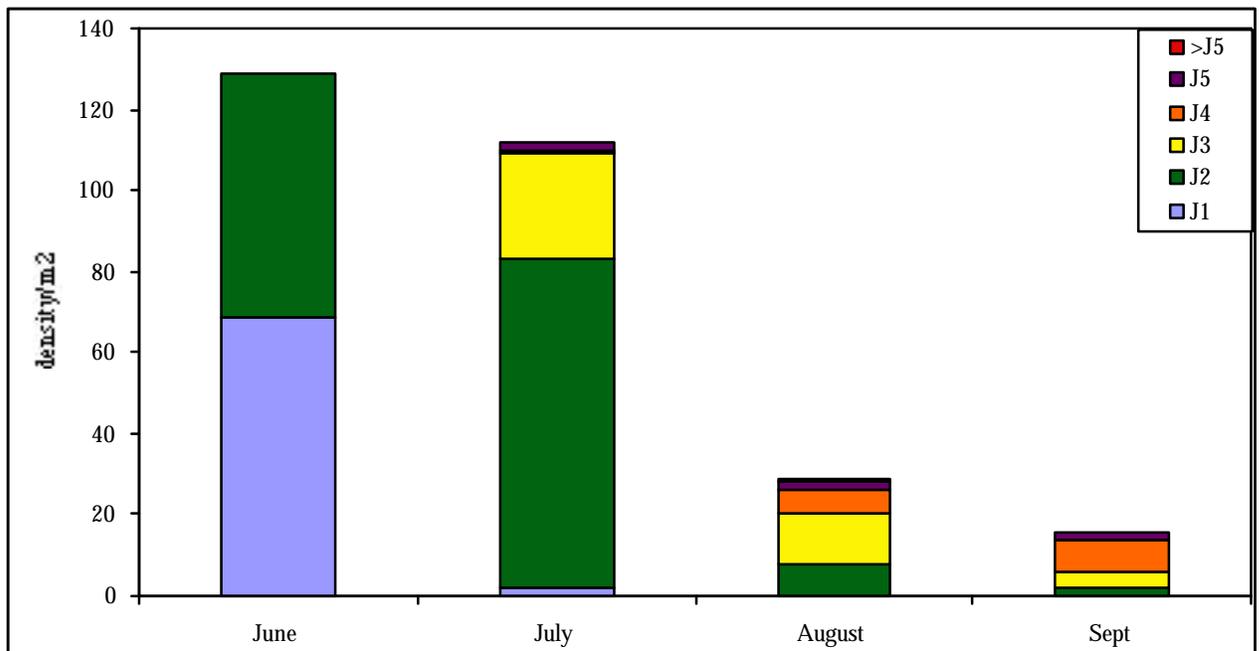
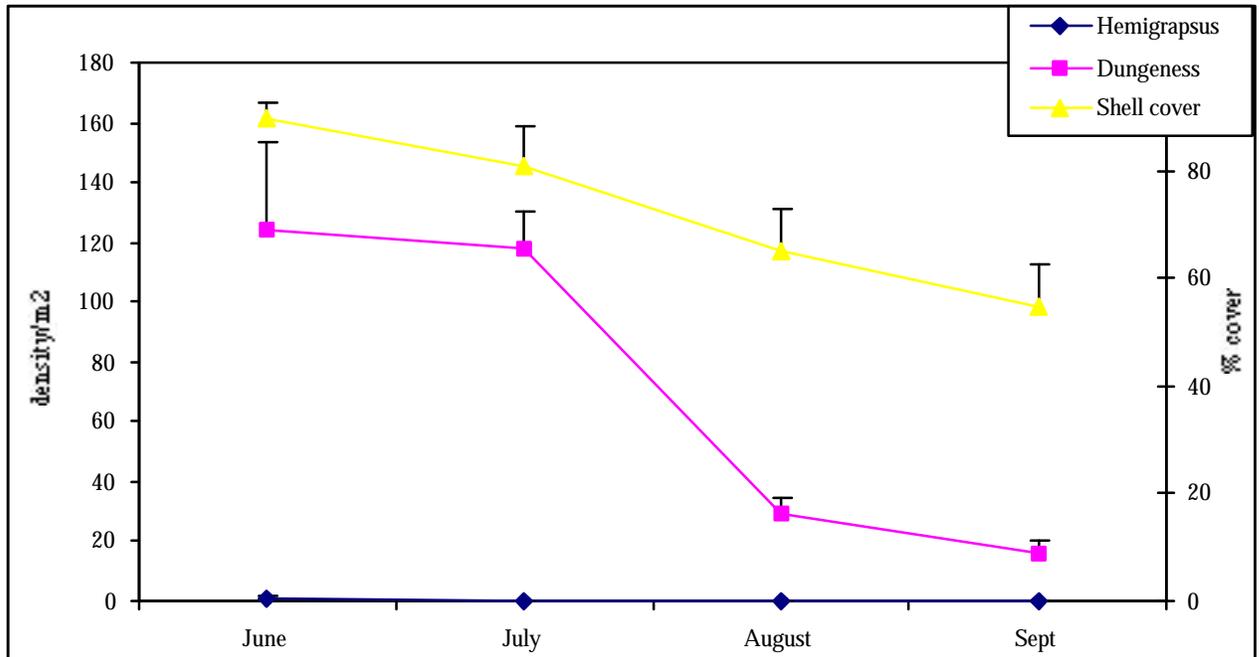


Figure 10. 2000 Down plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.

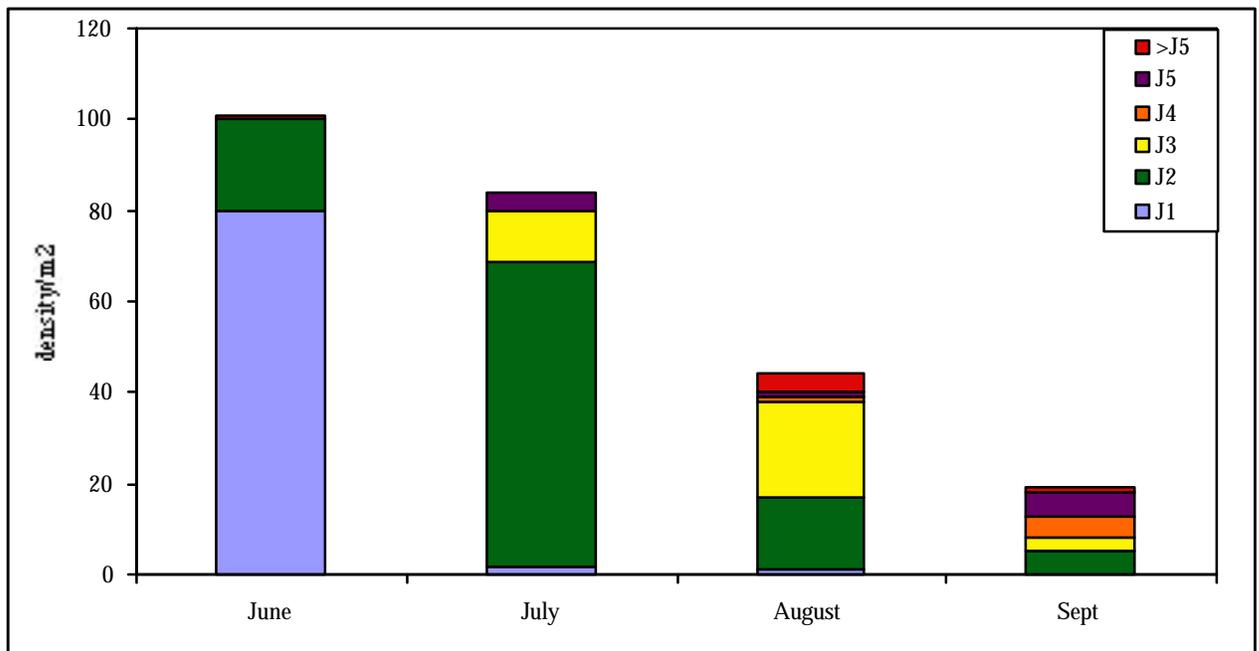
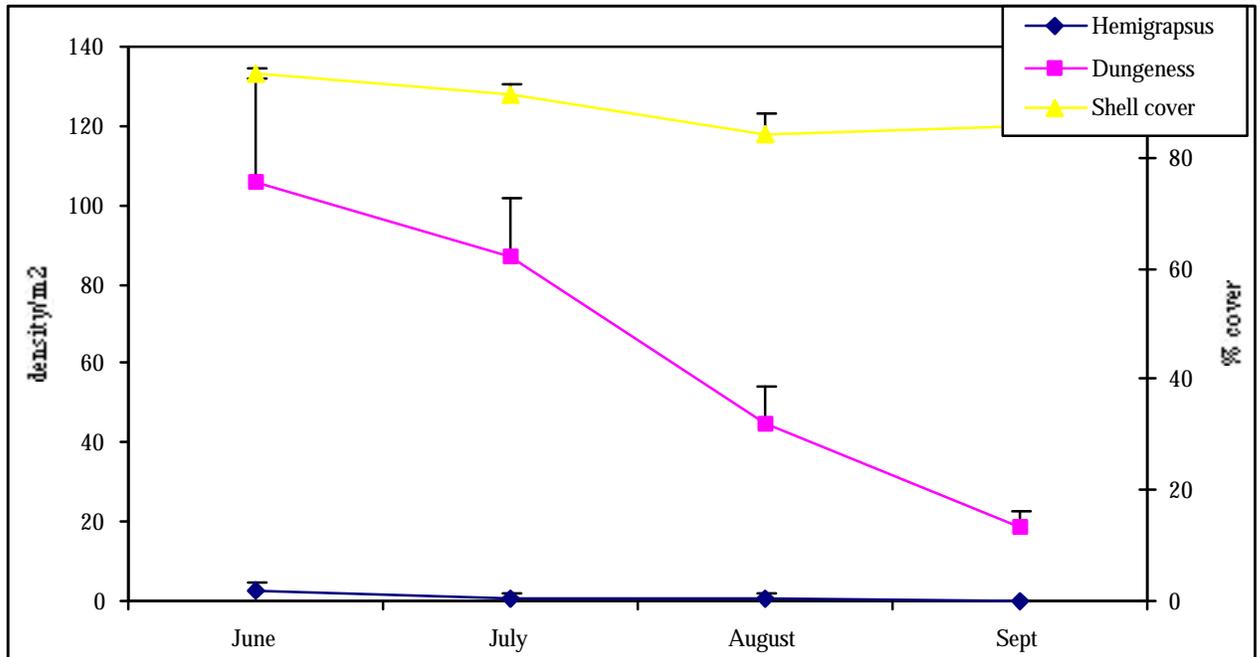


Figure 11. 2000 East plot data: Dungeness and Hemigrapsus densities, percent shell cover, and Dungeness crab instar compositions for June through September 2000.



Figure 12. Close-up view of refuge space available in new (top) and old (bottom) shell habitats during mid-summer 2000.

Instar composition

Crabs apparently settled primarily in late May soon before the initial sampling period, since instar composition data indicate almost exclusively J1 and J2 instars among the early June juvenile Dungeness crabs (Figures 3-11). As it typically takes about 30 days for instars to reach 3rd instars after settling as J1s, the fact that no J3s are present indicates that settlement began at the earliest a few weeks (<30 days) prior to the initial sampling. (Therefore had crab sampling been undertaken on the previous low spring tide in May 5-7, 2000, densities would probably have been nearly zero on all nine plots.) Because there are no initial spikes in density and also because all nine plots already have J2s by the first sampling period (June 3-5, 2000), the majority of settlement must have occurred more than a week before these data were collected in order to allow 1/2 –2/3 of the settlers to molt into the J2 instar class. These instars continued to grow in size while their numbers declined throughout the summer (Figures 3-11). There was evidence of some later cohorts of juveniles settling into both old and new shell plots, particularly on the 1995 Island (Figure 3) and the 1999 Overlay (Figure 8), although survival of these later cohorts was probably low due to cannibalism and refuge space occupation by larger instars. Even by the last day of August (the ‘early September’ sampling period), there were J1 instars in three of the plots (1995 Island, 1999 Up, and 1999 Overlay). Compared with summer 1999 data, however, where settlement was quite protracted throughout the summer, this late settlement was very minor, amounting to no more than 1-2 J1 instars per m² at any point after the beginning of June 2000.

Very few crabs seem to have remained in the habitat mitigation plots over the winter, since there were only J4 and larger instars in one plot in early June (1995 Island, Figure 3). Several J5s (21 • m⁻²) appeared in the 1996/1997 plot in early July (Figure 4), even though no larger instars were present in June. The June J1s and J2s (6-8 mm and 9-12 mm carapace width, respectively) would not have had time to grow to 20-26 mm during the sampling interval. Many of the other old shell plots show J5 instars appearing in July at higher densities than would be expected based on the instar composition of the previous month (1995 Island, 1997 East, 1999 Up, and 1999 Down). These crabs may have migrated into the plots from subtidal locations, although the impetus for doing so

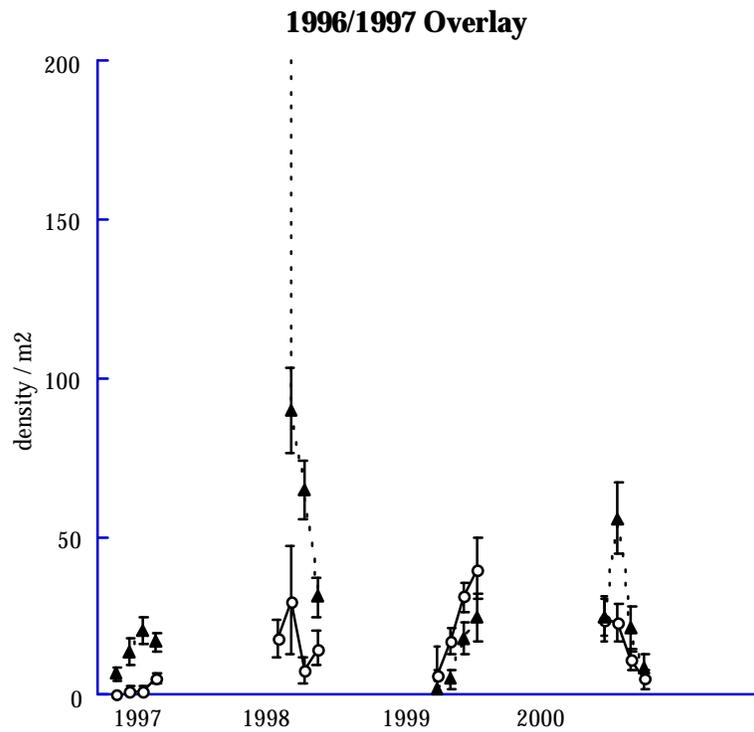
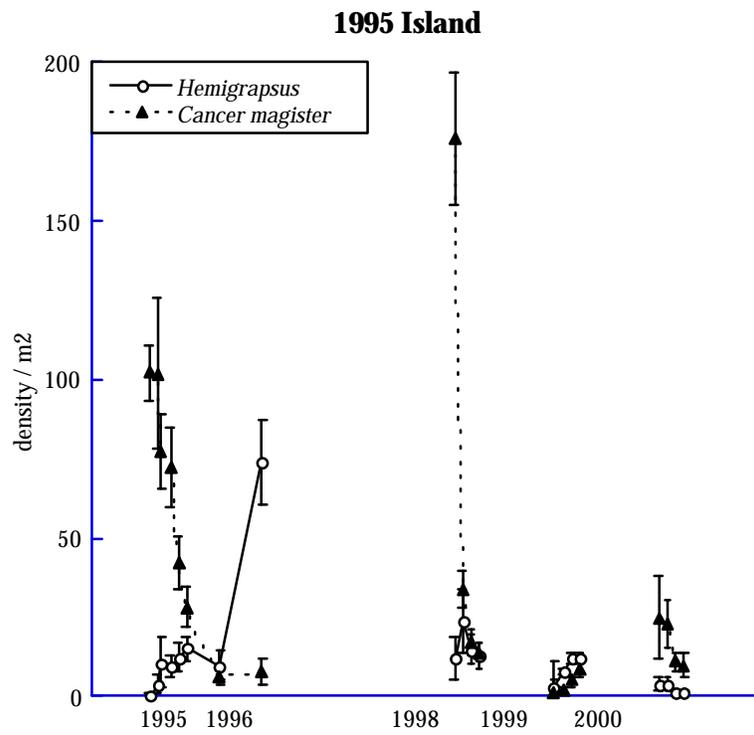


Figure 13 a-b. Crab density timelines for 1995 Island and 1996/1997 plots, showing densities for both species sampled from initial construction through summer 2000.

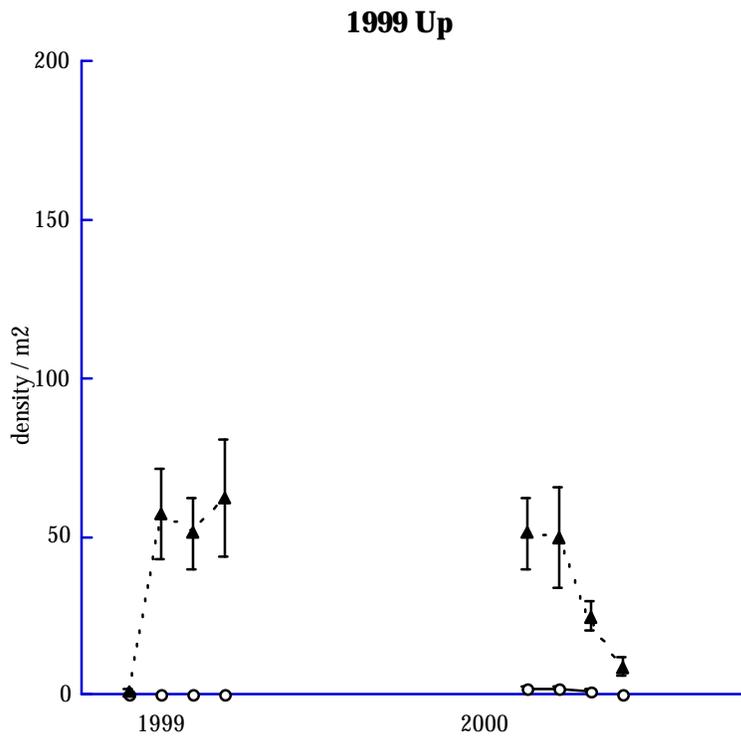
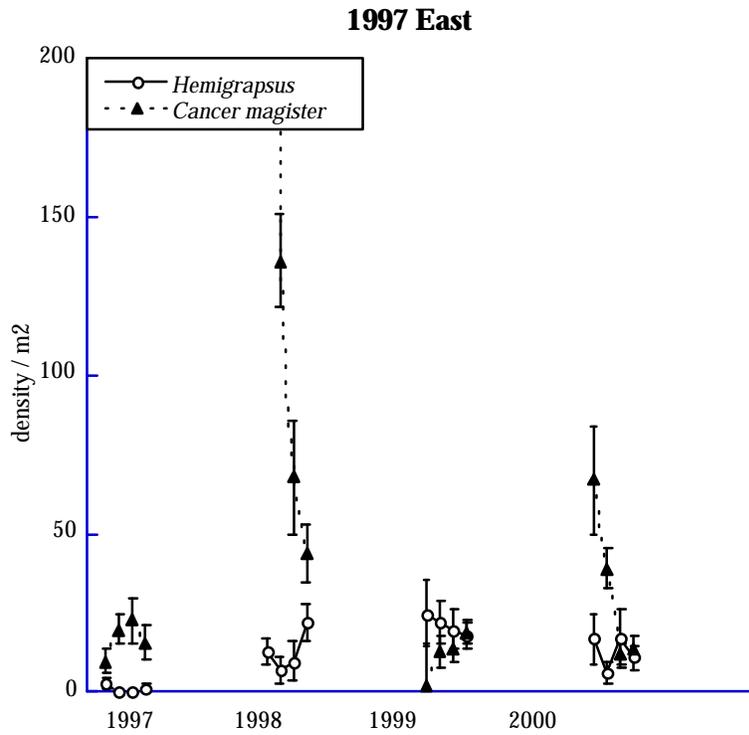


Figure 13 c-d. Crab density timelines for 1997 East and 1999 Up plots, showing densities for both species sampled from initial construction through summer 2000.

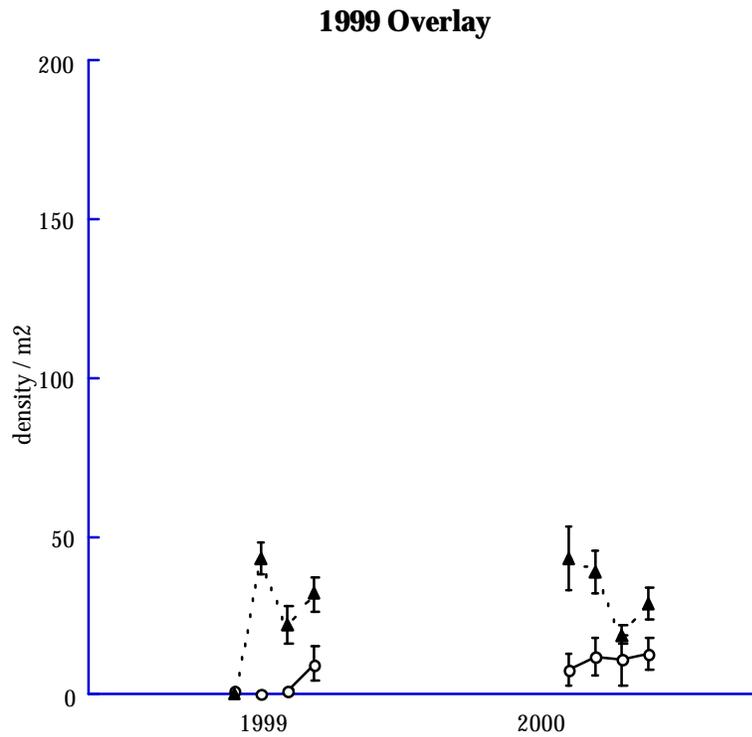
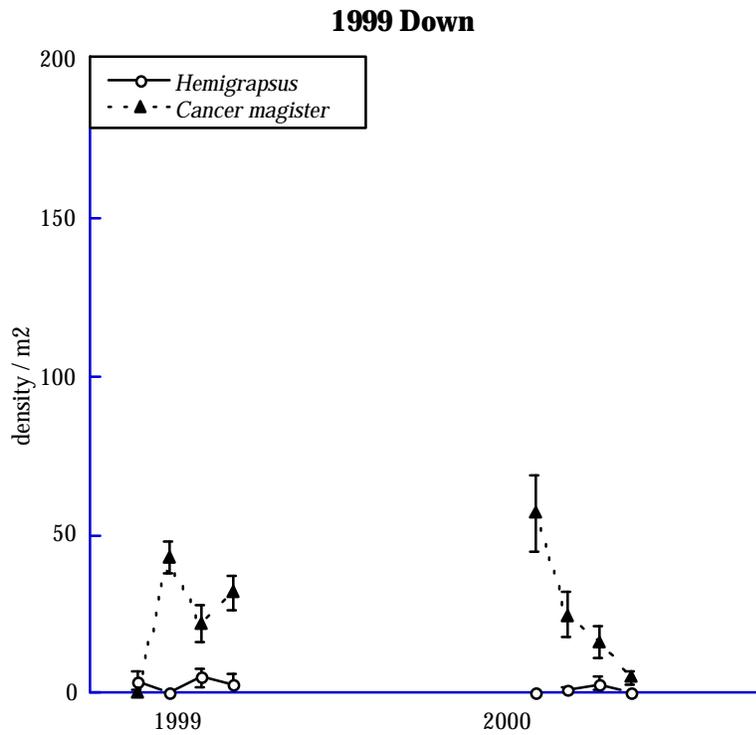


Figure 13 e-f. Crab density timelines for 1999 Down and 1999 Overlay plots, showing densities for both species from time of initial construction through summer 2000.

remains an open question. Looking at size class and densities of adjacent intertidal mitigation plots the previous month does not help to explain this phenomenon. Annual density comparisons show that 2000 is much more typical than was 1999 data in terms of the total abundance as well as the shape of the summer density trend (Figure 13 a-f). The extreme abundances seen in 1998 on the 1996/1997 (Figure 13b) and 1997 East (Figure 13c) plots in June and July are not seen in June and July 2000. Clearly, larval supply, initial settlement, and overall abundance were greater in 1998. The La Nina effect may have compromised larval settlement cues in 1999 causing protracted settlement and the resultant increasing summer densities, as well as possible lower success of settlers which might not have been able to overwhelm predators by settling en masse. Protracted settlement exposes juvenile crabs to greater risk of cannibalism too, since a larger range of instar size classes are present at a time. The increasing density trends in the 1997 data are more similar to 1999 patterns than other years.

Hemigrapsus density

Hemigrapsus oregonensis densities were very low on all three of the new 2000 shell plots and remained so for the entire sampling period (Figure 9-11). The highest *Hemigrapsus* density on new shell was 3 crabs • m⁻² on the 2000 East plot in June (Figure 11). The 95 Island, 1999 Up and 1999 Down shell plots also experienced very low *Hemigrapsus* densities (≤ 4 crabs • m⁻² over the whole summer). The 1996/1997, 1997E, and 1999 Overlay plots had much greater densities, 5-24, 6-17, and 8-13 crabs • m⁻² respectively. Although there has typically been a strong negative correlation between these two species on oyster shell mitigation plots in the past (Visser 1997), the only indication in summer 2000 data of such a pattern is on the 1997 East plot, where Dungeness densities decline as *Hemigrapsus* densities increase. Since Dungeness densities decline on all nine plots over the summer, however, and not just on the 1997 East plot, it is impossible to implicate *Hemigrapsus* in the decline in abundance on the only plot where their densities happened to increase noticeably over the summer. It seems that 2000 was a year where *Hemigrapsus* presence was not a major issue in juvenile Dungeness crab survival and use of the shell refuge habitat.

Summer 2000 *Hemigrapsus oregonensis* densities are similar to those of past years with the exception of the 1995 Island, which had extremely high *Hemigrapsus* densities in June 1996. Also notable is the fact that *Hemigrapsus* have hardly colonized the 1999 Up or 1999 Down shell plots, even though this is their second year after construction (Figure 13d-e). The 1999 Overlay plot has typical *Hemigrapsus* densities for an old shell plot (Figure 13f).

Mortality rates

Mortality rates were computed for each of the nine plots sampled during summer 2000 (Table 3) by fitting an exponential function of the form $y=ke^{-bx}$; where k is the y-intercept, or predicted initial Dungeness crab density in number of crabs • m⁻², b is the time interval in days over which the mortality rate operates, and x is the mortality rate. The mortality rate was then used in the production model to estimate the number of surviving crabs after the appropriate time interval. Since J4 crabs were chosen by agency and COE personnel as the production unit, the model applies the mortality rate over the amount of time it takes juveniles to reach J4 instars, 35 days for J2 instars and 20 days for J3 instars (when they have to be considered separately).

Table 3. Summary statistics for shell mitigation plots sampled in summer 2000.

Plot	Area (m2)	Shell cover June (%)	Plot-specific mortality	% Survival after 35 d	Prod / m2 (crabs/m2/mo)	Total production (# J4 crabs)
1995 Island	14662	50.6	0.0122	65	4	131071
1996/1997	48944	25.6	0.0315	33	3	129737
1997 East	10550	33.2	0.0205	49	8	115992
1999 Up	35514	30.4	0.0206	49	7	263045
1999 Down	35514	9.2	0.027	39	5	62349
1999 Overlay	33066	19	0.0066	79	10	211319
2000 Up	13750	94.4	0.0182	53	14	718935
2000 Down	21766	89.6	0.0264	40	15	1084198
2000 East	14553	95.4	0.0203	49	13	700245

Plot-specific mortality rates were computed for summer 2000 data using the original method of fitting the mortality function to total Dungeness crab density from monthly samples. J2 mortality rates, using only J2 and larger instars to fit the curve, as per the procedure described in the 1998 Grays Harbor crab mitigation report (Visser and Armstrong 1999), were not appropriate this year. Crab data for 2000 summer did not show a strong settlement peak of J1 instars as did the 1998 data, probably because the first sampling trip for summer 2000 was in early June instead of early May and densities had stabilized before sampling occurred. The height of settlement peaks on all plots in May 1998 (Figure 13a-c) compared to the relatively low peaks at the first sampling date in 2000 as well as instar composition graphs suggest that the initial spiked settlement pulse either did not occur or was missed by this year's sampling. It was thus not necessary to leave out J1 instars when computing 2000 plot-specific mortality rates since the high initial mortality on settling J1s did not occur during this year's sampling period. Using J2 mortality curves would have resulted in lower r^2 values for the fitted curves due to the nature of this year's data.

Survival rates were the highest (i.e. mortality rates the lowest) on the 1999 Overlay plot during summer 2000 (79% after the prescribed 35 day interval; Table 3). Crabs inhabiting the 1995 Island enjoyed the next highest survival, 65%, followed by the 2000 Up plot at 53%. The lowest survival rates were suffered by crabs on the 1996/1997, 1999 Down, and the 2000 Down plots, with 33%, 39%, and 40% respectively. These mortality rate patterns suggest that maybe shell plots constructed lower in the intertidal zone are less effective as crab habitat, but more analysis on tidal elevation data needs to be conducted before a conclusive statement can be made. Mortality rates cannot be explained by initial percent shell cover data, as the three highest survival rates this year were from plots with 19%, 51% and 94% shell cover. Likewise, the three lowest survival rates were on plots with 9%, 26% and 90% shell cover in June (Table 3).

In addition to computing the plot-specific mortality rates for the nine plots sampled during summer 2000, all previous data were reanalyzed and year- and plot-specific mortality rates computed whenever possible (Table 4). In several cases, averages had been used at the recommendation of Visser and Armstrong (1995) to make computing rough production estimates more straight-forward, even though data had been

Table 4. Annual mortality rates for new and old shell plots. Survival is the proportion of crab surviving to J4 instars after the 35 day interval it takes to molt from J2 to J4. All values are for South Channel plots except for 1991 new shell, which was constructed at PacMan. Average values are marked with an *.

Year	New Shell	Survival	Old Shell	Survival
1990	0.0195	0.51		
1991	0.0276	0.38	0.0216	0.47
1992	0.0179	0.53		
1993			* 0.0216	0.47
1994	* 0.0187	0.52	* 0.0216	0.47
1995	0.0136	0.62	0.0248	0.44
1996	0.0123	0.65	0.0096	0.71
1997	* 0.0158	0.58	* 0.0187	0.52
1998	0.0208	0.48	0.0343	0.3
1999	* 0.0168	0.56	* 0.0226	0.45
2000	0.0216	0.47	0.0197	0.52

collected to make calculation of plot-specific mortality rates possible. Whenever enough data existed to calculate year- and plot-specific rates, they were computed for more accurate production totals. There were some cases where average mortality rates still had to be used instead of year- and plot-specific ones because of the nature of the data collected in that year. During both 1997 and 1999 summers, settlement appeared to be fairly protracted and juvenile Dungeness crab densities increased throughout the summer on many of the plots sampled. Fitting an exponential curve to increasing density data results in a negative number for the mortality rate estimate, which is not biologically meaningful, so averages were used for these years. In some cases, crab density and percent shell cover samples were taken only once or twice during the summer, making it impossible to fit a mortality function or leaving too few degrees of freedom for parameter estimates.

Whenever it was necessary to use average mortality values, averages for new and old shell plots were computed separately using all data for that plot type at that location to date (Table 4). For example, the mortality rate used for the new shell plot constructed in 1994 at South Channel was the average of values from the initial year of each of the 1990 and 1992 plots, while the mortality rate for the 1997 was the average of new shell

plots constructed and sampled in 1990, 1992, 1995, and 1996. Mortality rates from the 1991 shell plot sampled in 1991 were not included in either average since this plot was constructed at PacMan, not at the South Channel site. The average value used for the 1994 shell plot was not included in the 1997 computation. Using this method to compute averages when necessary, instead of computing a running average each year using all available data, enables generation of production estimates which do not change with each years analysis of the latest data.

Juvenile Dungeness crab mortality rates on old shell plots during summer 2000 were fairly low compared to previous years (Table 4), the second lowest mortality rates ever measured on old shell plots. New shell plots during summer 2000 experienced the second highest mortality rates ever measured on new shell mitigation habitat (Table 5) and the highest ever at South Channel. At least part of this lower than typical survival from the initial year of construction may be attributed to the very poor shell longevity of the new shell, particularly the 2000 Down plot, which went from 90% to 55% in the four

Table 5. Annual production by new and old shell plots from 1990 through 2000. Black values are from South Channel mitigation sites; colored values are from PacMan mitigation sites. Note that unlike other tables, 'year' here is year of sampling, not year of plot construction, so 3.4 million crabs were produced by all nine new and old plots sampled during 2000.

Year	New	Old	Total	st.dev.
1990	109,710		109,710	29,172
1991	204,984	117,987	322,971	77,615
1992	2,586,894			
	640,071		3,226,965	670,204
1993		34,077		
		10,145	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
TOTAL	12,091,941	3,103,967	15,195,907	1,325,114

months sampled (Figure 10). Typically, shell cover remains higher on new shell plots during the first summer after construction.

Shell cover

Percent shell coverage data for old shell plots (Figure 14 bottom) stayed extremely constant over the four month sampling period of summer 2000 (Figures 3-11). The 1995 Island plot had high percent cover (51-68%; Figure 3), the 1996/1997, 1997E, and 1999 Up plots ranged from 22-37% cover (Figure 4-6), and the 1999 Down (Figure 7) and 1999 Overlay (Figure 8) plots were lowest with 7-19% cover. As expected, the new shell plots (Figure 14 top) had the greatest percent cover with 81-95% on all plots throughout the summer except for the 2000 Down plot which dropped to 65% in early August and then down to 55% by the end of August (Figure 10). With the exceptions of 1995 Island and 1999 Up, variability between estimates was very low (standard deviation $\leq 8\%$). These two mitigation plots were the most patchy, ranging from 0-10% oyster shell cover in some sections to 90-100% in others.

Shell cover can decrease over time due to sedimentation and accretion of particles coming down the Chehalis River as well as due to bioturbation, especially by burrowing shrimp and sinkage of shell habitat into the mud. Many of the shell plots sampled during summer 2000 show evidence of these events, declining percent shell cover as the summer progresses: 1999 Up, 2000 Up, 2000 Down, and 2000 East. As was documented last year (Visser 1999), percent shell cover was more constant on old shell plots compared to new shell plots (Figures 3-11). It was originally anticipated that overlay plots would experience greater shell longevity due to a base of original shell buried in the mud. It was hoped that this layer of buried shell would add stability to the overlying sediment and slow sinkage rates, but the data so far do not support the hypothesized percent shell cover difference between overlay plots and shell plots constructed over bare mud. Some of the plots showed an increase in shell coverage over the summer. Factors that may have caused an increase in exposed shell on the 1995 Island, 1996/1997, and 1997 East plots include storm scour, heavy rains, and change in currents.



Figure 14. Overview of new (top) and old (bottom) shell habitat. These pictures happen to be of the 2000 East and 1996/1997 habitats as they appeared in July 2000, but are typical of many shell mitigation plots in initial (top) and subsequent (bottom) years after construction.

Total Production

Total production for all plots sampled during summer 2000 was 3.42 million crabs (Table 5), 2.5 million of which were from the three new shell plots constructed in spring 2000 and 0.91 million were from the 6 shell plots sampled this year, but constructed in previous years. Of the new shell mitigation plots, 2000 Down produced the greatest number of crab (1.1 million), significantly more than did the 2000 Up and 2000 East plots, which produced about 0.7 million each (Table 3). All three new shell mitigation plots had similar percent shell cover in June, although the 2000 Down cover declined much more over the course of the summer than did the other two new plots (Figure 9-11). The shell plots constructed in 2000 had virtually no *Hemigrapsus* to compete with juvenile Dungeness crab for refuge space. Hence, the differences in total production were due in part to the differences in the sizes of the plots, as evidenced by the similarity of the average monthly production per m^2 of these three plots ($13\text{-}15 \text{ crabs} \cdot m^{-2} \cdot \text{month}^{-1}$; Table 3). Differences in settlement densities, which were higher on the 2000 Down plot ($124 \text{ crabs} \cdot m^{-2}$ in early June) than the other two ($82\text{-}101 \text{ crabs} \cdot m^{-2}$ in June) also contributed to the productivity differences.

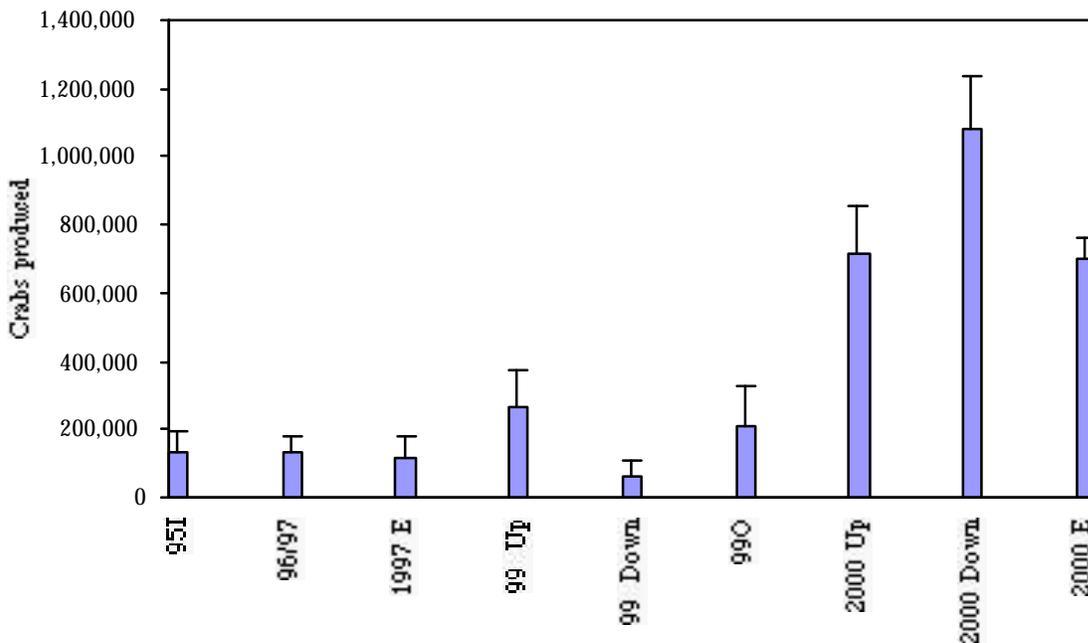


Figure 15. Annual crab production during summer 2000 by plot for each of the nine shell mitigation plots sampled in 2000.

All of the old shell plots produced significantly fewer crabs than did the new plots (Figure 15), a pattern which has held for all years and plots sampled (Table 5). Among the old shell plots sampled in 2000, the 1999 Up and 1999 Overlay produced the most crabs, 0.26 million and 0.22 million respectively (Table 3, Figure 15). The 1995 Island, 1996/1997, and 1997 East plots produced 0.12 - 0.13 million crabs each, while the 1999 Down plot produced only 0.06 million crabs over the four month sampling season. Looking at average monthly production per square meter shows that the 1999 Overlay, the 1997 East, and 1999 Up plots gave the highest productivity per area among the old shell plots (7-10 crabs per m²), followed by the 1999 Down, 1995 Island, and 1996/1997 plots with 3-5 crabs • m⁻². There was no evidence of early settlement that was overlooked by the model. The very few J3 instars present at the first sampling in early June were accounted for by applying the plot-specific mortality rates over a shorter molt interval. No instars larger than J3 were present in the June samples, suggesting that very few crabs which may have settled late in 1999 over-wintered on the intertidal shell plots.

Refuge space available was estimated as the product of percent shell cover and total amount of shell area created. Plotting crab production against actual refuge space available to the crabs, or effective plot area, shows which plots have greater than average productivity per unit area, after size of plot and the effects of varying percent shell cover have been separated out (Figure 16). If the only parameter of importance was the amount of shell available on the surface of the shell, plots would be expected to fall along a diagonal line of increasing production with increasing refuge space. Plots falling above the line show greater than expected production per square meter of available shell and plots falling below the line show less than expected efficiency of shell. Among the plots sampled in summer 2000, the 2000 Up and Down plots produced higher than the average number of crabs per square meter of refuge available, and the 1996/1997 and 1999 Up plots produced fewer (Figure 16).

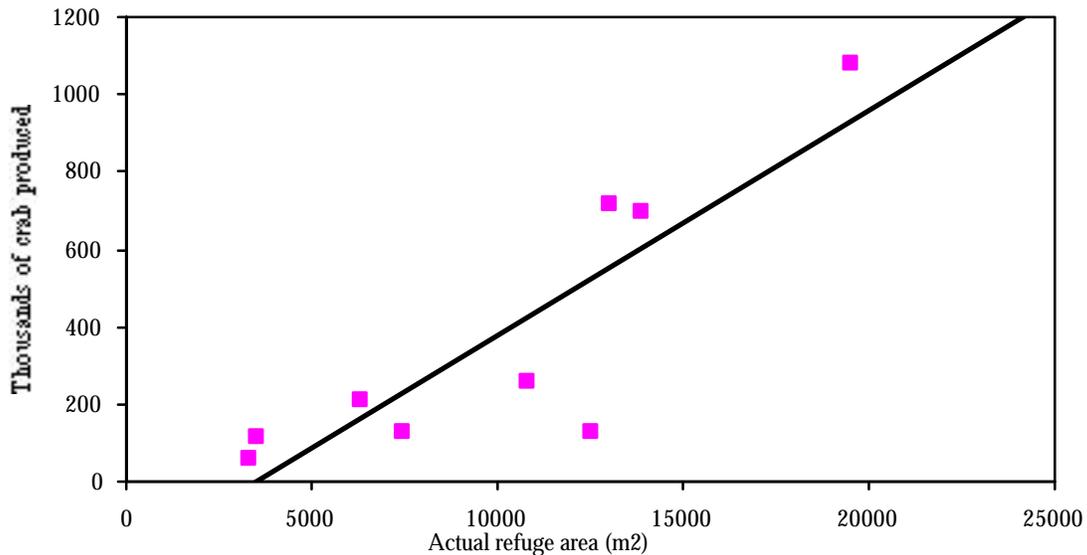


Figure 16. Crab production versus effective plot area for the nine plots sampled in summer 2000. Plots above line had greater than average prod/ m² and those below had lower prod/m².

Annual production comparisons

The cumulative crab production from 1990 through 2000 is about 15.2 million J4 crabs (Table 5). This total includes 0.86 million crabs produced on PacMan plots constructed in 1991 and 1992. Of this total, approximately 80% (12.1 million crabs) was from plots in their initial year after construction, and the remaining 20% (3.1 million) from all old shell plots sampled in subsequent years. Changes in total production on individual plots from past years are due to corrected and recalculated mortality rates in several cases, correction of 1999 Up and Down plot sizes, inclusion of J3 instars in some years, and the addition and updating of some data. Data from 1990 to 1994 may go up slightly after the addition of J3 instars into the production model where appropriate. At the time of this writing, the 1997 values are tentative and need to be rechecked after receiving copies of COE data files from 1997.

Of the nine plots created at the South Channel shell mitigation site since 1990, four of them (1992, 1994, 1996, and 1998 plots) yielded more than 91% of their total production in the first year after production (Table 6). All full mitigation plots produced 68% or more of their total in the initial year except one; the 1997 plot produced only 15%

of its total cumulative production in 1997. The test plot created in 1990 produced only 48% of its cumulative total in its first year.

Table 6. Initial and cumulative production for each mitigation plot constructed at South Channel.

Habitat	Area (m ²)	Production in Initial Year	Cumulative Production	% in initial year
1990 plot	4000	109,710	227,697	48
1992 plot	57600	2,586,894	2,732,554	95
1994 plot	46000	1,633,038	1,722,562	95
1995 plot	94000	2,054,273	2,674,028	77
1996 plot	96234	684,584	753,036	91
1997 plot	89280	275,729	1,789,639	15
1998 plot	18554	235,167	236,989	99
1999 plot	112906	1,164,115	1,700,827	68
2000 plot	50069	2,503,377	2,503,377	N/A

When annual production by each shell plot was graphed against plot size, almost all shell plots sampled in the initial year of construction fell above the simple linear regression fitted to the new and old data (Figure 17). This simple line $y = 8.72x + 36,690$, where y is annual production in number of crabs and x is size of plot constructed in m^2 , explained 15% of the total variability in the production data. Only the 1996 and 1997 shell plots fell below the line of average production in their initial year. The 1992, 1994, 1995 and 2000 plots were well above the line in their initial year (Figure 17).

Because many factors come into play in later years, including *Hemigrapsus* density and percent shell cover declining at different rates, production in the first year after construction was plotted against original plot size (Figure 18) to see if more than 15% of the variation in the data could be explained. A second order polynomial, $y = -0.0005x^2 + 68.1x - 276,000$, where y is number of crabs produced and x is size of original plot in m^2 , explained 52% of the variation in production among plots in their initial year after construction (Figure 18). Considering the known influences on productivity (larval supply, percent shell cover, *Hemigrapsus* density) as well as many others not analyzed so far (tidal elevation, rainfall, eelgrass density, hydrological effects,

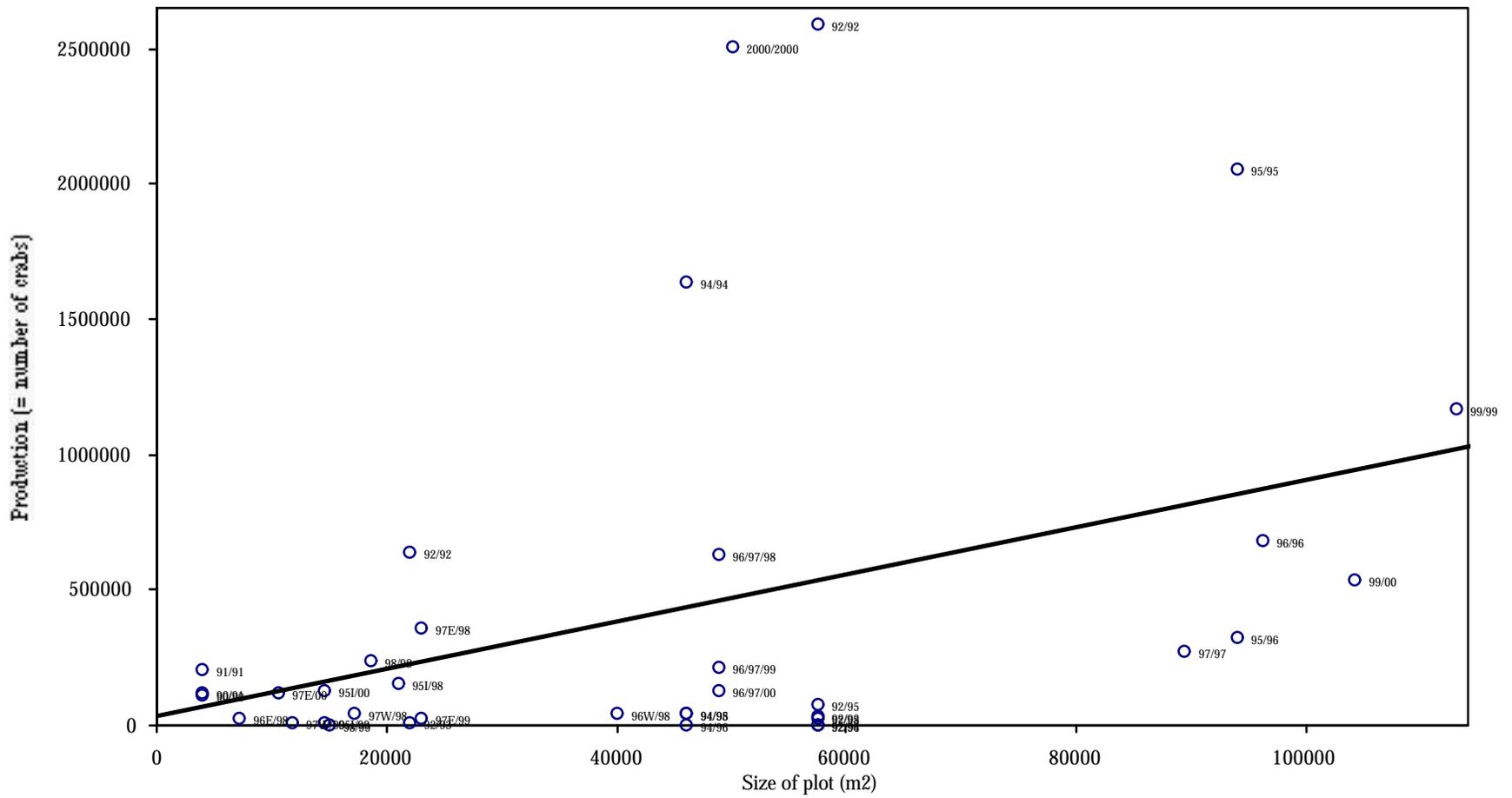


Figure 17. Annual production versus size of plot created for all plots sampled since 1990, new and old.

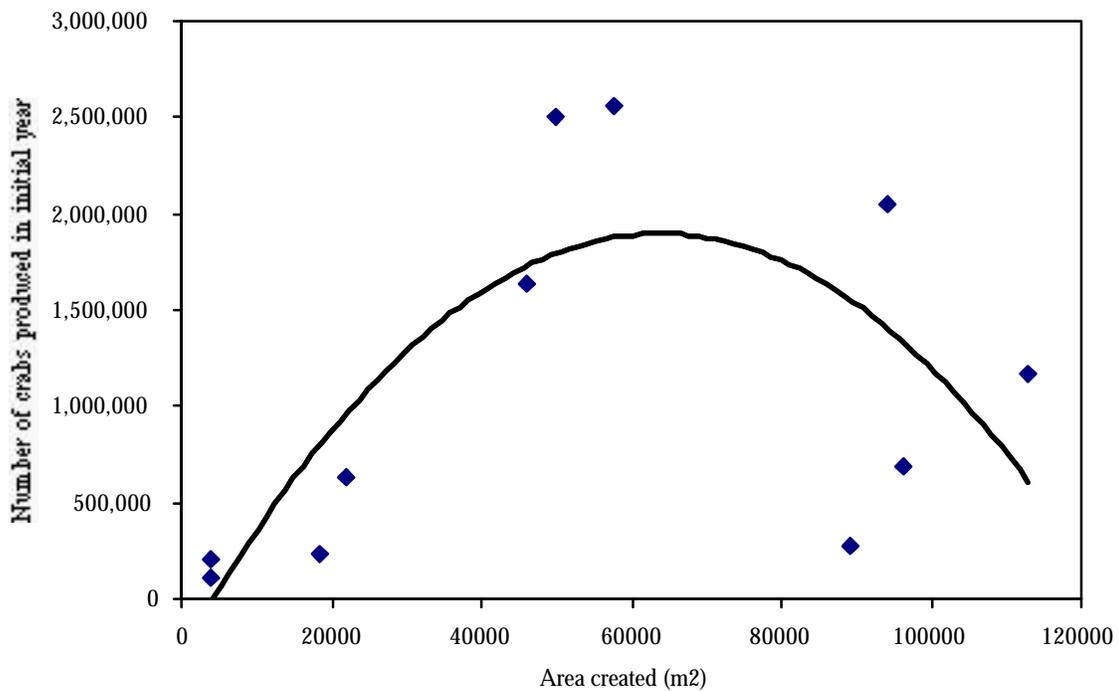


Figure 18. Production in initial year versus area of habitat created.

etc.) it is striking that simply initial area of plot constructed would play such a major role in explaining these data.

The shape of the curve fit to the initial summer's production versus original plot size suggests an optimal patch size between 40,000 and 90,000 m² (Figure 18). Intuitively, it is clear that smaller plots may be less effective per unit area as refuge habitat, due to edge effects. The smaller the size of the refuge patch, the higher the probability that a crab moving randomly around within the matrix of shell refuge space would happen to wind up at the border or outside of the refuge and hence be exposed to the risk outside the patch. What is more surprising is that that data suggest that it is possible to have too large a patch as well. Perhaps shell plots greater than 90,000 m² attract more predators by emitting strong enough chemical cues to make it worthwhile for predators to seek out the patch. Perhaps large patches of shell habitat create greater hydrological effects and change sedimentation or settlement patterns to the detriment of their effectiveness as juvenile Dungeness crab habitat.

Summary and Conclusions

Dungeness crab density patterns for summer 2000 were typical, with most of the settlement occurring in mid-May and densities decreasing steadily throughout the four month sampling season on most plots. Strong settlement peaks were not detected in this year's data. *Hemigrapsus oregonensis* densities were low on all plots sampled during summer 2000. Mortality rates were higher than usually seen for new shell plots, but strikingly low for crabs inhabiting old shell plots. A total of 3.42 million crabs were produced during summer 2000, 2.5 million of which were by new habitat created in spring 2000. This brings the grand total up to 15.2 million crabs produced by mitigation efforts in Grays Harbor since 1990. Analysis of initial production in the first year after plots construction and size of plot created suggests an optimal patch size between 40,000 and 90,000 m², with expected production during the first summer below 500,000 crabs for plots below 20,000 m² and above 110,000 m².

Primary goals for future mitigation efforts in Grays Harbor should include:

1. Surveying the remainder of the South Channel mitigation site for tidal elevation data, particularly over furthest east and north areas to complete the data set for South Channel mitigation area. Some elevation data for the central part of the shell mitigation site has been collected and is shown as depth contours on the map of the shell plots (Fig. 1). Collection of the remainder of this information for areas where 1998, 1997 West, 2000 Up and Down, 1997 East, 1996/1997, 2000 East shell plots have been constructed would make more complete data analysis possible. Results of tidal elevation comparisons among and within shell plots in terms of shell longevity, *Hemigrapsus* colonization, and Dungeness crab productivity as a function of elevation may help guide future decisions about shell placement.
2. Any new shell plots created should be between 40,000 and 90,000 m² in area at the time of initial construction, as this seems to be the optimal patch size for oyster shell mitigation plots in Grays Harbor.
3. New and old shell plots should continue to be sampled monthly during the summer.
4. Whenever budget constraints allow, new shell plots should be created annually, since they produce 80% of total production realized by mitigation and sampling efforts.

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