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Evaluation of an intensive fishery on dungeness crab, *Cancer magister*, in Fraser Delta, British Columbia

Évaluation d'une pêche intensive au crabe dormeur (*Cancer magister*) dans le delta du Fraser en Colombie-Britannique

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Abstract

The Dungeness crab fishery in British Columbia has been passively managed through sex and size limits. Only male crabs larger than or equal to 155 mm in carapace width may be harvested. The fishery is intensive with exploitation rates well over 90% in the Fraser Delta. The paper attempts to address three specific concerns: (1) is there a recruitment problem? (2) what is the impact of intensive fishing on yield and profit? (3) what scientific criteria could managers use to close the fishery?

To address the first concern, we examined the time-series (1995-2000) data on catch rates for sub-legal crabs. There is no strong evidence that small crabs are becoming less abundant. However, the time-series is short and we don't know the recruitment status before the intensive fishing, which has existed for a long time. Thus, it is unknown whether recruitment will increase, if exploitation rate decreases. The impact of intensive fishing on recruitment is yet to be determined.

To address the second concern, we used a length-based and an instar-based model to generate biological reference points to be used for managing the fishery. We calculated yield, revenue and profit per recruit, after some important biological parameters, such as natural mortality rate, vulnerability of different sized crabs to traps, probability of moulting, survival rate for newly moulted crabs, were estimated based on scientific surveys in the Vancouver Harbour. An intensive fishing also results in a great deal of catch-and-release of sub-legal sized crabs. Continuing fishing at a high ratio of sub-legal to legal sized crabs in the catch will result in a net loss in yield in the long-term, as some sub-legal sized crabs will die of handling mortality and could not contribute to the future yield. We conducted analyses on gain-or-loss in yield for continuing fishing at different ratios of sub-legal to legal crabs in the catch to determine threshold points, at which gain is balanced with loss in yield in the long term. To avoid losing yield in the long term, the ratio of sub-legal to legal crabs in the catch should not be allowed to rise above 19:1, 9.5:1, 6.5:1 or 5:1, if the handling mortality rate is, respectively, 5%, 10%, 15%, or 20%.

We provide the following recommendations to the managers based on these analyses:

(1) The current exploitation rate (> 90%) should be reduced to 65-75%. A level of reduction in Catch Per Unit Effort (CPUE) relative to the CPUE at the beginning of the fishery could be used to determine when to close the fishery.
(2) A ratio of retained crabs to discards should be used as a means of limiting effort and protecting stocks in conjunction with using CPUE measures, or in fisheries where it is difficult to use CPUE because of protracted moulting seasons.
(3) Efforts should be made to reduce the negative handling impacts. Tools may include longer soak times, earlier closure of the fishery or adjustment of the fishing season.
(4) Industry, management and science should use these models to assist in assessing the impact of intensive fishing on population dynamics, economic and social benefits for each fishery and in finding optimal management and assessment schemes.

Résumé

En Colombie-Britannique, la pêche au crabe dormeur est gérée passivement selon le sexe et des limites de taille. Seuls les crabes mâles dont la largeur de la carapace est supérieure ou égale à 155 mm peuvent être récoltés. La pêche dans le delta du Fraser est intensive, et les taux d'exploitation sont nettement supérieurs à 90 %. Dans ce rapport, nous abordons trois préoccupations précises : 1) Y a-t-il un problème de recrutement? 2) Quelles sont les répercussions d'une pêche intensive sur le rendement et les profits? 3) Sur quels critères scientifiques les gestionnaires pourraient-ils se baser pour fermer cette pêche?

Pour répondre à la première question, nous avons examiné une série chronologique (de 1995 à 2000) de données sur les taux de prises de crabes de taille inférieure à la taille réglementaire. Ces données n'offrent aucune preuve convaincante que le nombre de petits crabes diminue. Cependant, la série chronologique est courte, et nous ne savons rien du recrutement avant la pêche intensive, qui se pratique depuis longtemps. Ainsi, on ne sait toujours pas si une baisse du taux d'exploitation entraînerait un recrutement accru. Les répercussions d'une pêche intensive sur le recrutement demeurent à déterminer.

Pour répondre à la deuxième question, nous avons utilisé un modèle fondé sur la longueur et un autre fondé sur le stade larvaire afin de produire des points de référence biologiques pour la gestion de la pêche. Nous avons estimé certains paramètres biologiques importants, tels que le taux de mortalité naturel, la vulnérabilité aux casiers de crabes de différentes tailles, la probabilité de mue et le taux de survie des crabes qui viennent juste de muer, à partir des données de relevés scientifiques effectués dans le port de Vancouver. Nous avons ensuite calculé le rendement, les recettes et le profit par recrue. Une pêche intensive entraîne également un grand nombre de remises à l'eau de crabes de taille inférieure à la taille réglementaire. La poursuite de la pêche d'un taux élevé de crabes de taille égale ou inférieure à la taille réglementaire entraînera une baisse nette du rendement à long terme, étant donné que certains des crabes de taille inférieure à la taille réglementaire mourront après avoir été manipulés et ne pourront contribuer au rendement futur. Dans le but de déterminer les seuils où les gains compensent la perte de rendement à long terme, nous avons effectué des analyses du gain ou de la perte de rendement en fonction du taux de crabes de taille inférieure à la taille réglementaire capturés dans la pêche intensive future. Pour éviter toute perte de rendement à long terme, le rapport des prises de taille inférieure à la taille réglementaire sur les prises de taille réglementaire ne devrait pas être supérieur à 19 pour 1, 9,5 pour 1, 6,5 pour 1 ou 5 pour 1, si le taux de mortalité dû aux manipulations est respectivement de 5 %, 10 %, 15 % ou 20 %.

D'après ces analyses, nous faisons les recommandations suivantes aux gestionnaires :

(1) Le taux d'exploitation actuel (> 90 %) devrait être réduit à 65 - 75 %. Le rapport des PUE à un moment donné sur les PUE au début de la pêche pourrait être utilisé pour déterminer quand fermer la pêche.
(2) En plus d'utiliser les mesures relatives aux PUE, ou pour les pêches où il est difficile d'utiliser les PUE en raison de saisons de mue prolongées, le rapport des crabes conservés sur les crabes rejetés devrait être utilisé pour limiter l'effort de pêche et pour protéger les stocks.
(3) Il faudrait s'efforcer de réduire les répercussions néfastes de la manipulation par les mesures suivantes : une période de mouillage plus longue, une pêche plus courte ou un ajustement de la saison de pêche.
(4) L'industrie, les gestionnaires et les scientifiques devraient utiliser ces modèles pour évaluer les répercussions d'une pêche intensive sur la dynamique des populations, déterminer les avantages économiques et sociaux de chaque pêche et élaborer des plans de gestion et d'évaluation optimaux.

1. Introduction

The commercial crab fishery in BC has a very complex set of social and economic objectives. The BC coast is currently subdivided into 7 management areas from which commercial fishers select a single management area to fish and then work with area managers to achieve their social and economic objectives for that area. The term for the area selected is presently set for three years but this term will be reviewed prior to the next area selection in 2003. Each area has its own unique character depending on its size, geographic location, exposure to weather, proximity to markets and management objectives. Management objectives in turn vary depending on the stakeholders and their relative participation i.e. some areas are strictly commercial fishery in nature, while others are greatly influenced by First Nation Food, Social and Ceremonial (FSC) requirements and sports fishery demands. Commercial landings have been between 400 and 650 tonnes since 1990. Recreational harvest, although unreported, is believed to be insignificant compared to the commercial fishery except in very limited areas of Fraser Delta.

The management of the crab fishery from a recruitment overfishing perspective has historically been handled passively through sex (males only) and size limits (the current minimum legal size corresponds to carapace width (CW) of 155 mm measured from notch-to-notch). Additional management measures have been implemented to reduce sub-legal handling mortality through the use of escape rings (all areas) and avoidance of soft shell seasons (some areas). Recent restrictions on trap numbers in some areas have focussed on reducing effort levels and extending the fishing season in this highly competitive trap fishery. There is considerable variation in management between areas reflecting the diversity of this fishery, which is considered to be fully subscribed.

This paper was prepared in response to the commercial Dungeness crab fishing industry's and fisheries managers concerns about the effects of intensive fishing on yield and recruitment. The managers hope to identify problems that may be occurring and potential problems as a result of this intensive fishery and to develop a biologically based approach to tackle those problems coast-wide. The actual RWP is found in Appendix 2. To reduce the complexity of the problem, we confined our analysis to crab fishery management area I, the Fraser delta (including Vancouver harbour and Indian Arm and Boundary Bay). This was done for three reasons. Firstly, we have a consistent and extensive data set from this area; secondly, the crabs exhibit a more or less synchronous spring moult and finally, there is a softshell closure in place that permits before and after analysis of fishery effects.

Typically, male crabs in the Fraser Delta moult in the spring and are sufficiently hard to allow commercial harvest to commence in late June. Legal sized male crabs are rapidly fished down over a period of about 6 weeks after opening the fishery. Thereafter, catch remains low and relatively consistent until the close of the fishery. Soak times increase from less than 1 day at the beginning to over 4 days towards the end of the fishery, while catch-per-trap decreases from 5 to less than 1 legal sized males. Nearly all legal-sized male crabs are removed during the fishing season. Removal of crabs produces an abrupt truncation of the length frequency at just below the legal width near the end of the season.

The intense fishery also results in a great deal of catch-and-release of sub-legal sized crabs. At the end of the season, the ratio of sub-legal to legal sized crabs can be very high. There is evidence that crabs are injured due to catch-and-release. The overall injury rate in a fished area (Fraser River) is approximately 19% for males and 15% for females, while the injury rates in a similar unfished area (Vancouver Harbour) is 7% for both males and females. The incidence of injuries suggests that some crabs will die of the handling mortality, which will consequently result in fewer legal sized crabs to be harvested in the following fishing seasons. Fishing at a high ratio of sub-legal to legal sized crabs in the catch could result in a net loss in yield in the long-term, as a high proportion of sub-legal sized crabs could not make contributions towards future yield due to the handling mortality.

The paper attempts to address three specific concerns: (1) is there a recruitment problem? (2) what is the impact of intensive fishing on yield and profit? (3) what scientific criteria could managers use to close the fishery?

To address the first concern, we examined the time-series data on catch rates for sub-legal crabs.

To address the second concern, we used a length-based and an instar-based approach to conduct yield per recruit analysis, which examines the average amount of yield generated with various exploitation levels. Biological parameters used in the length-based approach were estimated based on the scientific survey data from a virtually unfished crab population in Vancouver Harbour. Vancouver Harbour, closed due to navigation concerns, is bounded on the west by the commercial fishery on the Fraser delta, and on the east by a similar fishery in Howe sound. As such it represents a population of crabs that is directly comparable to those adjacent areas in terms of the parameters under investigation. We also used the length-based approach to conduct profit per recruit analysis and an analysis on gain-or-loss in yield for continuing fishing at high ratios of sub-legal to legal crabs in the catch. The second model is instar-based. High and low values are defined for the parameter values and a two-level, factorial design is applied. Analysis of the experimental design determines which model parameters affect the impact of an intense fishery. The experimental design is also a means of acknowledging uncertainty in parameter values when conclusions and recommendations are made.

We address the final concern based on these analyses and provide managers suggested mechanisms to control the identified problems within the fishery. It is also our intention to develop a tool that stakeholders and managers could use to probe the various biological, economic and social objectives in the different management areas and develop action plans that meet their various needs.

2. Materials and Methods

2.1. Recent Recruitment Rate in the Fraser River Delta and Boundary Bay

If there was a decline in the settlement rate in the Fraser River delta and Boundary Bay, then one of the indicators would be a decrease in the number of small crabs. Since crabs are usually three years old when they become vulnerable to the traps, trap-surveys can only indicate settlement patterns of three years ago.

Scientific surveys using standardised traps with no escape rings are used to evaluate crab stocks in the Fraser River delta. Surveys were taken in June and October from 1995 to 2000. Standardised catch per trap effort (*CPUE**) was used as an indicator of abundance and its change with time was graphed (Fig. 2.1.1) and analysed using analysis of variance for linear regression (Snedecor and Cochran, 1989) to determine if there was a statistically significant relationship between year and *CPUE** (Table 2.1.1). Refer to Section 2.2.1 for the procedure of standardising catch per trap effort.

2.2. A Length-Based Approach for assessment of the impact of Harvest Effort

Research surveys in Vancouver Harbour were conducted at several different periods during the years 1991 and from 1993-2001. All surveys used standard research crab traps with escape ports closed (Table 2.2.1). In years 1994-2000, surveys were consistently carried out in both June and October with additional information at other times of the year. Information on sex, size, shell moult stage, injuries, missing limbs, presence of mating marks, and sometimes weight on caught crabs was obtained. In this paper, crab size refers to carapace notch-width (CW) (excluding the spines). These survey data were used to estimate some important parameters on the population dynamics, such as natural mortality rate, proportion of moulting, and moulting survival rate.

Male crabs with CW less than 130 mm were excluded in the analysis, as a review of the size frequency distribution of sampled male crabs showed reduced vulnerability to trapping for male Dungeness crabs smaller than 130 mm in CW (Fig. 2.2.1). Information on female crabs was not used in the analysis, as this is a male only fishery and females do not directly make contributions to yield. In the remaining of the section, the term, crab(s), was used to refer to male Dungeness crab(s) larger than or equal to 130 mm in CW, unless otherwise specified.

2.2.1. Standardisation of Fishing Effort

In Feb. 2001, effects of soak hours on crab catch rates were investigated. Soak hours varied from 1 to 21 hours for most sets with three sets soaked for 46 hours. Catch of crabs per trap (*CPT*) increased, in general, with soak hour (t) (Fig. 2.2.2). We used the following model to describe the relationship:

$$CPT = CPT_{\infty} \times \left(1 - \exp(-k \times t)\right) \tag{1}$$

where CPT_{∞} and k are the model parameters, denoting, respectively, the average level of saturation for the trap and the rate of increase in catch of crabs with soak time. CPT_{∞} and k were estimated to be 14.62 and 0.19 respectively, by minimising the sum of squared differences between the expected and observed catches per trap. For each set, soak hours, t, was converted to the standardised soak hours, t^*, in the following way:

$$t^* = \frac{1 - \exp(-0.19 \times t)}{1 - \exp(-0.19)} \tag{2}$$

Standardised fishing effort, E^*, was expressed as standardised trap hours, which equals to the product of standardised soak hours and the number of sampled traps, nt, for the set:

$$E^* = t^* \times nt \tag{3}$$

Standardised catch per unit effort, $CPUE^*$, is the number of crabs captured for one standardised effort:

$$CPUE^* = \frac{C}{E^*} \tag{4}$$

where C is the catch of crabs in numbers.

2.2.2. Natural Mortality Rate during Non-Moulting Period

Fig. 2.2.1 shows that legal sized crabs (>= 155 mm in CW) appear to be fully vulnerable to the research traps, as overall catches of these crabs decrease with the size. It is assumed that $CPUE^*$ for legal sized crabs is proportional to the abundance of these crabs. We used the catch data on legal sized crabs in June and October of 1994-2000 to estimate the instantaneous annual natural mortality rate. Crabs mainly moult during the spring of the year (Jamiesson et. al. 1998), although a small proportion of moulting must also occur between June and October, as a few crabs with moult stage of 2, 3 or 4 were observed in October samples. These soft shell crabs in the October samples were excluded in the estimation of the natural mortality rate. We assume that there was no migration of crabs into or out of the Vancouver Harbour or the amount of immigration is the same as that of emmigration. The reduction in the number of legal sized crabs was, therefore, due to natural mortality. Instantaneous annual natural mortality rate between June and October (a period of 4 months) in year y (1994<= y <=2000), M_y, was calculated as follows:

$$M_y = -\frac{12}{4} \times \ln\left(\frac{CPUEoct_y^*}{CPUEjun_y^*}\right) \tag{5}$$

where $CPUEoct_y^*$ and $CPUEjun_y^*$ are, respectively, $CPUE^*$ for legal sized crabs in October and June of year y. Calculated values vary approximately from 0 to 2 (Table 2.2.2). The reliability of the estimation is likely to be positively correlated with the amount of standardised effort spent. We, therefore, estimated the mean natural mortality rate, *M*, as the weighted mean of these estimates with the standardised efforts as the weight:

$$M = \frac{\sum_{y=1994}^{2000} M_y \times E_y^*}{\sum_{y=1994}^{2000} E_y^*} \tag{6}$$

where E_y^* is the sum of standardised effort spent in June and October of year y. *M* was estimated to be 0.5 with a standard error of 0.23. This annual natural mortality rate is used for all months except April when the mortality rate is expected to be higher due to moulting. It is termed as non-moulting natural mortality rate in this paper.

2.2.3. Proportion of Moulting

To estimate proportion of moulting and vulnerability coefficient for different sizes of crabs, we grouped the crabs into 13 classes from 130 to 190 mm in 5 mm intervals. The width classes were indexed consecutively from 1 for the smallest class to 13 for the largest one.

For simplicity, it is assumed that all moulting occurs simultaneously on April 1st, approximately 5.5 months after the October survey and 2.5 months before the next June survey. We also assume that crabs with moult stage of 1-5 in the June samples moulted on April 1st of the same year and those with moult stage of 6-8 did not moult in that year. The former is termed as new shell crabs and the latter is termed as old shell crabs.

The October survey results were used to predict the relative abundance of new and old shell crabs just before moulting on April 1st of the next year, while the June survey was used to back-calculate the relative abundance of old shell crabs just before moulting on April 1st. The relative abundance of the moulted crabs is simply the difference between these two estimates and the proportion of moulting is the ratio of the relative abundance of moulted crabs to the relative abundance of moulted and non-moulted abundance on April 1st. The proportion of moulting for width class i in year y+1, $p_{y+1,i}$, was thus calculated as follows:

$$p_{y+1,i} = \frac{CPUEoct_{y,i}^* \times \exp\left(-M \times \frac{5.5}{12}\right) - CPUEOjun_{y+1,i}^* \times \exp\left(M \times \frac{2.5}{12}\right)}{CPUEoct_{y,i}^* \times \exp\left(-M \times \frac{5.5}{12}\right)} \tag{7}$$

where $CPUEoct^{*}_{y,i}$ is the $CPUE^{*}$ for new and old crabs of width class i in the October survey in year y, $CPUEOjun^{*}_{y+1,i}$ is $CPUE^{*}$ for old shell crabs of width class i in the June survey in year y+1, and *M* is the non-moulting natural mortality rate (=0.5).

Estimated proportion of moulting for each width class in each year was presented in Table 2.2.3. Moulting probability was represented by two linear models, one for the width class between 130 and 150 mm and the other for the width class larger than 150 mm (Fig. 2.2.3)

$$\begin{cases} p_i = -0.001 \times MCW_i + 1.1016 & (if \quad 130 < MCW_i < 150) \\ p_i = -0.0103 \times MCW_i + 2.2507 & (if \quad MCW_i > 150) \end{cases} \tag{8}$$

where p_i is the estimated moulting probability for crabs of width class i and MCW_i is the mid carapace width for width class i. For the width class [185, 190) and [190, 195), the estimation of the proportions of moulting has a large variation probably due to relatively small size of catch data. They were not used to establish the linear model, as they do not appear so reliable.

2.2.4. Size-Dependent Vulnerability

Overall catch of sub-legal crabs was lower than legal sized crabs of 155-175 mm in CW in the Vancouver Harbour. Sub-legal crabs appear to be less vulnerable to the traps and the vulnerability seems to decrease with size, as overall catches of sub-legal crabs decreased with size (Fig. 2.2.1). Knowing size-dependent vulnerability is essential for estimating relative abundance of crabs based on surveys. We assumed that legal sized crabs are fully vulnerable, and used a linear model to describe the relationship between vulnerability coefficient and size for sub-legal crabs:

$$\begin{cases} v_i = 1 & (if \quad MCW_i >= 155) \\ v_i = 1 - a \times (157.5 - MCW_i) & (if \quad 130 < MCW_i < 155) \end{cases} \tag{9}$$

where v_i is the vulnerability coefficient for width class i, a is the model parameter, MCW_i is the mid carapace width for the width class i.

Previous studies showed that moult increment is correlated with pre-moult size of crabs (Butler 1961, Collier 1983, Warner 1987, Smith and Jamieson 1989, Jamieson et. al. 1998). Combining the data collected from British Columbia and California, Smith and Jamieson (1989) formulated the following equation for calculating the mean post-moult carapace width, *MW*, based on the pre-moult carapace width, *CW*:

$$MW = 1.069 \times CW + 18.07 \tag{10}$$

The distribution in post-moult sizes is normal, and the variance is nearly constant, which equals to about 10.8, over the range of approximately 80-175 mm in pre-moult carapace width (Smith and Jamieson, 1989). The mid carapace width crabs in width class i moult to was calculated using the above equation by setting *CW* to be MCW_i, the mid carapace width for width class i,.

The ratio (proportion) of crabs which moult from width class i into width class j (8 <= j <= 13; i < j), $r_{i,j}$, is:

$$r_{i,j} = \int_{L_j}^{U_j} \frac{1}{\sqrt{2 \times p \times 10.08}} \exp\left(-\frac{(x - MW_i)^2}{2 \times 10.08} \right) dx \qquad (11)$$

where L_j and U_j are the lower and upper bounds of width class j calculated as follows:

$$\begin{cases} L_j = 130 + 5 \times (J - 1) \\ U_j = L_j + 5 \end{cases} \qquad (12)$$

With the growth and vulnerability models, the size frequency and expected catches of new shell crabs in the June survey in year y+1 can be predicted based on the October survey results in year y. The unknown parameter a in Equation 9 was estimated by trials of various values until the best fit was reached between predicted and observed catches of new shell crabs in the June surveys for the six width classes (classes 8-13). These six width classes were chosen, because crabs smaller than 130 mm before moulting have little chance of moulting into one of these classes.

The relative abundance of crabs (new and old shell) in width class i during the October survey in year y, $Noct_{y,i}$ was calculated as follows:

$$Noct_{y,i} = \frac{CPUEoct^*_{y,i}}{v_i} \qquad (13)$$

where $CPUEoct^*_{y,i}$ is the $CPUE^*$ for crabs of width class i in the October survey in year y and v_i is the vulnerability coefficient for width class i from Equation 9. The fraction of new shell crabs in width class j during the June survey in year y+1, $f_{y+1,j}$ (8<=j<=13, i<j), was predicted as follows:

$$f_{y+1,j} = \frac{\sum_{i=1}^{j-1} Noct_{y,i} \times p_{y+1,i} \times r_{i,j}}{\sum_{k=8}^{13} \sum_{i=1}^{k-1} Noct_{y,i} \times p_{y+1,i} \times r_{i,k}} \qquad (14)$$

where $Noct_{y,i}$ is the relative abundance of new and old shell crabs in width class i during the October survey in year y, $p_{y+1,i}$ is the proportion of moulting for crabs in width class i in year y+1, and $r_{i,j}$ is the proportion of crabs which moult from width class i into width class j. The numerator and denominator represents, respectively, the relative abundance of new shell crabs of width class j and of the entire six width classes (classes 8-13) during the June survey in year y+1. The expected catch of new shell crabs of width class j (8<=j<=13) in the June survey in year y+1, $\hat{C}_{y+1,j}$, is:

$$\hat{C}_{y+1,j} = f_{y+1,j} \times \sum_{i=8}^{13} C_{y+1,i} \qquad (15)$$

where $C_{y+1,i}$ is the observed catch of new shell crabs of width class i in the June survey in year y+1. The goodness of fit between the expected and observed catches of new shell crabs was measured by the chi-square variable, $ChiSq$:

$$ChiSq = \sum_{y=1994}^{1999} \sum_{i=8}^{13} \frac{(\hat{C}_{y+1,i} - C_{y+1,i})^2}{\hat{C}_{y+1,i}} \tag{16}$$

The grid search method was used to find the value of a from Equation 9, which minimises $ChiSq$. This approach involves dividing the range for the parameter a into a large number of discrete narrow intervals, and then evaluating $ChiSq$ at the centre of each interval. The minimum value of ChiSq occurred when a was set to 0.037.

2.2.5. Survival Rate during the Month after Moulting

We assumed that within one month following moulting, crabs are particularly vulnerable and suffer from a higher natural mortality rate. We used the models for growth, moulting and vulnerability to predict $CPUE^*$ for new shell crabs in the June survey based on the October survey results in the previous year. A survival rate was estimated by minimising the error between predicted and observed $CPUE^*$ for new shell crabs in the June surveys. To estimate the survival rate for crabs with CW around 155 mm before moulting, we used five width classes (classes 4-8) as contributing classes, and classes 11 and 12 as recipient classes. These two particular classes were chosen as recipient classes because new shell crabs in the recipient classes are virtually all from these five contributing classes.

If a crab moults, the period between October and June of the following year represents seven months when the non-moulting mortality rate, *M*, applies and one month when moulting survival rate, *s*, applies. The relative abundance of soft shell crabs of the recipient classes in June of year y+1, $NNjun_{y+1}$, was predicted as follows:

$$NNjun_{y+1} = \sum_{i=4}^{8} Noct_{y,i} \times \exp\left(-M \times \frac{7}{12}\right) \times s \times p_{y+1,i} \times \left(r_{i,11} + r_{i,12}\right) \tag{17}$$

where $Noct_{y,i}$ is the relative abundance of new and old shell crabs of width class i during the October survey in year y, $p_{y+1,i}$ is the proportion of moulting for width class i in year y+1, and $r_{i,11}$ and $r_{i,12}$ are the proportion of crabs which moult from width class i into width class 11 and width class 12 respectively. As vulnerability coefficient for legal sized crabs is one, $NNjun_{y+1}$ is equivalent to the expected $CPUE^*$ for the new shell crabs of the recipient classes in June of year y+1, $\hat{U}^*_{y+1}$. Various values for the survival rate, *s*, were tried until the sum of squared differences, *SSD*, between the expected and observed $CPUE^*$ for the new shell crabs in the recipient width class was minimised:

$$SSD = \sum_{y=1994}^{1999} (\hat{U}^*_{y+1} - U^*_{y+1})^2 \tag{18}$$

where U^*_{y+1} is the observed $CPUE^*$ for new shell crabs in the recipient width classes in June of year y+1. The survival rate was estimated to be 62%, which is equivalent to an instantaneous annual mortality rate of 5.7 for one month.

The moulting survival rate for crabs larger than 130 mm in CW was also estimated. The survival rate was estimated by minimising the sum of squared differences between the predicted and observed $CPUE^*$ for the new shell crabs in the 6 width classes (classes 8-13). The predicted $CPUE^*$ for the new shell crabs in width class j (8<=j<=13) in June of year y+1, $\hat{U}^*_{y+1,j}$, was estimated as follows:

$$\hat{U}^*_{y+1,j} = \sum_{i=1}^{j-1} Noct_{y,i} \times \exp\left(-M \times \frac{7}{12}\right) \times s \times p_{y+1,i} \times r_{i,j} \qquad (19)$$

The sum of squared differences, *SSD*, between the expected and observed $CPUE^*$ is:

$$SSD = \sum_{y=1994}^{1999} \sum_{j=8}^{13} (\hat{U}^*_{y+1,j} - U^*_{y+1,j})^2 \qquad (20)$$

where $U^*_{y+1,j}$ is the observed $CPUE^*$ for new shell crabs in width class j in June of year y+1. The survival rate was estimated to be 64%, which is equivalent to an instantaneous annual mortality rate of 5.4 for one month. In the calculation of yield, revenue and profit per recruit, a survival rate of 0.63 was used.

2.2.6. Yield, Revenue and Profit Per Recruit

Conventionally, “recruit” in per-recruit analyses refers to an animal that has just grown old or large enough to be harvested by the fishery. To investigate the impact of handling mortality on sub-legal crabs, a recruit is defined to be a sublegal-sized crab that is at least partially vulnerable to the traps. Two size ranges are considered for the recruits; 130-155 mm and 130-135 mm. The former wide size-range is represented by a crab, which spreads among the five sub-legal width classes (classes 1-5) with proportions according to the estimated proportions in the Vancouver Harbour. The latter narrow size-range is represented by a single 132.5 mm crab. The yield-per-recruit considers a recruit at the time of harvest and estimates the expected accumulated amount of yield produced by the recruit in its whole life span for a given fishing mortality. Price and cost estimates are incorporated into the model in order to estimate revenue and profit per recruit.

Mortality rates, vulnerabilities and probability of moulting are taken from Table 2.2.4. No crabs larger than 210 mm in CW has been observed in the surveys in the Vancouver Harbour. Immediately after moulting into a size above 210 mm in CW, Crabs were assumed to die. This mortality was termed as "senescent mortality" in the paper.

The crab fishery near Vancouver starts in mid-July and effectively ends, three months later, around mid-October. We assume, for simplicity, crabs may only moult around April 1st, 5.5 months away from the end of the fishery and 3.5 months away from the beginning of the next year's fishery. Effect of various instantaneous fishing mortality rates and exploitation rates on yield, revenue and profit per recruit was examined. Legal sized crabs in the width class [155, 160) are likely to maintain another successful moult in a sense that they have little chance of moulting into a size above 210 mm in CW and thus do not suffer from senescent mortality. The impact of different rates of retaining these crabs on yield, revenue and profit per recruit was also studied. Crabs were grouped into 16 classes from 130 to 210 mm in 5 mm intervals. The width classes were indexed consecutively from 1 for the smallest class to 16 for the largest one.

The proportion of crabs of sub-legal width class i (1<=i<=5) among crabs of all the sub-legal width classes (classes 1-5) in the Vancouver Harbour, P_i, is estimated as follows.

$$P_i = \frac{C_i / v_i}{\sum_{j=1}^{5} C_j / v_i} \tag{21}$$

where C_i is the accumulated catch of crabs of width class i in all the surveys in the Vancouver Harbour, and v_i is the vulnerability coefficient for width class i. To start with the calculation, each sub-legal width class (classes 1-5) was assigned with the corresponding proportion of P_i (1<=i<=5).

Catch in numbers of crabs in width class i in year y, $C_{y,i}$, is proportional to the number of crabs in this width class at the beginning of the fishing season in that year, $N_{y,i}$, and instantaneous annual fishing mortality rate, *F*:

$$\begin{cases} C_{y,i} = 0 & (if \quad MCW_i < 155) \\ C_{y,i} = N_{y,i} \times \frac{F \times r}{Z}\left(1 - \exp(-Z \times \frac{t}{12})\right) & (if \quad MCW_i = 157.5) \\ C_{y,i} = N_{y,i} \times \frac{F}{Z}\left(1 - \exp(-Z \times \frac{t}{12})\right) & (if \quad MCW_i > 160) \end{cases} \tag{22}$$

where t is length of the fishing season in months.,), MCW_i is the mid-width for width class i, *r* is the retention rate for the caught crabs in width class [150, 155), and *Z* is the total instantaneous annual mortality rate and is calculated based on crab size:

$$\begin{cases} Z = M + F \times h \times v_i & (if \quad MCW_i < 155) \\ Z = M + F \times h \times (1 - r) + F \times r & (if \quad MCW_i = 157.5) \\ Z = M + F & (if \quad MCW_i > 160) \end{cases} \tag{23}$$

where *M* is the non-moulting natural mortality rate (= 0.5), *h* is the handling mortality (percentage mortality rate for capture and release) which was assumed to be 5%, v_i is the vulnerability coefficient for width class i from Equation 9. The exploitation rate, *E*, for legal sized crabs larger than or equal to 160 mm in CW was calculated as follows:

$$E = \frac{F}{Z}\left(1 - \exp(-Z \times \frac{3}{12})\right) \tag{24}$$

The relative abundance of crabs of width class j at the beginning of the fishery in year y+1, $N_{y+1,j}$, is composed of two groups of crabs. The first group comprises old shell crabs which did not grow since October of year y and survived the fishing and natural mortality. The second group comprises new shell crabs which came from smaller width classes due to moulting in the spring of year y+1.

$$N_{y+1,j} = N_{y,j} \times \exp\left(-Z \times \frac{t}{12}\right) \times \exp\left(-M \times \frac{12-t}{12}\right) \times \left(1 - p_j\right) + \sum_{i=1}^{j-1} N_{y,i} \times \exp\left(-Z \times \frac{t}{12}\right) \times \exp\left(-M \times \frac{11-t}{12}\right) \times s \times p_i \times r_{i,j} \quad (25)$$

where t is the months of fishing period (=3), Z is the total instantaneous annual mortality rate from Equation 23, M is the non-moulting natural mortality rate (=0.5), p_i is the moulting probability for crabs of width class i from Equation 8, s is the survival rate during the month of moulting (=0.63), and $r_{i,j}$ is the proportion of crabs moulting into width class j from width class i from Equation 11.

Catches in the fishing season of year y+1 and relative abundance of crabs in each width class at the beginning of the fishery in the subsequent year were calculated in the same way as described above. The simulation procedure continues until all the crabs (>99.999%) either died from natural (including senescent) or fishing mortality. The overall yield, $Yield$, is the summation of catches of the legal sized crabs in weight over the entire life span of the one recruit:

$$Yield = \sum_{y} \sum_{i=6}^{16} C_{y,i} \times W_i \quad (26)$$

where W_i is the weight for a crab of average size in width class i. Carapace width and weigh relationship was established based on the 180 crabs which were weighed in the surveys in the Vancouver Harbour (Fig. 2.2.4.):

$$W_i = 0.0001 \times MCW_i^{3.0957} \quad (27)$$

This $Yield$ is equivalent to yield per recruit, as it is produced by one recruit. The revenue per recruit, RPR, is:

$$RPR = \sum_{y} \sum_{i=6}^{16} C_{y,i} \times W_i \times \mathrm{Pr}\,ice_i \quad (28)$$

where $\mathrm{Pr}\,ice_i$ is the sale price for crabs of width class i. A cost model was used to generate the profit per recruit. Cost is assumed to depend on the exploitation rate, E, from Equation 24. We assumed that the cost is 10% of the revenue when E is 10%, and the cost increases in a linear fashion until 50% of the revenue when E is 100%. Thus, cost per recruit, CPR, is:

$$CPR = \frac{RPR}{18} \times (1 + 8 \times E) \quad (29)$$

The profit per recruit, PPR, is the difference between revenue per recruit and cost per recruit:

$$PPR = RPR - CPR \quad (30)$$

We also calculated $F_{0.1}$, a instantaneous fishing mortality rate at which the slope of the yield per recruit function is 0.1 times the slope near zero. We then translated $F_{0.1}$ to $E_{0.1}$, an equivalent exploitation rate, using Equation 24 where $F = F_{0.1}$ and $Z = F_{0.1} + M$.

When per-recruit means a single 132.5 mm crab, we assigned one crab to the width class [130, 135). Yield, revenue and profit per recruit and $E_{0.1}$ were calculated the same way as described above.

2.2.7. Consequence of Fishing at a High Ratio of Sub-legal to Legal Crabs in the Catch

Catching legal crabs will cause some sub-legal crabs to suffer from handling mortality. When the ratio of catching sub-legal to legal crabs is high, loss could exceed the gain if fishing continues. To examine the impact of this trade off, we calculated the gain in catching one legal crab and loss due to removing this legal crab and death of a fraction of sub-legal crabs caught together with this legal crab at various ratios of sub-legal to legal crabs. The loss was expressed in terms of the contribution these dead crabs would otherwise make to the future catch, if fishing had stopped. The retention rate for crabs of width class [155, 160) was set to be 100%.

We assume that the size distribution of sub-legal crabs caught together with the legal crab is distributed in each sub-legal width class the same way as those caught in the surveys in Vancouver Harbour. We also assume that this ratio of catching sub-legal to legal crabs occurs 2 months away from the beginning of the fishery in year y and 6.5 months away from the moulting in year y+1. If the ratio of catching sub-legal to legal crabs is ra, the number of sub-legal crabs caught with one legal crab is Ns $(ra = Ns/1)$. Among these sub-legal crabs, the number of crabs from width class i (1<=i<=5) which would die of handling mortality, $N_{y,i}$, is:

$$N_{y,i} = Ns \times P_i \times h \tag{31}$$

where P_i is the proportion of crabs of sub-legal width class i (1<=i<=5) among crabs of all the sub-legal width classes caught in all the surveys in the Vancouver Harbour and h is the handling mortality. Impact of four different handling mortality rates, 5%, 10%, 15% and 20%, were evaluated.

We assume that the size of the legal crab is 157.5 mm in CW. Thus, one crab was assigned to width class 6 and $N_{y,i}$ crabs were assigned to width class i (i = 1, 2 , 3, 4, 5) to start the calculation on how much yield these dead crabs would otherwise make to the future catches if fishing stopped.

The abundance of crabs of width class j at the beginning of the fishery in year y+1, $N_{y+1,i}$, was analogously calculated as for Equation 25:

$$\begin{aligned} N_{y+1,j} = {} & N_{y,j} \times \exp\left(-M \times \frac{10}{12}\right) \times \left(1 - p_j\right) + \\ & \sum_{i=1}^{j-1} N_{y,i} \times \exp\left(-M \times \frac{9}{12}\right) \times s \times p_i \times r_{i,j} \end{aligned} \tag{32}$$

where M is the non-moulting natural mortality rate (=0.5), p_i is the moulting probability for crabs of width class i, s is the survival rate during the month of moulting (=0.63), and $r_{i,j}$ is the proportion of crabs moulting into width class j from width class i. The first term represents old shell crabs that did not grow and the summation represents crabs that have moulted into width class j from smaller width classes.

We assume an instantaneous fishing mortality of 7.7 for a two-month fishing period, which is equivalent to an exploitation rate of 70%. The amount of catch in numbers, to which the crabs in width class i would contribute in year y+1, $C_{y+1,i}$, was calculated using Equation 22 by setting the months of fishing, t, to be 2 and the retention rate, *r*, to be 1.

The abundance of these crabs in width class j at the beginning of the fishery in year y+2 was calculated using Equation 25 by setting the months of fishing, t, to be 2. Calculation on catch and abundance continues in this manner until all these crabs (>99.999%) either died from natural (including senescent) or fishing mortality. The overall yield, $Yloss$, these crabs would make was calculated using Equation 26. This yield represents the loss for catching one more legal crab at this ratio of sub-legal to legal crabs in the catch. The yield gained by catching one such legal crab, *Ygain*, was calculated using Equation 27 by setting MCW_i to be 157.5.

Thus, the net gain in terms of yield for continuing fishing at this ratio, ΔY, is:

$$\Delta Y = Ygain - Yloss \tag{33}$$

A positive value of ΔY indicates a gain, and a negative value of ΔY denotes a loss in yield for catching one legal-sized crab at this ratio of sub-legal to legal sized crabs in the catch.

2.2.8. Change in CPUE and Ratio of Sub-legal to Legal crabs in the Catch

With an intensive fishery, *CPUE* for legal crabs decreases rapidly and the ratio of sub-legal to legal crabs increases quickly. To examine these changes, we plot *CPUE* against the months of year 2001 based on the commercial harvest log books (Fig. 2.2.7). We also examine the changes in the ratio of sub-legal to legal crabs with time based on the scientific surveys in Fraser Delta in 1995-2001 and based on a commercial sampling from Fraser Delta in 1995 (Table 2.2.5, 2.2.6).

2.3. An Instar-Based Approach for assessment of the impact of Harvest Effort

The instar-based model is described in Appendix 1. The instar-based analysis does not use CPUE as an indicator of abundance. Instead, it considers a range of parameter-values that are consistent with the catch-compositions observed in the Vancouver Harbour surveys. A full factorial design is imposed on the range of characteristics. For each experiment within the design, a full range of fishing effort is applied and the long-term impact of effort on yield is estimated.

2.3.1. The Impact of Harvest

The male crabs that show up in the traps are conveniently categorised into four groups:

1. Instar-1, newshell
2. Instar-1, oldshell
3. Instar-2, newshell
4. Instar-2, oldshell

The crabs recruit as newshell in Instar-1. The distribution of sizes for Instar-1, newshell crabs will be similar to the distribution of all Instar-1 crabs observed in Fig. 2.3.1 At the end of the year, some of the surviving crabs become Instar-1 oldshell crabs and others will moult into Instar-2, newshell crabs.

Fig. 2.3.1 shows size frequencies for male crabs caught in Vancouver Harbour. The distribution is dominated by two humps corresponding to the two dominant instars that get caught in the traps.

The size-frequency-distribution (SFD) is assumed to be normal for both instars. Maximum Likelihood Methods (Bain and Engelhardt,1992) were used to determine the characteristics of the two instars from the combined October surveys. In the October surveys, approximately 57% of the captured male crabs belong to Instar-1 with the mean and standard deviation of the notchwidth being 146.8 and 11.42 mm respectively. Approximately 42% of the male crabs belong to Instar-2 with the mean and standard deviation of the notchwidth being 172.1 and 8.86 mm respectively. In the June surveys, approximately 29 and 71% of the male crabs belong to Instar-1 and Instar-2. The observed ratio of Instar-1 to Instar-2 crabs is referred to as Obs.

It is assumed that Instar-2 crabs are fully vulnerable to the traps and all members of Instar-1 are equally vulnerable regardless of size.

Another useful characteristic of a crab population is k, the fraction of crabs that are newshell (moulted within the previous year). k has a theoretical range of one-half to one(Equ'n 2a in the appendix) which is corroborated by the range observed in Fig. 2.3.1. k is useful because it gives an upper bound to the natural mortality rate (Equ'n 3 of Appendix 1).

It's possible to choose parameter-values that approximately replicate the results of the Vancouver Harbour surveys. Fig. 2.3.2 was generated assuming a natural mortality rate of M=0.50 $year^{-1}$, k=0.95 and Obs =0.25. The catch composition is dominated by Instar-1, newshell crabs.

The calculations can be repeated with an assumed harvest. 98% of the legal-sized crabs are removed in a very short time. The predicted size-frequency distributions appear in Fig. 2.3.4. Fig. 2.3.5 shows the trap-SFD for an intensely fished area.

Fig. 2.3.4 assumes that there is no handling mortality. The simulation can be repeated assuming that h=0.10 (every time a sublegal crab is caught and released, there is a 10% probability that fatal injuries result). Fig. 2.3.6 shows the predicted SFDs when handling mortality occurs.

2.3.2. Sensitivity Analysis Using the Instar-Based Model

Various fishing efforts can be implemented in the Instar-based model. Fishing effort is measured in two different ways:

- $G = F * t_{harvest} \sim -\log(ExploitationRate)$ (see Fig. 2.3.3)
- $R = \dfrac{Number \;\; of \;\; SubLegal \;\; Sized \;\; Crabs}{Number \;\; of \;\; Legals \;\; Sized \;\; Crabs}$ at the end of the season

where F is the instantaneous annual fishing mortality rate, $t_{harvest}$ is the length of fishing season in year, and $ExploitationRate$ is the fraction of legal sized crabs harvested. G is closely related to traditional parameters of a fishery. R is easy to measure and dosen't have to be adjusted for trap-type or soak times.

Fig. 2.3.7 shows how fishing effort impacts the long-term yield-per-recruit.

It must be acknowledged that the calculations require values that are not well understood. For example, Smith and Jamieson (1991a) estimated much higher rates (2.3 to 2.8) of natural mortality for Dungeness crabs in the Tofino area and Gotshall 1978 estimated values between 0.54 and 1.78 for Northern California. The estimated value of M in Section 2.2.2 is a result of averaging five values ranging from zero to

2.1. It is useful to determine if the natural mortality rate impacts the optimum harvest effort. Fig. 2.3.8 shows the predicted yield of crabs that is harvested for various combinations of natural and fishing mortality.

The same analysis that is applied to natural mortality could be applied to the other sources of uncertainty for the estimated yield. However, such analyses give no information about how combinations of parameter values affect the estimated yields. (For example, is natural mortality still important if there has been a recruitment pulse?). A different method of analysis is needed.

Six sources of variability have been parameterised. High and low values have been chosen for each the parameters (see Table 2.3.2). High and low values of the parameters have been combined into the 64 scenarios (a full factorial experiment) shown in Table 2.3.3. None of the 64 scenarios should be considered correct, but reality likely lies somewhere amongst them. There are two advantages to this approach:

1. We can look at the results to determine if parameters have the most effect on the model predictions.
2. Any conclusions are not as dependent on our ability to measure natural mortality or abundance.

A range of G-values was applied to each scenario and the resulting yields and values of R were estimated. Results from eight of the scenario are shown in Fig. 2.3.9.

Fig. 2.3.9 demonstrates that there is a lot of scenario-to-scenario variability both in the maximum yield and in the fishing effort that corresponds to maximum yield. In the 64-scenarios, the R-values corresponding to maximum yield range from 0.06 to 1875.

A more consistent quantity is $R_{95\%}$, the R-value corresponding to 95.24% of the maximum yield. If fishing continues beyond $R_{95\%}$, yield can only increase by five percent. $R_{95\%}$ has a comparatively small range of 0.03 to 12.69.

$G_{95\%}$, the value of G corresponding to $R_{95\%}$ is also calculated

The experimental design is used to estimate main effects and second-order interactions on $G_{95\%}$ and $\log_{10}$ of $R_{95\%}$. Results are shown in Table 2.3.4

3. Results

3.1. Recent Recruitment Rate

The time-series plot of CPUE*s (Fig. 2.1.1) suggests that there was a trend of declining abundance in three of the sixteen cases:

- Boundary Bay, June, Oldshell, females
- Fraser River, June, Oldshell sublegal males
- Fraser River, June, Newshell, females.

The results on the analysis of variance for linear regression appear in Table 2.1.1, which indicates three statistically significant regressions (P-value < 0.05). However, there is no corroboration in the table. The June surveys indicate that the number of oldshell females is decreasing in Boundary Bay but a corresponding decrease is not observed for the October surveys or for oldshell sublegal males in the same location. Neither Table 2.1.1 nor Fig. 2.1.1 gives conclusive indication that small crabs are becoming less abundant between 1995 and 2000.

3.2. A Length-based Approach

The estimates of crab population parameters are presented in Table 2.2.4. The instantaneous annual natural mortality rate is 0.5 for the period between June and October when little amount of moulting occurs. Almost all crabs less than 150 mm in CW would moult in the spring, while the proportion of moulting decreases from 68% to 37% when the legal size of crabs increases from 152.5 to 182.5 mm in CW. Approximately 62% of newly moulted crabs survive the moulting. Legal sized crabs appear to be fully vulnerable to the research traps, while sub-legal sized crabs are less vulnerable and the vulnerability decreases with decreasing size.

Yield per recruit and $E_{0.1}$, and revenue and profit per recruit are presented in Fig. 2.2.5, where per recruit means one crab spreading among the five sub-legal width classes. Yield per recruit increases with the exploitation rate at least until the exploitation rate reaches 90%. $E_{0.1}$ was estimated to be 62-63% depending on the retention rate for the legal sized crabs between 155 and 160 mm in CW (Fig. 2.2.5A).

The shape of revenue per recruit relies on the price for different sizes of crabs. If the price is $10.00/kg for crabs between 155 and 170 mm in CW, and twice as much ($20.00/kg) for larger crabs, revenue per recruit increases with exploitation rate until about 90%, then flattens out (Fig. 2.2.5B).

The shape of profit per recruit also hinges on the price, when the cost model is incorporated into the analysis. If the price is $10.00/kg for crabs between 155 and 170 mm in CW, and twice as much for larger crabs, the profit per recruit is maximised when the exploitation rate is around 64% irrespective of the retention rate (Fig. 2.2.5C). When the price is $10.00/kg for all legal sized crabs, the profit per recruit is maximised when the exploitation rate is around 68% (Fig. 2.2.5D).

A lower retention rate for crabs between 155 and 160 mm in CW results in slightly lower yield, revenue and profit per recruit with the same exploitation rate (Fig. 2.2.5). Thus, the current retention rate of 100% probably should not be reduced.

When per recruit means one 132.5 mm crab, the shape of yield, revenue or profit per recruit is similar to that described above. $E_{0.1}$ was estimated to be between 63 and 67%.

For a given handling mortality rate, the gain in yield in the long-term declines linearly with increasing ratio of sub-legal to legal crabs in the catch (Fig. 2.2.6). For a given ratio of sub-legal to legal crabs in the catch, the gain decreases quickly with increasing handling mortality rate (Fig. 2.2.6). There is no gain in yield for continuing fishing when the ratio is 19:1, 9.5:1, 6.5:1 or 5:1 if the handling mortality rate is, respectively, 5%, 10%, 15%, or 20%. Fishing above this ratio would result in a net loss in yield. More yield could generated, when fishing below this ratio (Fig. 2.2.6).

Examination of changes in *CPUE* with time shows that $CPUE^*$ drops by approximately 85% one month after the starting the fishery (Fig. 2.2.7). *CPUE* drops by approximately 94% two months after the fishery, and remains unchanged thereafter (Fig. 2.2.7). The scientific surveys show that the ratio of catching sub-legal to legal males was approximately 1:1 at the beginning of the fishery, and the ratio increased by 15 times to 15:1 at the end of the fishery (Table 2.2.5). Commercial sampling data show that the ratio does not increase so quickly. The ratio was 0.8:1 at the beginning of the fishery in Fraser Delta in June, 1995, and increased to about 9.5:1 at the end of the fishery in October, 1995 (Table 2.2.6). More data needs to be collected from the commercial fishery to enhance our understanding on the change in the ratio of caught sub-legal to legal crabs.

3.3. An Instar-based Approach

3.3.1. The Impact of Harvest

Fig. 2.3.1, includes the SFD for captured crabs June in an unfished area and Fig. 2.3.2 shows the corresponding SFD predicted by the instar-based model. The model-predictions are a reasonable match to the survey results. The model also predicts that catch will be dominated by Instar-2, newshell crabs. There are a negligible number of Instar-1, oldshell crabs. Without a harvest, crabs with a notch-width greater than 180 mm comprise approximately 15% of the population and 20% of the biomass.

Fig. 2.3.4 and 2.3.5 show survey results and predicted survey results for a heavily harvested area. Some of the abrupt features predicted by the model are smoother in the survey data. The catch is dominated by Instar-2, newshell crabs. The impact of the harvest is most notable for Instar-2, oldshell crabs; the SFD is truncated at the legal size limit. There are also very few crabs with a notch width greater than 180 mm.

Fig. 2.3.6 shows the predicted SFD when caught-and-released sublegal crabs are subject to handling mortality. Handling mortality leads to a smaller number of legal-sized crabs.

Table 2.3.1 shows the estimated yield for the initial set of parameter values. Handling mortality results in a 5% decrease in the long term weight of the crab catch.

3.3.2. Sensitivity Analysis

Fig. 2.3.7 shows how yield is expected to vary with changes in the fishing effort. If the fishing effort is low, then fewer newshell crabs are caught. If the fishing effort is high, then fewer oldshell crabs are caught. To maximise yield, the trick is to determine (and be able to identify in the field) the fishing effort that is likely to maximise the harvest of crabs. For the parameter values that have been considered, the best value of G is 3 to 4 and the corresponding value of R is 5 to 15.

Fig. 2.3.8 shows the predicted yield of crabs that is harvested for various combinations of natural and fishing mortality. If the natural mortality rate is high, then the largest yields are associated with a large fishing effort. If the natural mortality rate is low, the optimum yield is associated with a relatively narrow range of low fishing effort.

Fig. 2.3.9 shows results for eight of the 64 scenarios shown in Table 2.3.3. Scenario 20 gives a very high yield. Scenario 15 gives a yield with little dependence on fishing effort and Scenario 59 needs a relatively narrow range of fishing-effort to result in near-optimum yield. There is a lot of variability from scenario to scenario and each scenario is considered to be equally probable.

One commonality amongst all the scenarios is that yield never increases by more than 5% after reaching R = 12.7 or G = 3.04.

Table 2.3.4 shows the main effects and the second order interactions on $\log_{10}$ of $R_{95\%}$. $R_{95\%}$ increases when:

- The natural mortality rate is low relative to the upper bound estimated from the k-value (indicates that the probability of moulting is high)
- The legal-size limit is higher than the current value.
- A large number of Instar-1 crabs appearing in research traps in a similar unfished area
- There has been a recent increase in the number of recruits..

Other main effects and the interactions are comparatively small.

Table 2.3.4 also shows the main effects and the second order interactions on $G_{95\%}$. A larger fishing effort is necessary to achieve near-maximum yield when:

- The natural mortality rate is high relative to the upper bound estimated from the k-value (indicates that the probability of moulting is high)
- The natural mortality rate and the k-value are both high (an interaction indicating that the probability of moulting is likely low).
- The recent recruitment rate is low
- The recent recruitment rate and the k-value are both high.

Other main effects and interactions are comparatively small.

4. Discussion

Scientific survey data from Vancouver Harbour, Fraser River, and Boundary Bay were used in our assessment models to evaluate the status of recent recruitment and the impact of intensive fishing on Dungeness crabs. Based on the analyses, possible approaches for adjusting the management scheme were proposed.

4.1. The Status of Recent Recruitment

In Boundary Bay and the Fraser River, there is no statistically significant evidence that the number of small crabs, which are vulnerable to the traps, declined between 1995 and 2001. Assuming the smallest crabs in the traps are three years old, these crabs are indicative of recruitment rates between 1992 and 1998. The data does not, however, allow us to compare the recent recruitment rate with a potential rate under reduced exploitation rate. It should also be noted that the analyses are only based on a rather short time-series of data (6 years). The impact of intensive fishing on recruitment is yet to be determined.

The potential impact of losing female crabs due to handling mortality on reproduction potential and yield is not examined in this paper. The timing of the opening of the Fraser fishery coincides with the annual female moult, which normally occurs 1 to 2 months after the major male moult. Females are therefore most vulnerable to injury just as fishing effort is highest. The only compensating feature is that approximately half of the female breeding population is below 130mm and so is not as susceptible to the trap gear as larger crabs. Female crabs remain a component of the bycatch throughout the summer, becoming especially abundant in trap catches in early fall. Near the end of October, the majority of female crabs extrude egg masses and remain relatively inactive and do not feed through the winter months while they incubate their eggs. Female crabs are, therefore, not particularly vulnerable to fishing effects over the winter period.

4.2. Impact of Intensive Fishing on Yield

Two different analyses (length-based and instar-based) looked at the impact of intensive fishing on yield. The length-based analysis uses estimated parameters to calculate yield per recruit, $E_{0.1}$, revenue per recruit, profit per recruit, and to conduct analysis on the consequence for continuing fishing at high ratios of sub-legal to legal sized crabs in the catch. The instar-based analysis uses a systematically-created set of 64 credible scenarios to deal with uncertainty in the parameter values.

An intensive summer fishery on legal-sized male Dungeness crabs exists near Vancouver, British Columbia, with exploitation rates in excess of 90%. Although the length-based yield per-recruit analysis indicates that such a high exploitation rate is needed to produce a high yield, $F_{0.1}$ strategy and profit per recruit analyses indicate that this high fishing level should be reduced.

Earlier theories on population dynamics emphasised the calculation of F_{max}, the level of fishing mortality maximising the average yield from each recruit entering the fishery. In short-lived species, such as Dungeness crabs, yield per recruit analysis often suggests an extremely high fishing mortality in order to achieve the maximum yield. It has been proved that fishing at such a high fishing rate over an extended period of time could deplete the spawning stock and reduce future recruitment (Clarke 1991). In addition, fishing at such a high rate may not be cost effective. In a precautionary approach for fisheries management, F_{max} should not be used as a Target Reference Point (TRP), and may only be regarded as a Limit Reference

Point for the stock (Caddy and Mahon 1995, Quinn and Deriso 1999). In replacement of F_{max}, Gulland and Boerema (1973) proposed to use, as a conservative reference point, $F_{0.1}$, which is the fishing mortality rate at which the slope of the yield per recruit curve as a function of fishing mortality is 10% of its value at the origin. The $F_{0.1}$ measure, although arbitrary, often appears to be in the right ball park (Hilborn and Walters 1992). It is, in a sense, a bioeconomic criterion in that a marginal yield of less than 10% was felt to be close to the point at which most fisheries administrators would consider further increases in fishing mortality or effort to be no longer economically worthwhile (FAO 1993). Indeed, our analysis on profit per recruit indicates that fishing with a very high exploitation rate is not cost effective. The $F_{0.1}$ strategy also reduces the chance of recruitment overfishing, as Deriso (1987) showed that for a broad range of models of stock dynamics that $F_{0.1}$ policy does not unduly reduce the spawning abundance. $F_{0.1}$ is now recommended to be used as a TRP (Caddy and Mahon 1995, Quinn and Deriso 1999). $E_{0.1}$, an exploitation rate equivalent to the instantaneous fishing rate of $F_{0.1}$, was calculated to be around 63% for the Dungeness crab population, suggesting that an exploitation rate could be reduced to 63%.

The shape of revenue per recruit relies on the price for different sizes of crabs. When higher prices are paid for larger crabs, smaller exploitation rate should be applied. Revenue per recruit does not practically increase beyond an exploitation rate of about 90%, when large crabs (>=170 mm in CW) are valued at twice the price paid for smaller legal sized crabs. As cost increases with fishing effort, profit actually drops for high exploitation rates. If the same price is paid for all crabs, the highest profit per recruit occurs for an exploitation rate of approximately 68%. If the price doubles for crabs larger than 170 mm in CW, the optimum exploitation rate is around 64%. It is, therefore, likely to be more profitable to have the current exploitation rate reduced. This would also reduces the chance of recruitment overfishing and reduces the mortality on sub-legal sized crabs, especially crabs of slightly smaller than the legal size. When a large fraction of legal sized crabs have been caught in an intensive fishery, great reduction in catch rate for the legal sized crabs might cause some of the crabs of 150-155 mm in CW to be illegally kept to "compensate" for the reduction in profit. Based on the scientific surveys in the Boundary Bay, the number of captured crabs between 150 and 155 mm in CW is only 64.7% of the number of captured crabs between 145 and 150 mm in CW. The scientific surveys in Vancouver Harbour shows that the number of captured crabs between 150 and 155 mm in CW is 104.5% of the number of captured crabs between 145 and 150 mm in CW.

Continuing fishing at a high ratio of sub-legal to legal sized crabs in the catch will result in a net loss in yield in the long-term, as some sub-legal sized crabs will die of handling mortality and could not contribute to the future yield. Fishing at lower ratios is necessary to generate more yield in the long-term. The threshold for such a ratio depends on the handling mortality rate, which is yet to be estimated based on future studies. If we assume the handling mortality rate is 10%, fishing should not continue, when the ratio of sub-legal to legal sized crabs approaches 9.5 in the catch.

Incidence of damage may be used to indicate the magnitude of fishing related mortality. The overall injury rate in the fished area (Fraser River) amounted to approximately 19% for males and 15% for females, while the injury rates in Vancouver Harbour were 7% for both males and females. This clearly shows a handling effect on both male and female crabs. Some studies have been undertaken in an attempt to quantify crab (and other crustacean) mortality resulting from repeated handling (Murphy and Kruse 1995; Kruse et al 1994). They failed to take into account sub-lethal effects such as shell conditions, size, cannibalism and predation within the trap on the bottom and resulted in inconclusive results. To investigate the handling mortality we need to consider these effects, which are probably cumulative and may only appear at some critical stages in the crabs life history, such as moulting or breeding.

The approach, used with the instar-model, is to consider a range of parameter values that are consistent with the range of observations. No conclusions are made unless they apply to the entire range of parameter values. The sixty-four scenarios represent a range of possible parameter values. In none of these scenarios was yield increased by more than 5% by harvesting after 12.68 sublegals were appearing in the traps for every legal-sized crab. This ratio is another useful limit reference point. If 12.68 sublegals were appearing in the traps for every legal-sized crab, then the season is probably already too long.

The 64 scenarios indicate that the natural mortality rate (relative to the k-value and the probability of moulting) is the most important of the parameters for determining when the crab fishery has almost reached the long-term maximum yield per recruit. Methods of estimating natural mortality and the probability of moulting from CPUE are presented in the length-based analyses, although the degree of reliability of using CPUE as an abundance index is unknown.

It should be noted that the analyses have not considered all the possible biological consequences of an intensive crab fishery. For example, Smith and Jamieson 1991b postulate that the intense harvests may harm the reproductive capacity of the crab stock. The intense harvest may affect species that are predators or prey to the large crabs resulting in complex ecological considerations. However, if there is no economic benefit to continuing the harvest, then there is no justification for accepting the biological risks (however small they may be) of continuing the season.

4.3. Approaches for Management Action

If the managers decide to reduce the exploitation rate, they could determine when to close the fishery based on a target level of reduction in CPUE from the initial level. As the fishing mortality is very high in comparison to natural mortality during the fishing season (summer-fall), the ratio of CPUE during the fishing period to the CPUE at the beginning of the fishing season reflects the percentage of the harvestable crabs that have been caught. For instance, if the exploitation rate is to be reduced to 70%, the fishery is to be closed when the reduction in CPUE relative to the CPUE at the beginning of the fishery is 70%. Based on the rapid reduction in CPUE (see Fig. 2.2.7), this means the fishery is probably to be closed within one month after opening the fishery.

If the managers want to introduce handling mortality into the mechanism of the fishery management, they could set a target level based on the ratio of catching sub-legal to legal crabs, at which the marginal gain is zero. This relies greatly on the knowledge of the handling mortality rate, i.e. the higher this mortality rate, the lower the ratio target level should be set. For example if the mortality rate is 10%, the target ratio would be 10:1; if the mortality rate is 20%, then the target ratio is 5:1.

The instar-analysis identifies four factors that make a crab population vulnerable to overfishing. Presumably these four factors are the same ones that make under-sized crabs vulnerable to handling mortality in an intense fishery. Of these four parameters, two (handling mortality and the number of sublegal crabs in the traps) can be managed. It should be noted that industry and managers have a number of options to manage problems like handling mortality. They could close the fishery when the target ratio is met or exceeded, close the season when there are a large number of softshell crabs present, increase the size of escape rings, and increase soak hours.

5. Recommendations

1) The current exploitation rate (> 90% should be reduced to 65-75%. A level of reduction in *CPUE* relative to the *CPUE* at the beginning of the fishery could be used to determine when to close the fishery.

2) A ratio of retained crabs to discards should be used as a means of limiting effort and protecting stocks in conjunction with using *CPUE* measures or in fisheries where it is difficult to use CPUE because of protracted moulting seasons.

3) Efforts should be made to reduce the negative handling impacts. Tools may include longer soak times, earlier closure of the fishery or adjustment of the fishing season.

4) Industry, management and science should use these models to assist in assessing the impact of intensive fishing on population dynamics, economic and social benefits for each fishery and in finding optimal management and assessment schemes.

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Table 2.1.1. Analysis of variance is used to determine if year is a good indicator of CPUE. The following table shows the resulting p-values.

			P-value	
	Month	Shell	Females	SubLegal Males
Boundary Bay	June	New	0.257794	0.23497
		Old	**<.01**	0.18512
	October	New	0.06974	0.283416
		Old	0.147085	0.291538
Fraser River	June	New	**<.01**	0.912064
		Old	**<.01**	0.82161
	October	New	0.920144	0.06633
		Old	0.869744	0.628751

Table 2.2.1. Survey months and number of sampled Dungeness traps in the Vancouver Harbour (the number in the brackets indicates the number of sets)

			Month			
Year	Feb.	Mar.	Apr.	June	Sept.	Oct.
1991	30 (3)					
1993					10 (1)	
1994				6 (1)		20 (2)
1995				27 (3)		21 (2)
1996				33 (3)		41 (3)
1997				30 (3)		29 (3)
1998			103 (10)	60 (6)		52 (5)
1999		65 (5)		62 (5)		69 (7)
2000	63 (6)			60 (6)		69 (7)
2001	342 (31)					

Table 2.2.2. Instantaneous Annual Natural Mortality Rate (M) between June and October for the Legal Sized Male Crabs in the Vancouver Harbour

Year	Catch		Number of Sets		Standardised Effort		Standardised CPUE		M
	June	October	June	October	June	October	June	October	
1994	128	84	1	2	34.14	111.8	3.75	0.75	2.094
1995	134	74	3	2	153.09	120.09	0.88	0.62	0.457
1996	209	216	3	3	183.64	229.19	1.14	0.94	0.246
1997	239	93	3	3	168.3	162.4	1.42	0.57	1.183
1998	360	325	6	5	336.13	293.84	1.07	1.11	-0.042
1999	584	266	5	7	308.73	219.84	1.89	1.21	0.582
2000	490	282	6	7	275.37	221.42	1.78	1.27	0.436

Table 2.2.3. Proportion of moulting for different width classes

Year	Carapace Width Class (mm)												
	[130, 135)	[135, 140)	[140, 145)	[145, 150)	[150, 155)	[155, 160)	[160, 165)	[165, 170)	[170, 175)	[175, 180)	[180, 185)	[185, 190)	[190, 195)
1995	1	1	1	1	0.6815	0.7452	0.6245	0.5541	0.18464	0.86411	0.38848	N/A[1]	1
1996	1	1	1	0.91703	0.94296	-0.21687	0.48663	0.51325	0.54367	0.57052	0.5741	0.08735	N/A[1]
1997	1	1	0.97323	1	0.86425	0.77194	0.89441	0.71694	0.3089	0.75477	0.36649	1	N/A[1]
1998	0.93257	1	1	0.98178	0.9535	0.60336	0.67752	0.59543	0.6254	0.40064	-0.01143	-0.01143	1
1999	1	0.90512	0.86018	0.95715	0.54558	0.80561	0.21664	0.33585	0.22997	0.14609	0.14609	-0.43048	-0.10692
2000	0.94936	0.77716	0.88858	0.91204	0.61004	0.71553	0.52647	0.38101	0.49356	0.5336	0.71247	0.78778	0.7524
MCW[2]	132.5	137.5	142.5	147.5	152.5	157.5	162.5	167.5	172.5	177.5	182.5	187.5	192.5
p[3]	0.980322	0.947047	0.953665	0.961333	0.766305	0.570795	0.571028	0.516097	0.39769	0.544955	0.3627	0.286644	0.66137

1 -- No catch of crabs in this width class in the October, so the proportion can not be calculated.
2 -- Mid carapace width for the width class
3 -- Mean proportion of moulting

Table 2.2.4. Estimations of Dungeness Crab Population Parameters

Parameter	Model	Symbol	Estimation	Condition
Instantaneous Annual Natural Mortality Rate during the period of non-moulting		M	0.5	
Survival Rate during the Month following Molting		s	0.63	
Proportion of Molting (p)	$p = a*MCW+b$	a	-0.001	MCW < 150 mm
		b	1.1016	
		a	-0.0103	MCW > 150 mm
		b	2.2507	
Vulnerability Coefficient (v)	$v = 1-b*(157.5-MCW)$	b	0.037	$130 <= MCW$ < 155 mm
		b	0	MCW >= 155 mm
Carapace Width and Weight (w) Relationship	$w = a*\mathrm{MCW}^b$	a	0.0001	
		b	3.0957	
Catch Per Trap (CPT) and Soak Hour (t) Relationship	$CPT = CPT_L*(1-\exp(k*t))$	CPT_L	14.62	
		k	0.19	

MCW -- mid carapace width of the width class in mm

Table 2.2.5. Ratio of caught sub-legal to legal male crabs from scientific surveys in Fraser Delta in 1995-2001

Season	Total Number	Number of Sub-Legal Males	Number of legal Males	Ratio (Sub-legal:Legal)
spring (pre-fishery)	26003	13262	12741	1.04089161
fall (post-fishery)	7640	7168	472	15.18644068

Table 2.2.6. Ratio of caught sub-legal males and females to legal male crabs from Commercial Samples in Fraser River in 1995

Month	Number Sampled	Number of Sub-legals & Females	Number of Legal Males	Ratio
June	1433	631	802	0.786783042
July	1568	907	661	1.372163389
Aug	968	717	250	2.868
Sept	828	613	215	2.851162791
Oct	199	180	19	9.473684211

Table 2.3.1.

Yield Per Recruit. M=.5, k=.95, ObsRat=.25, v=0.211, Pmolt=0.913,G=-log(.02)

		Newshell Sublegal-sized crabs	Oldshell Sublegal-sized crabs	Newshell Legal-sized crabs	Oldshell Legal-sized crabs	Total
Zero Handling Mortality	Number of Crabs	0.24265	0.00025	0.37992	0.00460	0.62742
	Weight (grams)	168.162	0.17701	304.581	3.69476	476.6148
Ten percent handling mortality	Number of Crabs	0.24265	0.00025	0.34998	0.00424	0.59712
	Weight (grams)	168.162	0.17701	280.641	3.40435	452.3844

Table 2.3.2 Parameter values used to define the 64 scenarios.

Parameter	Description	Low-value	High-Value	Comments
k	Fraction of small crabs that are new shell	0.55 The theoretical lower limit is 0.5	0.95 The maximum possible value is 1.0	
Obs	The ratio the number of observed members for Instar-1 and Instar 2	0.25 The value June in the spring surveys of Vancouver Harbour	1.0 The value observed in the October surveys of Vancouver Harbour	
M	The instantaneous natural mortality rate	.05 * log(k/(1-k))	.95 * log(k/(1-k))	log(k/(1-k)) is the theoretical upper limit
h	The probability that catch-and release of a sublegal-sized crab will result in death	.05	.50	The approximate range discussed in Tegelbert
Minimum Harvest Size (mm)	Notch Width	155 The current size limit	165 Approximately 95% of Instar-1 crabs are smaller than this size.	
N_{newsub}	The number of crabs to moult into Instar-1 in the current year	0.5 Corresponds to a year of low recruitment (Year-1, newshell)	2.0 Corresponds to a year of high recruitment (Year-1, newshell)	A value of 1.0 would correspond to a constant recruitment rate.
v	Relative vulnerability of small crabs to the traps.			Calculated from equation 4© in the appendix.
P_{molt}	The probability a newshell, Instar-1 crab will moult.			Calculated from equation 2 in the appendix.

Table 2.3.3 Parameter-values used in the Scenarios

Scenario	Natural Mortality	Handling Mortality	Obs	Minimum Harvest Size	k	Number of Instar-1 Crabs	Vulnerability of Small Crabs*	Probability of Molting*
1	0.010	0.050	0.250	155	0.550	0.500	0.047	0.17
2	0.191	0.050	0.250	155	0.550	0.500	0.002	0.01
3	0.010	0.500	0.250	155	0.550	0.500	0.047	0.17
4	0.191	0.500	0.250	155	0.550	0.500	0.002	0.01
5	0.010	0.050	1.000	155	0.550	0.500	0.188	0.17
6	0.191	0.050	1.000	155	0.550	0.500	0.008	0.01
7	0.010	0.500	1.000	155	0.550	0.500	0.188	0.17
8	0.191	0.500	1.000	155	0.550	0.500	0.008	0.01
9	0.010	0.050	0.250	165	0.550	0.500	0.047	0.17
10	0.191	0.050	0.250	165	0.550	0.500	0.002	0.01
11	0.010	0.500	0.250	165	0.550	0.500	0.047	0.17
12	0.191	0.500	0.250	165	0.550	0.500	0.002	0.01
13	0.010	0.050	1.000	165	0.550	0.500	0.188	0.17
14	0.191	0.050	1.000	165	0.550	0.500	0.008	0.01
15	0.010	0.500	1.000	165	0.550	0.500	0.188	0.17
16	0.191	0.500	1.000	165	0.550	0.500	0.008	0.01
17	0.147	0.050	0.250	155	0.950	0.500	0.359	0.94
18	2.797	0.050	0.250	155	0.950	0.500	0.002	0.14
19	0.147	0.500	0.250	155	0.950	0.500	0.359	0.94
20	2.797	0.500	0.250	155	0.950	0.500	0.002	0.14
21	0.147	0.050	1.000	155	0.950	0.500	1.434	0.94
22	2.797	0.050	1.000	155	0.950	0.500	0.008	0.14
23	0.147	0.500	1.000	155	0.950	0.500	1.434	0.94
24	2.797	0.500	1.000	155	0.950	0.500	0.008	0.14
25	0.147	0.050	0.250	165	0.950	0.500	0.359	0.94
26	2.797	0.050	0.250	165	0.950	0.500	0.002	0.14
27	0.147	0.500	0.250	165	0.950	0.500	0.359	0.94
28	2.797	0.500	0.250	165	0.950	0.500	0.002	0.14
29	0.147	0.050	1.000	165	0.950	0.500	1.434	0.94
30	2.797	0.050	1.000	165	0.950	0.500	0.008	0.14
31	0.147	0.500	1.000	165	0.950	0.500	1.434	0.94
32	2.797	0.500	1.000	165	0.950	0.500	0.008	0.14
33	0.010	0.050	0.250	155	0.550	2.000	0.047	0.17
34	0.191	0.050	0.250	155	0.550	2.000	0.002	0.01
35	0.010	0.500	0.250	155	0.550	2.000	0.047	0.17
36	0.191	0.500	0.250	155	0.550	2.000	0.002	0.01
37	0.010	0.050	1.000	155	0.550	2.000	0.188	0.17
38	0.191	0.050	1.000	155	0.550	2.000	0.008	0.01
39	0.010	0.500	1.000	155	0.550	2.000	0.188	0.17
40	0.191	0.500	1.000	155	0.550	2.000	0.008	0.01
41	0.010	0.050	0.250	165	0.550	2.000	0.047	0.17
42	0.191	0.050	0.250	165	0.550	2.000	0.002	0.01
43	0.010	0.500	0.250	165	0.550	2.000	0.047	0.17
44	0.191	0.500	0.250	165	0.550	2.000	0.002	0.01
45	0.010	0.050	1.000	165	0.550	2.000	0.188	0.17
46	0.191	0.050	1.000	165	0.550	2.000	0.008	0.01
47	0.010	0.500	1.000	165	0.550	2.000	0.188	0.17
48	0.191	0.500	1.000	165	0.550	2.000	0.008	0.01
49	0.147	0.050	0.250	155	0.950	2.000	0.359	0.94

50	2.797	0.050	0.250	155	0.950	2.000	0.002	0.14
51	0.147	0.500	0.250	155	0.950	2.000	0.359	0.94
52	2.797	0.500	0.250	155	0.950	2.000	0.002	0.14
53	0.147	0.050	1.000	155	0.950	2.000	1.434	0.94
54	2.797	0.050	1.000	155	0.950	2.000	0.008	0.14
55	0.147	0.500	1.000	155	0.950	2.000	1.434	0.94
56	2.797	0.500	1.000	155	0.950	2.000	0.008	0.14
57	0.147	0.050	0.250	165	0.950	2.000	0.359	0.94
58	2.797	0.050	0.250	165	0.950	2.000	0.002	0.14
59	0.147	0.500	0.250	165	0.950	2.000	0.359	0.94
60	2.797	0.500	0.250	165	0.950	2.000	0.002	0.14
61	0.147	0.050	1.000	165	0.950	2.000	1.434	0.94
62	2.797	0.050	1.000	165	0.950	2.000	0.008	0.14
63	0.147	0.500	1.000	165	0.950	2.000	1.434	0.94
64	2.797	0.500	1.000	165	0.950	2.000	0.008	0.14

*Calculated from other variables.

Table 2.3.4(a) Effects of the independent parameters on $R_{95\%}$

	M	h	Obs	Minimum Harvest Size	k	Nnewsub
M	-0.71	0.11	0.07	0.17	0.15	0.07
h		-0.12	-0.03	-0.01	-0.05	0.02
Obs			0.52	-0.01	-0.03	0.01
Minimum Harvest Size				0.55	-0.03	0.03
k					0.20	0.13
Nnewsub						-0.40

Table 2.3.4(b) Effects of the independent parameters on $G_{95\%}$

	M	h	Obs	Minimum Harvest Size	k	Nnewsub
M	1.16	0.18	0.11	0.04	0.80	-0.17
h		-0.18	-0.03	-0.03	-0.08	0.04
Obs			-0.12	-0.02	-0.04	0.03
Minimum Harvest Size				-0.02	0.01	0.11
k					0.37	0.49
Nnewsub						-0.64

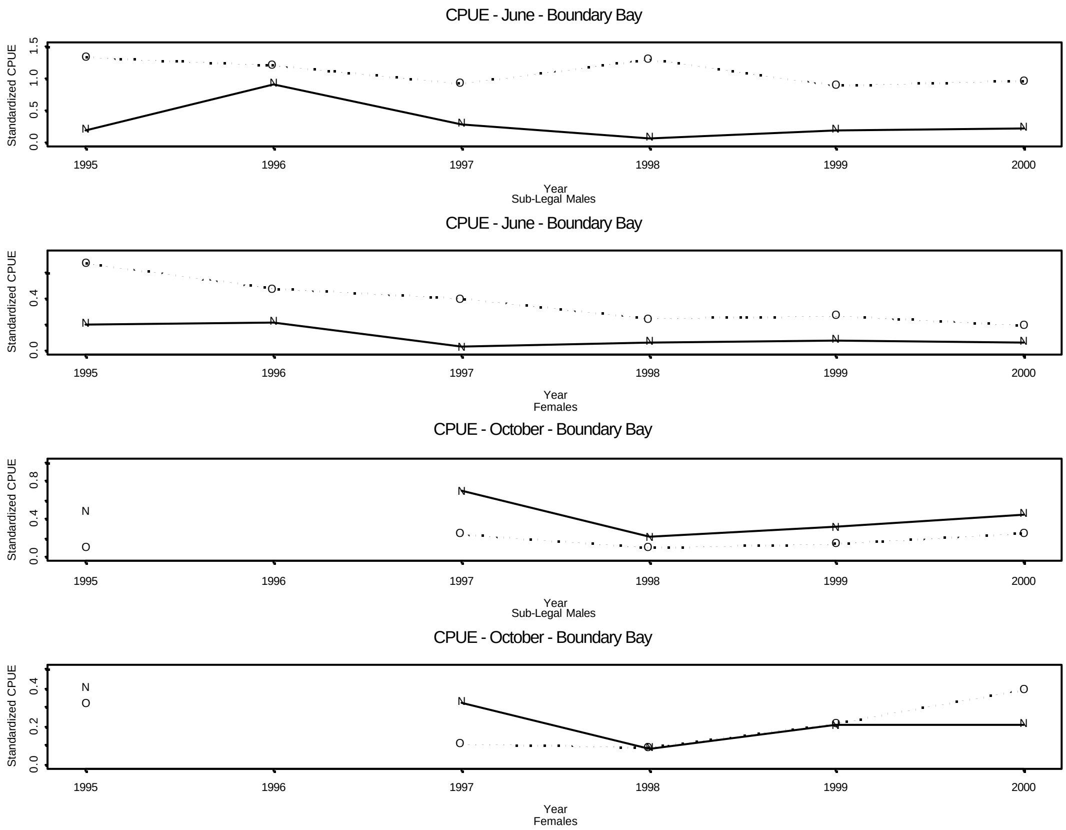

Fig. 2.1.1. Standardised CPUE for Boundary Bay and Fraser River delta. (Scientific traps).

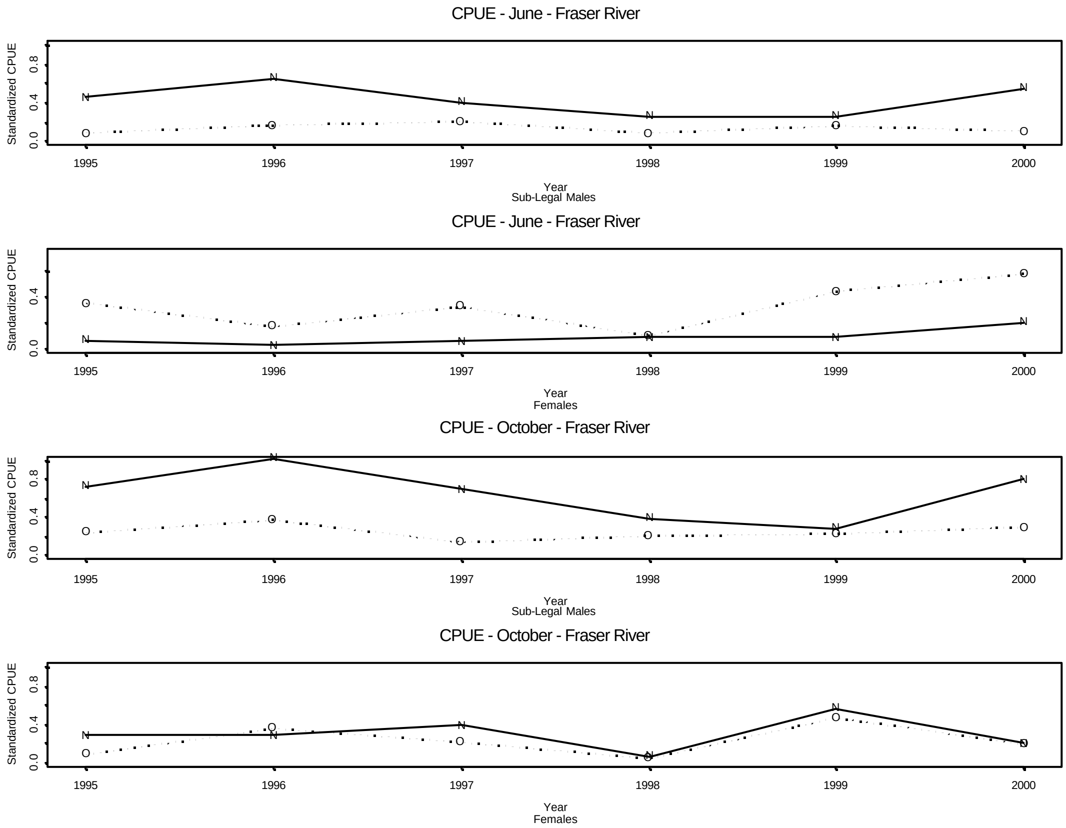

Fig. 2.1.1 Continued

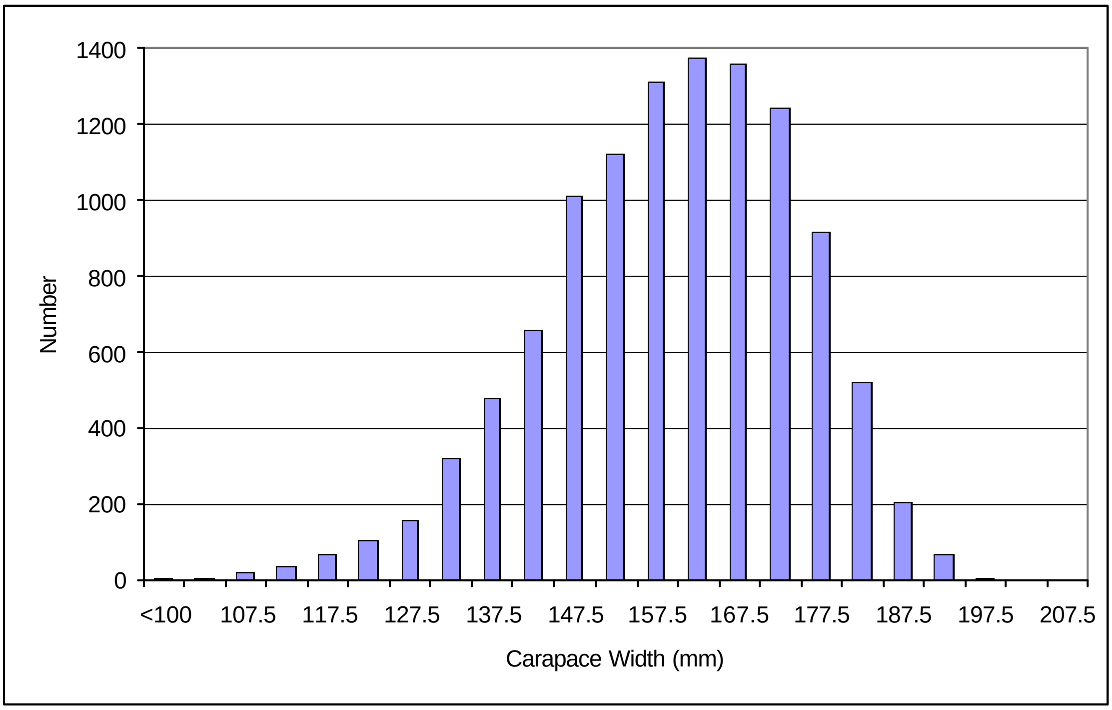

Fig. 2.2.1. Size Frequency Distribution for Male Dungeness Crabs Caught in All the Surveys from Vancouver Harbour.

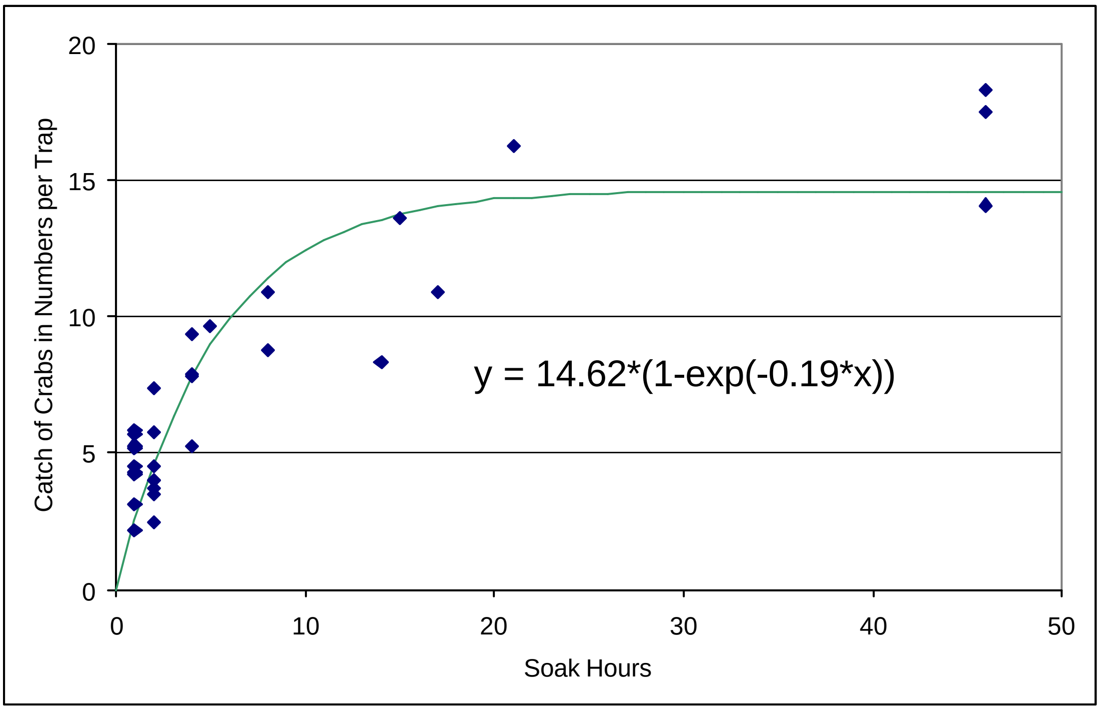

Fig. 2.2.2. Effect of Soak Hour on the Dungeness Crab Catch Rate.

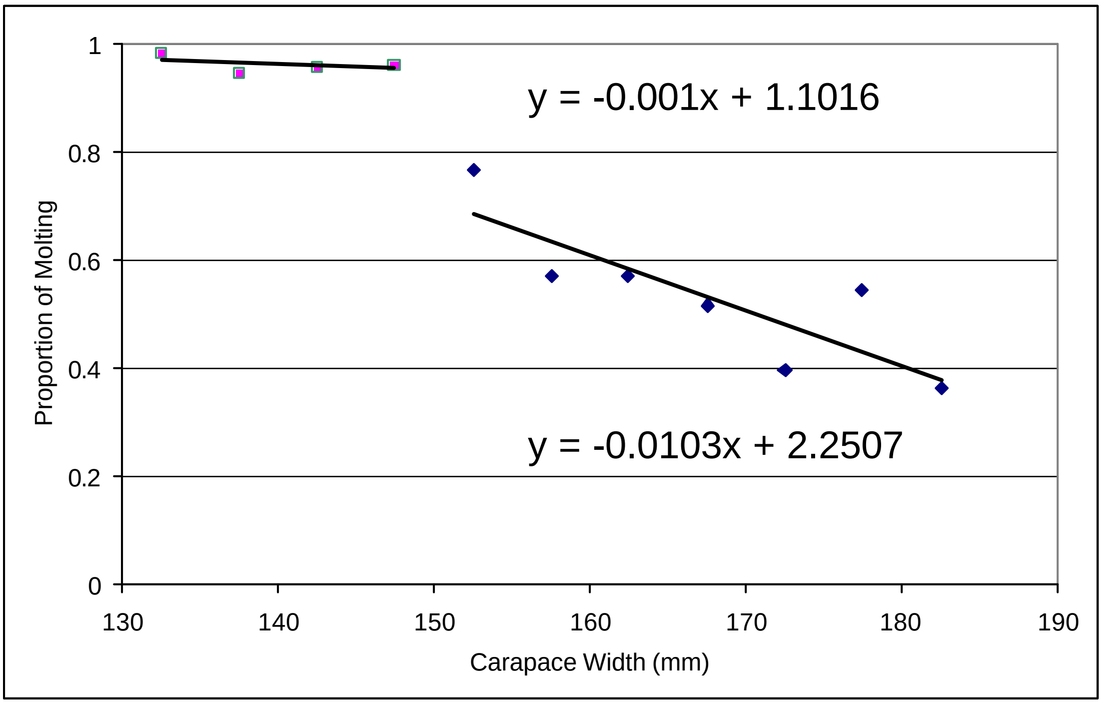

Fig. 2.2.3. Decrease in proportion of molting with crab size.

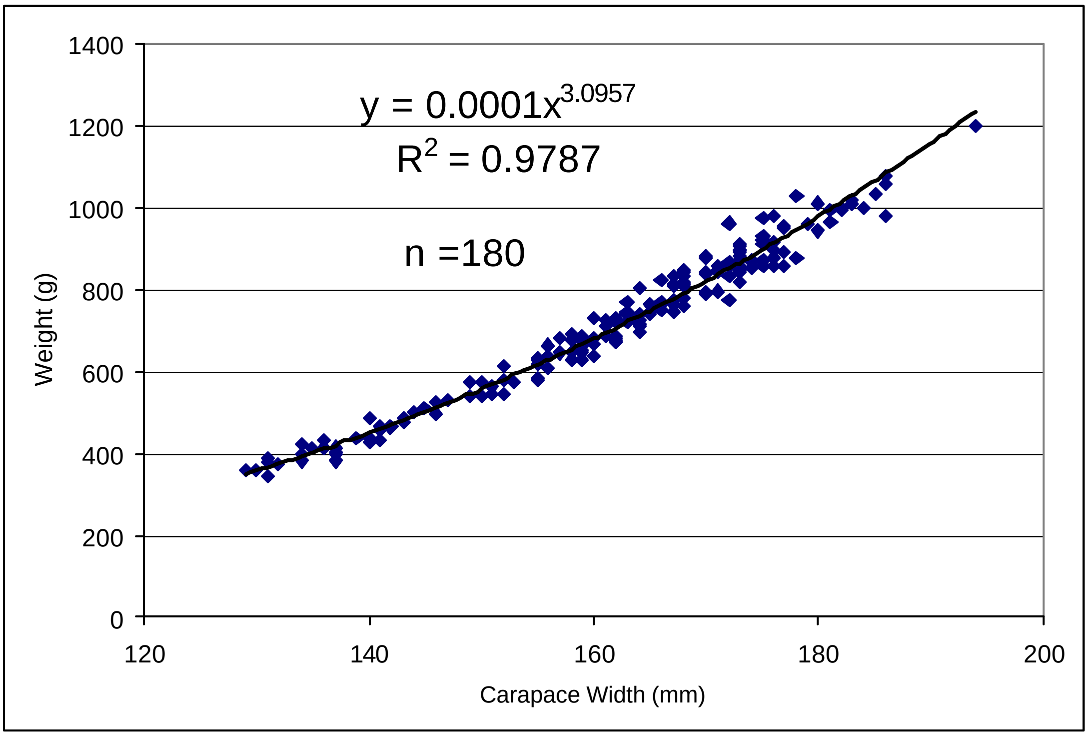

Fig. 2.2.4. Carapace Width and Weight Relationship

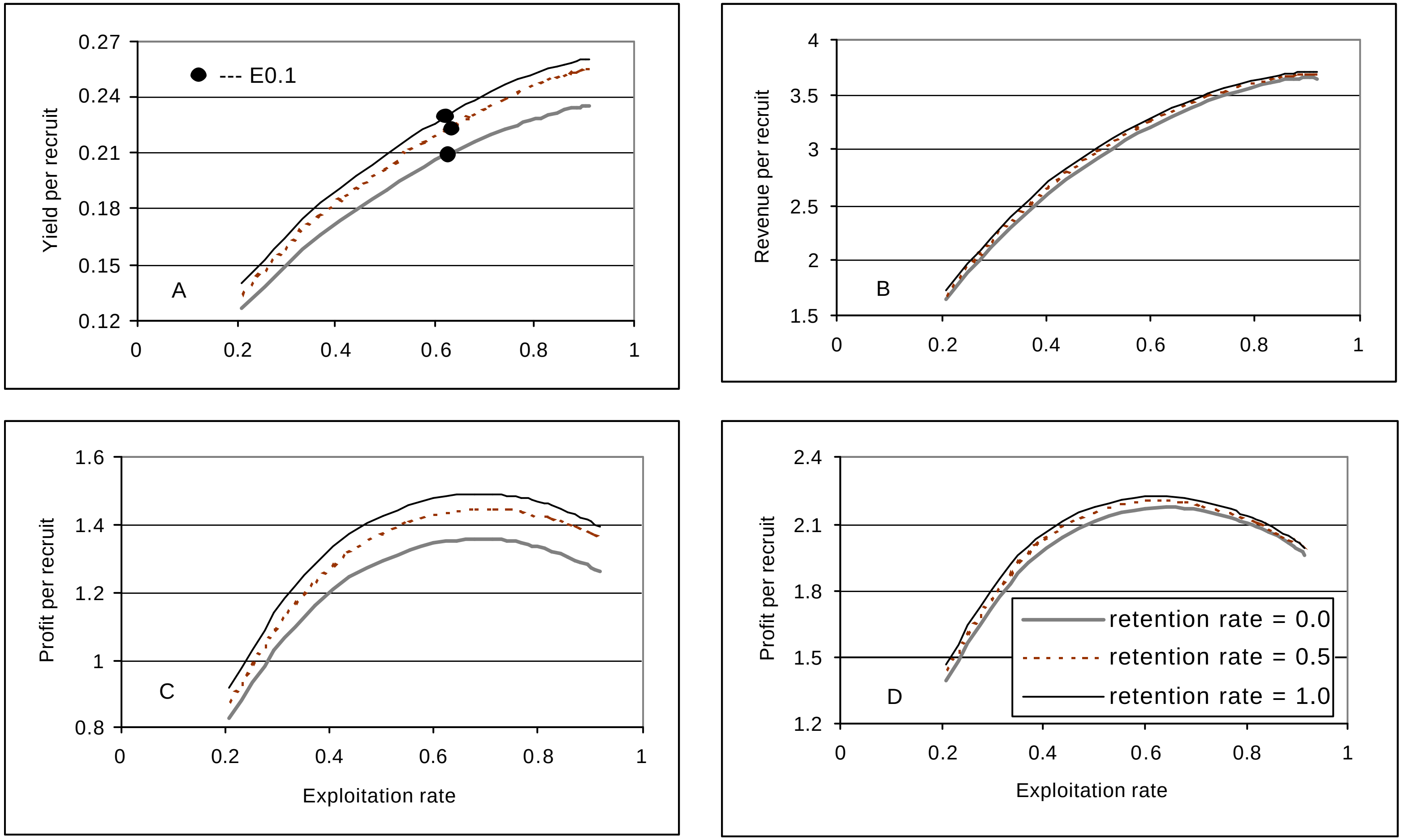

Fig. 2.2.5. Yield, Revenue and Profit per Recruit at the three different retention rate for crabs of 155-160 mm in CW.
(A -- Yield per recruit and E0.1; B -- Revenue per recruit; C -- Profit per recruit with same sale price; D -- Profit per recruit with higher price for larger crabs)
(per recruit means one crab spreading among the five sub-legal width classes)

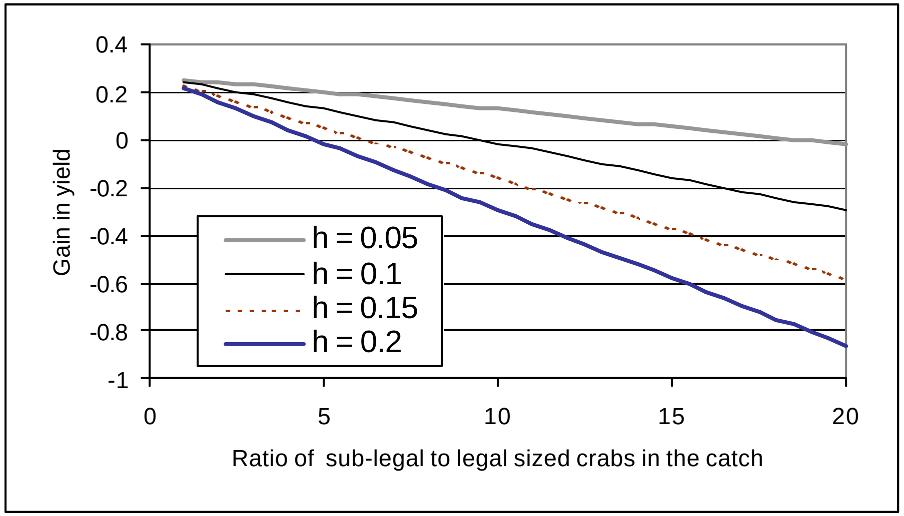

Fig. 2.2.6. Gain in Yield in Long-term for Catching One More Legal Crab at Various Ratios of Sub-legal to Legal Crabs in the Catch.

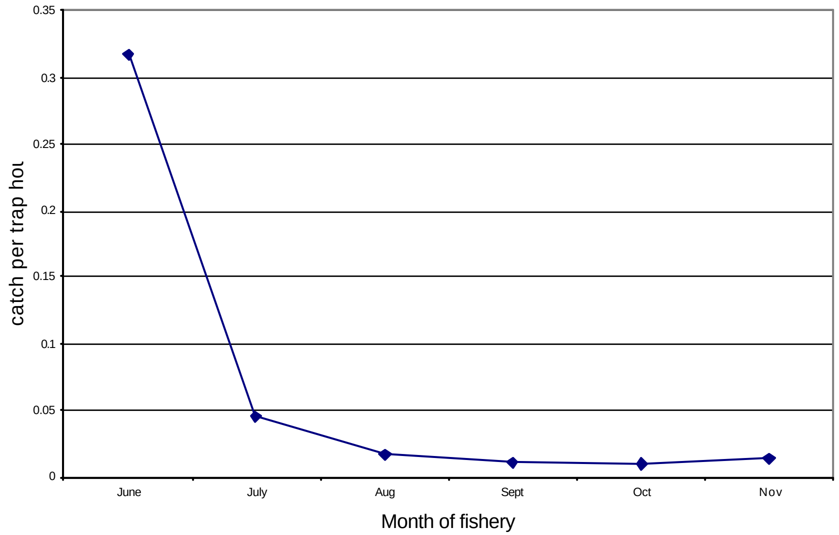

Fig. 2.2.7. Catch per Trap Hour of Legal Sized Male Crabs from 2001 Commercial Harvest Logs.

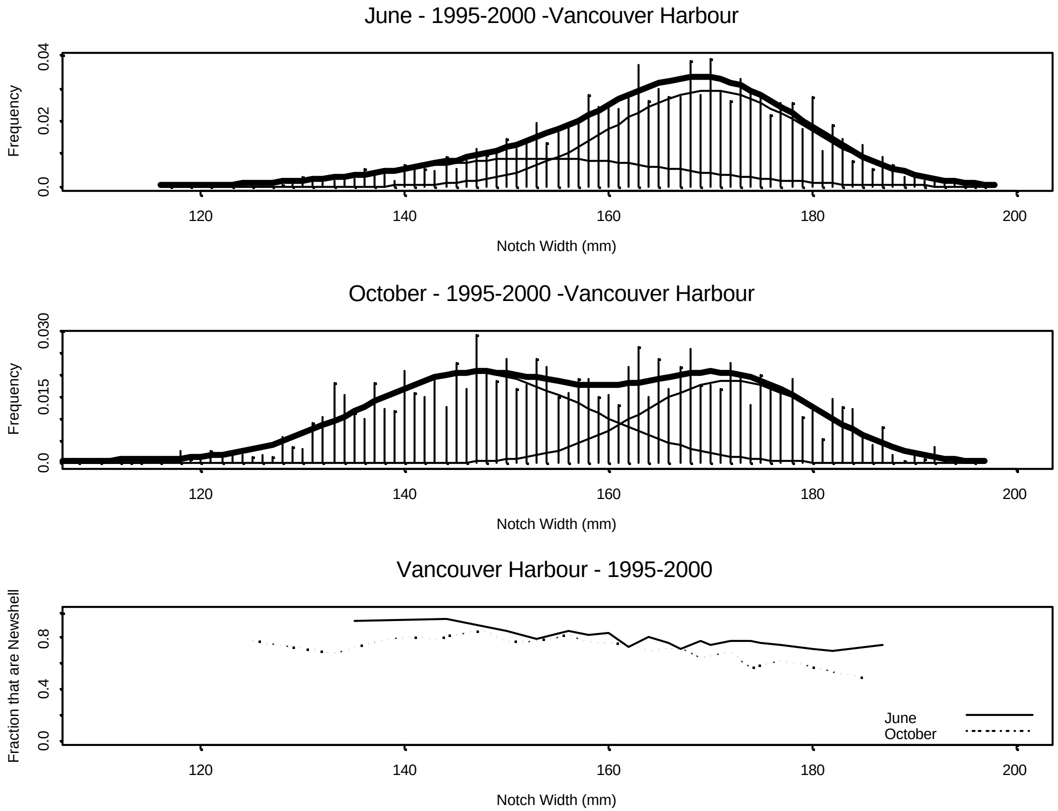

Figure 2.3.1. Male Crabs Captured in Vancouver Harbour.

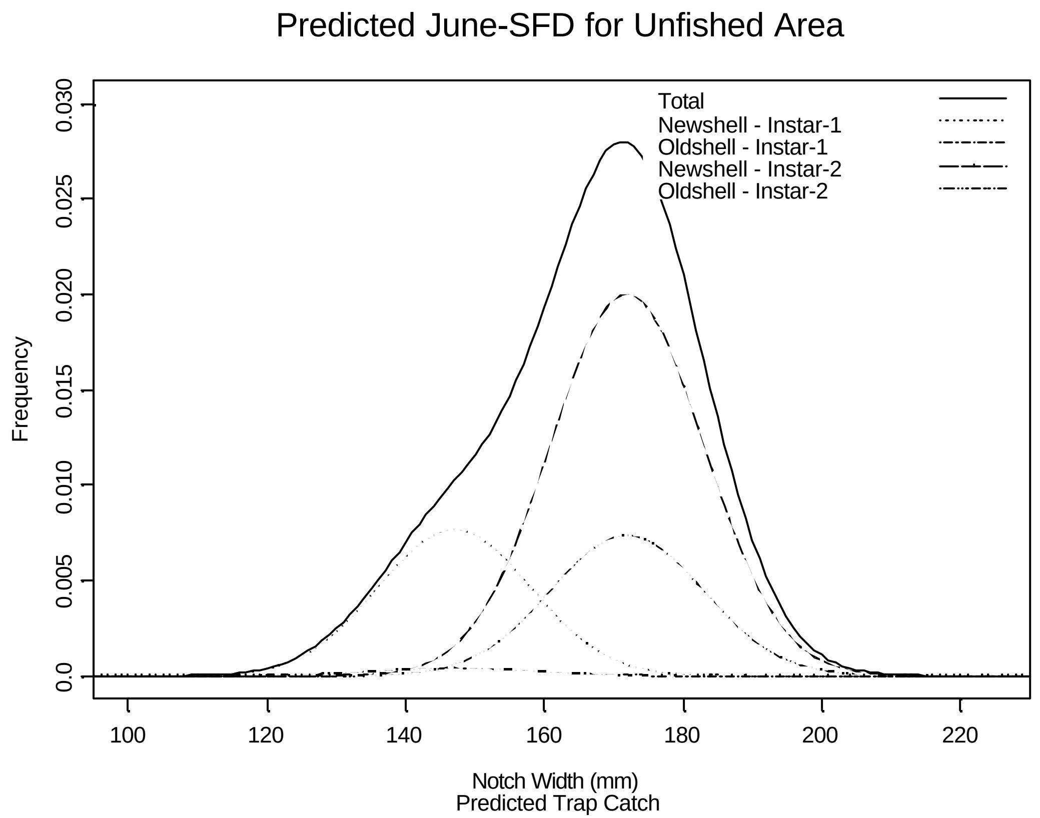

Figure 2.3.2 Predicted June SFD for Vancouver Harbour.

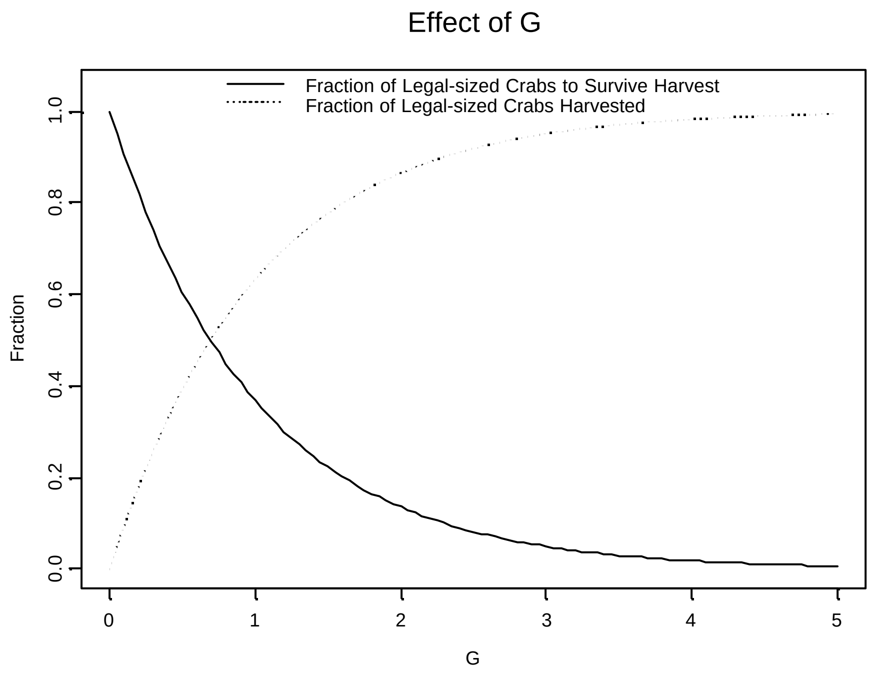

Figure 2.3.3. The effect of G on the Fraction of Legal-sized Crabs to Survive Harvest.

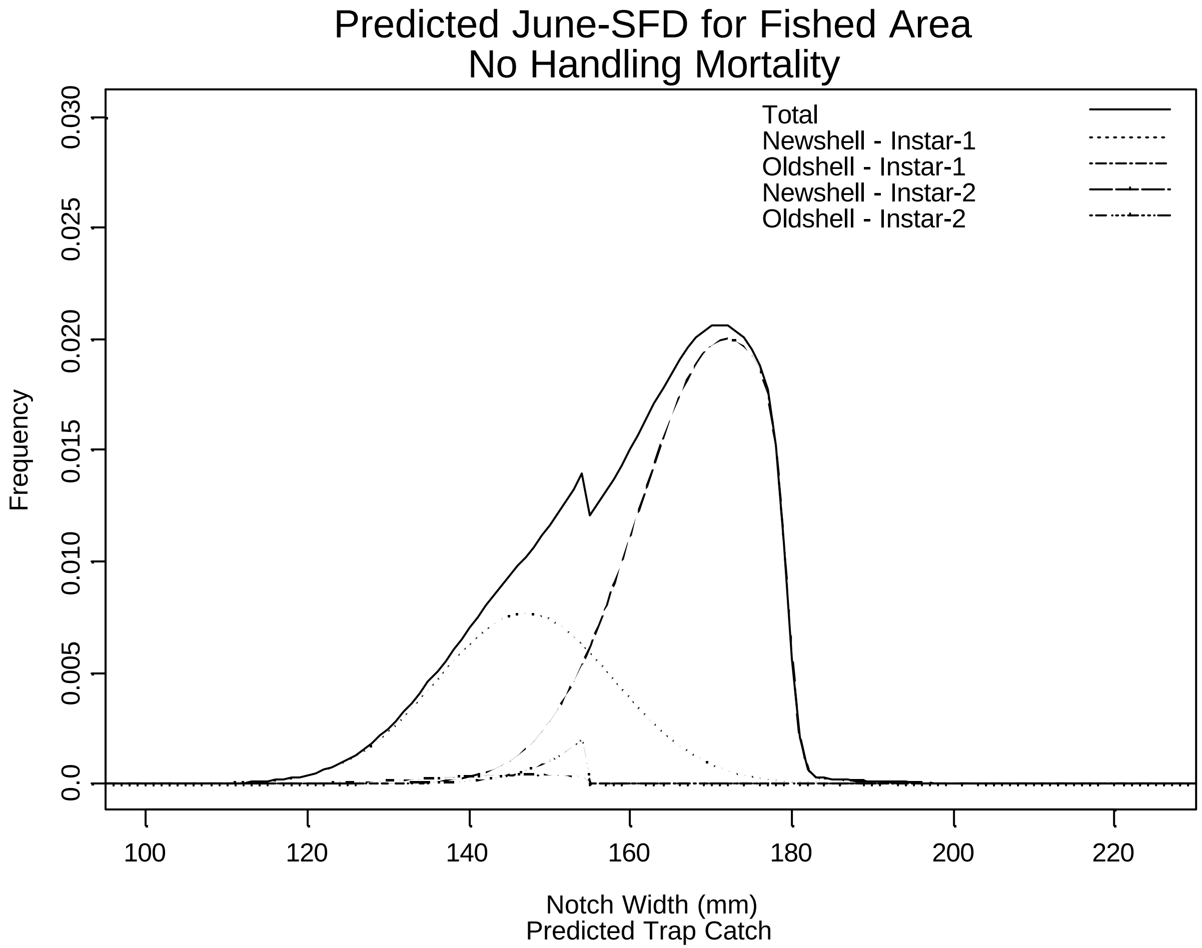

Figure 2.3.4. The Predicted Size Frequency Density when Vancouver Harbour is subjected to an Intense Harvest. No Handling Mortality.

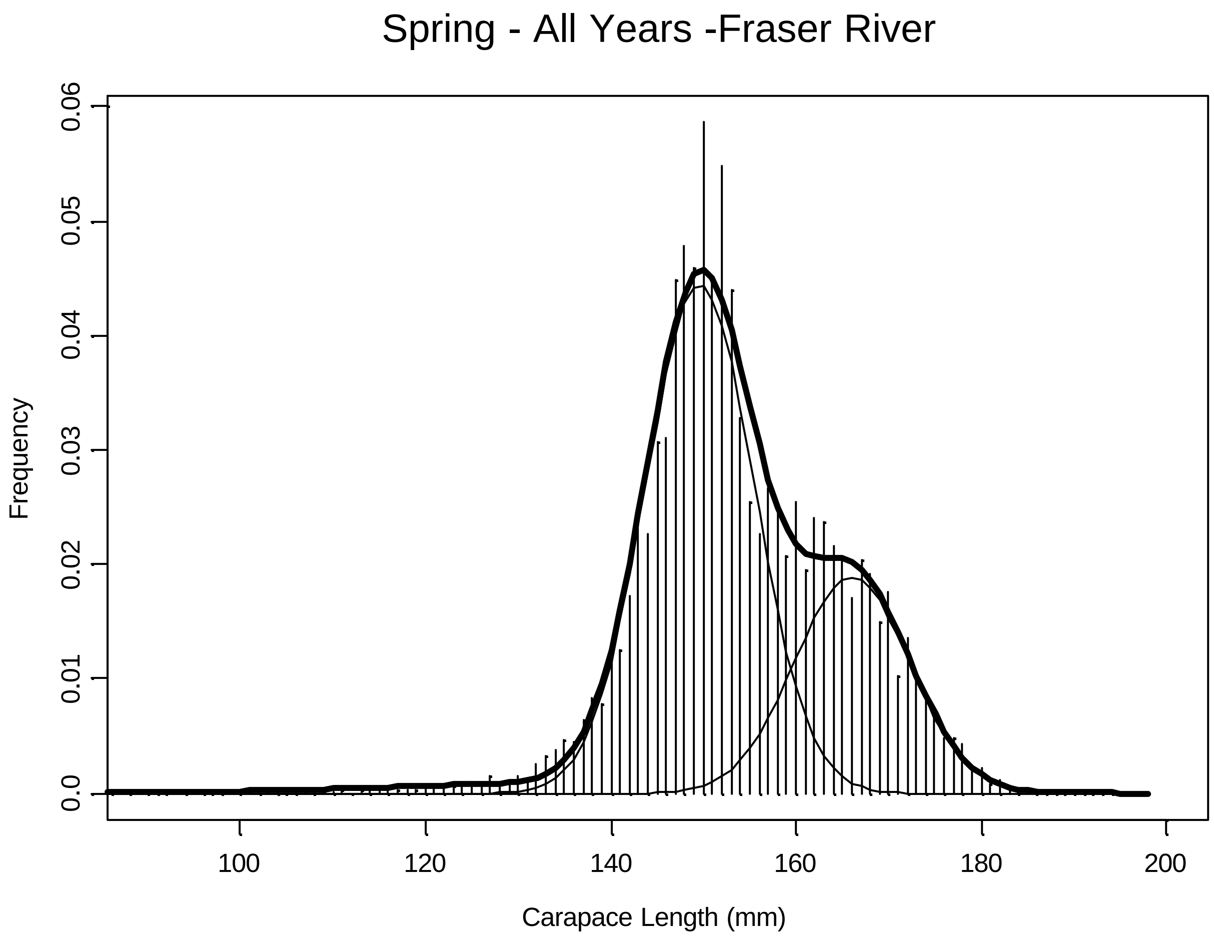

Figure 2.3.5. Size Frequency Density in an Intensely Harvested Area.

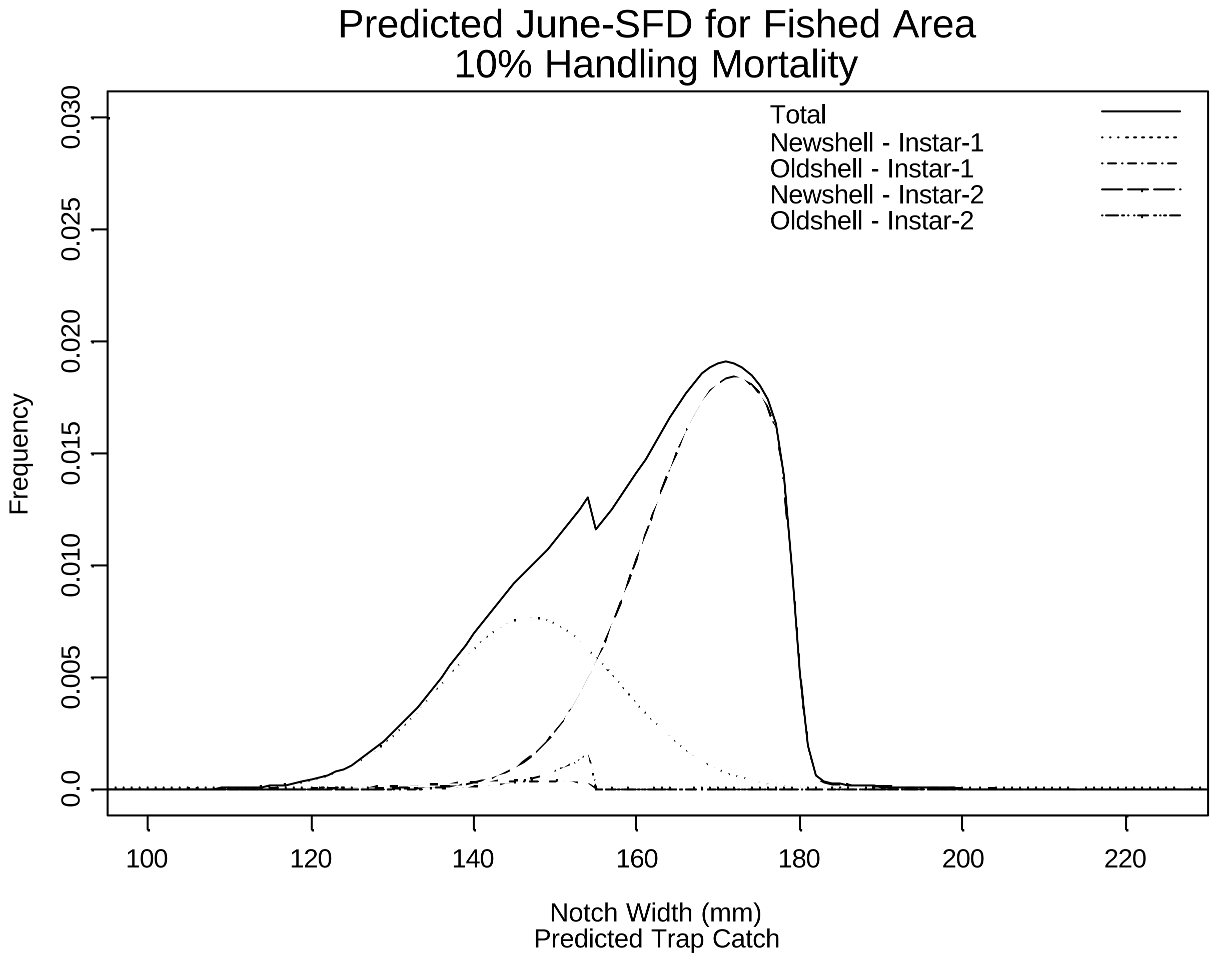

Figure 2.3.6. The Predicted Size Frequency Density when Vancouver Harbour is subjected to an Intense Harvest. Handling Mortality Occurs.

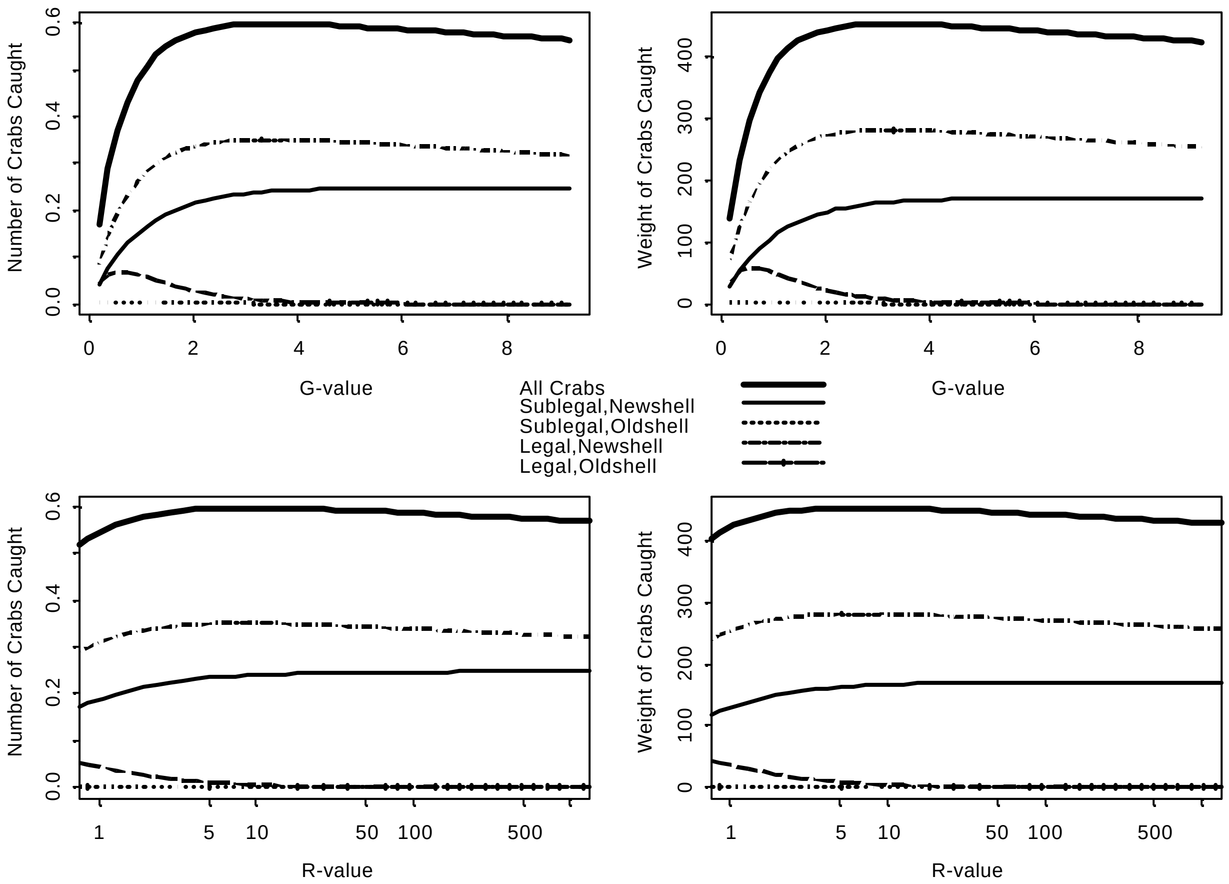

Figure 2.3.7. The Impact of Harvest Effort on Predicted Yield

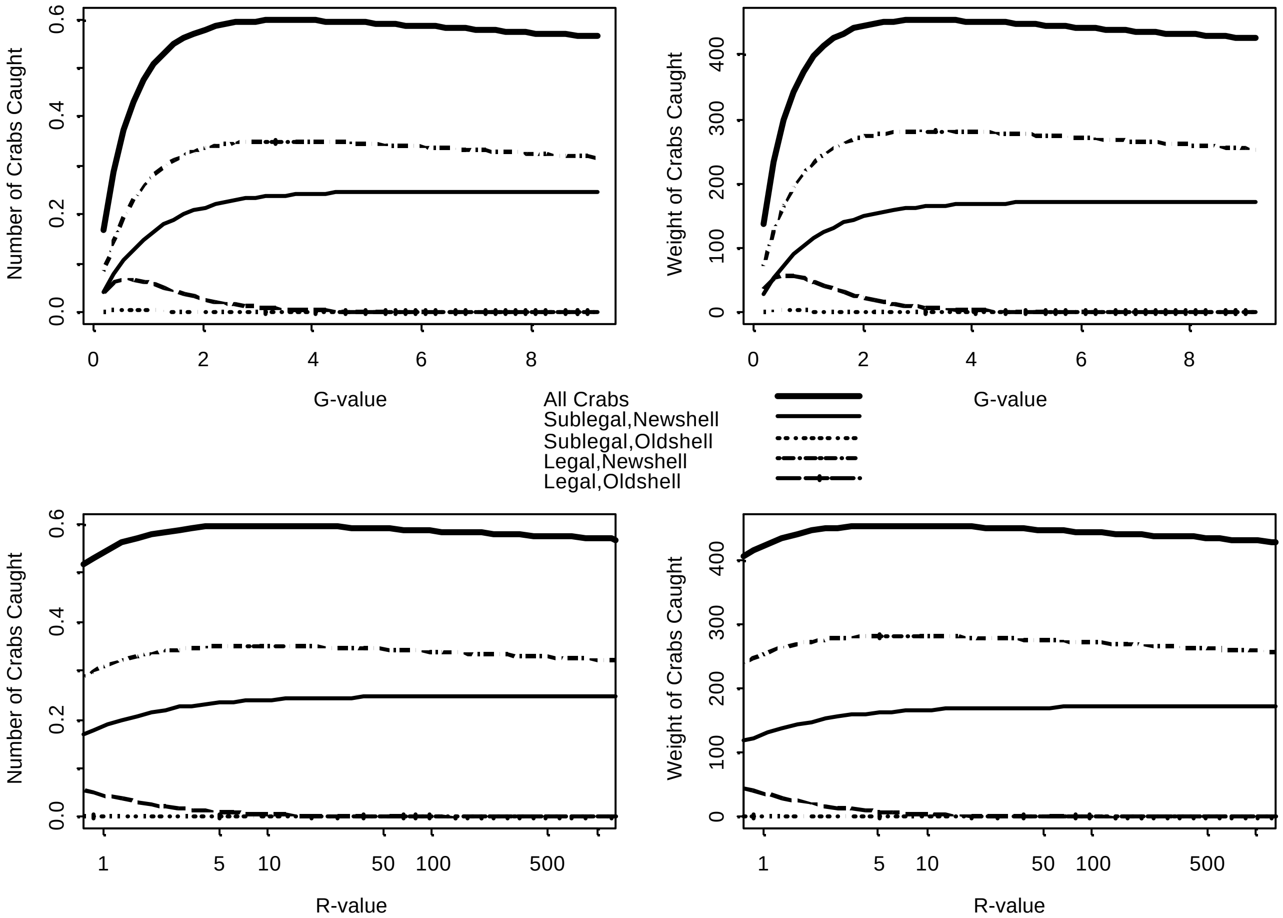

Figure 2.3.7 Continued

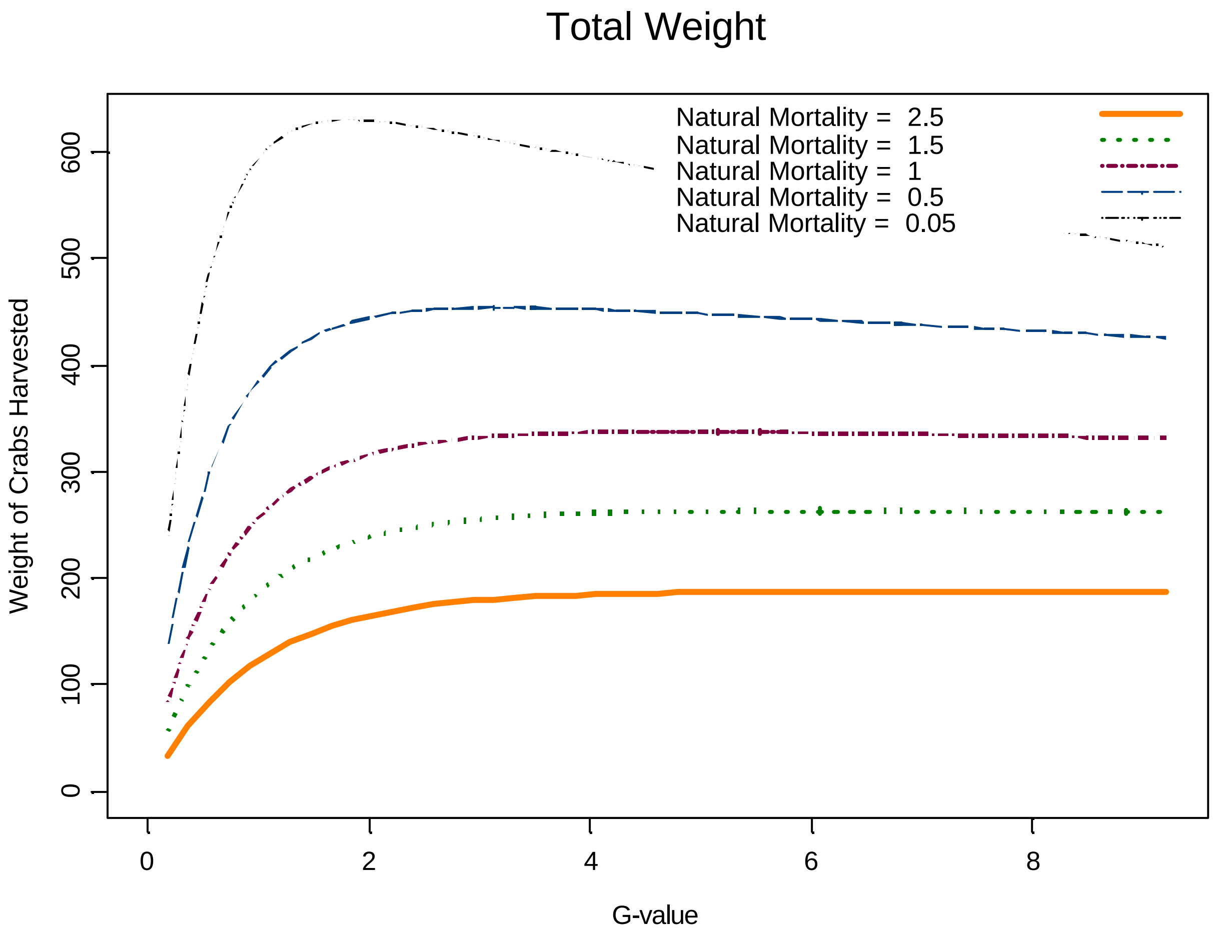

Figure 2.3.8. Predicted Yield for Various Combinations of Harvest Intensity and Natural Mortality Rates.

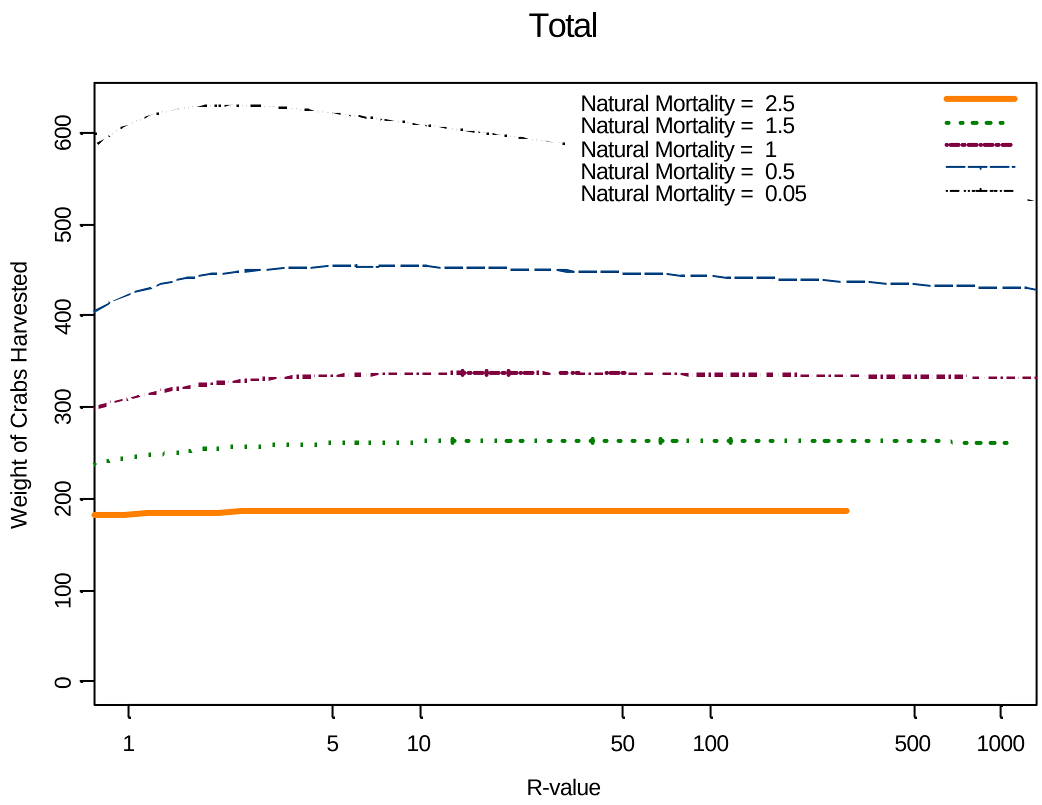

Figure 2.3.8. Continued

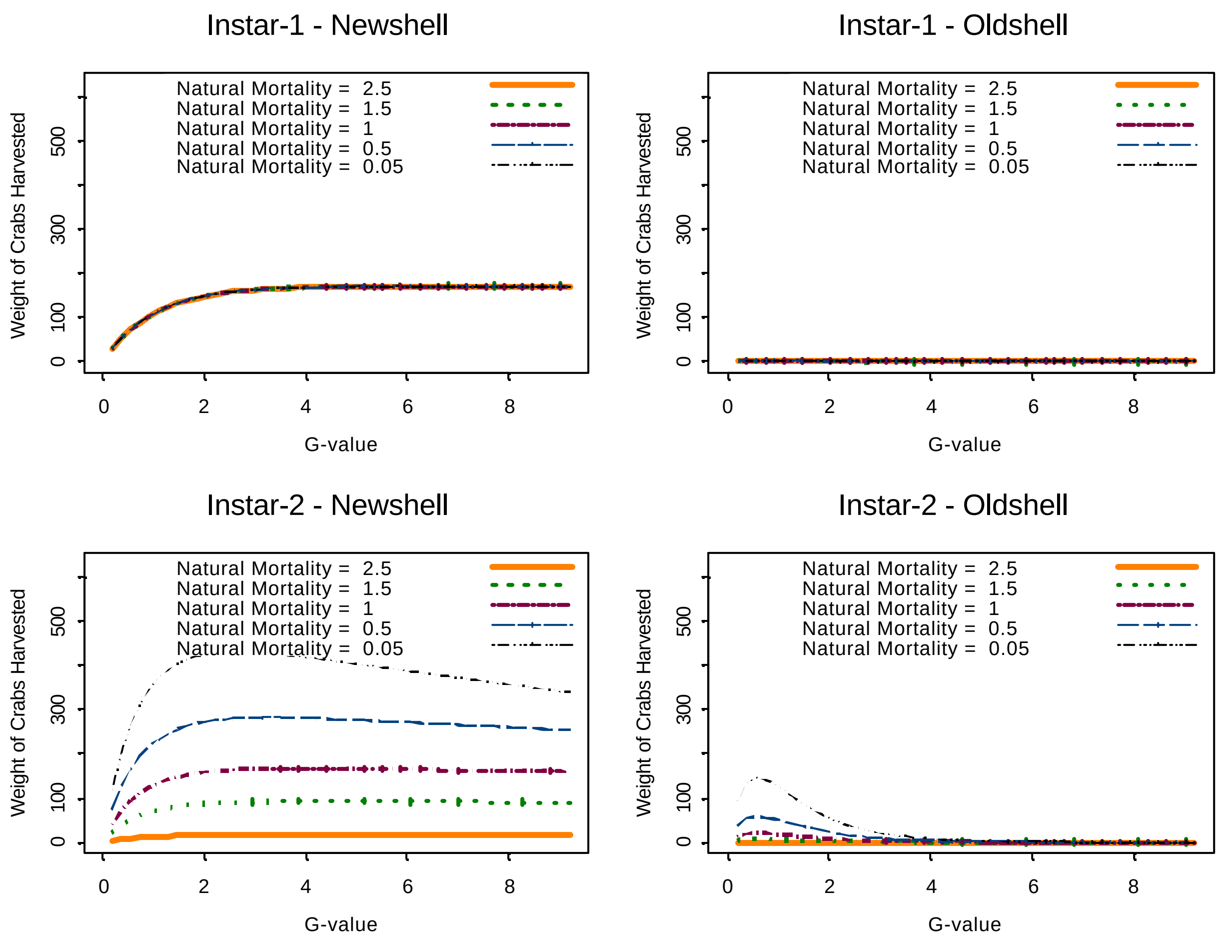

Figure 2.3.8. Continued

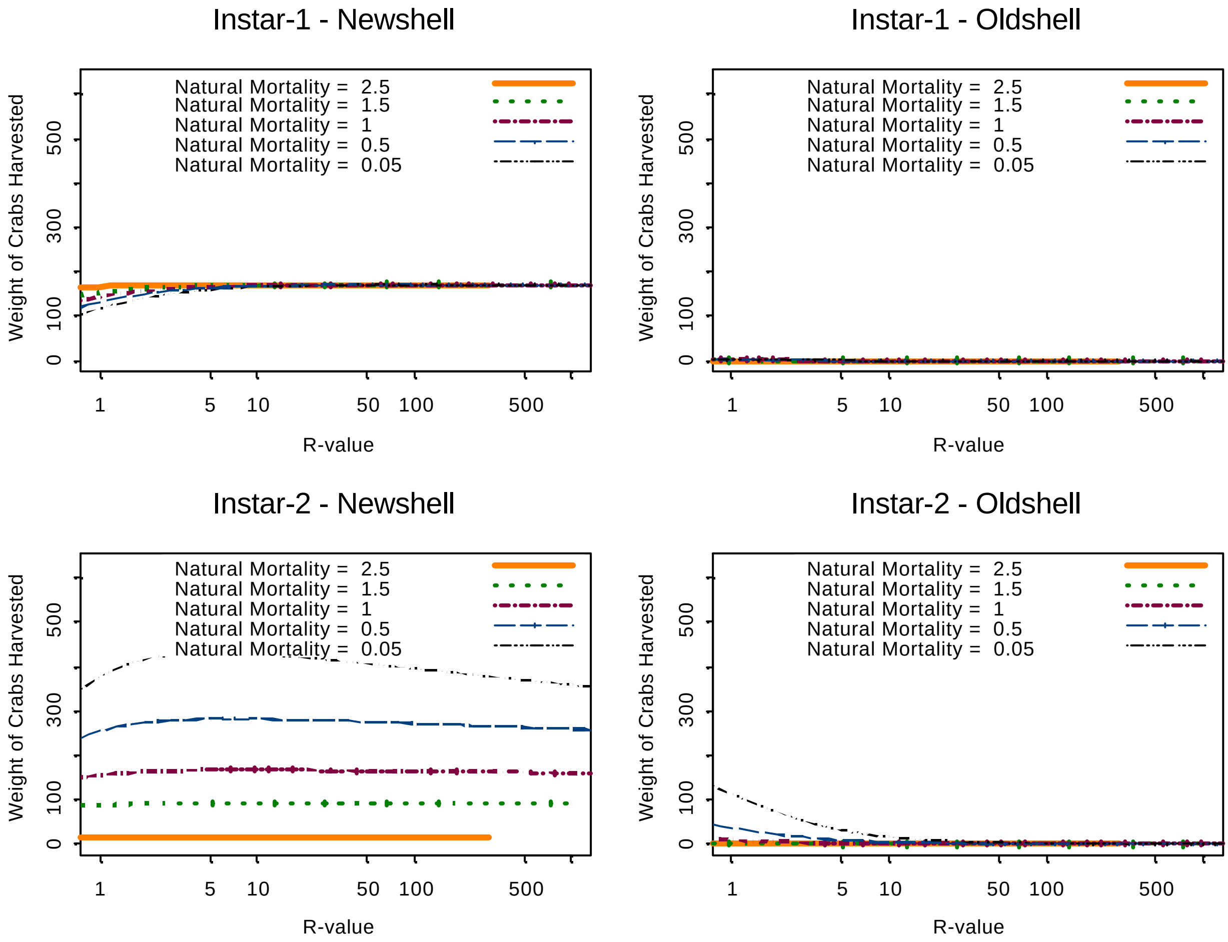

Figure 2.3.8. Continued

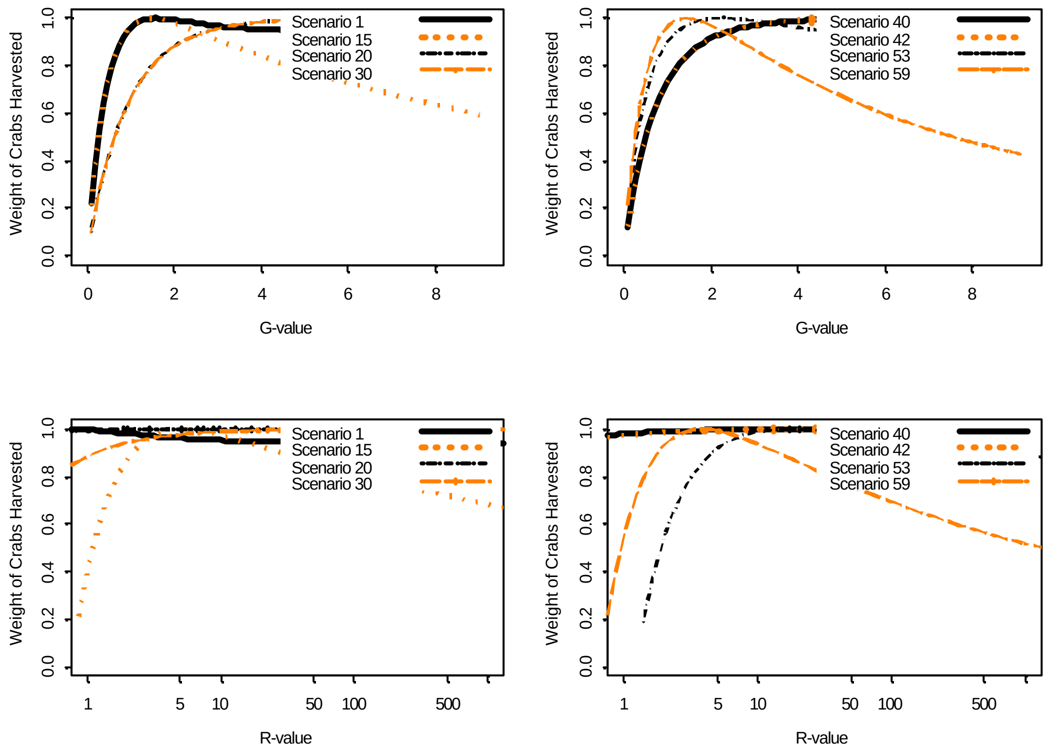

Figure 2.3.9. Predicted Yields for Eight of the Sixty-Four Scenarios

Appendix 1. A simple model for exploring determinants of optimum crab harvest

For a fully vulnerable population of crabs, the rate at which the number of crabs declines due to fishing is expressed by the differential equation (Quinn and Deriso):

$$\frac{dN}{dt} = -F*N \quad (1a)$$

- N is the number of crabs
- t is time
- F is the instantaneous fishing mortality rate

If the population is not fully vulnerable to traps, then the equation has to be modified slightly:

$$\frac{dN}{dt} = -v*F*N \qquad (1b)$$

- v is the vulnerability of crabs

What this means, is that if a trap-hour catches 10% of the fully vulnerable crabs, then it will also catch 5% of the crabs for which v=0.5.

Equation 1(b) still implies that all the captured crabs are removed from the population. In the case of sublegal sized crabs, only a fraction, h, of the captured crabs die and therefore are removed from the population. The rate at which sublegal-sized crabs die from handling is:

$$\frac{dN}{dt} = -h*v*F*N \quad (1c)$$

What this means, is that if a trap-hour catches 10% of the fully vulnerable crabs, then 2.5% of the sublegal-sized crabs will die if h=0.5 and v=0.5.

The rate at which crabs die from natural mortality is given by an instantaneous rate, M and the equation becomes

$$\frac{dN}{dt} = -M - h*v*F*N \qquad (1d)$$

The solution to the equation is

$$\frac{N(t)}{N(t=0)} = \exp(-(M + h*v*F)*t) \quad (1e)$$

As a convenience, N(t=0)=1 and the annual fishing effort is G=F*t. The number of crabs to survive one year is:

$$N(t+1) = N(t)*\exp(-M - h*v*G) \qquad (1f)$$

At the beginning of the harvest season, the number of oldshell crabs in the first instar is $(1-P_{molt})*\exp(-M-h*v*G)$.

If vulnerabilities are similar for oldshell and newshell crabs, then the fraction of crabs that are newshell is easy to measure. The predicted value is:

$$k = \frac{1}{1+(1-P_{molt})*\exp(-M - h*v*G)} \qquad 2(a)$$

which can be re-expressed as

$$P_{molt} = 1 - \frac{1-k}{k * \exp(-M - h * v * G)} \qquad 2(b)$$

Equation 1(b) gives useful constraints on the mortality rates. In order for P_{molt} to be greater than zero

$$1 - k < k * \exp(-M - h * v * G)$$
$$or$$
$$M + h * v * G \le \ln(\frac{k}{1-k}) \qquad (3)$$
$$M \le \ln(\frac{k}{1-k})$$
$$h * v * G \le \ln(\frac{k}{1-k})$$

The value of k gives an upper bound on the total mortality rate. The maximimum value of k is 1.0. For constant recruitment, k must be greater than 0.5

The probability of a n ewshell, sublegal-sized crab surviving one year is exp(-M-h*v*G). The probability of it surviving and moulting into a legal-sized crab is P_{molt} *exp(-M-h*v*G).

As a further simplifying assumption, all members of the first instar are sublegal and all members of the second instar are legal-sized. The rate at which crabs moult into the legal-sized instar is P_{molt} *exp(-M-h*v*G).

The probability of a newshell legal-sized crab surviving a year is exp(-M-G). Therefore the estimated number of legal-sized crabs that came from the original size range is P_{molt} *exp(-M-h*v*
G) *(1+ exp(-M-G)). At the beginning of the season, the ratio of sublegal to legal sized crabs expected to appear in the traps is:

$$Obs = v * \frac{1 + (1 - P_{molt}) * \exp(-M - h * v * G)}{P_{molt} * \exp(-M - h * v * G) * (1 + \exp(-M - G))} \qquad 4(a)$$

or in an area where there is no harvest

$$Obs = v * \frac{1 + (1 - P_{molt}) * \exp(-M)}{P_{molt} * \exp(-M) * (1 + \exp(-M))} \qquad 4(b)$$

or using equation 2(b)

$$v = Obs * (1 + \exp(-M)) * (k + k * \exp(-M) - 1) \qquad 4©$$

The fraction of legal-sized crabs that are harvested is

$\frac{F}{F+M*t_{season}} * \exp(-M * t_{season} - G)$ where t_{season} is the length of the season (in years) . Since the season is short and the instantaneous natural mortality rate is much less than the instantaneous fishing mortality rate, the fraction of legal-sized crabs that are harvested can be approximated as 1-exp(-G).

The length-weight relationship for male dungeness crabs was approximated as:

$$W = a * L^b \qquad (5)$$

- W is the weight in grams
- L is the notchwidth in mm
- a and b are constants estimated from survey data
  - a =0.0001312469
  - b =3.045421

A growth rate was chosen that would allow Instar-1 to grow into Instar-2 for Vancouver Harbour.

$$L_2 - L_1 * (1 + g_1) - g_0 \approx N(0, s_g^{\ 2}) \qquad (6)$$

- L_1 is the notchwidth before moulting
- L_2 is the notchwidth after moulting
- g_1=-.003227 is a constant
- g_0 =25.379 is a constant
- s_g =1.318 is a constant

PSARC INVERTEBRATE SUBCOMMITTEE

Request for Working Paper – Dungeness Crab – Intense Fishery Effects

Date Submitted: June 27, 2000

Individual or group requesting advice:
(Fisheries Manager/Biologist, SWG, PSARC, Industry, Other stakeholder etc.)
Crab trap industry and managers

Proposed PSARC Presentation Date: Dec. 2000

Subject of Paper (title if developed): Intense fishery effects on crab stocks

Stock Assessment Lead Author: Antan Phillips/ Jim Boutillier

Fisheries Management Author/Reviewer: Kim West/ Ivan Winther

Rational for request:
(What is the issue, what will it address, importance, etc.)
The effect of an intensive crab fishery on the crab population in the area. Data has been collected from FR and Boundary Bay for a number of years. Initial analysis of the data collected from Boundary Bay seems to indicate a lack of juvenile crabs in the area. There are a number of potential reasons for this, which need to be explored and solutions implemented in the management of the fishery. The potential effect on the Area J crab fishery is severe. The results of this paper will be used in other areas on the coast where intensive crab fisheries occur to prevent similar problems.

Objective of Working Paper:

(To be developed by FM & StAD)
To determine whether reproductive capacity, of crab stocks, is affected by an intensive fishery and if it is what are the possible causes. (handling, recruitment, overfishing).

To develop assessment tools (possibly a trap index) in intensive crab fisheries to allow managers to appropriately close the fishery inseason.

Develop an experimental sampling protocol to test out the various assessment tools for the 2001 crab season (possibly Fraser River or Boundary Bay).

Question(s) to be addressed in the Working Paper:

(To be developed by initiator)

Is there a problem / from the data available what does the problem seem to be (is it a recruitment problem, harvesting problem (USA or Canada) or a handling of undersized and female problem or something else) and how can we design a biological solution once the underlying reason has been identified.

Is there a way to monitor the fishery inseason and ascertain when the greatest proportion of legal size crabs have been removed. When to shut down the fishery to ensure that excessive handling of undersized and female crab does not occur (presently we close on an arbitrary date). Ensure that there is some scientific/biological basis developed for the inseason monitoring and closure of the fishery in these intensive crab fishing areas.