Grays Harbor Shell Mitigation Project 2001 Report

Crab Mitigation Project: GPS corrected plot areas, 2001 crab data, production summaries, and monthly sampling breakdowns

Final Report

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Scope and Objective

The primary objective for summer 2001 sampling efforts was to provide production estimates for juvenile Dungeness crab produced by the shell mitigation plots during this settlement and growth cycle. Since no new shell habitat was created during spring 2001, the goal was to monitor all old shell plots with reasonable shell coverage in order to ascertain their productivity in subsequent years. Monthly crab densities, instar size compositions, and percent shell cover data were collected in order to determine production estimates. Other factors, such as approximate tidal elevations, *Hemigrapsus oregonensis* abundance and size composition, and presence of eelgrass were monitored for each plot sampled.

A secondary objective was to update and correct all estimates of plot area by obtaining GPS coordinates for all 80 subplots as well as boundaries for the eight large plots sampled during summer 2001. These coordinates allow precise calculations of area and perimeter of each plot to be made, which are much more accurate than the area estimates obtained by hand measuring plot dimensions with a metric tape out in the field. The procedure performed by the production model (Armstrong et al. 1995) involves multiplying the result of an exponential function of juvenile crab density by percent shell cover by total plot area. Because of the multiplicative nature of this mathematical process, any errors in the plot area estimate can have a significant effect on the production value, or number of crabs produced by a given plot in a given field season.

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 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) 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 April to determine which sites would be sampled and to measure boundaries, map and mark those plots, sampling trips were made once monthly beginning in late May. The eight plots sampled during summer 2001 were the 1995 Island, 1996/1997 Overlay, 1997 East, 1999 Up, 1999 O/D (a combination of last years 1999 Overlay and 1999 Down plots due to loss of a significant amount of shell from the eastern end of the 1999 Down plot), 2000 Up, 2000 Down, and 2000 East (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.

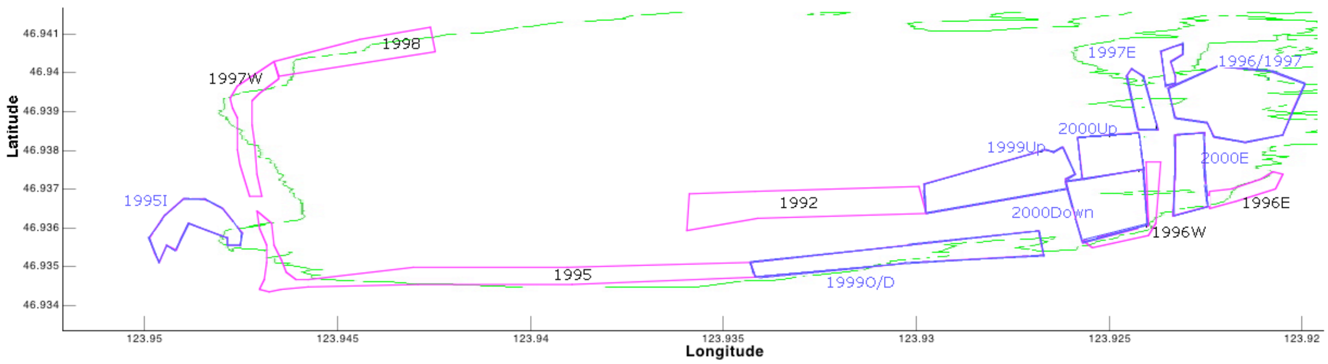


Figure 1. Map of the ACE shell mitigation plots in South Channel, Grays Harbor, WA.

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 eight plots sampled in 2001. 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. When no patches with 100% shell cover can be located within a plot, the quadrat is placed on the highest density shell patch present. 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 (for photographs of field protocol, see Visser 2000, 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.

Table 1. Sampling dates, times, and , tidal heights for 2001 summer data collection at South Channel shell mitigation plots.

Date	Low tide time	Low tide height
23-May	8:47 AM	-2.28
24-May	9:30	-2.54
25-May	10:15	-2.58
21-Jun	8:26	-2.84
22-Jun	9:12	-3.11
23-Jun	9:58	-3.12
20-Jul	8:05	-2.98
21-Jul	8:53	-3.24
18-Aug	7:44	-2.69
19-Aug	8:31	-2.86
20-Aug	9:16	-2.69

Note: The times and tidal heights listed above are for Aberdeen, Washington from NOAA tables posted on the internet. Corrections are not given, but since standard tide books list corrections for Westport and Aberdeen from Pacific Beaches times and heights, corrections for Westport can be computed as -0:56 minutes and -1.6 feet. Since the South Channel sites are located about halfway between these Aberdeen and Westport, actual times are about -0:28 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 eight 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. 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. 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 production of crabs per plot 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.

Results and Discussion

Plot areas

Our previous technique for area estimation (2000 and prior) involved measuring the lengths of the plot sides with flexible metric tape rolls in the field, approximately right angles in most cases, and using simple algebra to calculate area from those data. Because the production model uses plot area as a multiplier in calculations of production, any error in plot area estimate has a major influence on the resulting production estimate. Wind gusts, uneven surface of the mudflat, long distances, and other complications made it impossible to get exact measurements. A new method was therefore initiated in 2001 to improve area estimates utilizing current GPS technology.

GPS coordinates were obtained for each corner and inflection point along the plot boundary for each of the eight plots. Delays in processing the coordinate data by the US Army Corps staff prompted the writing of a portable custom code that could be run on any PC. The resulting program, GPSView, uses MATLAB™ to evaluate perimeter and areas based on latitude and longitude coordinates. Great Circle distances are calculated and area is determined using a discretized double integration technique to evaluate the line integral. The menu driven program can output the calculated data from multiple plot areas in a variety of formats including numerical and individual or composite graphics. Details of the program algorithm can be found in Appendix A.

The results were compared to values eventually reported by Corps personnel and the differences for all the plots evaluated did not differ by more than 0.407% for area computations and by 0.316% for perimeter computations. The results reported here as well as those used for production estimates are those from GPS View, since the exact algorithms and computational steps are known and can be described. The flexibility of an almost instant turnaround time, and custom update capability proved useful in the analysis process, particularly with the delays experienced. Ability to update maps and compute areas on a portable PC will be invaluable during the upcoming 2002 field season.

The area of many plots changed dramatically from previous estimates as a result of area computations using GPS coordinates. Five of eight plots were found to be smaller than 2000 estimates had reported (Table 2). While part of this change is certainly due to errors inherent in the previous technique of estimating plot area, some of the decrease in area is caused by the increased age of the shell and the associated effects of sedimentation and bioturbation which operate on the plots annually. The plots showing increased area relative to 2000 estimates are more likely to be a result of errors in the previous technique than are the decreases in area. Nonetheless, shell previously covered with sediment and therefore unusable as refuge habitat for juvenile crabs can reappear after storm scour and tidal runoff and current changes in South Channel.

Table 2. Plot areas: Previous and corrected using GPS coordinates and algorithmic computation of areas. Percent change represents both loss of shell coverage due to sedimentation, bioturbation, and storm scour since the 2000 sampling season as well as improved accuracy of estimates using GPS technology as opposed to direct hand measurement of plot dimensions.

Plot	**Area (m2)**		**% change**
	Previous	**GPS**	
1995 Island	14662	15522	+5.9
1996/1997	48944	42661	-12.8
1997 East	10550	7736	-26.7
1999 Up	35514	32566	-8.3
1999 O/D	34398	29561	-14.1
2000 Up	13750	13912	+1.2
2000 Down	21766	25175	+15.7
2000 East	14553	13695	-5.9

Dungeness crab density

Settlement of Dungeness crab megalopae was late and protracted in 2001, with crab densities not peaking until late June and 1st instars (J1s) generally below 20•m^{-2} in late May (Figures 3-10). Otherwise, Dungeness abundance patterns and size compositions were fairly typical. All plots showed much higher average juvenile Dungeness crab densities than 2000 summer data indicated (Visser 2001). Four plots (1997 East, 1999 Up, 1999 O/D, and 2000 Up) had peak densities over 200 crabs •m^{-2} in June, while the 1995 Island (Fig. 3) and the 1996/1997 plots (Fig. 4) peaked around 150 crabs •m^{-2}. The 2000 Down plot (Fig. 9) had lower peak settlement densities at 92 crabs •m^{-2} (Table 2) and the 2000 East plot (Fig. 10) peaked at only 59 crabs •m^{-2} in June.

Table 2. Summary densities and percent shell covers for plots sampled in 2001.

Habitat (construction year)		**May** (density /m2) mean	s.e.	**June** (density /m2) mean	s.e.	**July** (density /m2) mean	s.e.	**Aug** (density /m2) mean	s.e.
1995 Island	H	0.0	0.0	0.0	0.0	2.0	1.3	0.0	0.0
	D	56.0	9.5	185.0	18.5	20.0	4.9	4.0	2.2
	J2	5.0	2.2	76.0	9.3	12.0	3.6	0.0	0.0
	%	65.7	10.2	73.9	8.5	68.7	9.8	77.2	8.6
1996/1997	H	1.0	1.0	2.0	1.3	2.0	1.3	3.0	2.1
	D	26.0	6.0	149.0	39.8	34.0	8.4	23.0	3.8
	J2	2.0	1.3	45.0	8.9	14.0	3.4	4.0	2.2
	%	24.9	3.9	27.6	5.3	27.2	6.0	28.2	5.6
1997 East	H	6.0	2.7	2.0	3.2	2.0	1.3	4.0	3.1
	D	22.0	7.1	275.0	24.6	48.0	14.6	19.0	4.4
	J2	0.0	0.0	136.0	13.3	21.0	7.2	3.0	2.1
	%	36.4	9.2	35.0	9.3	34.8	9.5	35.0	9.1
1999 Up	H	0.0	0.0	0.0	0.0	1.0	1.0	2.0	1.3
	D	55.0	15.5	210.0	50.3	39.0	10.1	25.0	5.4
	J2	2.0	1.3	97.0	25.0	16.0	4.8	3.0	1.5
	%	23.4	4.5	20.4	3.8	22.1	3.8	17.6	3.6
1999 O/D	H	0.0	0.0	1.0	1.0	0.0	0.0	5.0	3.8
	D	36.0	5.8	229.0	26.6	8.0	1.3	16.0	3.1
	J2	3.0	3.0	142.0	27.4	5.0	1.7	0.0	0.0
	%	18.4	5.6	12.4	5.5	10.3	4.2	12.6	6.3
2000 Up	H	0.0	0.0	1.0	1.0	0.0	0.0	1.0	1.0
	D	28.0	5.7	219.0	33.2	30.0	4.9	12.0	3.2
	J2	1.0	1.0	96.0	19.1	13.0	3.0	2.0	1.3
	%	72.9	4.0	65.8	5.2	68.0	5.2	48.9	6.5
2000 Down	H	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0
	D	19.0	3.8	92.0	12.6	30.0	8.2	7.0	2.1
	J2	0.0	0.0	44.0	3.1	8.0	4.2	1.0	1.0
	%	51.3	8.3	34.4	7.9	44.1	8.6	32.2	6.2
2000 East	H	0.0	0.0	2.0	1.3	1.0	1.0	0.0	0.0
	D	22.0	3.1	59.0	11.1	13.0	3.0	8.0	2.5
	J2	0.0	0.0	27.0	6.0	7.0	2.6	3.0	2.1
	%	86.5	2.4	80.2	5.8	81.4	4.9	77.2	3.1

H = *Hemigrapsus* density D = total Dungeness density
J2= Dungeness 2nd instars % = percent oyster shell

These are the highest settlement densities observed on the habitat mitigation plots since 1998 and comparable with the highest densities recorded since the mitigation began. Clearly, the annual success of the mitigation project is strongly dependent on larval supply to the plots, since these high densities and resultant high productivity occurred when no new shell was present. Peak settlement densities are also strongly dependent on the timing of the sampling trips in relation to the actual days the megalopae enter the estuary.

Density curves were fairly steep for 2001 data, with crab densities dropping off quickly to 8 - 48 crabs $\bullet m^{-2}$ by July and 4 - 25 crabs $\bullet m^{-2}$ by August (Table 2). These densities seem low in comparison to the high peak densities of 90-over 200 crabs $\bullet m^{-2}$, but actually they are typical of juvenile Dungeness densities in July and August. The 1995 Island, the 2000 Down, and 2000 East plot densities declined to under 10 crabs $\bullet m^{-2}$ by the last sampling period (Table 2 and Figs. 3, 9, and 10), which interestingly are some of the lowest tidal elevations of the eight plots sampled in summer 2001.

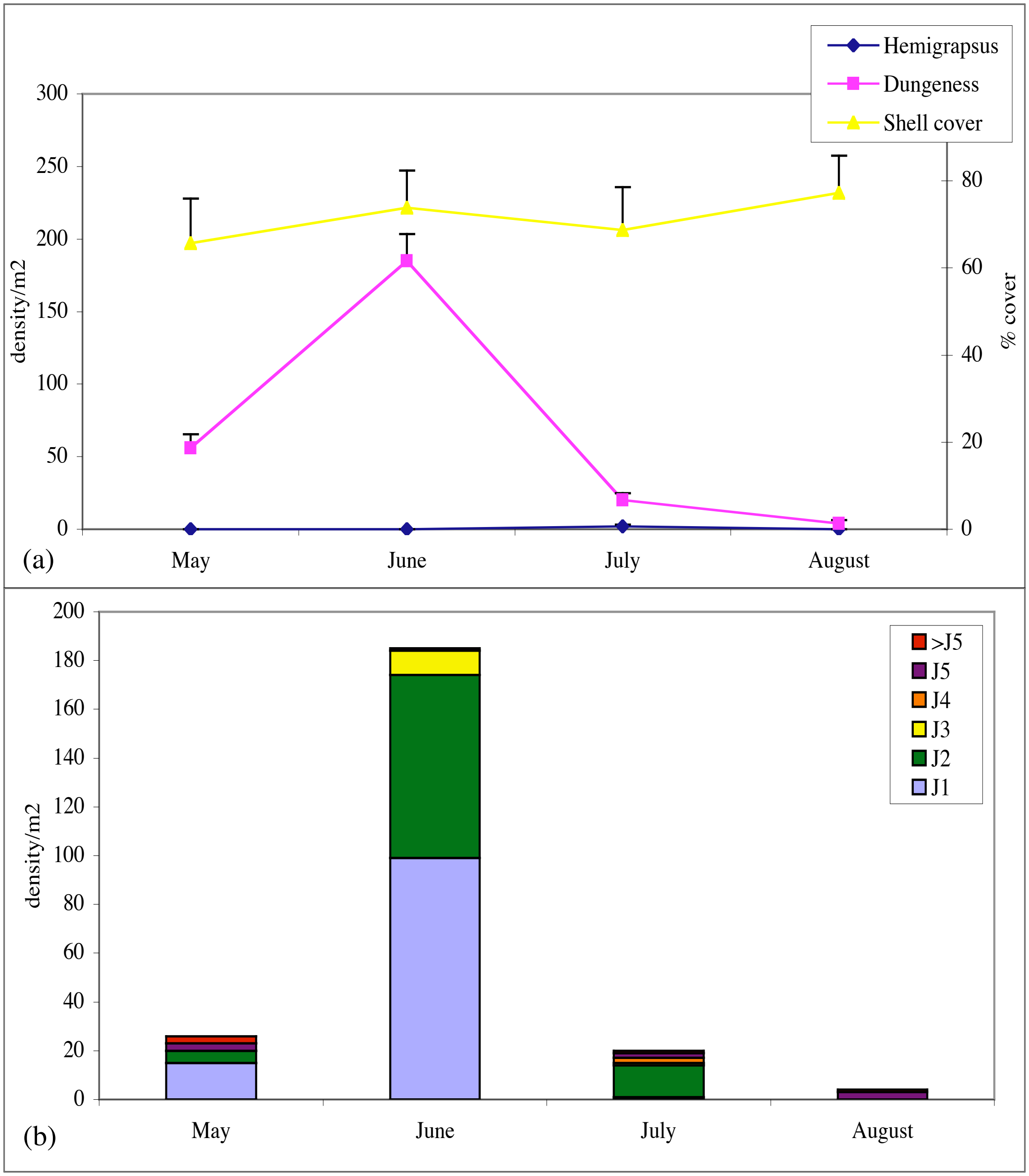


Figure 3. 1995 Island plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

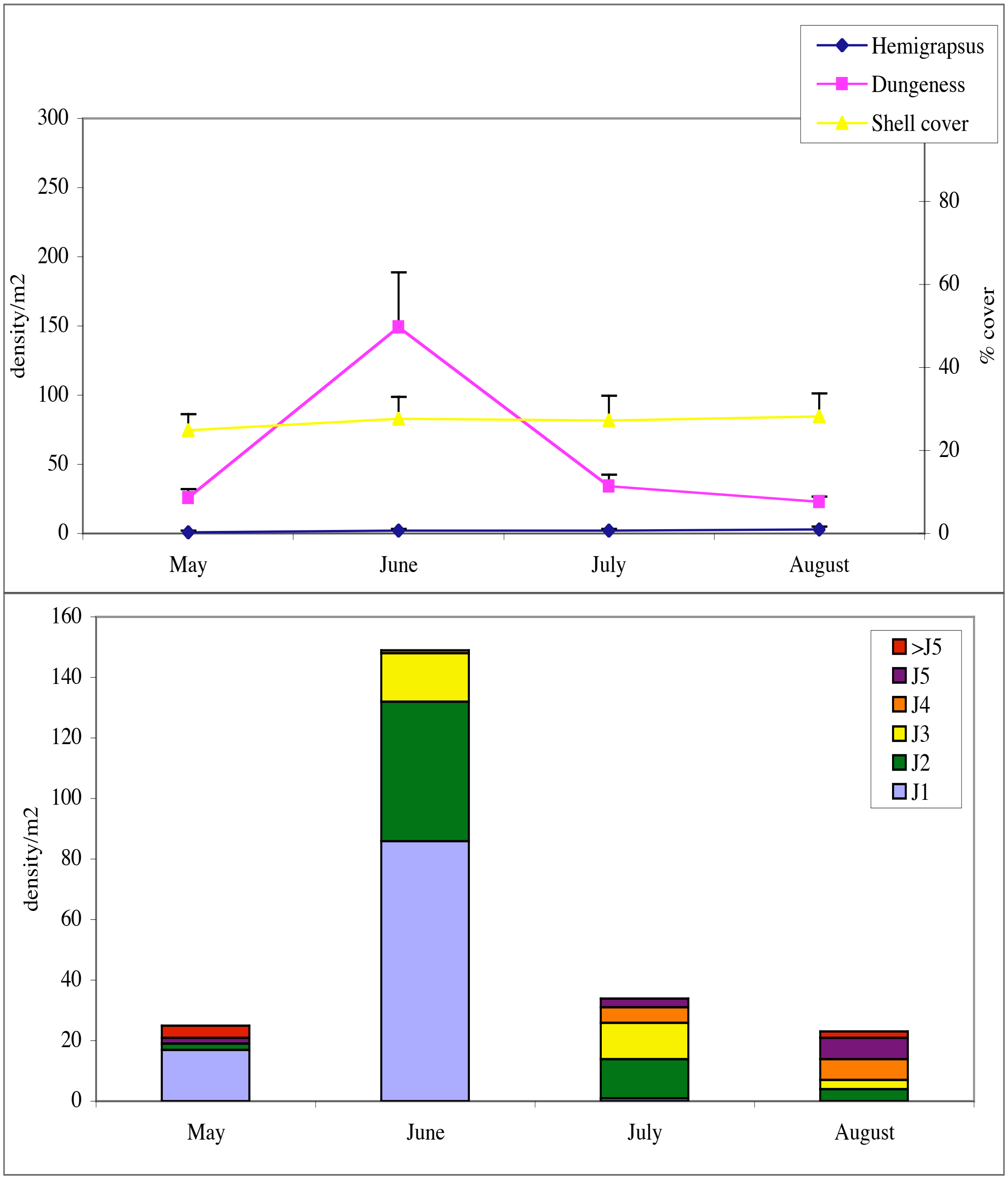


Figure 4. 1996/1997 plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

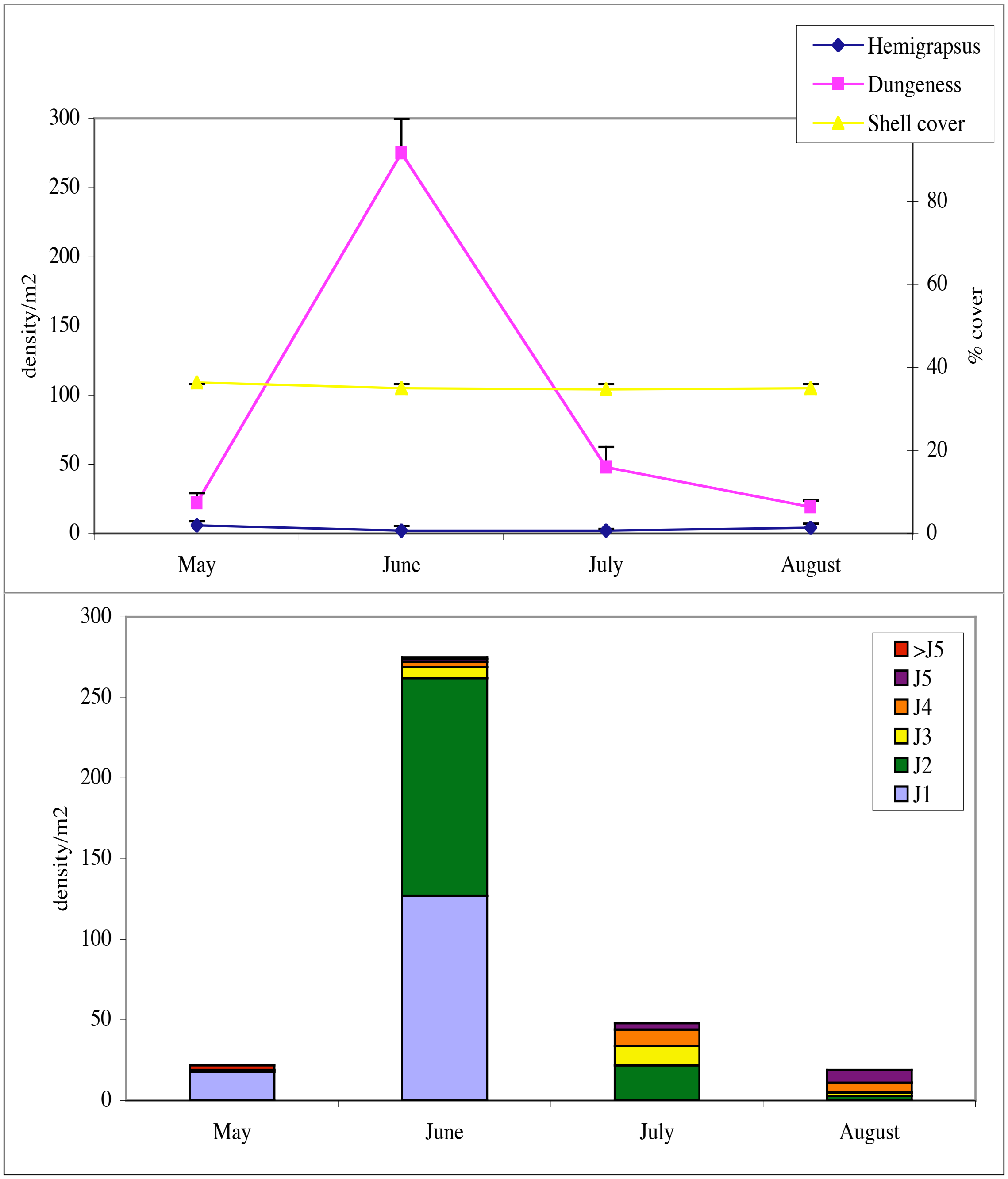


Figure 5. 1997 East plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

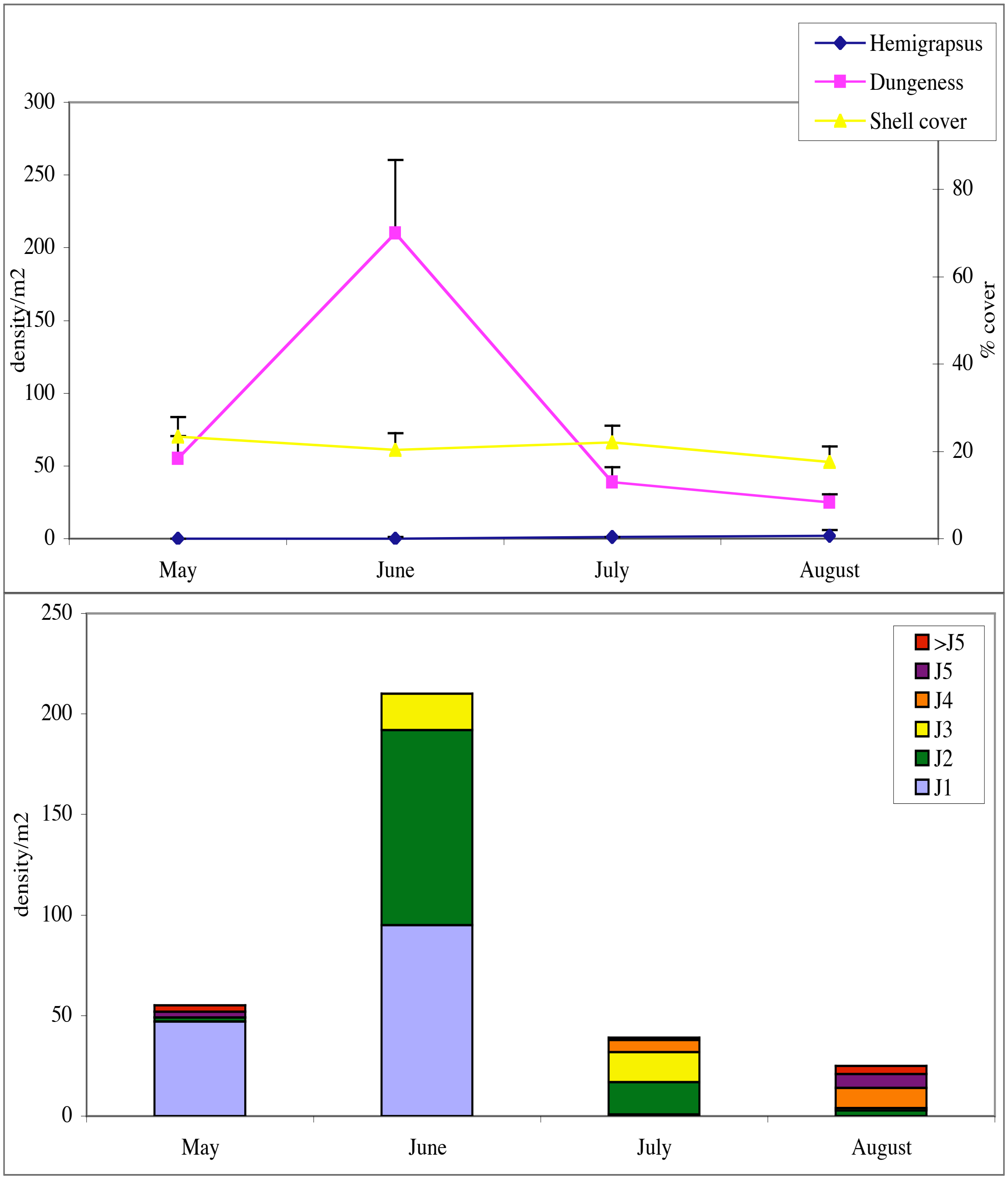


Figure 6. 1999 Up plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

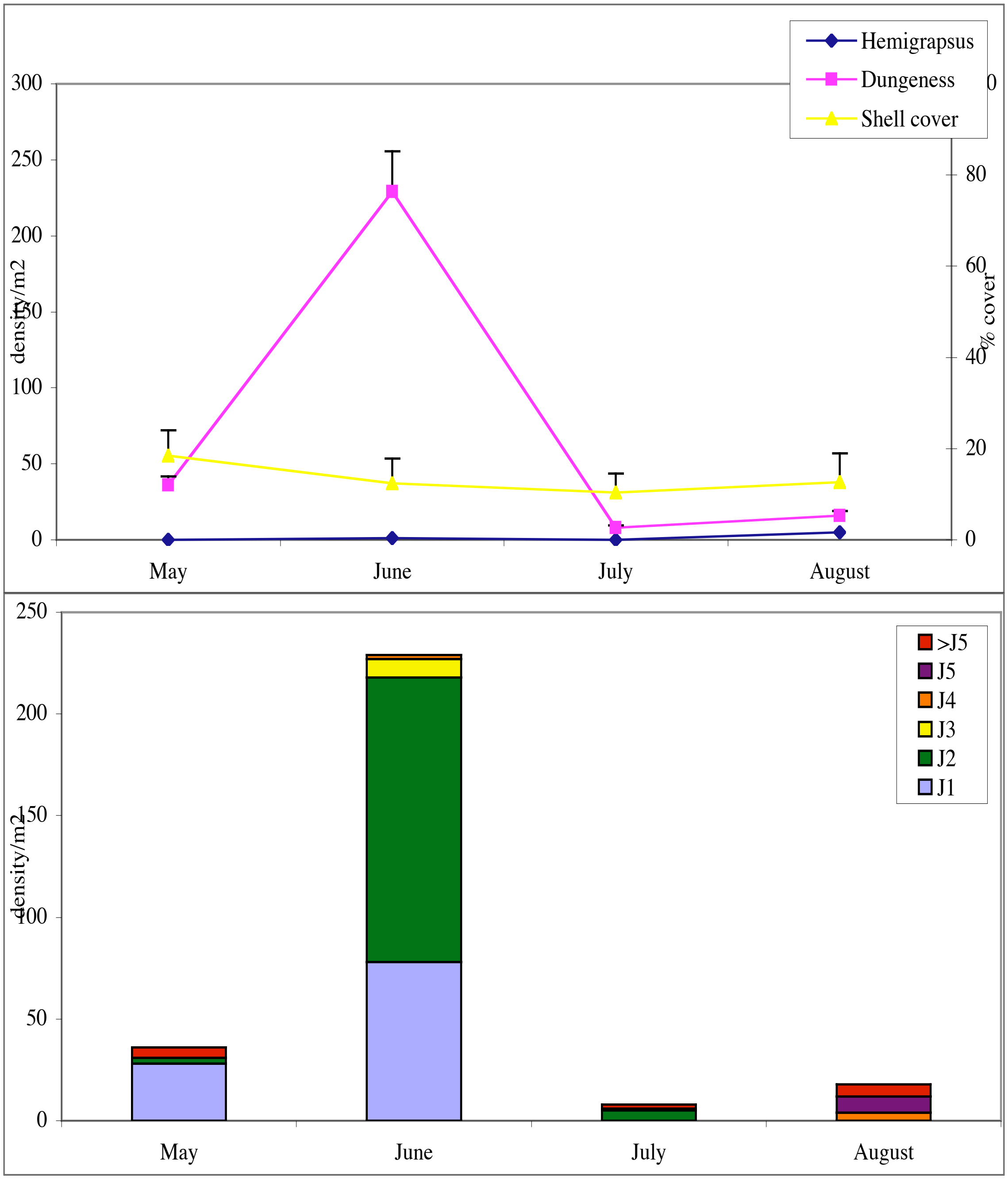
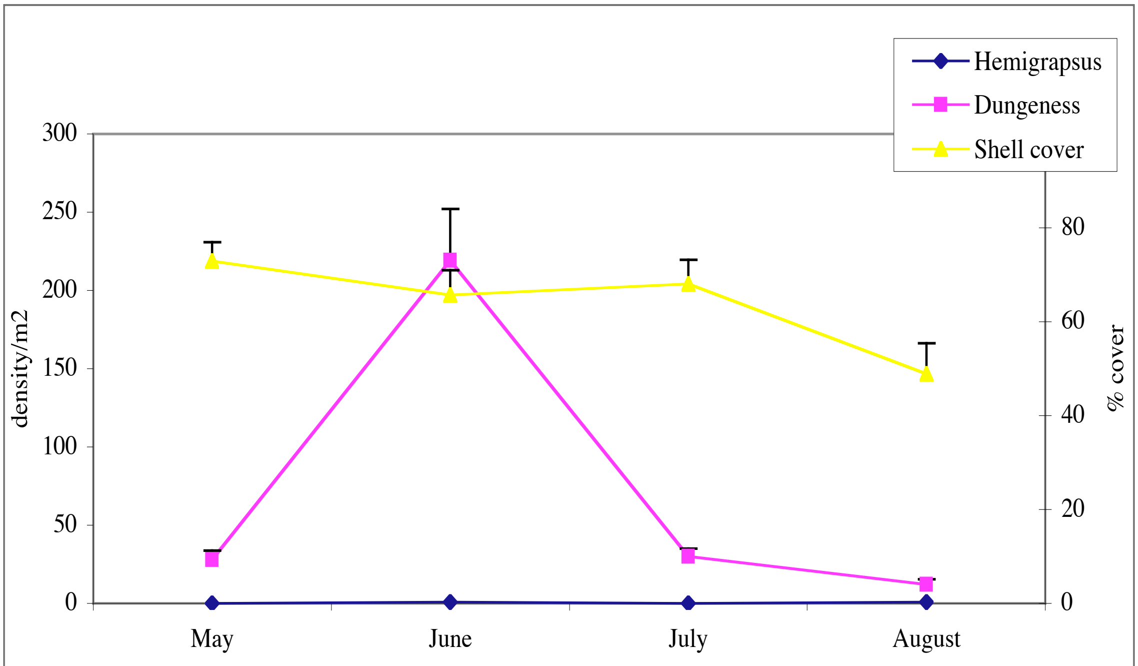


Figure 7. 1999 O/D plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.



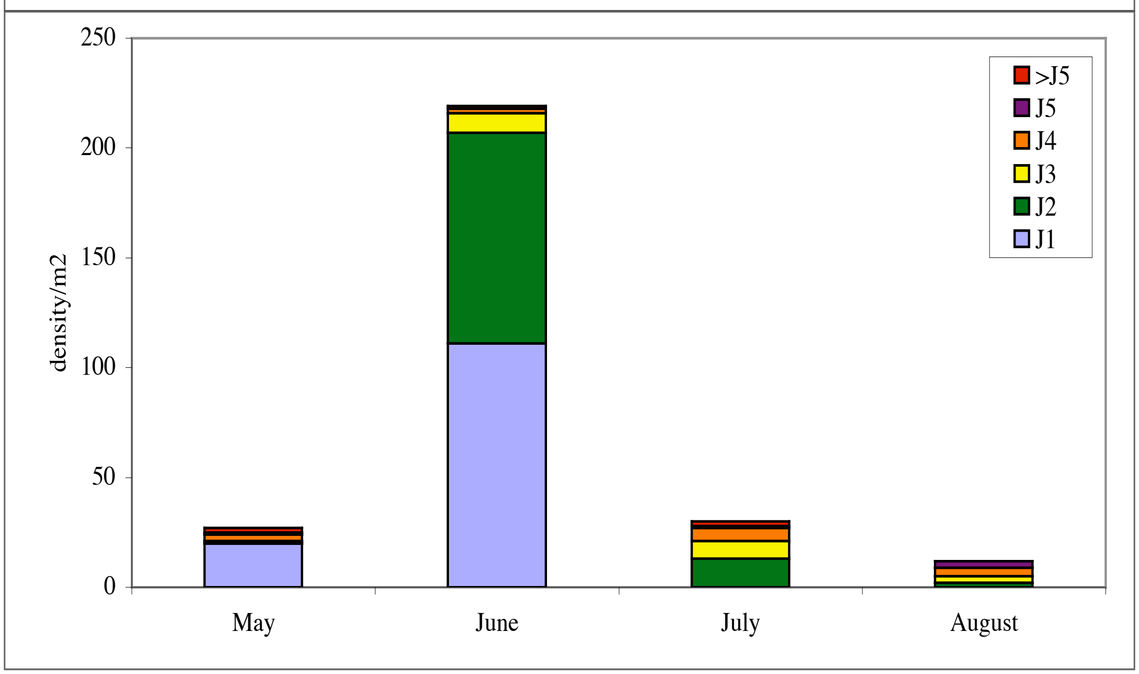


Figure 8. 2000 Up plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

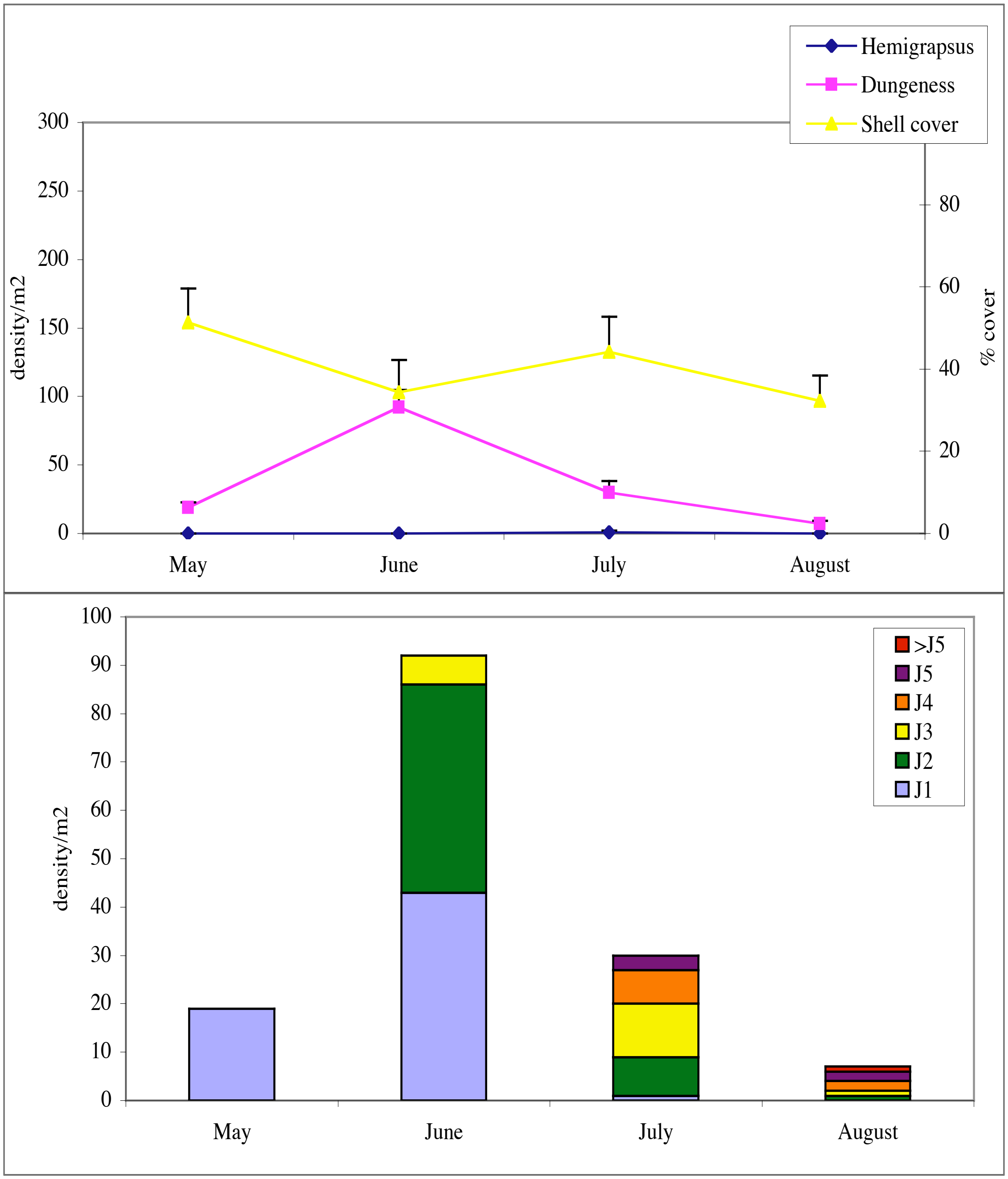


Figure 9. 2000 Down plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

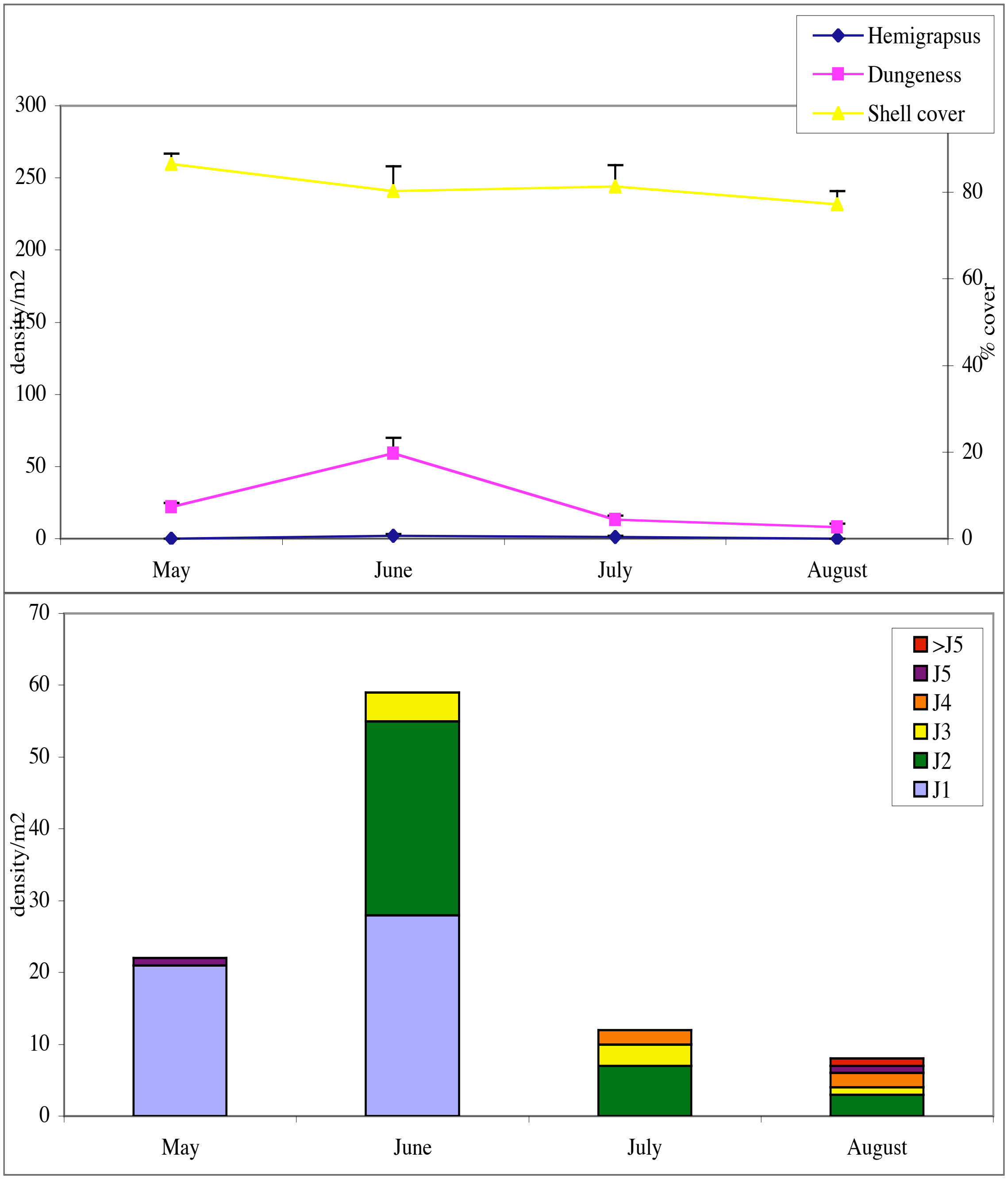


Figure 10. 2000 East plot data: (a) Dungeness and *Hemigrapsus* densities, percent shell cover, and (b) Dungeness crab instar compositions for May through August 2001.

Instar composition

Other than strikingly late settlement, Dungeness crab instar composition data shows fairly typical patterns. Even by late June (sampling took place June 21-23), almost half the crabs collected were J1s, indicating that megalopae were still entering the estuary about a week prior to the sampling period. Settlement was protracted during the 2001 field season, with newly settled J1s present in all eight plots in both May and June sampling periods. Metamorphosis from first to second instar takes place fairly quickly, individuals staying as first instars for only about a week. Thus, the size distribution of the crabs (Figs. 3-10) shows that peak settlement must have occurred in mid June, and that the lengthy settlement period lasted from early May to as late as late July in 2001. Crab density in June 2001 was among the highest of any year since the mitigation project began. The majority of these crabs must have entered the shell plots more than a week before the June 21-23 sampling to allow about half of the new settlers to molt into the J2 instar class. Very few crabs actually settled before mid May, since by the late May sampling period, there are extremely low densities of J2s. The first cohort generally has the best survival rates in the shell mitigation plots (Fernandez et al. 1993b), so low J2 densities in May are more likely to be due to low settlement rather than low post-settlement survival. Settlement continued into July, since seven of eight plots showed significant numbers of J2s present in the late July samples. The 1996/1997 and 2000 Down plots even show a few newly settled J1s in the July plots (Figs. 4 and 9).

As is typical, these instars grew and progressed through the next instar size classes while their numbers declined over the course of the summer (Fig. 3-10). There was no clear evidence of later cohorts in July or August this year, although the late and protracted settlement masked any distinct settlement phases. Small numbers of J1s were collected on four of the eight plots sampled (1 crab •m^{-2}) in July (Figs. 3, 4, 6, and 9). The presence of these J1s in late July samples could be the tail of a bell shaped settlement versus time distribution, or a separate mode. The nature of the sampling scheme and spacing of the samples makes it impossible to distinguish between these two alternatives.

The presence of large instars in May at low densities (<5 crabs •m^{-2}) indicates minor usage of the plots over the winter or migration up from subtidal locations into the intertidal shell mitigation plots before the initial sampling period in late May. The J5s and greater could not have settled early enough in 2001 to have grown that large by May and must be late-settling 2000 cohorts. By June, only three plots show instars larger than J3s, showing that many of these instars either did not survive or emigrated to subtidal locations where they live until maturity. By late August, fifth juvenile instars (J5) are present on all eight shell mitigation plots at densities below 8 crabs • m^{-2}. Because Dungeness crab generally begin to emigrate out of intertidal refuge habitats by this size, however, their abundance in intertidal samples is not indicative of their abundance in the overall population, only their abundance in the intertidal habitat.

Hemigrapsus density

As in the 2000 samples, *Hemigrapsus oregonensis* abundance was extremely low on all shell mitigation plots sampled and remained so for the duration of the season (Figs. 3-10). The highest *Hemigrapsus* density measured on any plot was 6 crabs • m^{-2} on the 1997 East plot in May (Fig. 5) and the average over the course of the 2001 summer sampling season was 1.22 crabs • m^{-2}. The *Hemigrapsus oregonensis* densities during summer 2000 were quite low as well, but 2001 data show even more extreme lack of their presence. It is surprising and interesting to note that *Hemigrapsus* have still not colonized older shell plots, even after as many as four years. Perhaps a general *Hemigrapsus oregonensis* recruitment failure is occurring in Grays Harbor estuary.

The strong negative correlation between abundance of the two species has characterized many years of the shell habitat mitigation history (Visser 1997), since about 1999 *Hemigrapsus* densities have been declining and in 2001 have reached levels where they could hardly be affecting the Dungeness crab population dynamics at all. There are many factors which operate over the course of the summer to influence decline in numbers of juvenile Dungeness crab on the shell plots and reduction in their use of the shell refuge habitat. These factors have included bioturbation and sedimentation causing loss of percent usable refuge area, predation by aquatic and avian predators during high and low tide respectively, cannibalism and behavioral interactions among the young of the year juvenile Dungeness crabs themselves, emigration to subtidal areas or to less suitable intertidal areas with less refuge, availability of prey and foraging resources, and competitive interactions with *Hemigrapsus oregonensis*. The steady decline in *Hemigrapsus* presence in the shell plots since 1999 and relative crash compared to the earlier years of the project suggests that *Hemigrapsus* is no longer impacting effectiveness and productivity of mitigation efforts. Dungeness survival and use of the shell refuge habitat must be controlled by other factors in this present phase of the project.

Mortality rates

Mortality rates were computed for each of the eight plots sampled during summer 2001 (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). Juvenile third instars (J3) are treated separately in cases where they are present in the first month of sampling, or in the first month of high crab abundance where J3 densities are higher than would follow from the previous J2 densities. In other words, when the mechanics of the production model and the monthly sampling scheme would otherwise miss them in terms of crabs produced by the shell habitat in a given year.

Plot-specific mortality rates were computed for summer 2001 data using the established method of fitting the mortality function to Dungeness crab density from the monthly samples. Only juvenile instars larger than J1s were used for finding the coefficients on the parameters in the mortality function. Because settlement densities were so high for 2001 data (particularly in June) and because J1 densities are so variable and J1s suffer very high mortality from cannibalism and predation as they molt, including these instars in the total natural mortality rate for the juvenile intertidal population would skew the estimates. The reported mortality functions (Table 3) are J2 mortality rates, or natural mortality for J2 and larger instars on the eight individual shell plots during summer 2001. During years when settlement occurs well before the first sampling period, it is not necessary to calculate mortality rates without J1 instars, because their numbers are not high enough to drastically affect the mortality function. They generally molt within 8-12 days to J2s and thus are not abundant for long. In years such as 2000, when the first samples were taken in early June, densities had stabilized and the massive mortality incurred by megalopae and the smallest J1 instars had already taken place by the time initial samples were collected. In effect, by taking J1 instars out of the computation of natural mortality and including only J2s and larger, 2001 computations and rates are made more comparable to years when peak settlement doesn't happen to coincide with sampling efforts. J2 mortality curves result in greater r^2 values for the curve fits than would using the total juvenile population in years like 2001 as well, when the sampling schedule results in data that includes peak densities.

Table 3. Summary statistics for shell mitigation plots sampled in summer 2001.

Plot	Area (m2)	Shell cover June (%)	Plot-specific mortality	% Survival after 35 d	Prod / m2 (crabs/m2/mo)	Total production (# J4 crabs)
1995 Island	15522	73.9	0.0511	17	5	216,913
1996/1997	42661	27.6	0.0168	56	12	564,331
1997 East	7736	35.0	0.0342	30	13	140,236
1999 Up	32566	20.4	0.0254	41	15	397,458
1999 O/D	29561	12.4	0.0374	27	11	164,619
2000 Up	13912	65.8	0.0366	28	9	586,804
2000 Down	25175	34.4	0.0324	32	5	99,893
2000 East	13695	80.2	0.0226	45	5	212,221

Survival rates were highest (over 40%) and mortality the lowest on the 1996/1997, 1999 Up, and 2000 East plots. (Table 3). Even the best survival, however, 56% after the 35 day average interval for a J2 instar to molt to a J4 instar on the 1996/1997 plot was low compared to past years. The lowest survival rates were suffered by juvenile crabs settling onto the 1995 Island, with a mere 17% of J2s residing there reaching the J4 production unit goal. As they did for 2000 data, mortality rate results suggest that crabs settling onto plots higher in the intertidal zone may enjoy lower mortality and thus higher survival. The four highest survival rates occurred on the four highest plots (1996/1997, 1999 Up, 2000 Up, and 2000 East. Without exact intertidal height data for all the plots, a definite conclusion cannot be made about this, but certainly this will be a valuable area to concentrate studies before determination of location for the new 2003 shell is made. Shell cover data does not predict survival rates at all, with the lowest survival from the 1995 plot having the second highest percent shell cover in June, while the 1999 Up plot among the highest survival rates and the second lowest percent shell cover (Table 3).

Average mortality rates for summer 2001 were among the lowest ever recorded since the beginning of the shell mitigation project in 1990 (Table 4). All cases where year-specific mortality rates could be computed they were, but in some cases this was not possible. 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 that do not change with each years analysis of the latest data. Since no new shell habitat was created in 2001 or in 1993, there are no average mortality rates for new shell in those years.

Table 4. Annual mortality rates for new and old shell plots, averaged across all new or old plots for a particular year. 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. Asterisks indicate years for which mortality rates were computed using past years data, either because too few samples were taken in that year (1993 and 1994), or because of unusual settlement patterns, which yielded negative mortality rates (1997 and 1999).

Year	New Shell	Survival	Old Shell	Survival
1990	0.0195	0.51	N/A	
1991	0.0276	0.38	0.0216	0.47
1992	0.0179	0.53		
1993	N/A		* 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
2001	N/A		0.0321	0.33

Average mortality rates for 2001 summer are strikingly high, and survival rates markedly low, even for old shell plots. The fact that such low success of juvenile crabs settling onto the shell plots occurred in a year with virtually no competition with *Hemigrapsus oregonensis* calls into question the now long-standing theory that interactions with this other crab species was limiting production of juvenile Dungeness crab on the shell plots. The interaction between these two species, especially competition for limited refuge space within the shell matrix, has consistently been a factor in explaining production results since 1991 (Visser 1997). Apparent recruitment failure of *Hemigrapsus oregonensis* in recent years, however, has changed the relative importance of influences on production (Visser et al., in progress). Although settlement was fairly late in 2001, larval supply, at least as measured by peak J1 and J2 densities, was high. Predation, temperature, rainfall or salinity, prey abundance, or other factors not included in this analysis could be affecting mortality rates. Shell cover and quality of refuge habitat, as well as patchiness of the shell and edge effects, certainly are influential.

Shell cover

Percent shell cover was low for many of the plots by August in 2001 (Table 2 and Figs. 3-10) than it was by the end of the sampling season in 2000, and no new shell was placed in spring 2001, so perhaps shell longevity is the culprit in limiting Dungeness crab productivity and inflicting higher than usual mortality rates on intertidal settlers this year. The average percent shell cover for old shell plots in June of 2000 was 28%, however, and in 2001 it was 43.7%, suggesting that at least at the start of the summer and when crabs were settling in, the refuge habitat on the plots was in excellent condition. By August, the average percent shell cover was 30.5% in 2000, while in 2001 it was 41.1%. These data do not suggest an obvious cause (nor even a trend in the right direction) for the very high mortality rates incurred by juvenile crabs on the mitigation plots this year. The plot with the lowest survival rate (17%) had the second highest average coverage of all eight plots over the course of the summer.

As might be expected, the three newest shell mitigation plots (created in spring 2000) had among the highest shell coverage (Figs. 8, 9, and 10). 2000 East had the highest shell cover (86.5 - 77.2%, Fig. 10). The oldest plot sampled during summer 2001 was the 1995 Island, and it had the second highest percent shell cover from May through August (65.7 - 77.2%, Fig. 3). The 2000 Up and 2000 Down plots ranged from 72.9 - 48.9% and 51.3 - 32.2% respectively (Figs. 8 and 9). The lowest percent shell cover was on the 1999 O/D plot, which went from 18.4 - 12.6% shell cover (Fig. 7). For the most part, percent shell cover stayed relatively constant on the shell mitigation plots during summer 2001. The 2000 Up plot (Fig. 8) shows the sharpest decline in percent shell coverage over the summer sampling season, but even that is only a loss of about 24% over three months elapsed time.

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. Some of the shell plots sampled during summer 2001 show slight evidence of these events, declining percent shell cover as the summer progresses: 1997 East, 1999 Up, 1999 O/D, 2000 Up, 2000 Down and 2000 East. Two 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 and the 1996/1997 plots include storm scour, heavy rains, and change in currents. Due to the protocol used for estimating percent shell cover, some of the variations (particularly the minor ones observed in the 2001 data) could be due to errors in the estimates of different individuals. These potential errors and the sometimes consistent variations of different individuals (optimists versus pessimists?) may indicate an advantage to having as many observers as possible doing shell cover estimates each tide.

Production

Total production for all plots sampled during 2001 was 2.38 million crabs (Table 5). Of the eight plots, the 2000 Up and 1996/1997 plots produced the most crabs at 0.59 and 0.56 million crabs respectively (Table 3). The 1999 Up plot produced 0.40 million crabs, while the 1995 Island and the 2000 East plot produced 0.22 and 0.21 million. The 1999 O/D plot produced 0.16 million crabs, while the 1997 East plot produced 0.14 million. The 2000 Down plot was the least productive this year, giving only 0.10 million crabs over the four month sampling season.

The nature of settlement patterns during summer 2001 necessitated treating J3 instars separately in production calculations, since there were significant numbers of J3s in June samples that were not accounted for by growth of J2s from the previous May samples. These juvenile crabs had either just settled into the shell refuge habitat by the May sampling period, or arrived just after samples were taken, grew through the J2 instar (the typical stage used as input in the model), and had recently molted into J3s by the June sampling period. The natural mortality function was applied to these individuals for 20 days, the average interval to molt from J3 to J4 instar, as opposed to the typical 35 day interval used for molting from J2 to J4. Production from these instars was added to the total monthly production in June and included in the summer total for each plot.

Since plot area has a major impact on total production, acting as a multiplier in the production model, comparing plot sizes (Table 2) can help put these production values into perspective. For example, the 1997 East plot is much smaller than all the others, it is not surprising to see its production near the bottom of the rank order of the eight plots. Comparing rank orders of plot area with rank order of production shows few major differences, with the exception of the 2000 Down, 2000 Up, and 1999 O/D plots. Both the 2000 Down and the 1999 O/D plots have fairly large plot areas (4^{th} and 3^{rd} largest respectively), and yet fairly low productivity (8^{th} and 6^{th} of 8 respectively). The 2000 Up plot on the other hand, is top ranking in terms of productivity, but 6^{th} of 8 in plot area.

Comparing rank orders of percent shell cover and productivity shows many differences, with four plots being 4 ranks different (1996/1997, 1999 Up, 2000 Down, and 2000 East), and the remaining four plots being two ranks different. Half the plots produced more crabs than might be expected based on the rank order of their percent shell cover (1995 Island, 1997 East, 2000 Down, and 2000 East). While certainly presence of shell is critical for juvenile Dungeness crab to settled and grow successfully to sizes where they can emigrate to the subtidal population and continue development, clearly, percent shell cover is not the best predictor of production for the 2001 dataset.

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 11). 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 2001, the 1999 Up, 1996/1997 and 2000 Up plots produced higher than the average number of crabs per square meter of refuge available, and the 2000

Down, 1995 Island, and 2000 East plots produced fewer (Figure 11). The 1997 East and 1999 O/D plots fell close to the average line. These results are quite different from those found in summer 2000, when both 2000 Up and Down produced better than average and 1996/1997 and 1999 Up produced much less than average. Apparently, productivity per meter squared of effective refuge area is not a factor inherent to the plot consistent across years.

The production model takes J2 crab density, mortality rate, plot area and shell cover into account to compute production. Since all plots are different areas and have different percent shell covers, it may be a more meaningful comparison to look at

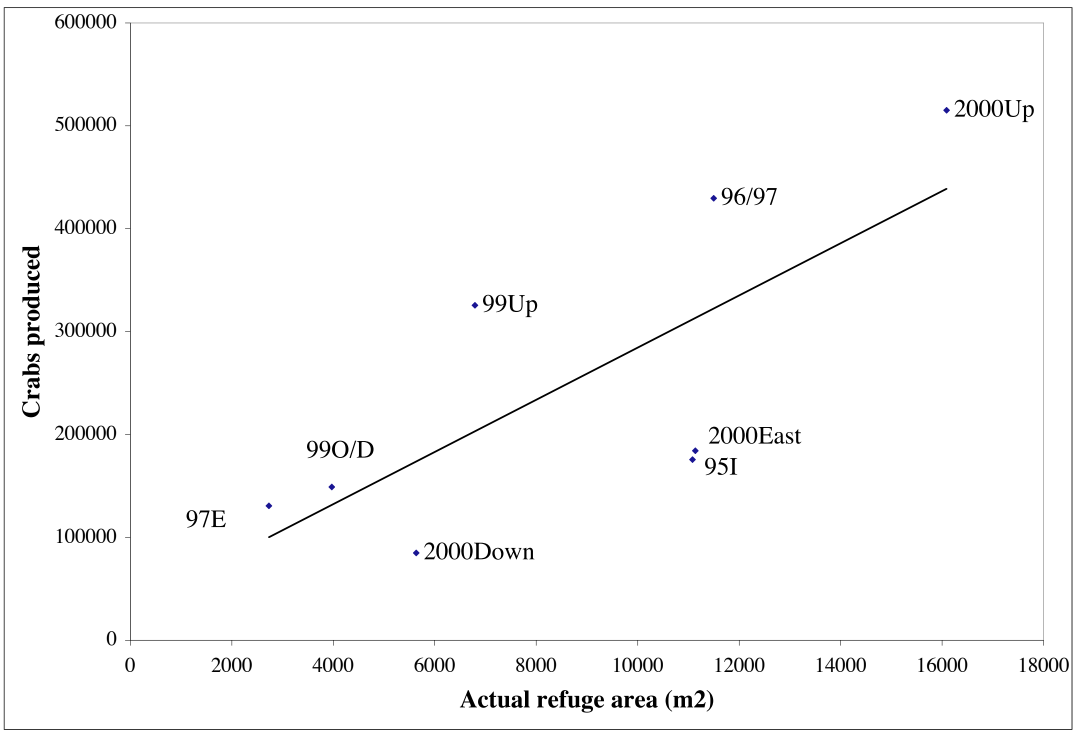


Figure 11. Crab production versus effective plot area for the eight plots sampled in summer 2001. Plots above the line had greater than average production per meter squared and those below had lower production per meter squared.

production on a per meter squared basis so as to compare actual productivity of a set area of habitat on each plot. These comparisons (Table 3) show that refuge habitat in the 1999 Up plot were the most productive, yielding 15 crabs • m^{-2} • month $^{-1}$. The 1997 East, 1996/1997, and 1999 O/D plots were next most productive, yielding 13, 12 and 11 crabs •

m^{-2} • month $^{-1}$, respectively. The 2000 Up plot produced 9 crabs • m^{-2} • month $^{-1}$, while the remaining three plots (1995 Island, 2000 Down, and 2000 East) produced only 5 crabs • m^{-2} • month $^{-1}$. It is an interesting correlation to note that the four most productive plots are all quite patchy, with remaining shell generally in piles isolated from other piles by varying distances of bare mud. Of these four plots, however, the 1999 Up plot is the least patchy, and it yielded the highest number of crabs • m^{-2} • month $^{-1}$, so more data needs to be taken on patchiness before a theory can be formed.

Intuitively, it seems that high percentages of edge effects may compromise the effectiveness of shell plots, since the smaller the size of the refuge space, the higher the probability that a juvenile crab would wander out and be exposed to predation risk outside the refuge. Comparing ranks of percent edge and ranks of annual production for 2001 gives only three plots differing by more than a rank of 1. The 1995 Island had fairly high percentage of edge (second highest) and yet yielded the third highest number of crabs this summer (Table 5). Similarly, the 2000 Down plot had an average percentage of edge (4th ranked of 8) and yet produced the most crabs during 2001 field season. The 2000 Down plot had only 2.58% edge, the 3rd least, and yet had the lowest production of all plots.

Table 5. Area, perimeter, and percent edge (perimeter * 100 / area) values for the eight plots sampled during summer 2001.

Plot	**Area (m2)**	**Perimeter (m)**	**%edge**
1995 Island	15522	705	4.54
1996/1997	42661	794	1.86
1997 East	7736	699	9.03
1999 Up	32566	828	2.54
1999 O/D	29561	1273	4.30
2000 Up	13912	474	3.41
2000 Down	25175	650	2.58
2000 East	13695	587	4.28

Tidal elevation data is not accurate enough yet to make a correlation between production and tidal elevation, but subjectively, the 1996/1997, 1999 Up, 2000 Up, and 2000 East plots are the highest of the eight plots sampled in 2001. These four plots had production ranks of 2, 3, 1, and 5, respectively, with an average rank of 2.75 (much lower than 4.5 which is the average rank for all eight plots). The lowest plots are the 1999 O/D and the 2000 Down plots, which have ranks of 6 and 8 respectively. Their average rank is 7, much higher than the 4.5 average rank for all eight plots. Without more detailed tidal elevation data, it is impossible to make specific recommendations about where the 2003 shell should be placed, but higher elevations seem to be better. With closer intervals between depth soundings and updated depth contouring, computations of average tidal elevation for each plot could be made.

Annual production comparisons

The cumulative crab production from the beginning of the Dungeness crab habitat mitigation project in 1990 through the end of the 2001 field season totals about 17.6 million crabs ± 1.7 million (Table 6). This total includes 0.86 million crabs produced on the PacMan plots constructed in 1991 and 1992. Of this total,

Table 6. Annual production by new and old shell plots from 1990 through 2001. Black values are from South Channel mitigation sites; colored values are from PacMan sites. 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	2,586,894			
	640,071		3,226,965	670,204
1993	N/A	34,077		
	N/A	10,145	44,222	27,042
1994	1,633,038		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
TOTAL	**12,091,941**	**5,486,443**	**17,578,383**	**1,733,216**

approximately 69% (12.1 million crabs) was from plots in their initial year after construction, and the remaining 31% (5.5 million) from all old shell plots sampled in subsequent years (Table 6, Fig. 12). Plots have been sampled varying numbers of years subsequent to their initial creation, depending on several factors, but mostly shell longevity. The number of subsequent years appear at the end of each bar, so that the 1998 plot was one of the least sampled, once in the initial year of construction (1998), and in one subsequent year (1999). Likewise, the 1995 plot was sampled one of the most, 6 times, once in 1995 just after construction and in 5 subsequent years (1996, 1998, 1999, 2000, and 2001).

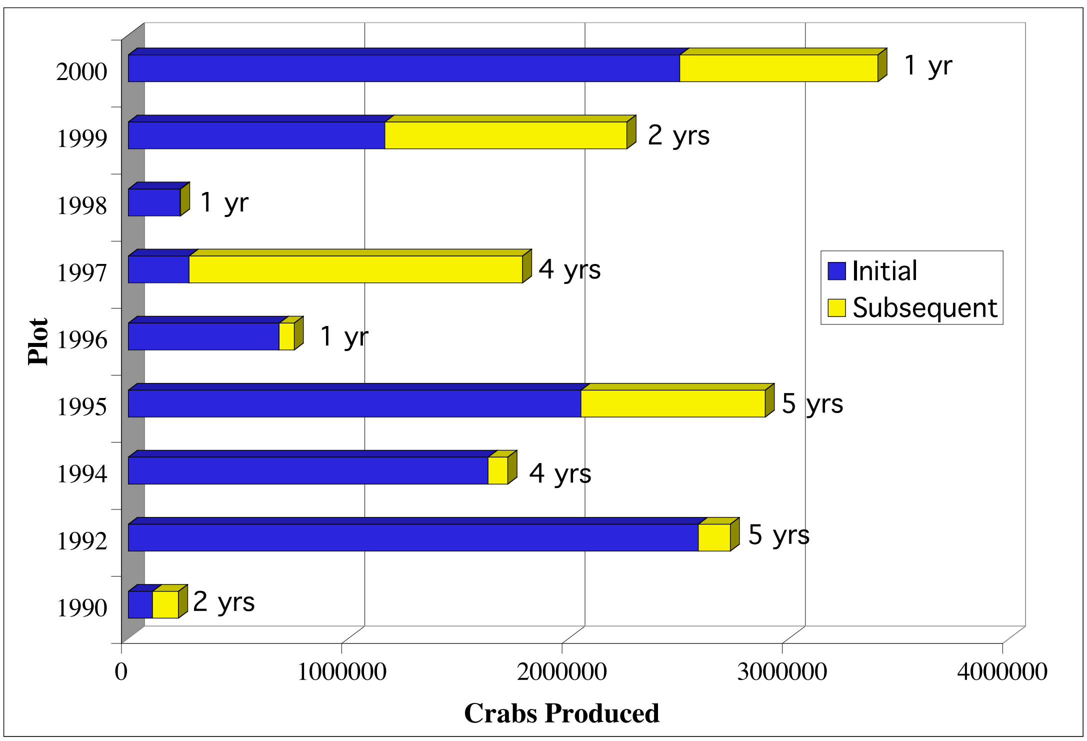


Figure 12. Production by the nine plots created by the Army Corps of Engineers at their South Channel Dungeness crab mitigation site. Colors show crabs produced in the initial year of construction (same as the name of the plot: 1990, 1992, etc.) and sum of crabs produced in all subsequent years sampled. The number at the end of each bar indicates the number of years subsequent to the construction that each plot has been sampled.

The 2001 season yielded the third highest production ever measured on the shell habitat mitigation plots, even though no new shell habitat was created this year (Table 6). It gave the highest annual number of crabs ever recorded from old shell, yielding almost twice the next highest number produced on old shell and 43% of cumulative production from old shell plots since the mitigation began. The total amount of area of old shell sampled was certainly the highest ever sampled, since no sampling effort was expended on new shell and shell longevity over the winter was quite high. The production results are still surprising, however, especially in the context of such low survival rates for 2001 juvenile crabs.

Of the nine plots created at the South Channel mitigation site since 1990, four yielded 91% or more of their total cumulative production in their initial year after construction (Table 7). The remaining mitigation plots produced between 48 and 74% of their cumulative total in their initial year, with the exception of the 1997 plot which produced only 11% in its initial year (Table 7).

Table 7. Initial and cumulative production for each mitigation plot constructed at South Channel. Note that the first column is for the shell plots, labeled by year of construction.

Habitat	Initial Area (m2)	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	2,890,941	71
1996 plot	96234	684,584	753,036	91
1997 plot	89280	275,729	2,494,206	11
1998 plot	18554	235,167	236,989	99
1999 plot	112906	1,164,115	2,262,904	51
2000 plot	50069	2,503,377	3,402,295	74

Sampling scheme

The typical sampling regime involves four monthly sampling trips during a summer field season, usually May, June, July and August. During a few summers (1993, 1994, and 1996), different sampling schedules were chosen for varying reasons.

Percentages of the total Dungeness crab production attributable to each monthly sampling trip were compared for all years to see how important sampling each month may be and, particularly for efforts late in the year, whether certain months were generally unproductive to merit ruling out. Averages were computed for years with at least four sampling trips (Table 8).

Due to the fact that sampling necessarily takes place during low tide series each month, there is considerable variability in the timing of monthly samples from year to year. For example, 2000 samples were taken very early each month, within the first few days of each month, while samples in 1998 were taken in the fourth week of each month. Doing this comparison by the day rather than by the calendar month would provide more detailed and informative data if actual decisions were being made about potentially eliminating a monthly sampling trip.

Table 8. Percentage of annual production attributable to samples taken in a given month. Only years where at least four sampling trips took place are included in the average.

Sampling year	May	June	July	August	September
1990	15.74	53.89	24.24	6.13	n/a
1991	6.05	58.68	23.83	9.71	1.73
1992	32.46	50.13	12.24	5.17	n/a
1993	n/a	100	n/a	n/a	n/a
1994	n/a	0	48.06	51.94	n/a
1995	0.126	69.67	21.66	5.75	2.8
1996	n/a	64.67	2.18	8.35	n/a
1997	22.69	42.45	23.24	11.62	n/a
1998	26.05	50.66	18.49	4.8	n/a
1999	0	25.73	64.42	8.15	n/a
2000	n/a	47.59	41.56	7.61	3.24
2001	1.51	83.75	12.27	2.46	n/a
Average	**13.08**	**53.62**	**26.88**	**6.82**	**2.59**

Sampling in mid-late August or early September gives consistently less than 10% of the annual Dungeness crab production in any given year, and an average of 6.8% and 2.6% of the annual production total. 1997 is the only exception, which cannot be considered representative, since production was extremely low and only new shell plots were sampled that year. In the event of budget cuts or logistical constraints, August and certainly September sampling trips could be trimmed without major impact on the production results. These decisions would be strongly influenced by the timing of the low tide series for any given year, and modified if possible as the field season progressed based on settlement patterns, but the averages are informative.

Summary and Conclusions

Corrections of plot area based on GPS data resulted in enlargement of three plots relative to 2000 estimated area and decrease in the remaining 5 plot areas. Changes in previous areas represent both loss of shell coverage due to sedimentation, bioturbation, and increases due to winter storm scour since the 2000 sampling season as well as improved accuracy of estimates using GPS technology compared to direct hand measurement of plot dimensions.. Settlement patterns during summer 2001 were not typical, with late and protracted settlement, as well as very high peak J1 and J2 instar densities in late June, with densities as high as 300 crabs • m^{-2} on some plots. *Hemigrapsus oregonensis* densities were virtually negligible on all plots. Mortality rates were very high for crabs settling into the mitigation habitat this season, although percent shell cover was slightly better than it was in 2000. Dungeness crab production was quite high for 2001, the annual sum across the eight plots sampled was 2.38 million crabs. This brings the cumulative sum since 1990 to 17.58 million crabs. Cursory analysis of sampling scheme indicates that August and September sampling trips generally contribute only about 6.8% and 2.6%, respectively, of the annual total crab production and therefore may be expendable depending on cost, personnel availability, and other considerations.

Primary goals for the 2002 sampling season in Grays Harbor should include:

1. Obtaining tighter intervals for depth surveys over the shell mitigation plots, particularly at the far western end of the mitigation site near the 1995 Island and western edge of the long 1995 strip of shell. These data will allow more accurate depth contouring to be done and approximate average tidal elevation data to be obtained for each plot.
2. Noting additional parameters for each of the ten subplots sampled on each large shell mitigation plot, such as patchiness. This information, noted as a factor rather than a measure, will be quick to assess and will give valuable additional information in terms of optimizing shell placement for 2003 spring shell habitat construction.

Primary goals for data analysis for 2002 autumn will include:

1. Rigorous statistical analysis of all historical data on the shell mitigation plots, using general linear modeling, in order to more accurately assess the relative contribution of the many factors influencing Dungeness crab production on the various shell plots. This process of data mining will help guide future sampling efforts and hopefully suggest new angles to investigate.
2. Obtaining data for parameters which may affect Dungeness crab survival and growth on the intertidal shell habitat, such as average annual (or monthly if available) rainfall, air temperature, and major storm events.
3. Using this new information to choose the most likely location for maximum productivity of juvenile crabs on the new 2003 shell plot(s).

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Appendix A: GPSView Program

GPSView is a MATLAB™ code written to evaluate perimeter and areas based on latitude and longitude coordinates. The user supplies a text file with a header line followed by the coordinates, each on a separate line. The code is menu driven and can output the data from multiple plots in a variety of formats including numerical and individual or composite graphics. A sample of the output and code header is detailed below

Code Header

Below is the header of the program that details the method used

```
%**********************************************************
% GPSView.m
% This calculates areas and perimeters from GPS data file
%
% K.Visser, Clarkson University, Feb 2002
%
%
% The code is designed as a research tool for the ACOE Dungeness Crab Mitigation Project
%
% Input format for any plot is of the form
%
% File header
% latitude1 longitude1
% latitude2 longitude2
% latitude3 longitude3
%     .        .
%     .        .
%
% Data can be input as 'degrees minutes', where the minutes can have digits
% after the decimal representing fractions of a minute in decimal form.
% The notation 'degrees' is not supported at this time.
% The notation 'degrees minutes seconds' is not supported at this time.
%
% Distances are determined using the Scaler, or 'Dot' Product relationship between
% two vectors A and B defined as:
%
%       |A| |B| cos(ø) = A • B
%
% where ø is the the smallest angle determined by A and B when their initial points coincide.

% Since the magnitude of A and B represent the distance from the center of the Earth
% to the point on the surface, and the the Earth is not a sphere,
% three distances are calculated based on radii at the:
%
%         a) earths equator:         3963 miles = 6377830.272 m
%         b) earths pole:            3950 miles = 6356908.800 m
%         c) average latitude of the measurements, linear approximation only, determined from:
%
%  The value of raverage:
```

```
%         ravg := (abs(((lat1 + lat2) / 180)) * (rpole - requator)) + requator;
%
% is used in this program
%
% When entering latitudes in the Southern Hemisphere, °S, or longitude, °E,
% these should be entered as negative numbers to distinguish them from latitude °N and longitude
°W
%
% Areas are determined around an enclosed curve using Green's Theorem leading to
%
%    A = ∫∫dA = 1/2∫xdy-ydx
% or
%    A = ∑xΔy - yΔx
%
%***********************************************************************************
```

Example Input and Output

Sample input, numerical output and graphical output is given below. Note the repeat of the first point in the input file. The points must define a closed curve:

Input file for edge points

```
1999 Up new est
46      56.181 123     55.776
46      56.219 123     55.553
46      56.237 123     55.555
46      56.2423        123     55.53948
46      56.286 123     55.5605
46      56.278 123     55.577
46      56.283 123     55.588
46      56.23   123     55.781
46      56.181 123     55.776
```

Input file for interior points

```
1999 Up Interior
46      56.255 123     55.552
46      56.222 123     55.571
46      56.271 123     55.587
46      56.259 123     55.626
46      56.243 123     55.610
46      56.239 123     55.662
46      56.218 123     55.670
46      56.229 123     55.710
46      56.201 123     55.748
46      56.224 123     55.764
```

Numerical output

Plot: 1999 Up new est

Area: -32565.5236 m^2
Perimeter: 827.5566 m
Number of GPS Boundary Points: 8

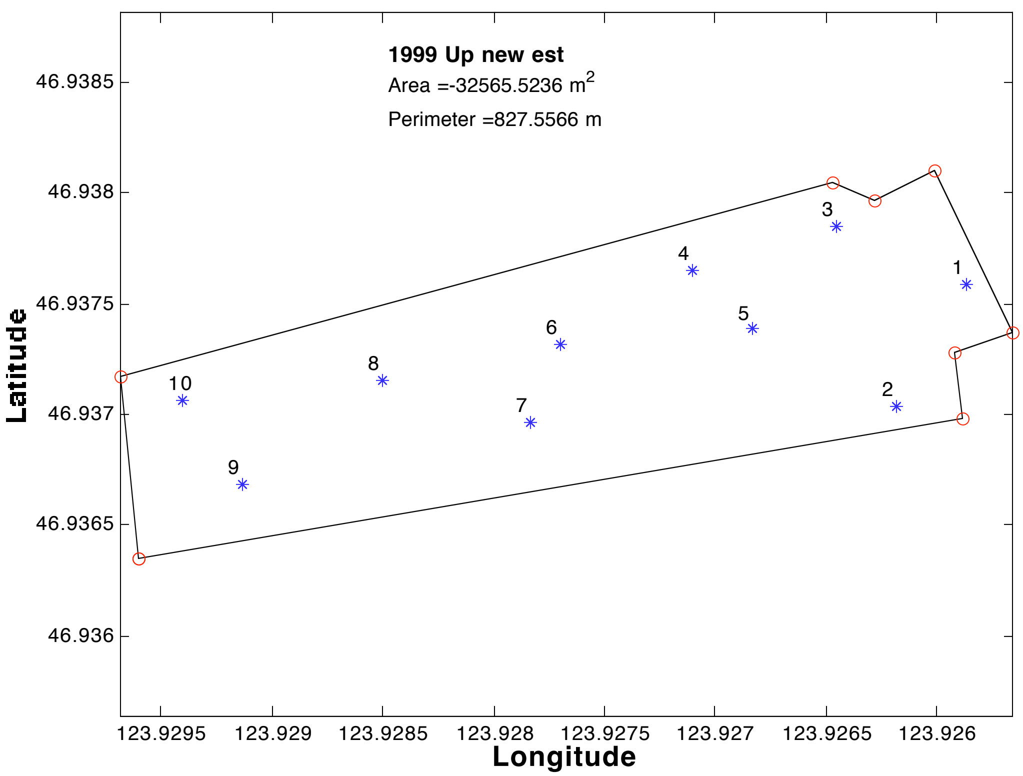
Boundary Points (8)

Point	Latitude	Longitude	Distance
1	46.9363°	123.9296°	290.655 m
2	46.937°	123.9259°	33.433 m
3	46.9373°	123.9259°	21.9441 m
4	46.9374°	123.9257°	85.1883 m
5	46.9381°	123.926°	25.5908 m
6	46.938°	123.9263°	16.7111 m
7	46.938°	123.9265°	263.0631 m
8	46.9372°	123.9297°	90.9711 m

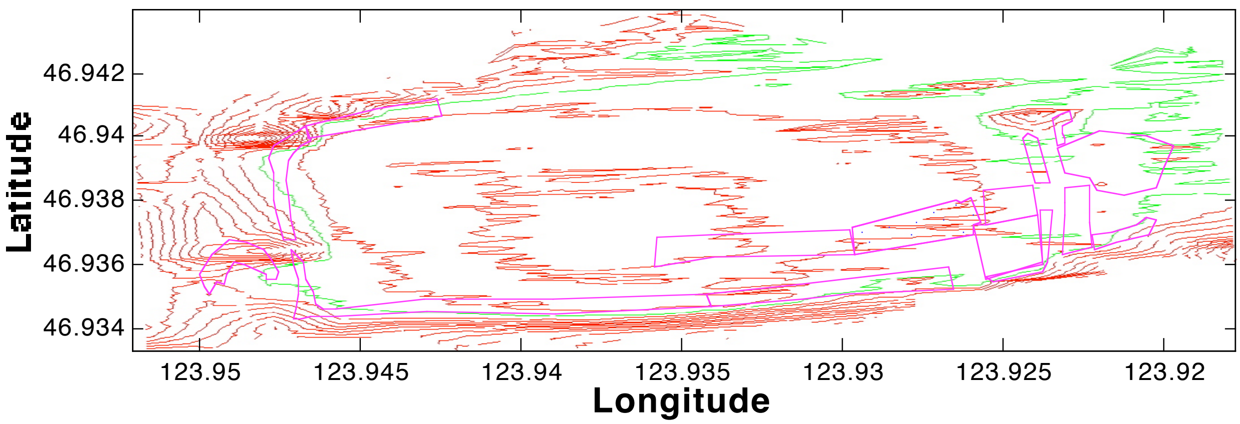
Interior Points (10)

Point	Latitude	Longitude
1	46.9376°	123.9259°
2	46.937°	123.9262°
3	46.9378°	123.9265°
4	46.9376°	123.9271°
5	46.9374°	123.9268°
6	46.9373°	123.9277°
7	46.937°	123.9278°
8	46.9372°	123.9285°
9	46.9367°	123.9291°
10	46.9371°	123.9294°

Graphical output, single plot



Graphical output, multiple plot with sounding contours



Appendix B. Contour map of South Channel.