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Reconstructing the Offshore *Pandalus jordani* Trawl Fishery off the West Coast of Vancouver Island and Simulating Alternative Management Policies

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Abstract

Shrimp trawl fisheries in Pacific Fishery Management Areas 124 and 125 have historically been a boom or bust fishery. We use research data and commercial catch and effort data to reconstruct the *Pandalus jordani* stocks off the WCVI and examine stock-recruitment relationships, changes in catchability, and fishing power differences between two separate research vessels, the GB Reed and the WE Ricker. We then use the results of the population reconstruction to develop and parameterize a simulation model for exploring four alternative management policies for this fishery. The results of the population reconstruction suggests that recruitment, in years of low spawning biomass, may be in the form of immigration; however, using a synthesis approach to reconstructing the population suggest there is a clear stock-recruitment relationship. Survey biomass estimates from annual research surveys are good predictors of pre-season vulnerable biomass, and in conjunction with a formal stock assessment model could be used to calculate annual total allowable catches. We also found that catchability had increased over the last 10 years, however, we are uncertain whether these changes are due to range collapse or improvements in fishing technology. Simulation results suggested that there were no long-term or short-term gains to be made by aggressively managing this fishery. To maintain an economically viable fishery, we suggest a cautious approach to management. The fishery in areas 124-5 should be closed in years when estimated biomass is less than 1,000 tonnes, and a maximum exploitation rate of 35% when the biomass exceeds 1,000 tonnes. We also suggest that consideration be given to setting up a quota-based management system in which annual TAC is based on pre-season stock estimates.

Résumé

Historiquement, les pêches des crevettes au chalut dans les zones de gestion 124 et 125 du Pacifique sont caractérisées par des cycles emballement-effondrement. Les auteurs se sont servis de données scientifiques et de données sur les prises et l'effort des pêches commerciales pour reconstituer les stocks de *Pandalus jordani* au large de la côte ouest de l'île de Vancouver et étudier les relations stock-recrutement, les fluctuations de la capturabilité et les différences de puissance de pêche entre les navires de recherche *G. B. Reed* et *W. E. Ricker*. Les auteurs ont ensuite utilisé les résultats de la reconstitution des populations pour mettre au point et paramétrer un modèle de simulation visant à analyser quatre différentes politiques de gestion de cette pêche. Les résultats de la reconstitution des populations laissent croire que, dans les années de faible biomasse des géniteurs, le recrutement pourrait consister en l'immigration; toutefois, la reconstitution des populations par une approche synthétique donne à penser qu'une relation stock-recrutement évidente existe. Les estimations de biomasse obtenues à partir des relevés de recherche annuels donnent de bonnes prévisions de la biomasse vulnérable avant la saison de pêche et pourraient être utilisées de concert avec un modèle formel d'évaluation du stock pour calculer le total annuel autorisé des captures. Les auteurs ont également observé que la capturabilité avait augmenté depuis dix ans, mais ils ne savent pas si cette hausse est attribuable à une réduction de l'aire de répartition des crevettes ou à des techniques de pêche améliorées. Les résultats de la simulation laissent croire qu'une gestion rigoureuse de cette pêche ne procurerait aucun avantage à court ou à long terme. Les auteurs suggèrent d'adopter une approche de gestion prudente pour maintenir une pêche économiquement viable. Dans les zones de gestion 124 et 125, on devrait fermer la pêche les années où la biomasse estimée est inférieure à 1000 tonnes et veiller à ce que le taux d'exploitation ne dépasse pas 35 % lorsque la biomasse est supérieure à 1000 tonnes. Les auteurs suggèrent aussi d'envisager la mise en œuvre d'un système de gestion par quotas dans lequel le TAC annuel serait fondé sur les estimations de la taille des stocks avant la saison de pêche.

1. Introduction

1.1 Request for Advice:

Managers are seeking advice for biological thresholds to effectively manage offshore WCVI pink shrimp trawl fisheries. In the last 25 years, shrimp numbers in PFMA 124-125 have shown large fluctuations, which is also reflected in commercial catch. Presently, there is little evidence of a stock-recruitment relationship in this region, however, time series do reflect persistence after large, anomalous, recruitment events. The major goal in this paper is to examine alternative management options for this fishery, and determine what biological thresholds are critical to managing this fishery in a pre-cautionary approach.

1.2 Objective:

The objective of this paper is to provide a protocol and decision-making criteria in order to manage the WCVI shrimp trawl fishery and to determine the thresholds at which point there would be no harvesting or discontinue harvesting. As a measure of management "success" two alternative objective functions are used to evaluate policy options: 1) Long-term yield, 2) Log-Utility function. A long-term yield approach operates to maximize the total catch over a specified time period, whereas the log-utility approach operates to maximize annual catch.

1.3 Background Information:

In order to meet the objectives of this report, several steps are required to develop a working model for examining management tactics on this fishery. We have broken this report down into 3 distinct sections: 1) stock reconstruction in Statistical Areas 124-125, 2) simulating alternative management policies and 3) recommendations based on the results of these analyses. In the first two major sections, we give a brief introduction to the problem, the data and assumptions, a description of the models and statistical approaches, interpret the results, and discuss the results in the context of any assumptions and its application to decision making in fisheries management. Finally, the report concludes with addressing the objective of this working paper followed by recommendations for fisheries managers.

We use historical information from the WCVI shrimp trawl fishery for a retrospective analysis in statistical areas 124 and 125. Shrimp trawl fisheries of the West Coast of Vancouver Island began after a coastwide survey of the area in 1972 (Webb and Lockner, 1974), and surveys in areas 124 and 125 have been carried out consistently for the last 25 years except in 1984 and 1986. We chose this area for study because of the long time series of fishery independent survey data and because of the interesting population dynamics that makes this fishery difficult to manage. In 1977, quotas were set for the Tofino grounds in response to record catches in the previous year, as well as signs of recruitment failure (Boutillier et al, 1998). Further North, the Nootka grounds were left unrestricted to monitor the response of the fishing fleet, and resulted in record catches in that area in 1978. By the 1980s, the offshore fisheries ceased due to depressed stocks, then started back up again in 1987. After the fishery began to expand back into area 124, the fleet consisted of a larger proportion of less efficient beam trawlers in contrast to otter trawlers in the late 1970s. Since 1987 there has been very few restrictions placed on this fishery, and at present is closed to fishing from April 16th, to April 30th and August 1st to March 31st. Further fishing opportunities are announced to the fishermen by appropriate management authorities.

In this paper we construct a simulation model for analysis of alternative management policies and exploring biological thresholds at which management action must be taken. This approach is generally referred to as passive adaptive management (Walters, 1986; Walters and Holling, 1990). We use four alternative management scenarios and view each scenario using a long term, and short term objective function. The simulation model is used to develop a set of control rules for harvesting the population using a precautionary approach, as well as comparing the results of a conservative manager to an aggressive manager. Rather than use typical Mote Carlo type simulations to explore policy options, we use the actual observed recruitment anomalies for the past 25 years, and compare the performance of each control rule to that of an omniscient manager. The results of this analysis should, however, not be taken as the final word; as time proceeds, research programs should continue and be modified on an experimental approach that ultimately leads to addressing uncertainties.

2. Reconstructing the WCVI *Pandalus jordani* stock using VPA

2.1 Introduction

Virtual population analysis (VPA) is a process by which catch-at-age data are transformed into numbers at age, by adding the catch back into a population that is dying at a constant rate. In this case, the rate of natural mortality is estimated using relative abundance data from research surveys. Using survey data and commercial logbook records, we reconstruct the West Coast Vancouver Island *P. jordani* fishery in statistical areas 124 and 125. Building on previous stock assessment work for this fishery (Boutillier, et al. 1998), we specifically focus on two interesting problems: 1) differences in fishing power between the two research vessels that have been used, and 2) describing the non-stationary patterns in the stock-recruit relationships for this stock.

Fishery independent surveys are intended to be an unbiased estimate of stock size; therefore, sampling protocol (such as gear used) should remain constant over time, or the data are standardized to reflect changes in protocol. For most of the available time series on relative abundance data for WCVI *P. jordani* stocks, the data were collected using two separate research vessels, the G. B. Reed from 1973 to 1985, and the W. E. Ricker from 1987 to present (Boutillier, et al. 1998). In the previous assessment of PFMAs 124-125, there was no adjustment made for differences in vessel fishing power that might exist between the two survey vessels. Here, we examine the differences in fishing power by treating data from each vessel as an independent time series (i.e. each vessel has its own catchability coefficient).

Previous work on offshore shrimp stocks have suggested that much of the variability observed in stock-recruit relationships is a function of environmental conditions (Hannah 1993; Boutillier, et al. 1998). In this analysis, we use a recruit per egg index as a measure of juvenile survival, and examine changes in juvenile survival rate over time. In latter sections of this paper, we will be discussing recruitment anomalies, and as a point of clarification, recruitment anomalies are analogous to changes in juvenile survival rates.

2.2 Description of the VPA Model

The stock was reconstructed using catch-at-age data, where the proportion at age in the commercial catch was assumed to be the same as in the fishery independent surveys. Proportion-at-age are estimated from length frequency data using a length frequency distribution analysis developed by Schnute and Fournier (1980).

The reconstruction assumes fishing mortality and natural mortality occur simultaneously. To reconstruct the population we used an iteration procedure to solve the following transcendental catch equation and its derivative using Newtons' method (Hilborn and Walters, 1992):

$$C_{a,t} = \left[1 - \frac{M}{Log\left(N_{a,t}\right) - Log\left(N_{a+1,t+1}\right)}\right]\left(N_{a,t} - N_{a+1,t+1}\right) \qquad 2.1)$$

The iteration proceeds using the iteration improvement:

$$x_{new} = x_{old} - \frac{f(x)}{f'(x)} \qquad 2.2)$$

where *f(x)* is the catch equation rearranged so all terms are on the left hand side and *f'(x)* is the derivative of equation 2.1 (after transformation) with respect to N_t. x_{new} and x_{old} refer to the numbers at age in a given year. Age 3 shrimp were estimated assuming the number of age 4 shrimp were negligible (in this assessment $N_{4\ \mathrm{years}} = 1$). The terminal numbers-at-age (the population size in 1999) was calculated using the terminal *F* assumption (equation 2.3). An alternative approach is to use a direct estimate of F from fishing effort data and a known catchability coefficient (q). Since q is an unknown, we chose to loop over a wide range of terminal fishing mortality rates, and update the vulnerability at age (V_a) schedules based on vulnerabilities-at-age observed in five years previous to 1999.

$$N_{a,1999} = \frac{C_{a,1999}}{\left(1-e^{-z_t}\right)}\left(\frac{F_{term}V_a + M}{F_{term}V_a}\right) \qquad 2.3)$$

After each iteration using equation 2.2, a second iteration was carried out to estimate the terminal numbers at age (updating equation 2.3). The model has converged when $x_{new} - x_{old} \sim 0$, and the vulnerabilities at age converge. There are 2 unknown parameters in which we use a relative abundance time series to estimate, the instantaneous natural mortality rate and the terminal fishing rate.

We also examine how the catchability coefficient for the commercial fishery changes with changes in stock size. Using the fishing rates estimated from the stock reconstruction we calculate the catchablility coefficient for each year using the relationship $q_t = F_t/E_t$. We then plot q_t versus N_t to determine whether q remains constant over the observed range of stock sizes.

2.3 Estimating VPA Model Parameters

We estimate a constant natural mortality rate and terminal fishing rate by fitting our VPA population to relative abundance data using the maximum likelihood estimate of the scaling parameter q (Walters and Ludwig 1994). Here we assume that measurement errors in the relative abundance data are multiplicative, and transform the relative abundance data into a Z-statistic:

$$Z = Log\left(Y_t / N_t\right) \qquad 2.4)$$

where Y_t is the relative abundance estimate and N_t is the predicted abundance from the VPA model. Recall that each element of N_t in equation 2.4 is a function of the terminal fishing rate and natural mortality rate. We use the following likelihood function to evaluate the parameters given the relative abundance data:

$$L\left(Y_t \mid F_{term}, M\right) = \left[\sum_t \left(Z_t - \overline{Z}\right)^2\right]^{-\left(\frac{N-1}{2}\right)} \qquad 2.5)$$

where W_t is a weight assigned to each year of observation. The above parameter estimation approach is a Bayesian approach, and in transforming the likelihood estimate to a probability distribution we used a uniform prior.

For the purposes of graphically displaying the uncertainty in our estimates of stock sizes, we re-run the VPA model using the upper and lower credible intervals for each parameter. The credible intervals (parameter values at 5% and 95% of the cumulative distribution) are taken from the marginal distributions of each parameter. The use of the upper and lower bounds for each parameter appear as error bars in the stock reconstruction. Although our stock reconstruction is based on point estimates of the two parameters in question, the uncertainty in these parameters is reflected in the marginal distributions (see section 2.5 for more detailed explanation).

2.4 Catch-at-Age and Relative Abundance Data

Logbook data for statistical areas 124-125 were used to compile the commercial catch statistics (Figure 2.1). Catch is reported in pounds and was converted to numbers by multiplying catch (in kilos) by the average number of shrimp per kilogram observed in the research surveys. Effort is reported in trawl hours and from 1979 to 1986 there was zero trawl hours reported in the two statistical areas. In our examination of changes in catchability, we omit the effort data from 1979 to 1986. To construct a catch-at-age matrix, we multiplied the annual catches by the proportion-at-age observed in the research surveys. Although some length frequency data are available from commercial catch sampling programs, we did not use these data for constructing our catch-at-age matrix, except for commercial samples taken in 1978, 79, and 80. Length frequency samples taken from the commercial catch in the late 1970s were significant in sample size to determine proportions at age. We found that these samples were comparable with research trawl surveys, and an increase in age-1 proportions over the course of the fishing season was also noted (this can be accounted for by summer growth).

The abundance indices shown in Figure 2.1 were converted from total biomass estimates interpreted from the research vessel data using a bicubic spline interpreter (Boutillier et al. 1998). We chose to use the abundance index as a relative abundance index for 2 reasons. First, in 1995 the commercial fishery caught more shrimp than were estimated total biomass from the survey data. Second, no previous attempts have been made to identify differences in fishing power between the two survey vessels. We address the latter issue by examining the differences in catchability between the W.E. Ricker and the G.B. Reed. If differences are found in the survey vessel catchability, then biomass estimates will be scaled by a vessel-specific catchability coefficient.

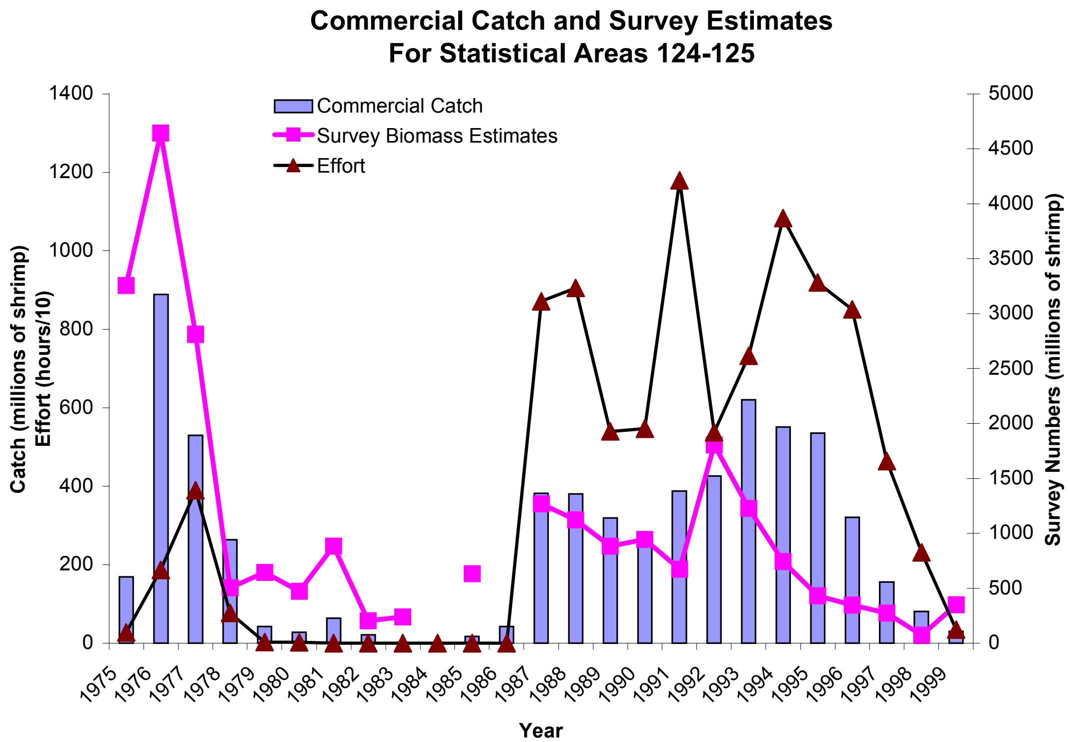

Figure 2.1. Commercial effort and landings reported in logbook records and relative abundance data used for estimating parameters in VPA. Data are for statistical areas 124-125 combined.

2.5 Stock Reconstruction

Recall that two separate survey vessels collected the relative abundance time series and no attempts have been made to correct for differences in fishing power. We also estimated the parameters treating the relative abundance time series as a single unbiased estimate of stock size (i.e. used the same scaling parameter for both survey vessels). Making the assumption that there are no differences in vessel fishing power leads to a less informative estimate of VPA parameters (i.e. the marginal distributions for model parameters had wider distributions). As a result, the following results in the stock reconstruction assume that there are differences in vessel fishing power, and the corresponding relative abundance data are scaled by separate parameters.

The maximum likelihood estimate (MLE), from the joint distribution, for terminal fishing rate and natural mortality rate are 0.18 and 0.96, respectively. We use the maximum likelihood estimates for the VPA reconstruction. The marginal distributions for each of these parameters are shown in Figure 2.2. The survey data contain very little information about natural mortality rates, as shown by the wide distribution for this parameter. The estimated fishing rate in 1999 was 0.18 with lower and upper credible intervals of 0.1 and 0.44, respectively. An alternative approach (and perhaps a more traditional approach) is to use the MLE estimates for each parameter, and resample the data (bootstrapping) to determine 95% confidence intervals. Although this method has its statistical merits, we have represented all of the uncertainty in parameter estimates using a Bayesian approach. Clearly, from the marginal distributions shown in Figure 2.2, the model is much more sensitive to changes in estimates of the terminal fishing rate.

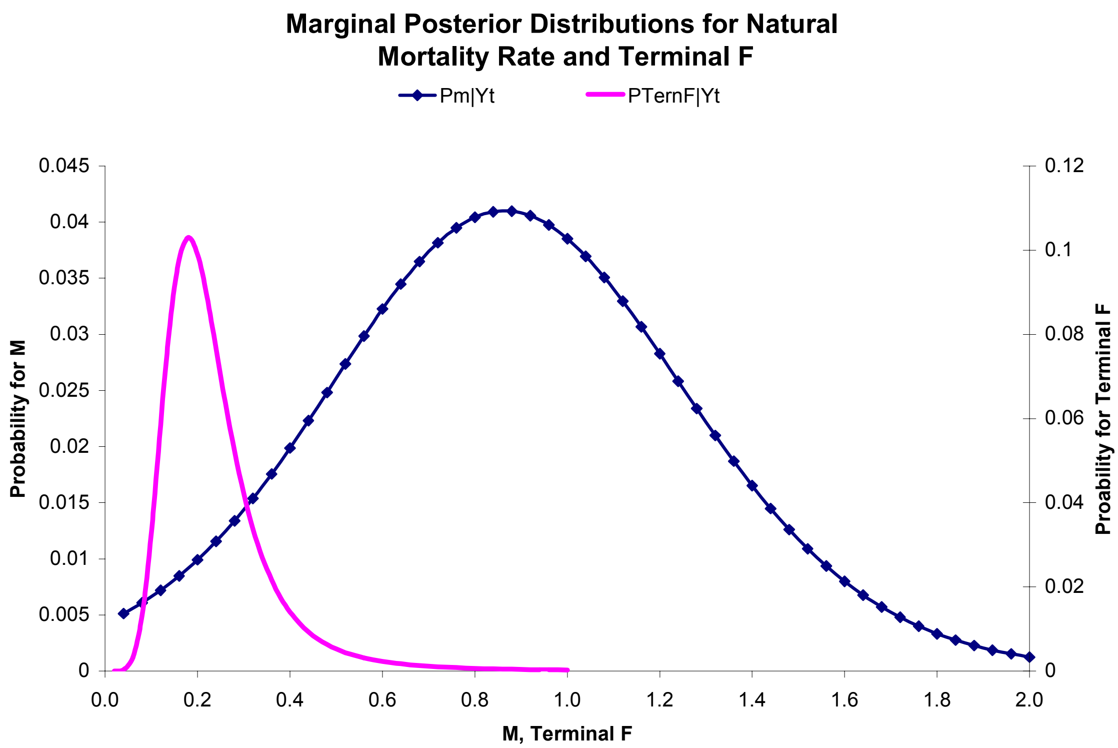

Figure 2.2. Marginal probability distributions for terminal fishing rate and natural mortality rate for *P. jordani* in statistical areas 124-125 combined.

For later convenience, the reconstructed population is expressed in millions of shrimp (Figure 2.3). Also shown on this figure are the relative abundance data, which have been re-scaled according to the research vessel catchability coefficient (see Figure 2.5). Estimates of abundance range between 45 million shrimp (or 193 tonnes) in 1983 to 5,526 million shrimp (or 23,178 tonnes) in 1975 (see Table 2.1). The estimate for 1999 biomass, prior to the start of the fishery, is 1,814 tonnes which is higher than the 805 tonnes estimated directly from survey data (a difference of 1,009 tonnes). The terminal fishing rate and vulnerabilities largely dictate the calculated terminal numbers-at-age; therefore, if the survey data are accurate then we have under-estimated terminal fishing rate and/or over-estimated natural mortality rate. Furthermore, numbers of shrimp are converted to biomass using the average number of shrimp per kilo; therefore estimated biomass is also subject to errors in average weight. The average number of shrimp per kilo in 1999 was 430, compared to the average over the previous five years of 278 shrimp per kilo.

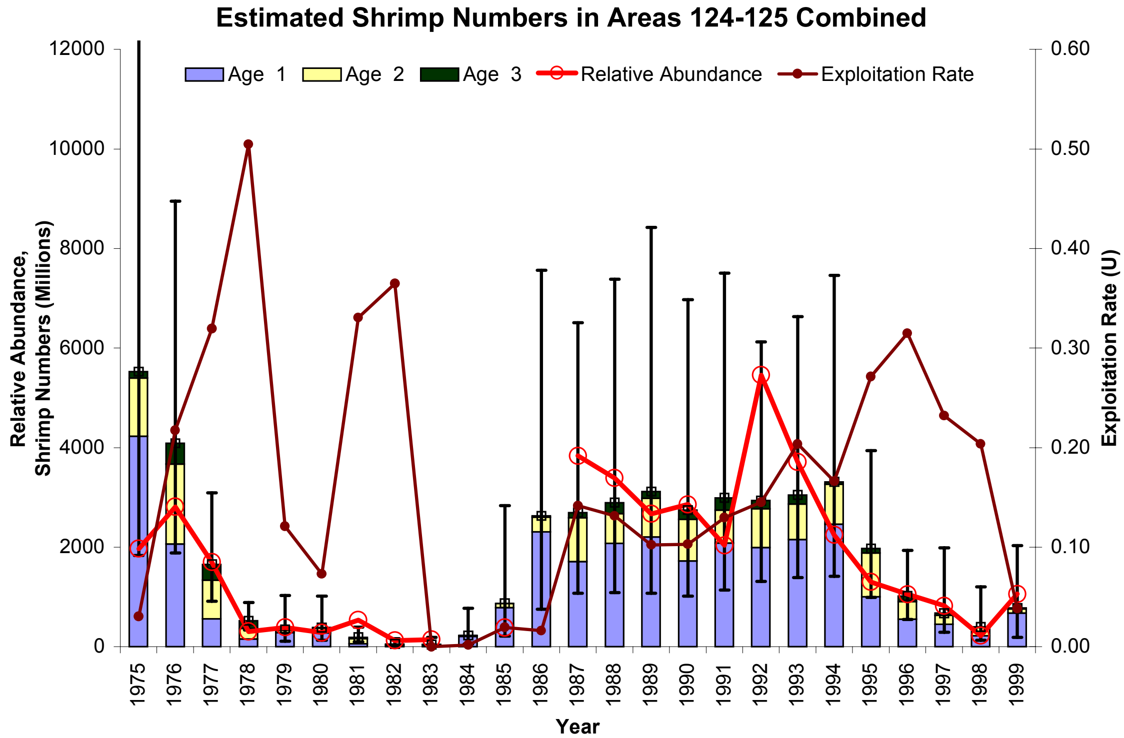

Figure 2.3. Reconstructed *P jordani* population for SW Vancouver Island, and relative abundance time series. The error bars correspond to the total population numbers using the upper and lower credible intervals for terminal fishing mortality and natural mortality.

The relative abundance indices, more or less, reflect the changes in biomass as calculated in the stock reconstruction model. In table 2.1 we present the survey biomass estimates after they have been scaled by the catchability coefficient for each research vessel. In general, the survey numbers (data presented in Figure 2.1) track changes in overall abundance, however, we noted that survey estimates prior to 1987 tended to over-estimate and surveys after 1987 tended to under-estimate the reconstructed biomass.

Exploitation rates have varied considerably over the entire time series shown in Figure 2.3. In general, exploitation rates have been high during low stock sizes and low during abundant years. The average exploitation rate over the last 25 years is 17%, and from 1988 to 1998 the average exploitation rate is 19%. The highest exploitation rate observed (U=0.49) was in 1978, a year of low abundance and relatively low fishing effort. Note, however, that the exploitation rates shown in Table 2.1 are calculated using the total reconstructed biomass estimate, not the vulnerable biomass estimate. Therefore, in comparison to exploitation rates estimated by Boutillier et al. (1998) these are conservative. In the last 10 years, fishing effort has increased substantially in these two areas compared to the early 1970s when shrimp were also abundant. We found that the commercial catch rate (as measured by tonnes/trawl hour) were relatively uninformative about the recent decline abundance, however, we did not examine changes in catch rates within each fishing season. An in-season assessment of changes in catch rates may be more informative about changes in stock size as the fishery proceeds.

Table 2.1. Population estimates from VPA using maximum likelihood estimates of terminal fishing rate and instantaneous natural mortality rate. Numbers of shrimp are converted to biomass using the average number of shrimp per kilo measured in research cruises. Exploitation rate is expressed as catch divided by vulnerable population biomass and unscaled survey estimates are calculated using the bicubic spline interpreter.

Year	Numbers (millions of shrimp estimated from VPA)	Shrimp /Kg	Biomass (tonnes) N*S/Kg	Survey Estimates (scaled) Millions of Shrimp	Survey Estimates (Unscaled) Millions of Shrimp	Catch (tonnes)	Effort (trawl hours)	Exploitation Rate on Vulnerable Biomass
1975	5525.6	238.4	23177.9	1969.1	3257.055	706.4	275	0.07
1976	4087.3	257.7	15860.7	2807.2	4643.271	3423.4	1867	0.34
1977	1658.3	296.4	5594.8	1699.5	2811.122	1860.0	3894	0.44
1978	522.6	228.4	2287.9	304.2	503.1383	1130.0	769	0.63
1979	349.4	248.9	1403.9	389.6	644.4097	159.0	26	0.28
1980	384.5	291.9	1317.3	285.9	472.9081	78.2	20	0.12
1981	192.5	249.2	772.5	534.0	883.2433	272.0	0	0.46
1982	58.3	223.1	261.3	123.9	204.9111	102.5	0	0.53
1983	45.0	232.9	193.2	144.3	238.7073	0.0	0	0.00
1984	225.6	250.0*	902.2	N/S		1.7	0	0.01
1985	874.3	271.7	3218.3	381.9	631.6965	73.8	0	0.07
1986	2631.3	230.0*	11440.4	N/S		190.0	0	0.05
1987	2696.7	216.5	12455.7	3836.5	1268.798	1818.2	8714	0.27
1988	2893.0	236.5	12235.0	3390.9	1121.445	1811.6	9054	0.31
1989	3116.9	243.7	12789.8	2669.8	882.9614	1311.8	5397	0.21
1990	2743.4	272.2	10080.6	2857.8	945.1461	1186.9	5466	0.22
1991	2990.5	232.4	12867.9	2039.1	674.3827	2133.2	11798	0.33
1992	2935.4	246.7	11898.7	5456.2	1804.488	1712.4	5377	0.28
1993	3047.7	256.0	11904.9	3710.5	1227.124	2239.9	7327	0.38
1994	3312.4	278.1	11910.9	2244.0	742.1438	1989.5	10834	0.36
1995	1971.7	268.0	7357.1	1305.1	431.6195	1968.7	9195	0.42
1996	1019.0	280.6	3632.3	1053.5	348.4087	1179.1	8505	0.54
1997	673.4	270.1	2493.3	822.9	272.1363	573.3	4640	0.45
1998	397.1	318.0	1248.9	225.0	74.40468	227.3	2312	0.31
1999	781.1	430.5	1814.5	1060.0	350.5789	63.6	347	0.09

* Indicates interpolation of shrimp per kilo in the absence of survey data.

Due to size selectivity of the fishing gear, the calculated biomass indices from survey data are estimates of the vulnerable population, not the total population. The estimated vulnerable biomass calculated using the VPA is a product between the numbers at age and the vulnerability-at-age. We then compare the VPA vulnerable biomass to the survey biomass indices in Figure 2.4. The vulnerable biomass estimate for the period between 1975 and 1985 are less than biomass indices calculated from the survey, and from 1987 to present, vulnerable biomass is greater than biomass indices. The relative annual difference between the two biomass estimates is calculated by dividing annual difference by the mean difference over the entire time series. The biomass indices shown in Figure 2.4 have not been re-scaled, and the results of the population reconstruction suggest that these biomass indices are fairly decent predictors of vulnerable biomass. By not scaling survey data, it easier to see how data prior to 1987 tends to over-estimate biomass, and under-estimates after 1987 (Figure 2.4).

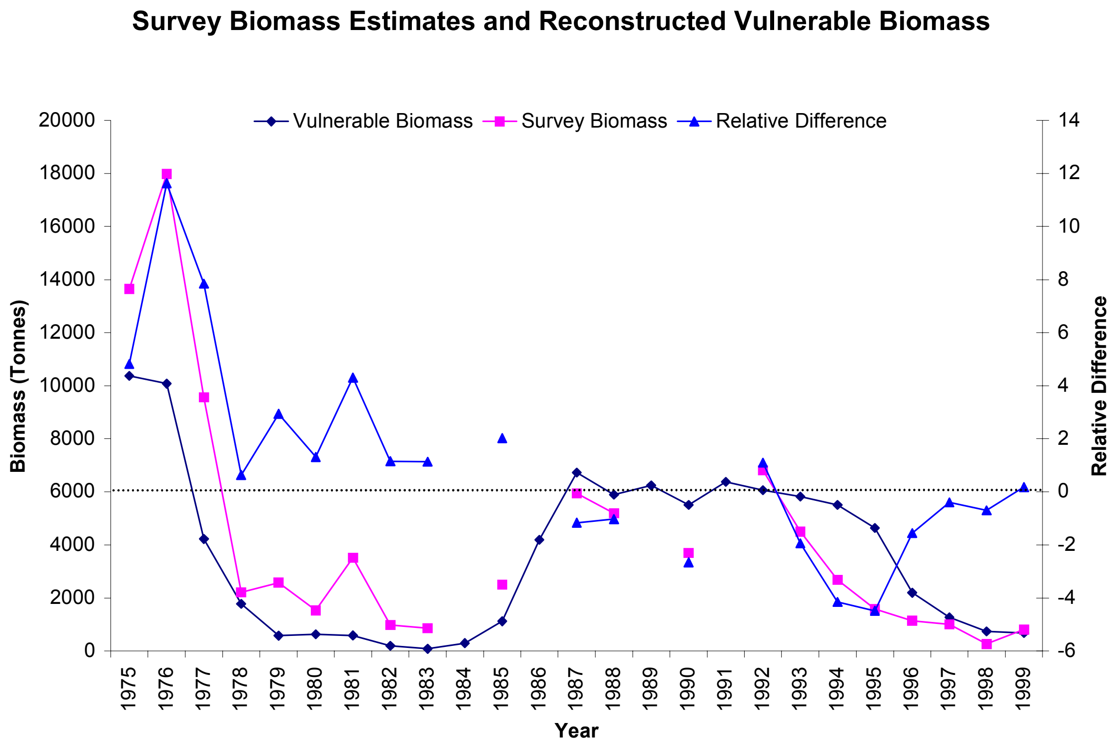

Figure 2.4. Vulnerable biomass estimated from the VPA model, biomass indices calculated from the survey data, and the percent difference between biomass indices and reconstructed biomass.

2.6 Research Vessel Fishing Power and Catchability

The fishing power between the two research vessels appears to be markedly different. Figure 2.5 shows the relative abundance data plotted against the reconstructed population in Figure 2.3. The slope of each line approximates the scaling coefficients calculated using equation 2.4. Population estimates from survey data collected aboard the GB Reed tend to be an overestimate (slope = 1.1338), whereas, biomass estimates from the WE Ricker tend to be an underestimate (slope = 0.4665).

It is possible, however, that the differences observed in the two slopes are the result of a change in natural mortality rate after 1987, and there is no difference in fishing power between the two survey vessels. As it turns out, this alternative hypothesis is quite easy to test by using two different mortality rates; one for 1975-86 and one for 1987-99. We carried out such as test and found that the natural mortality rates would have to increase from 0.3 to 1.3 to explain the data. Although natural mortality rates are variable from year to year, we felt that a sudden 4-fold increase in natural mortality was an unrealistic explanation of the data.

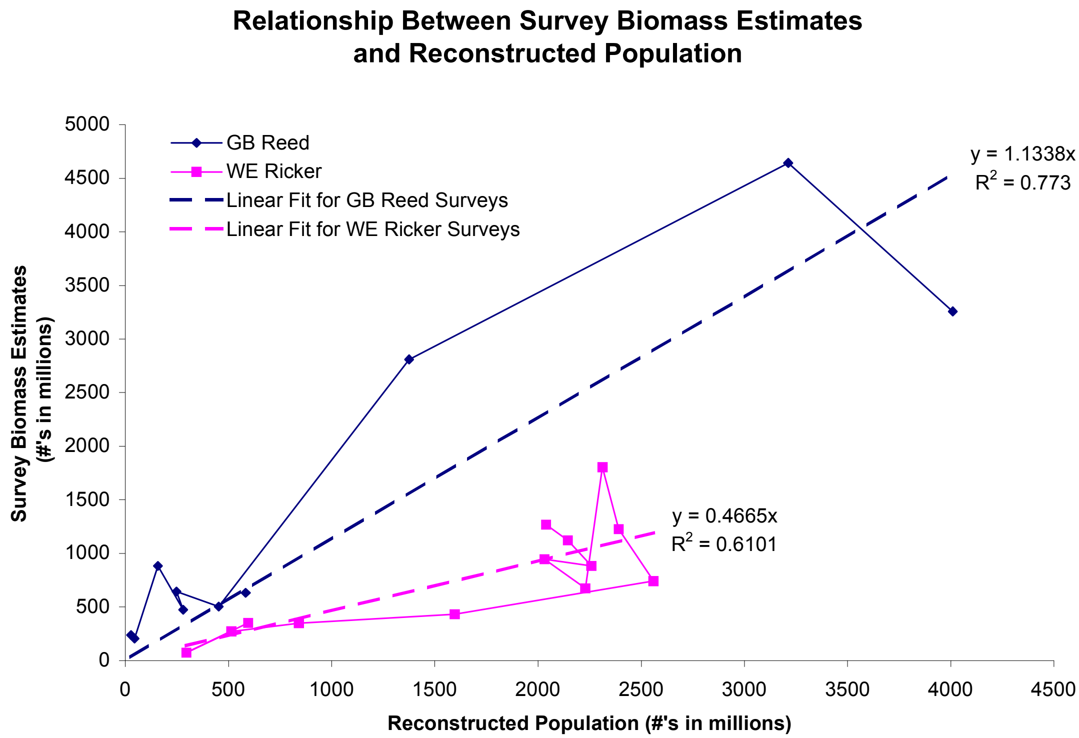

Figure 2.5 Survey indices from research cruises aboard the GB Reed from 1975 to 1985 and the WE Ricker from 1987 to 1999. Note that no surveys for areas 124-125 were conducted in 1984 and 1986.

An important result of the stock reconstruction that is of particular concern for fisheries management is the observed increase in catchability at low stock sizes (Figure 2.6). We choose to omit effort data prior to 1987 because the fishery was closed in one or both areas during the early 1980s and catch rates were almost 3 times higher in the 1970’s (uncertain if effort was under-estimated). Nevertheless, given the contrast observed in stock size between 1987 and 1999, there was a 6.7-fold increase in catchability for the commercial fishery. The highest catchabilities have been observed in recent years and it is difficult to discern whether this change reflects improvements in fishing technology, or a range contraction during low abundance years.

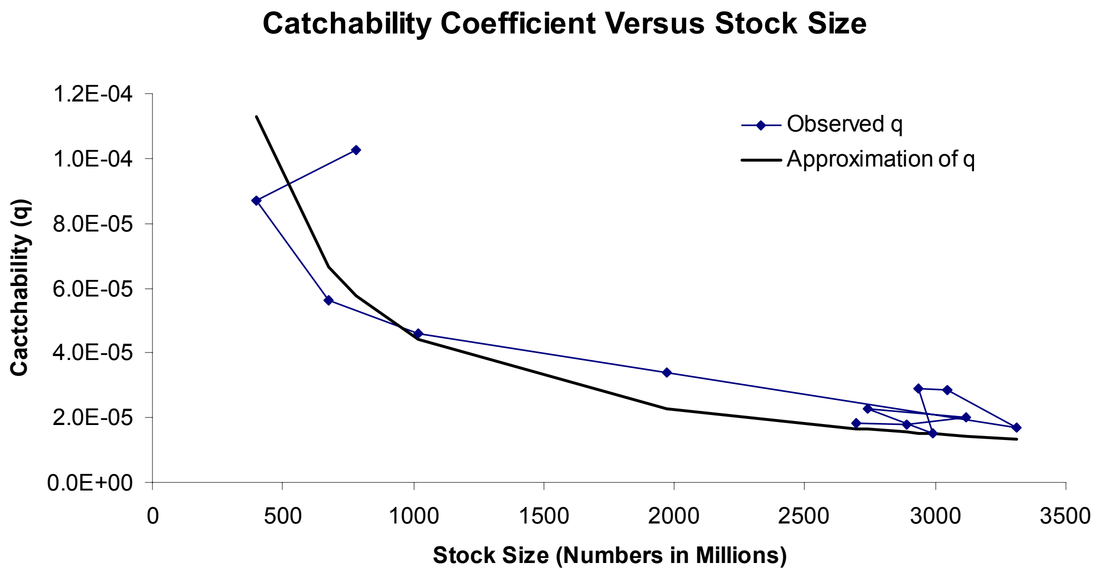

Figure 2.6 Calculated catchability coefficients (q = F/E) versus stock size from 1987 to 1999, and the approximation of q using the MLE for alpha (see section 3.7).

2.7 Stock-Recruitment Relationship

The stock recruitment-relationship for area 124-125 is shown in Figure 2.7. For this analysis we used a fixed fecundity at age schedule adapted from Hannah (1995), and we assumed roughly 1% and 35% of the age 1 and 2 shrimp are females, and 95% of 3-year-old shrimp are females. To calculate fecundity-at-age we multiplied the average length-at-age by the fecundity at length estimated by Hannah (1995). Because the fishery occurs prior to the spawning season, our estimates of annual egg production are multiplied by the fraction that survive the harvest process in that year. Total annual egg production is the product between number of sexually mature individuals (estimated from the VPA reconstruction) and fecundity at age. Recruits are the numbers of age 1 shrimp in the VPA model produced one year later.

Previous work on recruitment dynamics for these two areas used age 2+ shrimp as an index of spawning population size, and age 2 shrimp (two years later) as the recruiting age class (Boutillier et al., 1998). In years where survey estimates were not conducted, spawners and recruits were interpolated using linear regression methods. Boutillier, et al. (1998) also examined relationships between recruitment and environmental variables. There results failed to explain highly variable recruitment episodes, but did suggest that there is a net transport of larvae by ocean currents to the north.

In our assessment of stock-recruitment, we also found large recruitment events occurring in the presence of little spawning biomass (suggesting that much of the observed recruitment be in the form of immigration). In the relationship shown in Figure 2.7, there are two general production regimes, a period of low production during the late 1970s and early 1980s, followed by an increase in production. The most recent data suggest another decline in production for area 124-125. The stock-recruitment data, as they are presented here, are indicative of cyclic population dynamics, and it is unclear as to whether or not these dynamics are associated with changes in juvenile survival rates, or due to immigration processes.

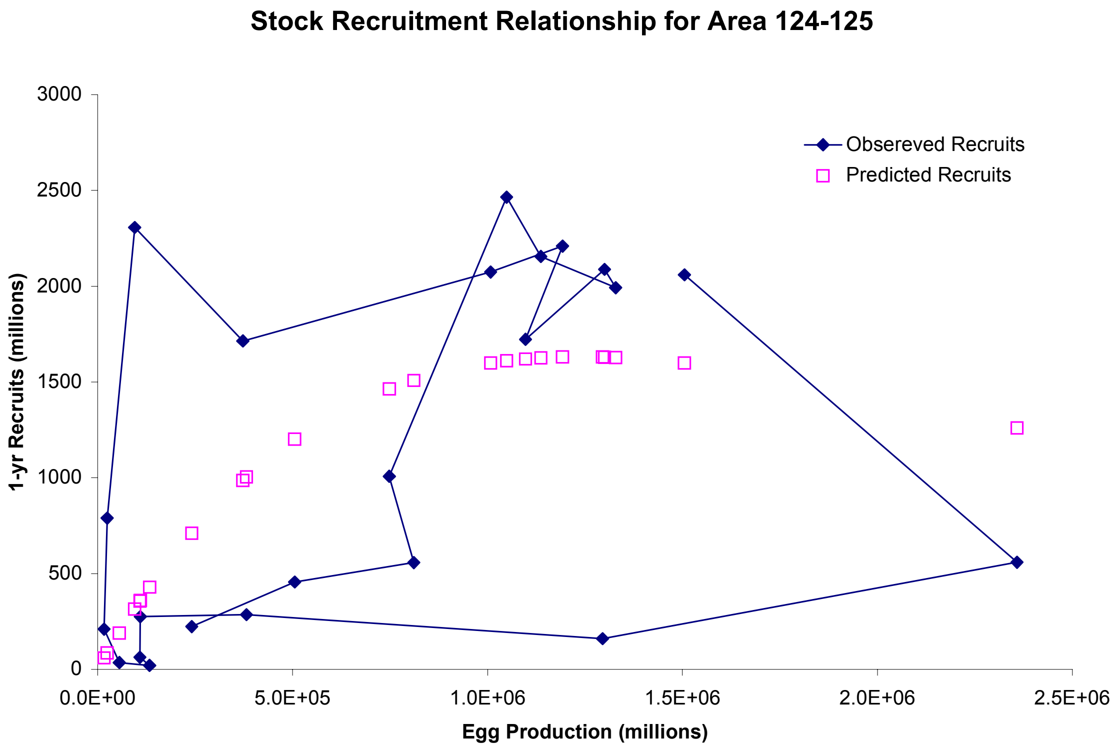

Figure 2.7. Stock recruitment relationship for area 124-125 combined. Recruits are numbers of 1-year old shrimp, and egg production is a function of age structure and fecundity at age. Predicted recruits are calculated using a Ricker stock-recruitment function.

Other studies on stock-recruitment relationships in shrimp also show similar variability in recruitment, and many attempts have been made to correlate the apparent anomalies with physical or environmental time series (Caputi, et al. 1998; Hannah 1993; Boutillier, et al. 1998). We observed a non-stationary pattern in egg to recruit survival rates (Figure 2.8), that is, at the same level of egg production in different years we observe large changes in juvenile survival rates. For example, in 1980, 1982 and 1986, levels of egg production were relatively similar, yet the juvenile survival rates for these three years were markedly different. In Figure 2.8, annual egg production is a function of stock size, and the density-dependent juvenile survival rate follows two distinct paths. During a stock collapse (1975 to 1984), juvenile survival rates are depressed and during a rebuilding phase (1985 to 1988) juvenile survival rates were higher. In the late 1970s until the mid 1980s density-dependent juvenile survival rates were lower than the period between 1985 and 1995. In the last 4 years, there appears to be another shift occurring to a lower survival rate regime. It is possible that these apparent changes in density-dependent survival rates are correlated with some external, or environmental variable, but we make no such comparisons. Once again, we cannot attribute the observed changes in juvenile survival rates to either changes in environmental conditions or immigration of juveniles into areas 124-125.

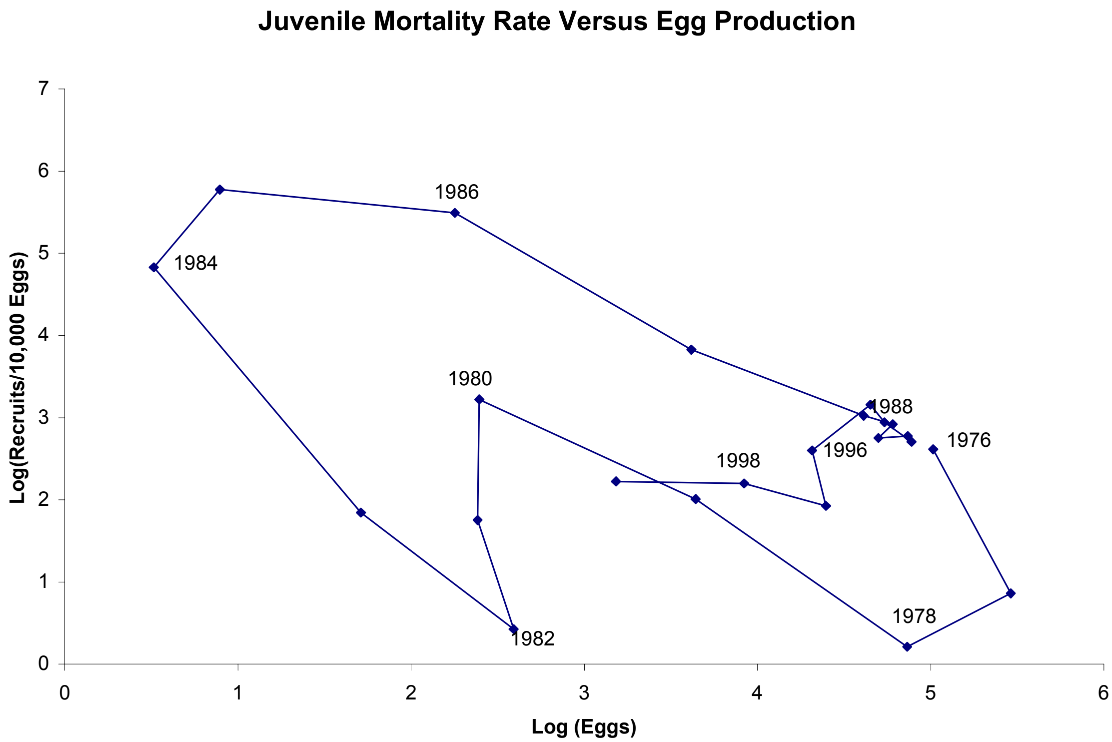

Figure 2.8 An index of juvenile survival rate from 1975 to 1999 for areas 124-125 combined.

2.8 Discussion

The results of the stock reconstruction suggest *Pandalus jordani* populations in areas 124 and 125 undergo large fluctuations in stock size over periods, and the patterns in juvenile survival rates appear to be cyclic in nature. Our estimate of a high natural mortality rate is consistent with findings of other *P. jordani* stocks (Boutillier et al., 1998; Hannah, 1995). The 1999 biomass estimate also reflects an increase in biomass estimated from the research cruise, and last year's exploitation rate is most likely below 20%. The overall average exploitation rate observed over the last 25 years approximately 17%, based on the estimated abundance carried out using the VPA model. As we will see in section 3, this may be underestimated due to an over-optimistic stock reconstruction. Using the confidence intervals shown in Figure 2.3, our estimated average exploitation rates (catch/total population size) over the last 25 years range from 14% to 33% in areas 124-5 only. Much of the total fishing effort for BC shrimp trawl fisheries occurred in areas outside this study, and exploitation rates estimated here do not apply to areas elsewhere.

Another source of error with the estimated population size using VPA is aging errors. In this analysis we assumed that age-structure in the commercial catch is the same as research surveys sampled prior to the start of the fishery. Then simply multiply the total commercial catch by the proportion-at-age found from research data. Ideally, both the commercial catch and research catch should reflect the same proportions at age, provided vulnerability-at-length is equal for both gear types. Another concern is aging errors that arise through the analysis of length frequency data (Hilborn and Walters, 1992). The research surveys in areas 124 and 125 are designed to minimize such errors that would occur by omitting a large portion of the stock. In general aging errors lead to errors in estimates of the proportion-at-age in the stock, which funnel down to errors in estimated stock-recruitment relationships.

It is also important, from a management perspective, that biomass indices are proportional (i.e. a linear function of the true biomass) to the true stock size. In our initial stock reconstruction's we scaled the survey data from the two different research vessels with the same scaling coefficient and failed to find a linear relationship. Our initial findings suggested hyperstability between survey data and stock size. However, once we accounted for differences in fishing power between research vessels, we did find a linear relationship between stock size and biomass indices (Figure 2.5). The largest difference observed in the proportions-at-age estimated by the VPA model and the survey data are the one-year-old shrimp, indicating that one-year-old shrimp are not fully recruited to the fishing gear. The survey indices shown in Figure 2.1 are not a good estimate of total biomass due, in part, to size selectivity of the fishing gear; however, the biomass indices in recent years are conservative estimates of the vulnerable population (Figure 2.4).

Boutillier et al. (1998) identified some of the potential biases in research survey data (most of which have been corrected for) and noted that no attempt has been made to identify, or correct, potential differences in fishing power between the two main survey vessels. Differences in the size of the vessel, horsepower, towing speed etc. could all contribute to differences in fishing power (Hilborn, 1985). We observed large differences in vessel fishing power, and as a result survey estimates calculated from data collected aboard the G.B. Reed have been scaled downward, and survey estimates calculated from data collected aboard the W.E. Ricker have been scaled upward. One problem of concern here is the treatment of the survey data. Biomass indices for this reconstruction were a sum of independent biomass estimates for area's 124 and 125. The rational we used for summing the biomass estimates is based on the assumption that shrimp in these two areas come from the same unit stock. The concern is that in 1989 and 1991 there were no surveys conducted in area 125. Therefore, we suspect that our biomass indices for these two years under-represent total biomass.

It is possible to estimate a probability distribution for pre-season biomass estimates just prior to the start of the fishery. This procedure would require updating a stock assessment model using the pre-season research survey data. Using a Bayesian framework, a prior distribution for stock biomass would have a lower bound of the fraction of last year's stock that survived the fishery and natural mortality. The upper bound of the prior distribution could be set at an arbitrary doubling of the stock, or predicted growth based on information about stock-recruitment processes. Due to the lack of understanding about environmental effects on recruitment processes (see Hannah, 1993; Boutillier et al., 1998; and Caputi, et al. 1998) we would advise against making such predictions in the absence of survey data. Furthermore, in recognizing the uncertainty associated with predicting next year's biomass, we also recommend that the lower bound of predicted stock size be used as an absolute biomass estimate for calculating TACs. This method is generally referred to as a proven production potential method (Pease and Walters, 1992; Walters and Pearse, 1996). We strongly recommend that the above procedure be explored in an effort to better understand stock dynamics; model development processes are beneficial for understanding the dynamics, and providing management advice as demonstrated in the next section. In addition to forecasting stock sizes, research efforts should focus on trophic interactions that directly effect natural mortality rates. While research on environmental factors is useful, there is little a manager can do to change the environmental conditions (Walters and Collie, 1988).

In previous assessments of shrimp stocks in areas 124-5, the shrimp in each area were classified as separate stocks (Ian Perry, Pers Com.). The justification for doing so stems from a recruitment advection hypothesis that is growing in credibility. Our analysis does not refute the advection hypothesis; we just simply grouped the data for the two areas in order to address management concerns. One of the difficulties in splitting the two areas and running separate population dynamics models for each area is addressing the issue of linkage between the two stocks. Albeit, such a major re-structuring of the models may lead to different predictions about optimal harvest rates. We believe, however, by using a proven production potential method (Pearse and Walters, 1992; Walters and Pearse, 1996) to set TACs, they will be conservative.

2.9 Summary

The historic biomass indices from annual surveys do reflect changes in absolute biomass and are conservative estimates of vulnerable biomass. We also noted that annual commercial catch rates are uninformative about declines in stock size. We believe the commercial catch rates are biased because of changes in catchability associated with either a range collapse or recent advancements in fishing technology. To tease apart the association between catchability and improvements in fishing technology, a rebuilding of the stock must occur. The catch rate data do not suggest a proportional decline in catches with a decline in biomass indices; suggesting management tactics to limit exploitation rates have failed. Pre-season forecasts of absolute biomass are possible; however, we recommend the use of lower bounds on stock size estimates to hedge against uncertainty.

3. Simulating Alternative Management Options

3.1 Introduction

The purpose of this section of the report is to examine alternative management options for the WCVI shrimp trawl fishery. To do so, we first develop a simulation model, which is initialized using equilibrium assumptions and parameters estimated from the VPA model. A dynamic model is used to simulate the response of shrimp populations to alternative management options (“harvest rate rules”). For the purposes of comparison, we also use the simulation model as a "synthesis model", or reconstruct the WCVI shrimp stocks by driving the simulation model with observed catches. The synthesis approach is similar to VPA, however, it introduces an additional parameter for each year of the reconstruction. In this case the additional parameter is a recruitment anomaly parameter which is an estimate of changes in juvenile survival rate (from 0-yr to 1-yr) for each year of the model. In addition to recruitment anomalies, an initial age structure anomaly is used to initialize the population age structure in the first year of the analysis.

For simulating alternative management options we fit the simulation model to the VPA model using a recruitment anomaly time series. The recruitment anomaly time series is assumed to be some environmental process that is fixed in time and directly impacts juvenile survival rates in the population. We then use the simulation model to explore alternative harvest rules for managing the WCVI shrimp trawl fishery, and use it to develop management decision-making criteria. For predicting optimal fishing effort for a given stock size estimate, we propose a model that recognizes changes in catchability associated with changes in stock size.

3.2 Developing the Simulation Model

Using the results of the stock reconstruction in section 2, we parameterize an equilibrium model using two leading parameters, the unfished stock size (N_o) and the relative improvement in juvenile survival rate at low stock sizes (k). For simplicity, we used the estimated natural mortality rate from the VPA (M=0.96), and we assume that age 2 and 3-year-old are fully vulnerable to the fishing gear, and 27% of age 1 shrimp are vulnerable. Given a stock of size N_o, a natural mortality rate and a vulnerability at age schedule, we can calculate equilibrium recruits using:

$$R_o = \frac{N_o}{\sum_a S_a} \qquad 3.1)$$

Where S_a is the proportion of recruits that survive to age a. Using R_o we can calculate the equilibrium egg production as:

$$E_o = R_o \sum_a S_a F_a \qquad 3.2)$$

where F_a is the fecundity at age. For this analysis we chose an arbitrary fecundity-at-age schedule of 10, 875, and 3800 eggs per 1, 2, and 3-year-old shrimp, respectively. The model is structured as such, that the exact numbers of eggs produced by a shrimp of a given age is irrelevant; however, the relative differences in fecundity-at-age is important. The fecundity-at-age schedule reflects the relative number of each age class that are female multiplied by the fecundity at age estimated from Hannah et al., (1995). Given these equilibrium values of recruitment versus egg production, we can calculate parameters for a stock-recruitment relationship. For this case, we use a Ricker stock-recruitment curve:

$$R = a \cdot E_o \cdot e^{-(bE_o)} \qquad 3.3)$$

In this form *a* corresponds to the maximum survival rate through the origin of the stock-recruitment curve. This is expressed as a multiple (*k*) of E_o/R_o. The parameter *k* is referred to as a juvenile survival rate compensation parameter; in other words it is the relative improvement in juvenile survival rate as the annual egg production approaches zero. The *b* parameter is solved by re-expressing equation 3.3 in terms of *b*. To estimate the equilibrium recruitment, stock size and yield we calculated the number of eggs per recruit as a function of fishing rate (*f*) using:

$$\phi_e = \sum_{ages} S_a e^{-fV_a} F_a \qquad 3.4a)$$

and expressing recruitment as a function of eggs per recruit (phi_e):

$$R = -Ln\left(\frac{1}{a \cdot \phi_e}\right) / b \cdot \phi_e \qquad 3.4b)$$

The equilibrium population size as a function of fishing mortality is calculated using equation 3.5:

$$N = R \sum_{ages} S_a e^{-fV_a} \qquad 3.5)$$

The equilibrium yield is the exploitation rate multiplied by the population size. The purpose for carrying out this analysis is to use the results from the population reconstruction to estimate stock recruit parameters for *Pandalus jordani* and to calculate an optimal exploitation rate under a unit stock assumption.

3.3 Simulating Dynamic Responses to Alternative Harvest Regulations

We used a dynamic age-structured model to simulate alternative management policies for area 124 and 125 *P. jordani* stocks. Numbers-at-age were propagated over time using:

$$N_{a+1,t+1} = N_{a,t} e^{-(M + F_t V_a)} \qquad 3.6)$$

Annual recruits were calculated using a Ricker-type stock-recruitment relationship, multiplied by an annual recruitment anomaly:

$$N_{1,t+1} = aE_t e^{(-(bE_t + (1-W_t)))} \qquad 3.7)$$

where W_t is the annual recruitment anomaly in year *t* calculated from the reconstructed stock-recruitment relationship. The total number of eggs produced each year (E_t) is sum of numbers at age multiplied by the fecundity at age schedule. Annual recruitment anomalies are calculated in each year using the observed stock-recruitment data and equation 3.7, solved for W_t.

The model is initialized using the predicted equilibrium recruits multiplied by a survivorship schedule (*Ro**lx*). Additional model parameters include an initialization anomaly for each age class in recognition that the population is probably not at equilibrium in the first year. We fit the simulation model to the VPA model by driving the model with observed commercial catches to calculate annual instantaneous fishing mortality rates (F_t). After fitting the simulation model to the reconstructed population we then use the model to investigate alternative management policies or "feedback" control rules.

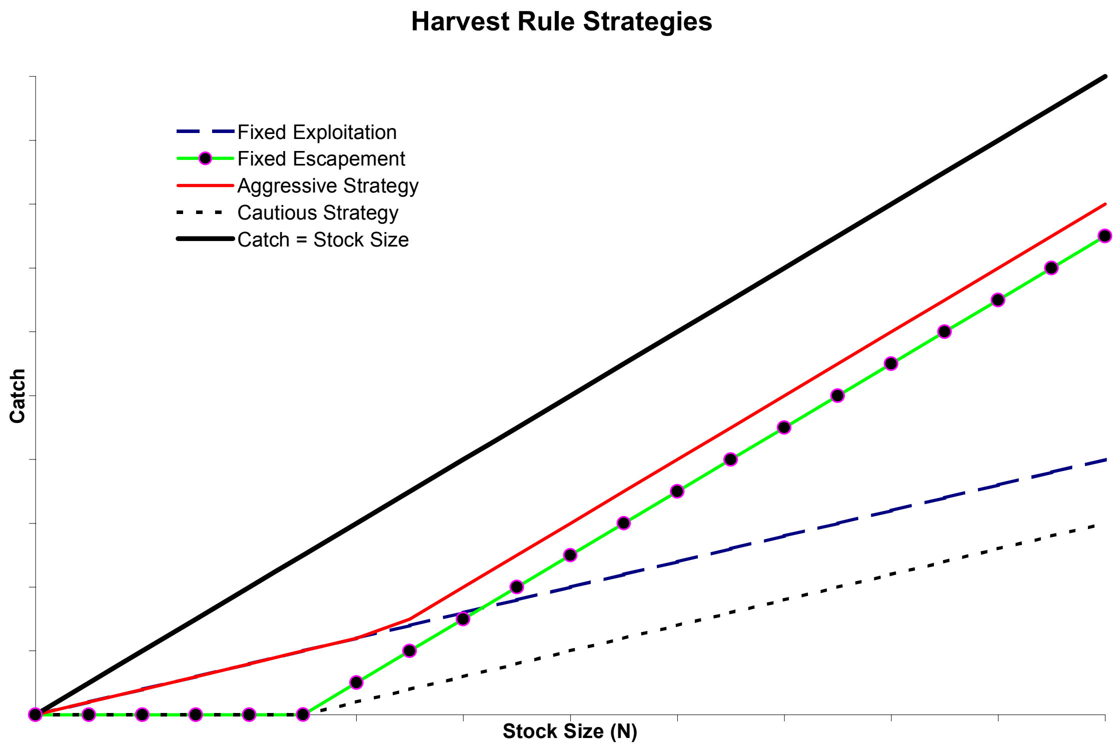

Figure 3.1 Hypothetical harvest control rules explored using the simulation model.

Four separate harvest control rules were examined; a fixed exploitation rate rule, a fixed escapement rule, an aggressive harvest policy and a cautious harvest rule (Figure 3.1). The following equations are used to calculate total allowable catches (TAC) using the four control rules shown in Figure 3.1:

$$TAC = U * N_t \qquad 3.8)……\text{Fixed exploitation rate}$$

$$TAC = \begin{Bmatrix} 0, N_t \leq Esc \\ Nt - Esc, N_t > Esc \end{Bmatrix} \qquad 3.9)……\text{Fixed Escapement}$$

$$TAC = \begin{Bmatrix} U * N_t, N_t \leq Esc \\ Nt - Esc, N_t > Esc \end{Bmatrix} \qquad 3.10)……\text{Aggressive strategy}$$

$$TAC = \begin{Bmatrix} 0, N_t \leq Esc \\ U * (N_t - Esc), N_t > Esc \end{Bmatrix} \quad 3.11)\ldots\ldots\text{Cautious strategy}$$

All harvest rate rules are used to calculate a TAC by harvesting a fraction of the vulnerable population. We compared each of the control rules using two different objective functions: 1) the sum of total annual catches (long-term objective function) and 2) a log-utility function (the sum of log catches + log of population size). The first objective function maximizes long-term yield, whereas the second objective function maximizes annual catches. In order to prevent an upward bias in estimating optimal exploitation rates we include population size in the last year in the objective function; thereby, maximizing the long term catch and future population size. By including the annual population size in the short-term (log-utility) objective function we are placing value on what is left on the fishing grounds in terms of future recruitment. In order to evaluate each harvest control rule, we compare the results of each management strategy to that of an omniscient manager. By definition, an omniscient manager is one that can foresee the future and therefore, can determine optimal annual exploitation rates to maximize either of the two objective functions. Open loop optimization policies, such as the omniscient manager exercise, are often best described using dynamic programming techniques; however, Deriso (1985) shows that optimal exploitation rate rules are best approximated using a fixed harvest rate when maximizing a log-utility function. Conversely, a fixed escapement rule is best when maximizing a long-term yield function.

3.4 Synthesis Approach

The simulation model structure in the previous two sections provides a simple framework for a forward (so call "synthesis model") approach to reconstruct the *P. jordani* stocks. Here we drive the model with observed catches and use the unfished stock size (N_o) and k as leading parameters. We also estimate the recruitment anomaly (Wt in equation 3.7) time series by fitting the model predicted stock size to the relative abundance data from the research surveys using the same Z-statistic and likelihood formulation used in section 2.3. We also use a penalty in the likelihood calculation that effectively minimizes the variance in the recruitment anomaly time series.

$$\theta_{wt} = \left[\sum (w_t - \overline{w})^2\right]^{\left(\frac{N-1}{2}\right)} \quad 3.12)$$

By adding this penalty to the likelihood function, it forces the non-linear search routine to effectively search "harder" on the two leading parameters. To some degree, the leading parameters are influenced by the random variability in juvenile survival rates, and the intent of including recruitment variance in the likelihood estimation is to minimize this effect. The results of the synthesis reconstruction are shown in Figure 3.2. There were a total of 29 parameters used in this reconstruction, and the resulting fit to the survey data was greatly improved.

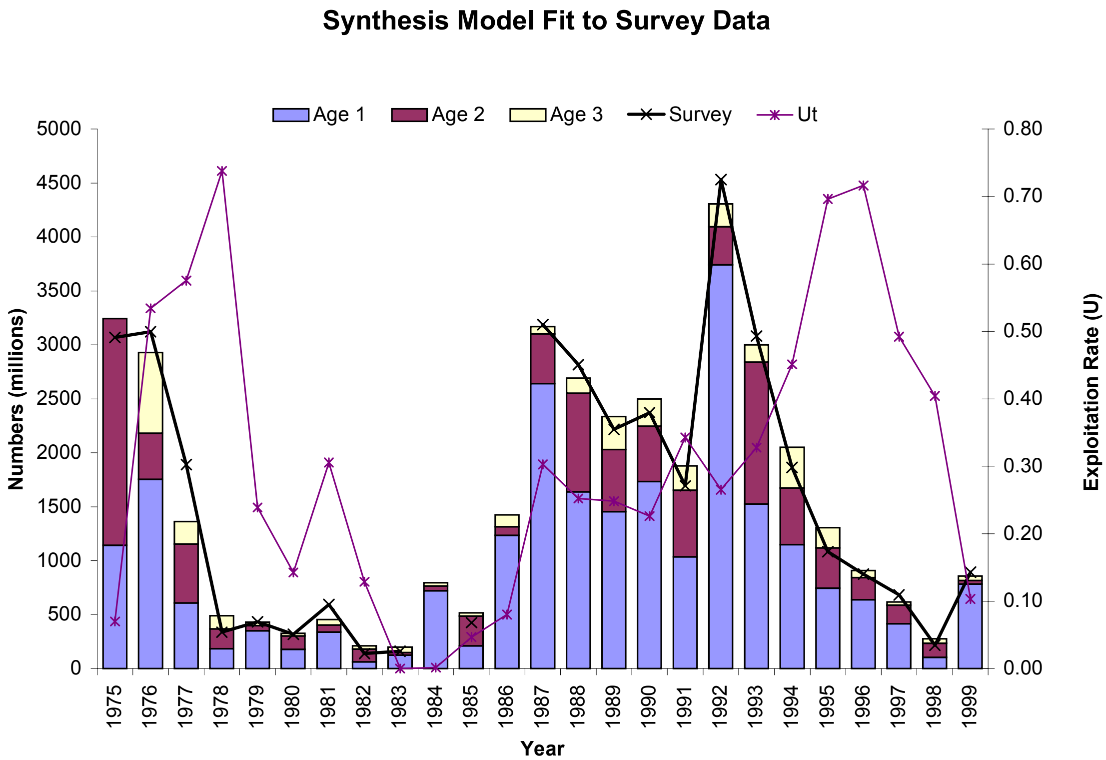

Figure 3.2 Reconstruction of Area 124-125 *P. jordani* stocks using a synthesis modeling approach.

In contrast to the VPA assessment, stock size estimates for the early 1990s are much higher than previously thought in comparison to stock size estimates in the mid 1970s. Overall, the synthesis model predicts lower stock sizes under the assumption of constant natural mortality rate of 0.96, and a fixed vulnerability-at-age schedule. For this analysis we assumed age 2 and 3 shrimp were fully vulnerable to the fishing gear, and 27% of age 1 shrimp were vulnerable (average vulnerability-at-age estimated from the VPA). As a result of lower stock size estimates, the observed exploitation rate time series is also much higher than that observed in the VPA model.

The resulting stock-recruitment relationship from the synthesis model is very different from that constructed using the VPA numbers (Figure 3.3). We used the same method to calculate annual egg production, and recruits are the number of 1-year-old shrimp calculated using a Ricker stock-recruitment function multiplied by an estimated annual recruitment anomaly that best explains the survey data. The observed recruitment from the synthesis model appears to flatten out at an asymptote of approximately 2 billion shrimp, where as the VPA data show evidence for a dome shaped relationship. Furthermore, relative improvement in the juvenile survival rate (*k* parameter) was less using the synthesis approach. One of the major differences observed between the two reconstruction approaches is the absence of high recruitment events during periods of low egg production.

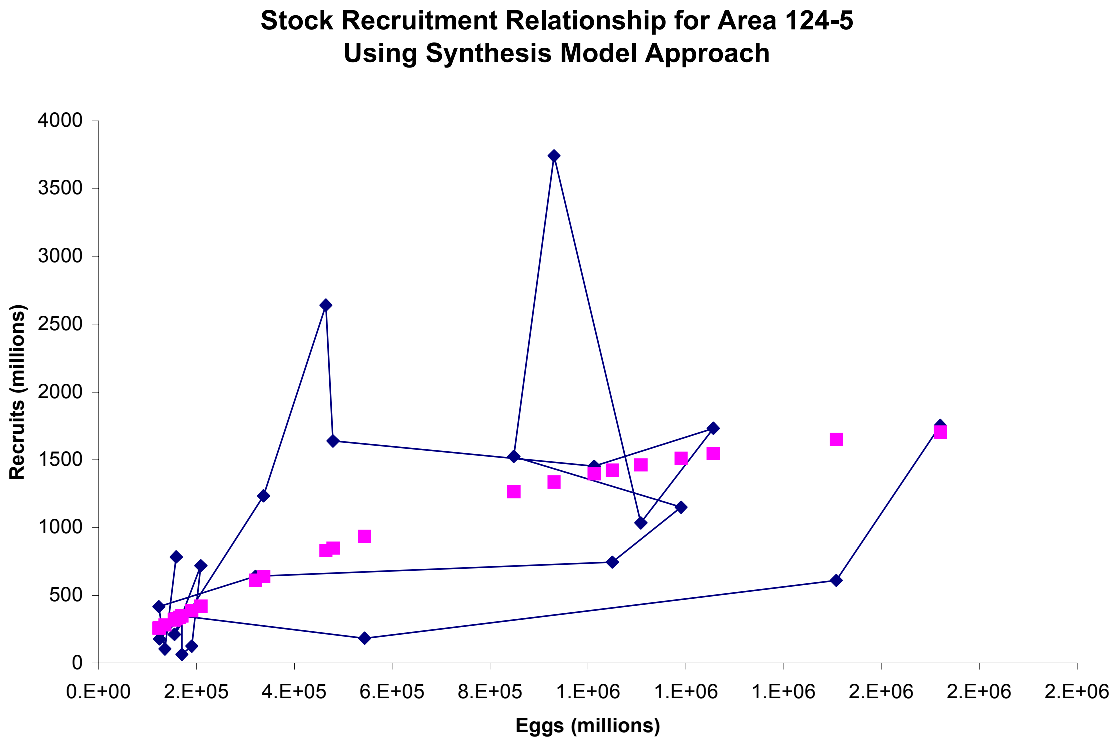

Figure 3.3 Egg production versus 1-year-old recruits, as calculated by the Synthesis model, for areas 124 and 125 combined.

The synthesis approach was carried out merely for comparison with the VPA reconstruction, as we did not use any formal statistical analysis to address uncertainty in parameter estimates. The results of the synthesis model are confusing in that unfished stock size (N_o) and relative improvement in juvenile survival rate (*k*) are confounded. That is the data are equally likely to have come from a large, unproductive stock, or a small, productive, stock. However, the preliminary results from this analysis warrant further investigation because of the encouraging relationship observed between egg production and recruitment at low stock sizes, and there is significant contrast in the relative abundance data that may separate the two confounding parameters.

3.5 Fitting the Simulation Model to the VPA Data

To fit the simulation model to the population numbers estimated from the VPA model, we used the same criterion as fitting the synthesis model to the relative abundance data, but used the VPA data instead. Again, the model was initialized using equilibrium recruits, natural mortality rate of 0.96, age 1 shrimp were 27% vulnerable and age 2 and 3 were assumed to be fully recruited. An initial age structure anomaly and a recruitment anomaly time series were estimated by allowing the model to vary these parameters to best fit the VPA numbers. Closer examination of the recruitment anomaly time series shows that much of the stock-dynamics has been driven by recruitment failure. Here a recruitment anomaly value less than 1 implies a decrease in juvenile survival rate, and a value greater than 1 implies an improvement in juvenile survival rates. The period between 1976 and 1983, we estimated a below average juvenile survival rate, and from 1984 to 1993 an above average survival rate.

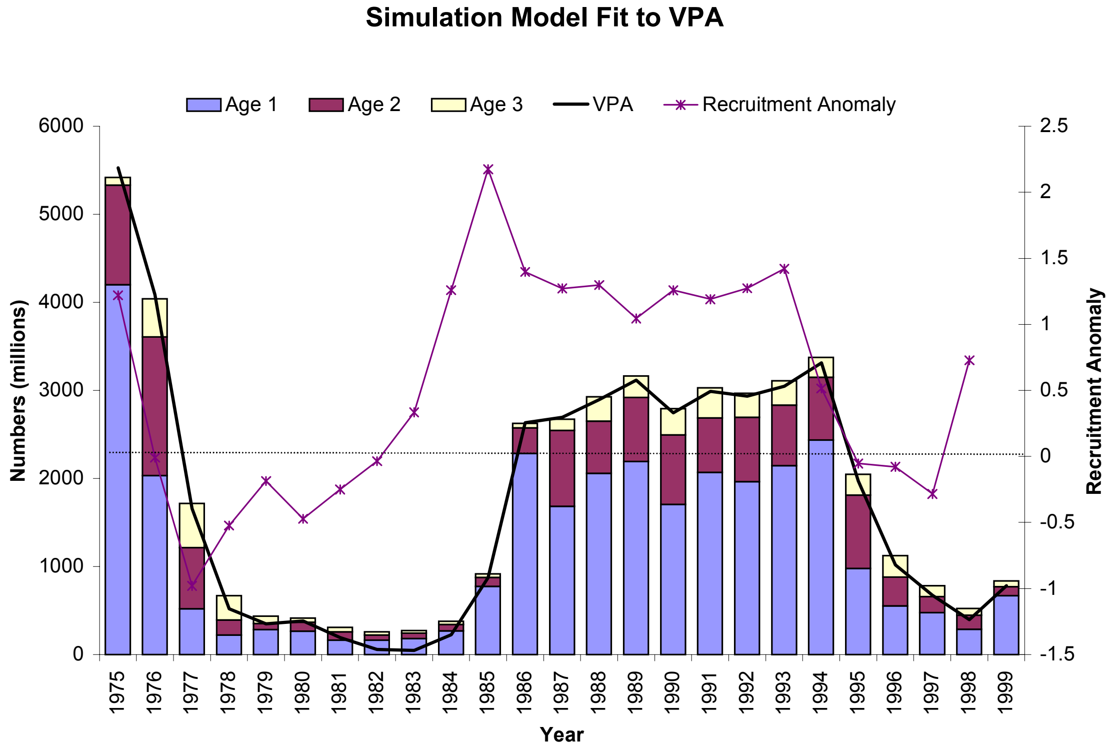

Figure 3.4 Simulation model fit to the VPA model data and estimated recruitment anomaly time series.

The recruitment anomaly time series shown in Figure 3.4 was treated as fixed environmental, physical or spatial process that effects juvenile survival rates. For all simulations exploring alternative management options, this time series remained fixed. An alternative approach would be to generate a stochastic recruitment time series and examine relative impacts of alternative management options using Monte Carlo simulations. We felt, however, that it was best to proceed with our best estimate of the observed anomalies in order to avoid unnecessary arguments as to whether recruitment anomalies are auto-correlated.

3.6 Performance of Harvest Control Rules

In order to design appropriate decision-making criteria for managing the WCVI shrimp trawl fishery, we must first determine which harvest system is appropriate (or optimal). Table 3.1 summarizes simulation results of the harvest control rules outlined in section 3.3. We present here two ways that evaluate the performance of each harvest control rule, a long-term yield objective function and a log-utility function. Recall, the long-term yield objective function is the sum of annual catches plus the population size in the last year, and the log-utility function is the sum annual log catches plus log of population size. Overall, we found that average annual yields obtained by each control rule best approximate the omniscient manager using the log-utility objective function and in practicality this function is better suited for the fishery because of the high negative penalty associated with closing the fishery.

Table 3.1 Simulation results comparing four different harvest control rules to the observed harvest rates, and that of an omniscient manager. Simulations were carried out using the sum of annual catches (long term yield) as one objective function, and the sum of log catches plus log population size as a second objective function. Percent average yield is a comparison of average annual yields for each policy with that of the omniscient manager.

	Objective Function Value	% of Average Yield	Avg. Harvest Rate	Var. Harvest Rate	Min Yield	Max Yield	Avg. Yield	Years Closed
	Long-Term Yield							
Omniscient Manager	9970		0.238	0.070	0	2173	365	12
Observed Management	7177	68%	0.244	0.021	0	889	250	1
Fixed Exploitation Rate	6339	68%	0.281	-	40	670	250	0
Fixed Escapement (N = 1549)	7787	91%	0.219	0.058	0	1700	333	11
Aggressive Manager	7790	92%	0.225	0.054	6	1697	334	0
Cautious Manager	8408	94%	0.245	0.040	0	1196	344	8
	Log-Utility Function							
Omniscient Manager	300		0.274	0.013	31	830	314	0
Observed Management	249	79%	0.244	0.021	0	889	250	1
Fixed Exploitation Rate	295	73%	0.229	-	40	551	228	0
Fixed Escapement (N = 1602)	171	106%	0.214	0.056	0	1677	332	11
Aggressive Manager	296	95%	0.243	0.014	35	1516	298	0
Cautious Manager	298	94%	0.252	0.006	20	793	296	0

Our results also conform to the findings of Deriso (1985), where under a long-term yield objective a fixed escapement policy is preferred, and under a log-utility objective a fixed exploitation rate is preferred (column 1 in Table 3.1). When evaluating the fishery in terms of average annual yields, the fixed escapement rule out performs the fixed exploitation rate rule. However, the cost of increasing annual yields also results in closing the fishery for 11 years. A surprising result of the simulations was the comparison between the aggressive versus cautious approach. In terms of average annual yields, there is little, or nothing, to be gained by putting the stock at risk by intensive harvesting. For example, using the log-utility function, the difference in average annual yields for aggressive management versus cautious management is 2 tonnes per year. The main difference between the two management objectives is the cautious approach tends to maximize recruitment to the fishery in years when juvenile survival rates are good, and the aggressive approach tends to fix recruitment in each year, good or bad. Using either of the two objective functions, there were no short-term or long-term gains by aggressively managing the fishery. Under a precautionary and risk adverse approach to the management of the WCVI shrimp trawl fishery, the safest harvest control rule is a combination of fixed exploitation rate with a closure occurring when the stock reaches a target escapement (the cautious harvest rule).

3.7 Determining Optimal Fishing Effort and Biological Thresholds

Thus far in this paper we have been discussing managing the fishery by using some harvest control rule, which is quite straight forward in a simulation model. By using a seasonal opening we do not limit catch or exploitation rate for the WCVI shrimp trawl fishery. The problem here is translating a level of fishing effort into an exploitation rate. In the past, we have made the dangerous assumption of constant catchability, and we have already shown that catchability increases as stock size decreases for the WCVI shrimp trawl fishery. Catchability may also increase with improvements in fishing vessel technology, and fishing gear. The key issue here is to determine what level of fishing effort is required to reach the target exploitation rate.

In recognition that catchability increases with decreases in stock size, we choose to approximate catchability using the following relationship:

$$\hat{q}_t = \frac{\alpha}{N_t} \qquad 3.13)$$

where we estimated alpha by fitting equation 3.8 to the estimated data shown in Figure 2.7. The optimum fishing effort required to reach a target instantaneous fishing mortality rate is simply $E_t = F_{target}/q_t$. We can now substitute this equation into our simulation model to predict annual optimum fishing efforts given an estimate of stock size. This approach relies heavily on our estimate of alpha; therefore, to calculate annual fishing efforts we recommend that the upper bound for alpha be used (i.e. over estimate catchability).

Using the cautious harvest rule, we can calculate the probability of achieving a 35% exploitation rate for a range of annual fishing efforts by using the relationship between stock size and catchability (see Figure 2.7 for example). The relationship between fishing effort and alpha is now expressed as $E = F_{opt}/\alpha$*Escapement. The distribution shown in Figure 3.5 reflects, more or less, our uncertainty in changes in catchability with changes in stock size.

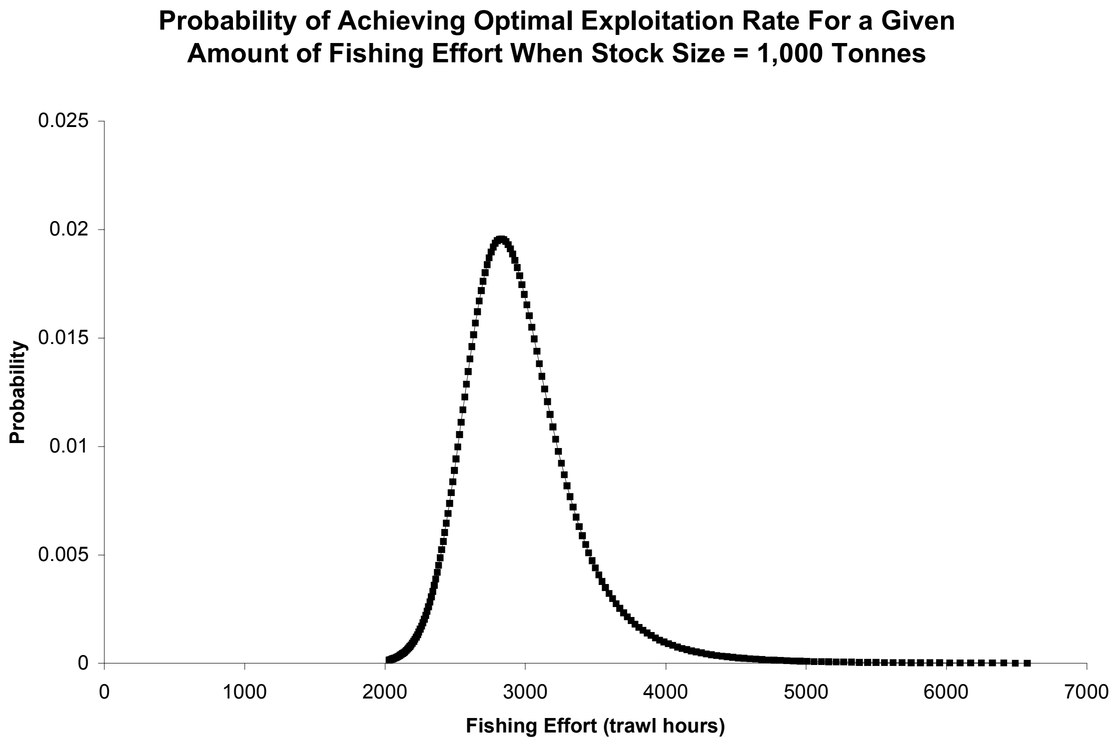

Figure 3.5. The probability of achieving an exploitation rate of 35% for a given amount of fishing effort when the stock size is at the minimum escapement target of 1,000 tonnes.

Using a precautionary and risk-adverse approach to managing shrimp stocks in Areas 124-125, the maximum fishing effort level should not exceed 2,200 trawl hours (corresponding to the lower credible interval in Figure 3.5) when the stock size is at a minimum escapement target of 1,000 tonnes. It is important to note here, that calculating annual fishing effort in this manner does not reflect the uncertainty in our estimates of stock size. The purpose of this exercise was to recognize that range collapses associated with a decrease in stock size increases q, and our effort calculations should reflect changes in catchability.

In the previous section we presented results of replaying the WCVI shrimp trawl fishery using four different control rules. We can use these results as base for determining optimum escapements and/or optimum exploitation rates (Table 3.2). Under the fixed exploitation rate rule, the optimum harvest rate ranges between 23% and 28% depending on whether we evaluate the fishery over the short term or long term, respectively. We recommended earlier using the cautious manager control rule, and under this approach 35% (short-term objective) or 58% (long-term objective) of the available surplus would be harvested, and in years where biomass estimates are less than the target escapement the fishery would be closed.

Table 3.2 Optimum harvest rates and or escapement targets under the four different control rules. Note the escapement targets are expressed in millions of shrimp.

Harvest Rate Control Rule	Long-Term Yield Objective		Log-Utility Objective	
	Target U	Target Esc	Target U	Target Esc
Fixed Exploitation Rate	0.281	-	0.229	-
Fixed Escapement	-	1549.7	-	1602.4
Aggressive Manager	0.02	1557.7	0.161	1968.9
Cautious Manager	0.587	784.3	0.353	301.9

The objective of this working paper is to provide protocols and decision-making criteria for managing the WCVI shrimp trawl fishery. In Figure 3.6, we provide a graphical representation of the harvest control rules that have been optimized using the log-utility function. Using the recommended cautious management approach, no harvesting should occur when stock estimates are below 300 million shrimp (1,000 tonnes), and when surplus is available, no more than 35% of the surplus should be harvested.

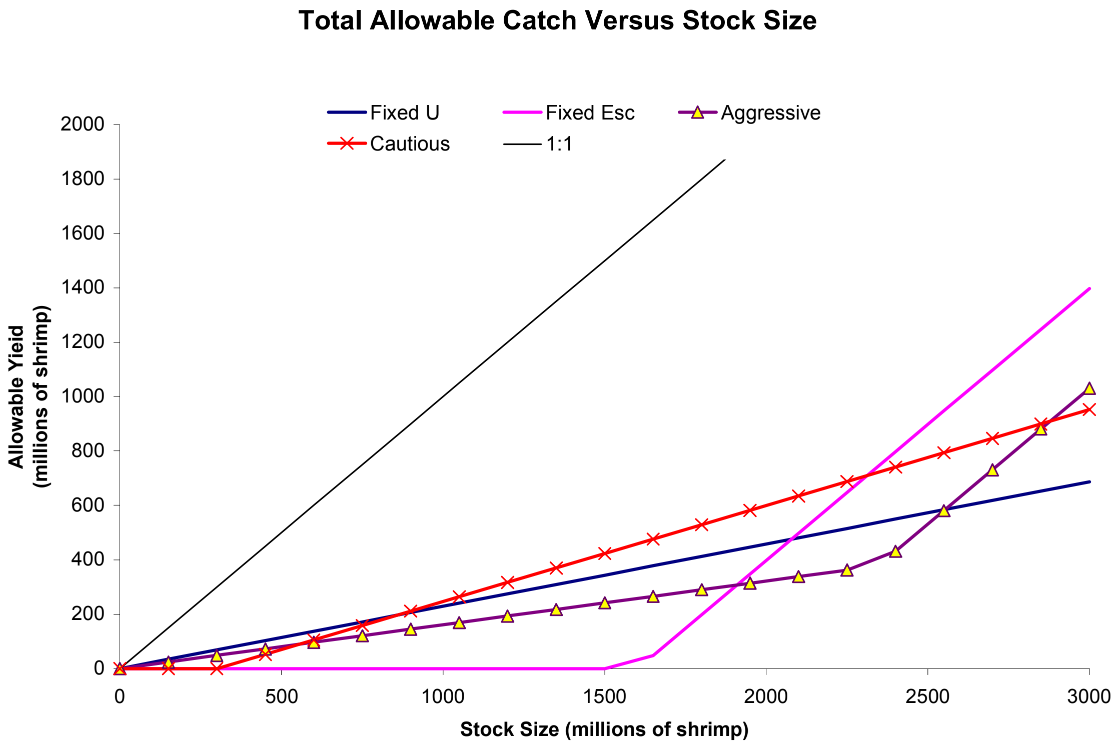

Figure 3.6 Yield options versus stock size using the four different control rules, optimized using the log-utility function,

For the basis of comparing how the recommended cautious harvest control rule compares to historical removals in this fishery we have overlaid the observed yields versus estimated stock size on the cautious control rule in Figure 3.7. We have provided both catch versus vulnerable biomass, as calculated in the VPA, and catch versus survey biomass. Based on the historical removals in this fishery, the major changes associated with managing this fishery using the cautious harvest control rule would be a reduction in allowable catches when the stock size is below 1,500 million shrimp. The pattern observed in Figure 3.7 may also reflect the economic issues associated with the cost of fishing.

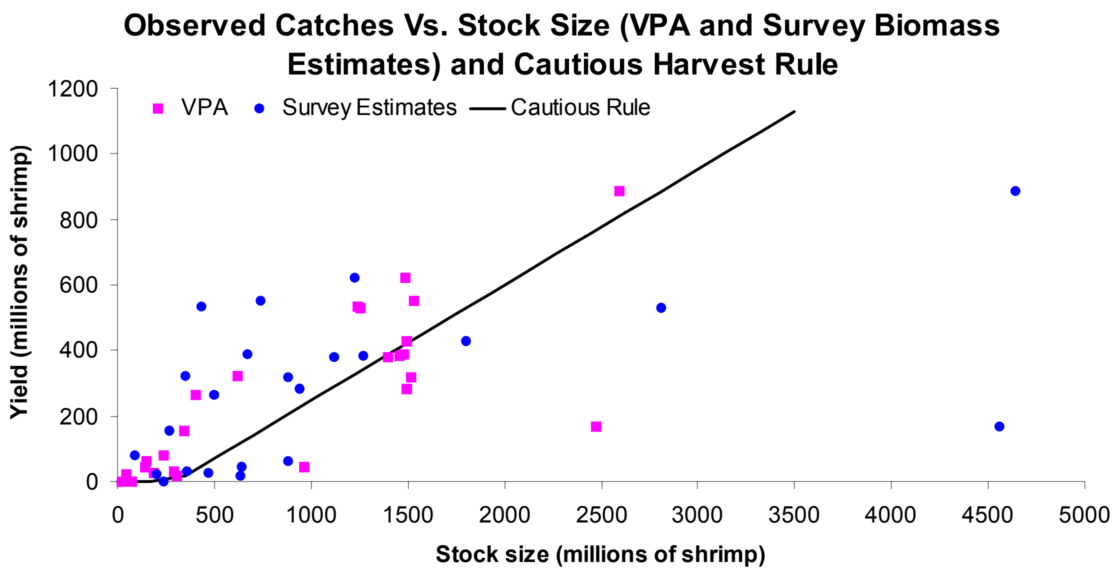

Figure 3.7 Observed yields versus stock size (calculated using VPA and Synthesis methods) and the optimized cautious harvest control rule (Esc = 300, U = 0.35).

3.8 Discussion

In contrast to the stock reconstruction using the VPA method, the stock synthesis approach shown in section 3.4 fit the survey data much more precisely. However, in addition to assuming constant natural mortality, fixed vulnerability-at-age schedule, and fixed fecundity-at-age, we also added 29 additional parameters to the model. Given the additional flexibility in the model structure, it is of no surprise that a better fit is achieved. This interesting result of the synthesis approach was the emerging stock-recruitment relationship (Figure 3.3). In this assessment we did not predict any large recruitment events during periods of low egg production, suggesting, for the first time, a relationship between egg-production and recruitment for *P. jordani* in areas 124-5 combined. In contrast to the stock-recruitment relationship calculated using the VPA data, the relative abundance time series data suggest that recruitment be much reduced during years of low egg production.

After fitting the simulation model to the VPA model, the resulting recruitment anomalies are in general agreement with recruit abundance and regression models fits of Boutillier et al. (1998). The general pattern is a recruitment failure from 1975 to 1980, which led to a rapid decline in stock size, followed by an improvement in survival through the mid 1980s. For the next 10 years catches in area 124-125 reached a stable level, and estimated recruitment anomalies were also stable, relatively speaking, during this time period. Recently, however, both biomass indices and our estimated stock size are showing a similar decline to that observed in the late 1970s. Exploitation rates were also increasing during the late 1990s, suggesting recruitment over fishing may have caused the decline. The purpose of replaying the history of the WCVI shrimp trawl fishing was not to describe failures in management or search for explanations about recruitment variation, but to ask whether or not we can safely apply a harvest rule that is robust to curve balls from mother nature.

In section 3.6 we were able to provide estimates of stock sizes for which management actions should be taken in order to avoid over-fishing the stock. Furthermore, we also demonstrated that there is nothing to be gained by using an aggressive harvest control rule in comparison to a cautious approach. Using a pre-cautionary approach, harvesting should not occur when biomass estimates are below 1,000 tons, and in years where there is available surplus, no more than 35% of the surplus should be harvested. These estimates are strictly for statistical areas 124-125 combined. As shown in Table 3.1, this policy approximates the optimal (or omniscient) policy at 98%.

Areas 124 and 125 make up only two of three PFMA's for the WCVI offshore shrimp trawl fishery. In recent years the fishery has expanded into area 123 and we have chosen to ignore this area in this assessment document for data limitation reasons. However, this does not mean we can't extrapolate the harvest control rules for this area. For the cautious harvest control rule, the minimum escapement target, also referred to as limit reference point under the precautionary approach, is 40% of the unfished stock size (No= 2,463 million shrimp for area 124-5). To extend this rule to area 123, we recommend that 40% of the unfished stock size be set as the minimum escapement target and 35% of the available surplus be harvested. If, however, an estimate of the unfished stock size does not exist then we recommend using a fixed exploitation rate of 23% for setting TAC's.

The key issue is not calculating stock size thresholds, but what is the current stock size, and can we be sure pre-season biomass indices are not over-estimating absolute abundance. In both our reconstruction assessments, survey data since 1987 has under-estimated absolute abundance, and if we treat the biomass indices as an absolute abundance it won't be long before accusations of under-utilization are made. Estimates of absolute abundance will require interpretation of biomass indices using more formal stock assessment techniques as discussed in section 2.8.

The ramifications of safely managing to a higher TAC for fewer years results in more frequent closures of the fishery. Harvesting the entire available surplus followed by poor recruitment into the fishery results in a protracted period of recovery, much like we observed in the early 1980s. This of course assumes that recruitment comes from within the stock. Much of the evidence collected so far indicates recruitment to an area may be a result of spawning occurring on more southerly grounds. This evidence is also described by a shift in fishing effort distribution. For example in 1977, the distribution of total fishing effort in areas 124 and 125 was 83% and 17%, respectively; whereas, in 1978 the distribution changed to 19% and 81% in areas 124 and 125. In other words, a strong cohort that was present in area 124 resulted in strong recruitment in area 125 in subsequent years. Ideally, to test the recruitment advection hypothesis area 124 should be closed to fishing, and area 125 should remain open and fished at unsustainable rates. The predicted outcome of such an experiment would show no recruitment over fishing effects if the recruitment advection hypothesis was correct. We are not advocating this experiment; in fact it may pose a large risk to the entire fishery North of area 125 if the hypothesis is true. However, the hypothesis is worth investigating from a management perspective, because if source-sink dynamics were occurring, then it would pay to protect the source population, and live off the surplus production (Roberts, 1998).

In our assessment we failed to discern whether a large component of the variability observed in annual stock sizes is a result of fishing dynamics, or simply due to an environmental component affecting recruitment to the fishery. Previous assessment on these stocks has shown some correlation with environmental parameters (Boutillier et al, 1998). Regardless if the observed variability is due to fishing effects or environmental effect the best management objective is to stick with a harvest rule. In this assessment we suggest using a cautious rule (35% of available surplus) be harvested. A word of caution here, by no means should this rule be carved in stone! As additional information is gained about the dynamics of the stock and the response of the fishing fleet, the harvest rule parameters should be re-evaluated.

Under the current management regime, fishing effort is restricted using a seasonal opening, and management options consist of shortening or lengthening the duration of the fishing season. Ultimately, the intent of effort restrictions is to limit exploitation rates. An alternative approach to limiting exploitation is to restrict area openings such that only a fraction of the stock is exposed to fishing (Walters, *in Press*). In the shrimp by trawl management plan, there is no basis for closing an area to limit exploitation rates on a stock, and we feel that this is an option that should be implemented (especially when uncertainty about stock size is large). Seasonal openings, in principle, limit the maximum effort that can be exerted by the fishing fleet, and its purely a judgement call on the part of management to estimate what fraction of the maximum fishing effort will be allocated on each of the fishing grounds (see Gillis, et al. (1993); or Walters and Bonfil (1999) for predictive models). To estimate the length of the fishing season, we have proposed a new approach to calculating optimal fishing effort to achieve a desired exploitation rate. This approach is aimed at compensating for changes in catchability associated with changes in stock size (Martell and Walters, *in review*) not for changes in fishing technology (Robins et al. 1998). Also, delaying the opening of the fishery is another alternative to restricting fishing effort, and it allows for additional growth and larger shrimp, which fetch higher prices at the dock.

3.9 Summary

Using an alternative method to reconstruct the *P. jordani* fishery in areas 124-125, we were able to show a reduction in recruitment associated with a reduction in egg production. Although no formal statistical analysis of this procedure was carried out, the biomass indices suggest a stock-recruitment relationship for this stock. Having no predictive capabilities about forecasting recruitment, the best management strategy is to proceed cautiously using a fixed escapement rule that only permits 35% of the annual surplus to be harvested. Furthermore, unlike a true fixed escapement policy, this approach favors population growth under good recruitment regimes and allows fisheries statistics to be collected over a wide range of stock sizes. In recognition that changes in catchability do occur, as a result of stock distribution changes, we have developed a method for estimating fishing effort required to achieve a desired exploitation rate.

4. Recommendations

The intent of this paper was to construct a simulation model of what we know about the dynamics of the stock and investigate various management strategies to aid in development of decision rules for managing this stock. For the most part we have done this; however, along the way we encountered several problems with the survey data, and made assumptions in order to carry out this task. One such assumption that has a great deal of influence on the stock reconstruction is assuming that proportion-at-age are the same in research surveys as in commercial catch. Another easily violated assumption is constant natural mortality over time, and across age classes. From a management perspective, uncertainty in changes in catchability associated with changes in stock size, or developments in fishing technology have a pronounced effect on determining a level of fishing effort required to attain a target exploitation rate. In light of these assumptions and uncertainty in stock-size and catchability we suggest the following recommendations (not in order of importance):

- Continue collection of catch-at-age data from the commercial fisheries and incorporate proportions-at-age caught by commercial fisheries into stock assessment models.
- Alternate geo-statistical models should be investigated (e.g. Kriging interpolation) for analysis of research data in attempts to better plan research cruises and reduce the variance in population estimates.
- Further investigations about changes in natural mortality over time are required, as natural mortality rates largely dictate the level of sustainable exploitation.
- Continue fishery independent survey programs, as these data are required for forecasting stock size estimates and total allowable catches.
- In recognition of changes in catchability and the uncertainty associated with managing the fishery through seasonal access we recommend that the WCVI shrimp by trawl fishery move to a quota-based system. Total allowable catches (TACs) for each area are calculated prior to the opening of the fishery, and based on research survey data and prior assessment using more formal stock assessment techniques.
- TACs should be calculated using a conservative approach (pre-cautionary), where no more than 35% of the annual surplus (1,000 tonnes is the minimum escapement target for areas 124 and 125 combined) is harvested, and this rule should be re-evaluated as additional information is acquired.
- Further investigations about stock-recruitment processes should be carried out to better understand the effects of exploitation and environmental components that limit recruitment.

5. Acknowledgements

We would like to thank many of the people directly involved in collecting the survey data, from the cooks to the Captains, officers and crew, and especially efforts of the fishing masters on the GB Reed and WE Ricker. Also many thanks to all of the technicians who spent endless hours staring through microscopes sexing shrimp in 20-foot swells. Also, discussions with three graduate students, Heather Bears, Ashleen Downes, and Janet Yu, were helpful in developing a simulation model for exploring management policies.

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Appendix I.

PSARC INVERTEBRATE SUBCOMMITTEE

Request for Working Paper

Date Submitted: Mar.1, 1999 (*revised Dec. 1999*)

Individual or group requesting advice: Rick Harbo, Laurie Convey, Kim West, Dale Gueret
(Fisheries Manager/Biologist, Science, SWG, PSARC, Industry, Other stakeholder etc.)

Proposed PSARC Presentation Date: Jan. *revised to June* 2000
(outline any timing concerns for the provision of advice)

Subject of Paper (title if developed): Determination of biological thresholds for the west coast of Vancouver Island offshore shrimp stocks

Lead Author(s): Boutillier et al.

Fisheries Management Author/Reviewer: Harbo/Convey

Rational for request *(What is the issue, what will it address, importance, etc.)***:**

Biological thresholds for the offshore shrimp stocks on the west coast Vancouver Island are required for management of the shrimp trawl fishery and to make an in-season assessment for the 2000/01 season.

Objective of Working Paper:
(To be developed by FM & StAD for internal papers)

To provide a protocol and decision-making criteria in order to manage the west coast offshore shrimp trawl fishery.

Question(s) to be addressed in the Working Paper:
(To be developed by initiator)
To be reviewed and amended by the managers

How have historic biomass indices from the annual west coast surveys compared to annual historic landings? An analysis of recent surveys (last 5 years?) on the West Coast Vancouver Island, providing confidence limits surrounding biomass estimates. A review of annual historic landings relative to biomass estimates from the surveys.

What is the relation between the annual May biomass estimates and the stock biomass (e.g. linear, non-linear?)?

Can an estimate of absolute abundance be made?

Can critical thresholds, at which point there would be no harvesting or no further harvesting, be provided? What are they?
Recommendation of a minimum biomass threshold level, for select areas of the west coast Vancouver Island offshore fishery (WCVI), or as a group. Include a critical threshold level at which point we would not open the fishery or there would be no further harvesting. Thresholds may also be developed based on harvesting (CPUE) rates.

Provide a protocol for an in-season recommendation for the duration of the WCVI seasonal opening for the 2000/01 fishery (opens June 1, 2000).

Given that there is a strong environmental component to this fishery, what type of fishery and management options are available (keeping in mind the objective is for a sustainable fishery)? As we discussed, what are the ramifications of managing to a higher TAC for fewer years or of a more conservative TAC over a longer period? What are the yield options? What kind of fishery would the options provide; would it be a steady fishery or a fishery with high fluctuations in harvest between years?
Include resultant effects on the fishery. Include recommendations.

Given that this fishery is currently managed by a seasonal opening, what are the recommendations for a change to this strategy? Refer to arguments that seasonal openings do not control effort. This may belong in the introduction – why management options are needed.

Consideration may be given to: How can the annual May survey, or optimally, the survey(s) in prior years be used to predict, set or adjust annual quotas *in advance* of the fishing season?

Management Objectives for this fishery:
A pre-cautionary and risk adverse approach to the management of the fishery, for conservation of the stocks and a sustainable fishery. To maximize the value of the fishery and consider the goals of stakeholders in the economics of the fishery (*noting that the industry is in some state of flux at the moment and it is unknown whether a quota-based or open fishery will be considered in the long term*). The objectives as they relate to the economics of the fishery, will go hand in hand with the options that this paper will provide. Minimizing the bycatch of eulachons would also be a management consideration.