Trapped by Uncertainty?
A Decision Framework for Evaluating Escapement-Based Management Procedures for the Spot Prawn (*Pandalus Platyceros*) Fishery in Howe Sound, BC

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ABSTRACT

Fisheries and Oceans Canada (DFO) recently adopted the precautionary approach (PA) to fishery management that aims to ensure resource sustainability by demonstrating the application of reference points and formal decision rules. DFO and the Pacific Prawn Fishermen Association are interested in evaluating the current prawn management strategy in Howe Sound, BC, under PA requirements. This study identifies and evaluates the main components of the prawn fishery management strategy that influence the prawn population in Howe Sound, BC. Then, uses a closed-loop simulation feedback control system, management strategy evaluation, to evaluate the performance of management options in the presence of uncertainty. Results from these evaluations highlight the trade-offs and help identify the best options for mutual ecological and economic gain for the Howe Sound prawn fishery.

Keywords: Spot prawn; fisheries model; management strategy evaluation; trade-off analysis; Howe Sound

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CHAPTER 1

GENERAL INTRODUCTION

Fisheries and Oceans Canada (DFO) recently adopted a decision-making framework that incorporates the Precautionary Approach (PA) into fisheries management (DFO 2006). The main tools for implementing the PA are technical reference points and harvest control rules that incorporate uncertainty about the state of fish stocks into management decision making scenarios (FAO 1996). Reference points are derived from quantitative analyses and specify population states useful for management of fish stocks and fisheries (e.g., biomass at maximum sustainable yield, B_{MSY}) (Caddy and Mahon 1995). Harvest control rules are predetermined management actions that attempt to control the amount of fishing effort or catch, usually as a function of stock status, and may include environmental and economic considerations (Gabriel and Mace 1998, Deroba and Bence 2008).

To satisfy and ensure compliance with Canada's Federal Framework for the Precautionary Approach, DFO (2006) PA guidelines include: (1) a requirement for prior notification about undesirable outcomes (i.e., low fish stock abundance) that could result in fishery closures; (2) formulation of harvest control rules that specify regulatory actions to be taken when deviations from operational targets and constraints are detected; (3) adoption of a management plan only after the plan has effectively demonstrated an ability to avoid undesirable outcomes for the resource and fishing communities; and (4) participation of fishery stakeholders in the development of management objectives (Caddy and Mahon 1995, de la Mare 1998).

Application of a precautionary approach to fisheries management has been slow in Canada and throughout the world (Garcia 1994, de la Mare 1998, Hilborn et al. 2001, Cadrin et al. 2004). The primary reason for the slow start is that fishery management objectives are not well defined nationally or domestically (de la Mare 1998). Additional barriers to implementation include a lack of data or money to estimate the population abundances required to implement specific management strategies (e.g., TAC systems in exploitation-based strategies) (Beddington and Rettig 1983, Boutillier and Bond 2000) and uncertainty in estimation of production parameters and reference points required to determine thresholds in escapement-based strategies (de la Mare 1998, Cadrin and Pastoors 2008).

Spot prawns (*Pandalus playtceros*) are one of many shrimp species for which implementing the PA to fishery management presents a considerable challenge (Cadrin et al. 2004, DFO 2009). Similar to other shrimp fisheries, they suffer from uncertainty in population parameters which propagates to uncertainty in estimation of appropriate reference points (Cadrin et al. 2004). These uncertainties are a concern because shrimp and prawn fisheries represent one of the largest shares of economic value in internationally traded fishery markets (Anderson et al. 2011, FAO 2010). Shrimp fishery markets continue to grow because finfish populations and fisheries have yet to recover from low, unproductive levels. Furthermore, shrimps and other invertebrates have increased in abundance as a result of reduced predation pressure (Pauly et al. 2002, Worm and Myers 2003, Essington et al. 2006, Anderson et al. 2011). Thus, a harvest management strategy for spot prawns must meet fishery objectives, be implemented effectively, and present sustainable outcomes for the fishery.

The British Columbia spot prawn fishery is managed using an escapement-based strategy. This strategy attempts to keep the spawning stock size at a constant level from year-to-year, which is accomplished by removing all biomass over the escapement target level (i.e., the surplus). The appropriate escapement level can be based on stock recruitment analysis (Walters 1975, Hall et al. 1988, Hilborn and Walters 1992, Caddy 2004). Simulation analyses have shown that taking surplus stock above the escapement goal produces the highest possible average annual harvest; however, it also maximizes year-to-year variability in yield (Larkin and Ricker 1964, Reed 1979, Hilborn and Walters 1992, Eggers 1993). Therefore, an escapement-based strategy is considered optimal when the management objectives are to maximize long-term catch while avoiding exploiting populations at low abundances. The choice of an escapement-based strategy for the BC spot prawn may be attributed to the prawn's semelparous life cycle (i.e., spawns once then dies) where the spawning stock size required to maintain the population at optimal levels can be estimated more readily than estimates of total population abundance which are required for exploitation-based strategies. Furthermore, the BC spot prawn fishery does not collect data regarding the area fished by a trap which makes it more difficult to generate estimates of absolute abundance for exploitation-based strategies (Miller 1975, Boutillier and Bond 2000).

DFO recently reviewed the implications of implementing an alternative exploitation-based strategy for the BC spot prawn fishery and found the escapement-based strategy is still preferred because it maximizes long term landings, an important objective for the fishing industry (Boutillier and Bond 1999a). However, both DFO and the Pacific Prawn Fishermen Association (PPFA) agreed that there is a need to evaluate (via simulation modelling) the escapement-based procedure to ensure that it is robust to uncertainty in population parameters and implementation. I address this need in the following two chapters. In Chapter 2, I evaluate the main components of the current (hereafter referred to as the status quo) escapement-based management strategy that could influence the prawn population in Howe Sound, British Columbia (Figure 1). In Chapter 3, I use a closed-loop feedback simulation to assess the potential future consequences of applying the prawn management procedure given uncertainties in the population (as identified in Chapter 2 analyses). I evaluate trade-offs in conservation and catch objectives to assess how uncertainty in fishery components, under a range of plausible scenarios about alternative environmental and management procedure conditions, affects future performance of the fishery. The results of this study can facilitate justification of a larger, more rigorous look at spot prawn management in British Columbia.

CHAPTER 2

EVALUATION OF THE MAIN COMPONENTS OF THE SPOT PRAWN FISHERY MANAGEMENT PROCEDURE IN HOWE SOUND, BC

Introduction

Problems and uncertainties in the analysis of three key fishery processes; stock-recruitment, catchability, and effort dynamics assessments, are pervasive in the fisheries literature (Hilborn and Walters 1992, Walters and Martell 2004). Temporal variation in trap fishery catchability (*q*) represents one of the most serious biases in fisheries stock assessment (Hilborn and Walters 1992). Variation in *q* can arise due to changes in fishing gear, interactions between the stock and the area fished (i.e., density-dependent *q*), shifts in populations due to environmental effects, and changes in size compositions of the stock (Arreguin-Sanchez 1996, Walters and Parma 1996, Harley et al. 2001, Marchal et al. 2003). Spatio-temporal trap fishing effort dynamics represent the numerical response of fishers to population abundance and are an important driver of fishery exploitation rates (Hilborn and Walters 1992). Thus, the examination of a fleet's response to regulatory changes is also a key factor in the evaluation of a fishery management procedure.

Highly complex models that attempt to generate hypotheses about how a fishery might work and that simulate the managed system as a whole are vulnerable to mis-specification; therefore, conditioning the model simulations based on known features of the fishery and empirical data can help to avoid this mis-specification (Sainsbury et al. 2000). For example, the most recent stock-recruitment (SR) relationship for the spot prawn does not consider the uncertainty of the estimates nor has the output been used to inform management decisions in the fishery (Boutillier and Bond 2000). Therefore, the goal of this Chapter is to use historical fishery data to estimate these three key fishery processes that are critical to the performance of the BC prawn management procedure in

Howe Sound, BC (Figure 1). Specifically, I characterise the SR relationship using a Bayesian approach to estimating the range of uncertainty associated with optimal escapement values (S_{MSY}). To estimate q, I develop in-season depletion models for historical commercial fishing data from Howe Sound based on ten-year increments. To estimate the trap fishing effort responses, I examine the relationship between annual prawn fishing effort and annual indicators of prawn density over a ten-year period. However, effort responses in Howe Sound are not expected to be a major cause of concern because the number of fishing vessels in Howe Sound has remained relatively low between 2000 and 2012 (average of 15 vessels; B. Ennevor, DFO, pers. comm. 2012). The results of the parameter estimation will be used as input to the simulation model (Chapter 3) and to examine the potential consequences of implementing management decisions under a range of uncertain conditions.

Methods

Spot Prawns and the fishery in How Sound, British Columbia

Spot prawns range from Alaska to southern California, occupying rocky substrate from the intertidal to 500 metres depth (Butler 1980). They are protrandic hermaphrodites (undergo sex change from male to female) with a 4 year semelparous life cycle. In the change from the male to the female stage they pass through a transitional stage, with breeding occurring in both the male and female stage (Figure 2). Females tend to spawn in the fall and carry the eggs externally until larvae hatch and are released, which normally occurs in March. The larvae spend approximately 3 months in the planktonic stage prior to settling as immature males then spend approximately 15 months as immature males, 1 year as mature males, 8 months in the transitional phase and completing their lifecycle females. Prawn sexual stage can be determined externally based on subtle morphometric changes to the swimming appendages (i.e., pleopods). The maximum observed carapace length (CL) recorded in BC for male and female prawns are 48 mm and 61mm, respectively (D. Rutherford, DFO, pers. comm. 2010).

A commercial prawn fishery has operated in British Columbia since the early 1980s. The targeted prawn fishery is a trap-based fishery whereby a typical string of prawn gear consists of approximately 50 traps set along weighted ground lines. The fishery targets age-2+ individuals at depths of 40 to 100 metres. By regulation, all egg-bearing females caught prior to July 1st must be released immediately upon capture. DFO implements additional harvest tactics to regulate fishing effort and to protect prawn populations from both growth and recruitment overfishing (Table 1). The bulk of the harvest tactics are input controls that include limited vessel entry, restricted fishing days, seasonal closures, area closures, restricted effort levels (number of traps), restricted haul frequency to once per day, and minimum size limits. For example, during development of the prawn fishery (early 1980 to mid-1995), the commercial fishing season was open year-round (Figure 3). However, by 2000 the fishing season was restricted to a maximum of 60 to 70 fishing days.

Howe Sound offers a unique opportunity to study recruitment dynamics because a dioxin contamination affected approximately half of Howe Sound (PFMA 28-3, 4, 5 and part of 1; henceforth called the Experimental Management Area, EMA) and required a fishery closure from 1988 to 1994 (Hagen et al. 1997, Boutillier and Bond 2000). DFO has conducted fishery-independent and fishery-dependent surveys in the entire Howe Sound area since 1985. Despite the closures, an avid commercial fishery persisted in Howe Sound. By the mid- to late-1980s, there were up to four commercial prawn vessels fishing in Howe Sound on a weekly basis. And by 2000, interest in commercial fishing in Howe Sound peaked at between six and nine vessels fishing per week, with an average of 15 vessels using the area over the course of the season (Table 2 and Table 3, Figure 3). Total landings in Howe Sound since 2000 have ranged from 65,000 pounds to 154,000 pounds with an average of approximately 107,000 pounds (Figure 3, Table 3). The high variability in catch yield is a known consequence of implementing an escapement-based management procedure.

In 2000, a spike in overall catch per unit effort (CPUE) indicates that the newly implemented single daily haul limit (Table 1) effectively increased the catch efficiency in Howe Sound (Figure 4). Consequently, the implementation of the weekly escapement-based management strategy has had limited success in maintaining the March MMI since 2000 (Figure 5). Fishery independent surveys demonstrate this failure as the median spawner index value in March (week 50), just before prawns spawn, is below the preagreed escapement-based management value (Figure 5). Therefore, my analysis of stock-recruitment, catchability, and effort dynamics in Howe Sound (below) can help clarify the potential consequences of the increased CPUE and inability to meet management objectives.

Data Sources for Prawns in Howe Sound

Commercial fishery data consist of weekly records of catch (pounds) and effort (number of traps) submitted by each vessel in accordance with log book licence agreements set out by DFO (DFO 2011). In-season SI records are provided by on-board monitors. Although these records are available from 1985 to 2010, I chose to focus my analyses on 2000 to 2010 because the escapement-based management procedure was implemented without any major changes during this time (Table 1). Catch and effort are estimated at the Howe Sound spatial level to protect the privacy rights of individual fishers.

Biological data from the Howe Sound prawn population, including numbers-at-stage, average weight-per-stage, and length-at-stage, were obtained for the period 1980 to 2010 from fishery-independent surveys. These surveys operate for approximately 10 days in both Spring (February) and Winter (November) (Figure 5) because this timing should take advantage of non-fishing periods to gain independent pre- and post-fishing assessments that help to establish relative indices of natural mortality and recruitment. However, to date these fishery-independent surveys have not been used to improve stock assessments.

The fishery-independent surveys were designed to collect a representative sample of the prawn population over time and space by using a fixed-station design (same locations used year-after-year via GPS referencing). Traps are set throughout Howe Sound within a target depth range of 50 to 100 meters. Twenty standardized traps spaced at 20 m intervals along a 380 m groundline (a "string") are baited with pet food grade tuna, which is consistent with historical commercial fishing practice (Rutherford et al. 2004). Each string soaks for 18-24 hours. Upon gear retrieval, prawns are enumerated according to the following stages: male, transitional, female, ovigerous female, or spent female (Butler 1980). The total weight, by stage, is recorded at the string level. Individual carapace length measurements are taken as a random sample from each string, measured as the distance from the eye socket to the end of the carapace. I also use numbers-at-age data, estimated in Boutillier and Bond (2000), to assess the prawn stock-recruitment relationship in Howe Sound. Reconstructing numbers-at-age for more recent years was outside of the scope of my research.

The main data used to implement the escapement-based management procedure is the spawner index (SI), which is assumed to index only those prawns that escape entrapment and thus, will contribute to the spawning population in March. These SI data are collected during the commercial fishing season by on-board fishery monitors to ensure that standard sampling protocols are followed. The weekly index is based on the catch rate of future spawner prawns as in equation 1

$$(1) \qquad SI_w = \frac{1}{I_w} \sum_{i=1}^{n} \frac{N_{stage2,i} + N_{stage3,i}}{T_i},$$

where n is the total number of strings sampled during week w, $N_{stage2,i}$ and $N_{stage3,i}$ are the number of sexual stage 2 (transitions) and 3 (females without eggs) individuals, respectively, counted for string i, T_i is the number of traps sampled in string i, and I_w is the total number of strings sampled during the week (Table 2).

The premise of the escapement-based strategy is that the commercial fishery will close once the weekly SI drops to a pre-determined target escapement value, which is called the minimum monthly index (MMI), and represents the minimum number of prawns that must escape the fishery in a month. Because prawns spawn in March, MMI values are derived from an estimate of the number of spawners observed per trap in March (henceforth called the March MMI). MMI values for weeks preceding March 31 follow an exponential model of the form,

$$(2) \qquad MMI_w = MMI_{March} e^{Mw}$$

where the weekly natural mortality rate $M = 0.025$ week^{-1} (i.e., 1.3 yr^{-1}), MMI_w is the target MMI value in week w required to attain the March MMI (MMI_{March}) (Figure 5, Table 2).

The baseline March MMI value of 1.7 female spawners per trap was originally estimated from a limited series of fishery-independent surveys in Knight and Kingcome Inlets that compared survey catches to indices of stock recruitment from historical commercial observations (Cadrin et al. 2004). The exact details of this analysis are unknown, but anecdotal reports suggest that managers assumed that "good recruitment" would continue if the SI remained close to this March MMI value (Table 2). Because the exact data and analysis methods used to develop the baseline MMI value were unknown, prawn managers decided to increase the baseline MMI values in Howe Sound by 25% based on the following rationale: first, managers speculated that closing the commercial fishery at higher SI values would provide a buffer that should mitigate against the additional catch taken by the Howe Sound recreational fishery, which exerts additional pressure on the prawn populations. Second, a stock-recruitment analysis using data from Howe Sound fishery-independent surveys estimated a March MMI of 3.9 females per trap, which is over double the baseline March MMI value (Boutillier and Bond 2000). Although the updated management value of baseline MMI + 25% (henceforth referred to as the status quo MMI procedure) attempted to incorporate both of these considerations, the status quo March MMI value still remains well below the Boutillier and Bond (2000) estimate (Table 2).

Stock-Recruitment Parameterization

In this section, I estimated parameters for a Ricker model based on spawner (age 3+) and recruit (age 1+) data from 1986 to 1995 fishery-independent prawn trap surveys in the Howe Sound EMA. I use the Ricker model to maintain consistency with Boutillier and Bond (2000).

The estimation procedure involves three steps. The first is parameterization of the SR relationship for prawns in Howe Sound, which involves fitting the Ricker model in the form of:

$$(3) \qquad R_t = S_{t\text{-}1} e^{(a\text{-}bS)} e^{\varepsilon}$$

and treating this as a linear regression:

(4) $$\log\left(R_t / S_{t\text{-}1}\right) = a - bS + \varepsilon$$

where *a* and *b* are parameters, S_{t-1} is the estimated number of age-3+ prawns that contribute to the estimate of the maximum number of recruits, R_t, (age-0 prawns) in year *t*, and ε is the residual error, which I assume is $Normal\left(0, \sigma^2\right)$.

In the second step, I use a Bayesian approach to quantifying the uncertainty in Ricker *a* and *b* parameters through the application of Bayes Theorem:

(5) $$p\left(\Theta \mid Y\right) = \frac{L\left(Y \mid \Theta\right) \times p\left(\Theta\right)}{p\left(Y\right)}$$

where Θ represents the vector of parameter values $\left(a, b, \sigma^2\right)$, *p*(Θ|*Y*) is the posterior probability distribution of the parameters given the observed SR data from the EMA (*Y*), *L*(*Y*|Θ) is the likelihood of data given the parameters, *p*(Θ) is the joint prior probability distribution of the parameters, and *p*(*Y*) is the marginal probability distribution of data (Gelman et al. 1995, Cooper and Miller 2007).

Because little prior knowledge about the model parameters exists, I did not include a prior probability distribution for *a* and *b*. This method is an objective Bayes approach where the posterior distribution is proportional to the likelihood (Link et al. 2002). Thus, I define the likelihood of the SR data as the product over all data points (Θ) as follows:

(6) $$L\left(Y \mid \Theta\right) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[- \frac{d^2}{2\sigma^2} \right]$$

where σ^2 is the residual error variance and d^2 is the squared residual, i.e.,

(7) $$d^2 = \left(Y - \hat{Y}\right)^2$$

where *Y* and $\hat{Y}$ are the observed and predicted logarithms of recruits-per-spawner, respectively. I approximated the joint posterior distribution of the parameters via *Monte Carlo Markov Chain* (MCMC) simulation and a Metropolis-Hastings algorithm. MCMC simulations utilize stochastic jumps in parameter space, where each jump is conditionally dependent on the previous sample in order to converge on the stationary distribution (i.e., the posterior distribution) (Gelman et al. 1995). I used "MCMCpack" from the R library to approximate the joint posterior distribution for the parameters based on 400,000 iterations with a burn-in of 10,000 and then thinned by 1000 to avoid serial correlation in the sampled parameter values.

The third step is a re-parameterization of Ricker *a* and *b* model parameters to steepness (*h*) and the unfished spawning stock level (S_o). Steepness is defined as the proportion of maximum recruitment produced when spawning biomass is 20% of the unfished spawning stock level. Parameterization of the simulation model used in Chapter 3 requires these alternative parameters because *h* and S_o simplify the calculation of management targets and thresholds (Mace and Doonan 1988). I apply the following calculations to each row of the MCMC output to obtain the joint posterior distribution of *h* and S_o:

$$h = \frac{1}{5}\exp\left[\left(a + \log\left(f\right)\right)/1.25\right] \tag{8}$$

$$S_o = \frac{1.25\log\left(5h\right)}{b} \tag{9}$$

where the constraint $h > 0.2$ is required for the Ricker model. The spawning potential ratio (ϕ) was estimated to be 0.071 using incidence functions (Walters and Martell 2004) under a natural mortality rate assumption $M = 0.88\ \text{yr}^{-1}$ based on findings from Boutillier and Bond (2000).

I characterized uncertainty in the Ricker SR curve by finding the 2.5th and 97.5th percentiles of the joint posterior probabilities associated with each *h* model prediction. I then extracted the modeled values of *a* and *b* associated with these 95% percentile bounds and used Equation 3 to estimate recruitment over the range of observed stock sizes (i.e., 0 to 1 million prawns). The above percentiles of *h* will represent alternative productivity assumptions in Chapter 3.

Depletion Analysis to Parameterize Catchability

Catchability (q) reflects the efficiency of the Howe Sound prawn fishery as the proportion of a stock caught by one unit of fishing effort (Arreguin-Sanchez 1996, Marchal et al. 2003). When q is assumed constant, CPUE can be used as an indicator of population biomass. However, the validity of a linear relationship between CPUE and abundance has been debated in the literature (Hilborn and Walters 1992, Rose and Kulka 1999, Harley et al. 2001). A non-linear relationship is characterized by β in the following relationship (Harley et al. 2001):

$$CPUE = qN^{\beta} \tag{10}$$

where CPUE is considered hyperstable when $\beta < 1$ and hyperdepleted when $\beta > 1$. Under a hyperstability scenario, CPUE will appear relatively constant, despite a decline in underlying population abundances (Hilborn and Walters 1992). On the other hand, hyperdepletion is exhibited when q decreases with stock size and CPUE declines faster than abundance such that the stock appears depleted when it is not (Hilborn and Walters 1992). Although I assume a proportional relationship between CPUE and abundance ($\beta=1$), I estimate annual catchabilities to determine whether there is evidence of changes over time or in association with changing abundance.

I estimate annual catchability values using a DeLury depletion model estimator (Hilborn and Walters 1992). This model predicts average CPUE for a given week (w) as a linear function of the cumulative trap effort (E) up to that week:

$$\log[y_w] = \log[b_0] - b_1 E_w \tag{11}$$

where the cumulative effort over the whole fishing season (E_W) is:

$$E_w = \begin{cases} 0 & w = 1 \\ \sum_{i=1}^{i=w-1} E_i & w > 1 \end{cases} \tag{12}$$

and the parameters are:

$$b_0 = qN_0$$
$$b_1 = q$$

where N_0 is the initial prawn biomass at the beginning of the commercial fishing season. The DeLury estimate assumes that all prawns are equally vulnerable to fishing (Hilborn and Walters 1992).

Three alternative linear model fits describe the relationship between average CPUE during a given week and cumulative fishery effort up to that week (Table 5). In each case, q is represented by the linear model slope. Model 1 assumes that a single relationship applies over all years by estimating a common slope and intercept. Model 2 allows the average CPUE level to vary among years, possibly because of varying initial prawn abundance, by estimating independent intercepts and a common slope. Model 3 allows for independent relationships in each year by estimating independent slopes and intercepts. I use analysis of covariance (ANCOVA) to determine the minimal adequate model based on the explanatory power of each model (Crawley 2007). Models were fit via a stepwise procedure beginning with the most complicated model (Model 3) and removing non-significant terms until only a minimal adequate model is left to describe the relationship between CPUE and cumulative effort (Crawley 2007). Because the model summary output in R represents Helmert contrasts, it is difficult to reconstruct the slopes and intercepts from the estimated parameter values (Crawley 2007). Therefore, I ran individual linear regression models for each year to estimate q, initial prawn abundance at the beginning of the year (N_o) and CPUE. Linear models are fitted in R using OLS regression via the "lm" function (Crawley 2007).

Effort Dynamics Model Parameterization

The data consist of weekly trap counts, total weight landed (in pounds), pounds-per-trap (CPUE), the spawner index (SI), and number of traps used to estimate the SI. Weeks 20 and 23 in 2000 were removed because trap effort was extremely low. I also removed effort from 2004 because it was not representative of the Howe Sound fishery due to partial closures early in the season. My analysis assumes that trap effort is measured without error, which is a reasonable assumption in Howe Sound where fishers tend set their maximum allowable trap limits and are required to record trap effort in fishery logbooks (DFO 2002).

Relationships between trap fishing effort and week; trap fishing effort and fishery SI; trap fishing effort and fishery CPUE; and trap fishing effort and survey CPUE (i.e., survey SI) were investigated in preliminary analyses. All relationships were deemed non-significant except those between trap fishing effort and week, and trap fishing effort and fishery SI.

I assume the relationship between the weekly (*w*) number of traps (*T*) deployed in the fisheries and the fishery SI value obtained in the previous week has the form (Link and Peterman 1998),

(13) $$T_w = \alpha SI_{w\text{-}1}^{\;\beta+\varepsilon_w}$$

where the coefficients α , β were estimated separately for each year via OLS regression, i.e.,

(14) $$\log\left(T_w\right) = \log\left(\alpha\right) + \beta \log\left(SI_{w\text{-}1}\right) + \varepsilon_w .$$

Three alternative linear model fits describe the relationship between the number of traps fished per week and the fishery-dependent SI derived in the previous week (Table 6). Similar to the catchability analysis, Model 1 has a common slope and intercepts, Model 2 has a common slope and independent intercepts, and Model 3 has independent slope and intercepts. I again use a stepwise ANCOVA model selection procedure to identify the minimal adequate model fit for the data (Crawley 2007). Linear models are fitted in R using OLS regression (Crawley 2007).

Results

Stock-Recruitment Parameterization

The Bayesian analysis of the Ricker SR model produced an MCMC acceptance rate of 41%, which is within the target range (30 to 50%) for models with only a few parameters of interest (Gelman et al. 1995). Posterior mean estimates of steepness and unfished spawner abundance are h = 0.64 and S_o = 501,351 prawns, respectively (Table 7). The posterior distributions of h and S_o are both relatively symmetrical (Table 7, Figure 6).

The posterior mean values of h and S_o generated an expected Ricker SR curve that is nearly identical to the SR curve produced by Boutillier and Bond (2000) across the range of observed stock sizes (Figure 7). However, my SR curve appears slightly more productive at low stock sizes and less productive at high observed stock sizes than the Boutillier and Bond (2000) curve (Figure 7).

The joint pairwise posterior distribution of h and S_o show typical correlation patterns (Figure 6). The consequence of such correlation is that even slight changes in h around 0.4, can result in large differences in the estimates of S_o (Figure 6).

Depletion Analysis to Parameterize Catchability

As expected, the in-season trends in CPUE are negative such that increases in the cumulative number of traps fished over the course of the season leads to decreases in the CPUE (Figure 8). The depletion analyses showed that in-season trends of CPUE are significantly correlated with cumulative effort in most years, with the exception of 2004 ($p \leq 0.05$; Table 8). I selected Model 2, with common slope and independent intercepts, as the minimal adequate model based on my stepwise ANCOVA to explain this relationship between CPUE and E_W for a number of reasons. First of all, when I removed the interaction between year and E_W from Model 3 to form Model 2, the ANCOVA results indicated the model simplification was justified because it caused a negligible reduction in the explanatory power of the model; indicated by the non-significant p value of 0.12 (Table 5). However, when I further removed year from Model 2 to form Model 1, there was a significant reduction in the model explanatory power ($p = <2e^{-16}$; Table 5). The selection of Model 2 suggests there are no significant differences in q between years. The estimated mean of q from 2000 to 2010 was $6.75e^{-06}$ (Table 8) and independent intercepts indicate that regardless of the initial biomass (N_o) at the beginning of the commercial season, the depletion pattern is consistent between years. As expected, N_o and q are significantly correlated ($p = 0.014$) such that larger estimates of q are associated with smaller estimates of N_o. Predicted N_o ranges between 186,724.2 and 349,049.9 prawns (Table 8).

Effort Dynamics Model Parameterization

The number of traps fished per week follows a dome-shaped pattern over the course of the fishing season whereby the number of traps fished at the beginning and end of the season are below the mid-season level (Figure 9). The average weekly effort does not appear to be related to the ultimate length of the fishing season (Figure 10).

I did not detect any significant relationships between weekly trap fishing effort and the SI collected during the same week. When trap fishery effort was offset by one week, the relationship between spawner index (SI) and the number of traps fished the following week roughly follow a non-linear pattern (Figure 10). I selected Model 1, with common slope and intercept, as the minimal adequate model (Table 6). The estimate of residual error from Model 1 is 0.59 on 64 degrees of freedom (35 observations were deleted during data quality control) (Table 9). Estimated α and β parameters from the best-fit model were 7.23 and 0.68, respectively.

Discussion

Stock-Recruitment Parameterization

Understanding the stock-recruitment process, including the uncertainty, is required to effectively manage stocks and prevent recruitment overfishing (Cadrin et al. 2004). When I accounted for uncertainty in the SR relationship, the range of *h* values indicated that stock productivity is highly uncertain (i.e., the 95% confidence interval of *h* = 0.40 to 0.96). Near the upper confidence limit of *h*, the spawning stock could potentially be fished down to around 20% of unfished levels and still be producing nearly maximum recruitment, while near the lower confidence limit of *h*, the stock may have difficulty compensating when it is fished to lower spawning stock biomasses. Because the estimated *h* values encompass such a wide range, it could also be possible that the relationship between spawning biomass and recruitment is weak such that changes in recruitment are almost entirely driven by environmental factors instead of spawning stock biomass (e.g., Mangel et al. 2010). Despite the range of possible influences on stock productivity, the range of *h* values I estimated provide an important starting point to evaluating the robustness of management procedures to uncertainty in the stock-recruitment relationship (see Chapter 3).

Most shrimp fisheries lack the detailed information required for informative stock-recruitment assessments (Koeller et al. 2000, Cadrin et al. 2004). The development of reference points from stock-recruitment parameters has more commonly been applied to salmon, groundfish and other temperate finfish species (Myers et al. 1999, Dorn 2002, Michielsens and McAllister 2004, Mangel et al. 2010). However, the prawn fishery in Howe Sound exhibits similar features to these finfish fisheries, such as defined population boundaries, semelparous life history and limited fishery bycatch. Because life history data was not available for prawns, I made some simplifying assumptions about the spawning potential ratio (ϕ) in order to re-parameterize the Ricker model in terms of h and S_o. I also used an observation error model, which tends to make the stock look more productive at low stock sizes than it really is (Walters and Martell 2004). However, my best-fit estimates of the Ricker curve versus the Boutillier and Bond (2000) curve are essentially indistinguishable given the uncertainty.

Time-series biases in the stock-recruitment relationship are likely because I have a relatively short time-series of SR data and because there are likely process errors in recruitment, e.g., environmental effects (Hilborn and Walters 1992, Dorn 2002). Additionally, the escapement-based procedure holds the spawning stock size at a relatively constant level via removal of the surplus, which does not always enable a clear understanding of the relationship between the spawning stock and recruitment because very large or very small spawning stock sizes are rarely observed (Hilborn and Walters 1992, Dorn 2002). However, despite the short time series of SR data collected (9 years or 2 full prawn life-cycle generations) in the closed area (EMA), these populations were not subject to escapement-based harvest rules and may have produced spawning stock biomasses that range from low to near-MSY levels. Nevertheless, time-series bias is a risk that I was not able to fully quantify and therefore I will examine the management consequences of the possible mis-specification of h and S_{MSY} in Chapter 3.

Depletion Analysis to Parameterize Catchability

Despite all of the potential reasons that catchability (*q*) could change from year-to-year (e.g., Arreguin-Sanchez 1996), I did not detect any significant differences in the Howe Sound *q* between 2000 and 2010. Some plausible explanations for these similarities include the single haul and gear restrictions, including allowable mesh size and a cap on total allowable traps per licence that may constrain biases normally caused by increased catching capacity of the fishing gear (Arreguin-Sanchez 1996). However, inter- and intra-annual variation in catchability is likely occurring in Howe Sound, but not on a scale that results in significant differences in *q*. For example, prawn fishers have observed within season changes in the size composition and distribution of the Howe Sound prawn stock from 2000 to present (B. Ennevor, DFO, pers. comm. 2012). Environmental factors, such as water temperature or ocean circulation patterns (Miller 1990), are likely factors influencing the timing of prawn moults, which is a possible cause of these changes in population composition and distribution patterns. Additionally, the "skipper effect," in which some vessel captains are more skilled at finding and catching fish (Squires and Kirkley 1999), may also contribute to some within-season variability. However, the same group of fishers have been using the Howe Sound fishing grounds for the past six to ten-plus years (C. Sporer, PPFA, and B. Ennevor and D. Rutherford, DFO, pers. comm. 2012). Thus, these fishers probably developed patterns of fishing behaviour and local knowledge such that *q* for their collective group appears relatively consistent over the years (Hilborn and Ledbetter 1979).

My estimate of mean catchability (2000 to 2010) is lower than catchability estimated by Boutillier and Bond (2000) possibly because they used fishery-independent survey data to estimate *q* whereas I used in-season commercial CPUE and catch data. Fishery-independent surveys utilize traps with smaller mesh sizes but less efficient bait types than those used by commercial fishers (Rutherford et al. 2004). Thus, Boutillier and Bond (2000) likely estimate survey catchability, while I estimate fishery catchabiltiy. Alternatively, the significant correlation found between the estimates of initial population abundance (N_o) and *q* may indicate the presence of a bias in the DeLury estimator (e.g., Ralston and Tagami 1992). The DeLury estimator requires all individuals of the exploitable biomass to be equally vulnerable to fishing gear, and if this requirement is not met, N_o may be under- or over-estimated and estimates of q may also be skewed. Therefore, future research could assess the magnitude of this potential bias using a simulation approach.

Although my depletion analysis provides a baseline for estimating catchability and its uncertainty for the commercial fishery, I make some limiting assumptions in my analysis. For example, because CPUE is not independent of the cumulative effort data, my depletion analysis violates assumptions of independence. Also, the DeLury estimator assumes that catch rate is directly proportional to cumulative effort (Hilborn and Walters 1992); but, I used a non-linear relationship with CPUE being negatively associated with cumulative effort (which is in the exponent) and therefore does not reflect a directly proportional relationship. This estimator also assumes that fishing effort is evenly distributed via random search, which is likely false in Howe Sound because fishers target known prawn aggregations. Another issue with the DeLury estimator is that estimates of q and N_o can be biased as a result of measurement error and/or inconsistent values of q between targeted age classes of prawns. Bias in q is a serious problem in fisheries stock assessment; however, I did not examine it further due to time and scoping restrictions of my research. Future research could use simulation models, such as the one described in Chapter 3, to investigate the consequences that non-proportionalities between CPUE and stock abundance have on future fishery performance.

Effort Dynamics Model Parameterization

The trend of low trap effort in the last week of the fishery suggests that a low level of CPUE may provide a signal that fishing in a particular year is not profitable enough to warrant further effort. Although effort patterns in Howe Sound did not reveal any inter-annual differences in the way vessels distribute trap effort over the season, the trap response was significantly related to the spawner index from the previous week. However, this relationship may not be a good predictor of trap effort because the high variability in weekly CPUE index (i.e., the SI) may limit the value of SI as a predictor variable (van Oostenbrugge et al. 2001).

By focusing on effort responses at the Howe Sound level, I may have missed economic and social cues of the fishery and as a result, had difficulty finding a convincing pattern in fishing effort dynamics. A number of external factors could be generating the noise in trap effort data, including temporal scale and social and/or economic cues. For example, prawn fishers may decide where to fish on a daily versus weekly basis to capitalize on the sedentary nature of prawns. It is plausible that fishers could extirpate localized aggregations of prawns within a few days, which would suggest that the previous day's CPUE is a good indicator of today's trap effort (Shester 2010). Alternatively, the different risk-based choices fishers make when placing and moving their traps could also lead to the scattershot of CPUE and effort data (van Oostenbrugge et al. 2001, Shester 2010). For example, vessels that fish out of Howe Sound typically land prawns live and distribute their landings directly to local restaurants or customers at the wharf. These locations can be more preferable because they provide the competitive advantage of being closer to port (Eales and Wilen 1986). Fishers may also be influenced by the social cues of others, whereby anecdotal comments of good fishing grounds can lure fishers to particular areas. However, competition between fishers and the risk of local biomass depletion might reduce the level of information sharing in Howe Sound (Dreyfus-Leon and Gaertner 2006).

The effort dynamics model is limited because it cannot be used to predict fishing effort in the first week of the commercial fishery when there is no spawner index information collected prior to the fishery opening. Future research could examine a more suitable metric for estimating trap effort in the first week of the fishery. Preliminary analysis suggested that using SI information collected in the spring, fishery-independent, survey to generate trap effort in the first week was not useful to inform initial commercial fishing effort likely because fishers do not have access to the survey information. Also, the majority of prawns caught in the spring surveys are spawning females which subsequently die and are therefore unavailable to the fishery. Anecdotal evidence suggests that fishers tend to base their decisions on the previous year's CPUE and/or they conduct exploratory analysis (using a recreational fishing licence) prior to the season opening to determine where they will distribute trap effort in the first week of the fishery. My research only briefly examines fishing effort dynamics, and therefore leaves numerous options for future research on BC prawn fishery dynamics. Of particular relevance would be an economic-based choice model to examine the effect of declining CPUE and area closures on the distribution of trap effort (e.g., Hiddink et al. 2006). Furthermore, examination of how vessel crowding on certain grounds affects spatial and temporal trap effort allocation (e.g., Vignaux 1996) could also be useful to inform effort dynamics models. However, without auxiliary information to support such detailed analyses, my effort dynamics model uses the best available knowledge to inform the operational model in Chapter 3.

Conclusion

Use of the historical datasets to quantifying uncertainty around S_{MSY}, q, and fishing fleet dynamic parameter estimates in Howe Sound provides an important step to support further research on prawn management procedures. Uncertainty in key processes can affect the decisions of fishery managers by encouraging either risk prone behaviour - avoiding difficult decisions in the hope that better ocean conditions will spur improved production (Hilborn and Walters 1992) - or risk averse behaviour in which ad-hoc fishery regulations attempt to limit possible damage of associated with assessment biases. Several approaches are available to avoid these traps by accounting for uncertainty and make better-informed decisions as a result (e.g., Smith 1993, Peterman and Anderson 1999). For example, understanding and evaluating the consequences of variability in stock-recruitment productivity (e.g., 95% quantile range of h values: 0.4 to 0.96) can be used to develop a range of plausible management options under different productivity scenarios. Because I found that catchability is constant over time, this reduces the risk of managing a stock that is in a hyperdepeleted state. And, quantifying a relationship in fishery trap effort enables predictions of how fishers will response to different management actions. The simulation model in Chapter 3 is a tool that can be used to evaluate potential consequences to future fishery performance under a variety of these empirically-derived fishery parameters.

CHAPTER 3

EVALUATING ESCAPEMENT-BASED MANAGEMENT PROCEDURES FOR THE SPOT PRAWN FISHERY IN HOWE SOUND, BC

Introduction

Process, observation, and implementation error are pervasive uncertainties in fisheries assessment and management (Hilborn and Mangel 1997, Robb and Peterman 1998, Harwood and Stokes 2003). These uncertainties can cloud management decisions and may result in economic or ecological risks. For example, implementation error in the 1993 Atlantic cod fishery collapse resulted from management goals based on commercial CPUE data that overestimated abundance when the realized stock biomass was much lower (Myers et al. 1997). This resource collapse provides a valuable demonstration of how unaccounted-for uncertainty can leave lasting negative consequences on a fishery. Despite this realization and the subsequent availability of sophisticated stock assessment tools, many fisheries continue to have difficulty considering all uncertainties through to the decision making process (Peterman 2004).

Management of the Howe Sound prawn fishery currently ignores uncertainty in the escapement-based management procedure by using single-point estimates of the escapement-based minimum monthly index (MMI) to make in-season closure decisions (Boutillier and Bond 2000). Achieving exact MMI values is challenging; data from the 2000 to 2010 commercial fishery show that in-season spawner index (SI) values dropped below the pre-specified MMI management values before a closure decision was implemented (Figure 5). Spawner index values collected after the commercial fishery (i.e., from surveys conducted in November and February) subsequently demonstrate a general difficulty in achieving the escapement goal for the March spawning event (Figure 5). However, the overall effectiveness of the prawn escapement-based procedure is unknown because no management goals have been set for the fishery and the pre-specified decision rules have never been formally tested (e.g., by simulation modelling). Without developing a formalized procedure to evaluate the escapement-based procedure, prawn managers may continue to be trapped by uncertainty; making decisions with incomplete knowledge of how their actions will influence the future performance of the fishery.

Management procedure evaluation (MPE) is a method used to account for uncertainty in fisheries management and to evaluate the expected consequences of alternative decision-making procedures (de la Mare 1996, Dichmont et al. 2006, Cox and Kronlund 2008). MPE distinguishes the relative performance of pre-specified policy choices under a sufficiently wide range of possible environmental, economic, and even political scenarios (McAllister et al. 1999, Walters and Martell 2004). Clearly specified management goals are also required to evaluate procedure effectiveness (Punt and Donovan 2007). Therefore, my objective is to use MPE to evaluate the performance of the current, status quo, escapement-based management procedure through its application to the Howe Sound spot prawn fishery. I will test the management procedure performance across a range of plausible uncertainties in environmental and fishery dynamics, as characterized by empirical data from Chapter 2. I will also evaluate the trade-offs associated with applying alternative escapement-based management approaches.

Methods

I evaluate the outcomes to the BC spot prawn fishery using a closed-loop feedback simulation model (Figure 11), implemented with R statistical software (mseR, Kronlund et al. 2009). Briefly, mseR software provides a tool to evaluate outcomes of fishery management procedures by making predictions about future fishery performance (e.g., abundance, yield, depletion, etc.) that would result from consistent application of assessment methods and decision rules (de la Mare 1996, Cox et al. 2008, Rochet and Rice 2009). A management strategy has four components: (*i*) operational objectives, (*ii*) specific fishery monitoring data and stock assessment methods, (*iii*) harvest control rules that relate estimates of stock status to catch limits, and (*iv*) a prospective evaluation of the entire procedure using a set of performance statistics (de la Mare 1996, Cox et al. 2008).

Because the objectives I evaluate do not encompass the full spectrum of stakeholder interests of the conduct for the fishery, I implement what is considered a management procedure evaluation (Cox and Kronlund 2008).

Management procedures and their evaluation

This section describes my simulation approach to developing and testing two alternative management procedures for the prawn fishery. The operating model for the fishery incorporates known fishery and biological parameters to best reflect the "real world" in which candidate procedures can be tested (Kell et al. 2006, Cox and Kronlund 2008). I developed eight versions of the operating model to represent key scenarios that I felt bracket plausible stock conditions. Plausibility was determined by conditioning the operating models to existing fishery data. I then present two versions of an escapement-based management procedure that consist of (i) a stock assessment step in which simulated data from the operating model are interpreted, and (ii) a decision step in which the escapement-based harvest policy translates the assessment information into a fishery closure decision. Both procedures have a strong assumption that catchability and selectivity remain constant over time. The distinction between the management procedures is thereby in the method by which the escapement-based rule was derived.

Operating model

The operating model, assessment methods, and decisions rules, as well as performance evaluations in this paper are carried out using a modified version of mseR software (Kronlund et al. 2009). The following sections describe modifications in going from mseR to mseR_prawn, which represents the Howe Sound prawn fishery. Select model notation and parameter settings are provided in Table 10.

Population productivity is represented by the Ricker stock-recruitment model for both convenience of parameterization and to maintain consistency with Boutillier and Bond (2000). The unfished spawning stock biomass (S_o) and steepness (h) variables determine the stock-recruitment relationship (*see* Chapter 2); capturing uncertainty in stock-recruitment productivity is a critical component of this MPE (Butterworth and Punt 1999, Cox and Kronlund 2008).

The mseR_prawn software uses a single-sex, fully age-structured model that includes a sex change in the year just prior to spawning. The hermaphroditic life-history of *Pandalus platyceros* is implicitly represented in the model by assuming that all age-3 male prawns (immature) transition to all females (mature) at age-4. Thus, the entire age-4 population at the end of their 4th year represents the spawning population. Prawn death after spawning is implemented through a 5th age class as a placeholder for spent (soon to be dead) females.

Natural mortality (*M*) estimates were taken from the literature (Boutillier and Bond 2000). Although *M* is often considered to be constant in fisheries assessments, this is rarely the case in the real world (Fu and Quinn 2000, Ramirez-Rodriguez and Arreguin-Sanchez 2003, Cadrin et al. 2004). Realistic analyses should take account of uncertainty in *M*, particularly when there could be a time-trend caused by changing levels of predation, for example (Fu and Quinn 2000 – see below). Therefore, I use a random-walk *M* to represent year-to-year variation with σ_M as the estimated standard deviation in log *M* residuals around their expected values as per the following equation:

$$(15) \qquad M_t = M_0 \exp\left[\sigma_M \varphi_t - \sigma_M^2 / 2\right]$$

where $\varphi_t \sim N(0,1)$. Note that Equation (15) assumes natural mortality is also independent of prawn abundance. A full evaluation of auto-correlated *M* or perhaps density-dependent *M* was beyond the scope of my 699 research.

An area scalar parameter was used to represent prawn habitat area in Howe Sound because the spawner-recruit data from Boutillier and Bond (2000) was collected from only a small section of Howe Sound.

Weekly prawn fishing effort is generated from modelled spawner index values along with the effort dynamics model derived in Chapter 2 from empirical data (i.e., defined by α, β and catchability (*q*) parameters). Catchabiltiy is represented as the mean of *q* values estimated in Chapter 2.

Although I estimated parameters for catchability and effort dynamics from empirical data, operating model parameters were further refined by qualitatively matching the model output with historical catch, CPUE and season-length data from Howe Sound in 2000 to 2010. This conditioning step for the operating model is important to establish credibility of the management procedure simulations because it ensures that the model outcomes are at least consistent with historical data and structural assumptions of the scenario (Cox and Kronlund 2008). I based each conditioning scenario on the status quo management procedure and median stock-recruitment operating model parameters (S_o = 501,351 pounds and h = 0.64) (Figure 12). I then tested a range of length-weight and von Bertalanffy growth parameter (L_∞ and k) scenarios against my crude estimates of weight-at-length from Howe Sound prawn data (e.g., one pound of prawns contains approximately 15 prawns with a 34mm carapace length) where estimates of prawns per pound are an output of mseR. The values I selected for length-weight slope and power parameters are comparable to those estimated for other pandalid shrimp species (e.g., Vafidis et al. 2008). Age at 50% and 95% selectivity were estimated as approximately 3.2 and 3.6, respectively, based on an analysis I conducted using catchability coefficients reported in Boutillier and Bond (2000) (Figure 13). The mseR model constrained my parameter input values for age at 50% selectivity to < 3 due to an error in the uniroot function. Therefore, I represent age at 50% selectivity as 2.9.

Model conditioning generated a set of operating model parameter values that best represent the Howe Sound fishery (Table 10). Operating model output (i.e., median average catch, season length, and median average depletion) was not sensitive to changes in error assumptions about natural mortality (i.e., σ_M); therefore, I do not explore further assumptions about natural mortality error in this report. However, operating model output was sensitive to changes in prawn habitat area, productivity, and recruitment error parameter values.

Operating Model Scenarios

Candidate management procedures are evaluated against eight operating models that represent a range of key uncertainties about the Howe Sound prawn stock. Operating model scenarios (S1 to S8) result from setting three uncertain factors at two levels each (Table 11). Scenarios are applied consistently across the two alternative management procedures.

Prawn habitat area, i.e., the geographical area occupied by the Howe Sound prawn population, is uncertain because my estimates of unfished spawners (S_o) are derived from the Experimental Management Area (EMA), which represents only half of Howe Sound (i.e., approximately 23 km^2 surface area). However, all of Howe Sound is available for the fishery thus, my estimate of S_o must be scaled such that it reflects the unfished spawner level for the entire spatial area of Howe Sound. I used depth contour maps provided by DFO (H. Nguyen, DFO, pers. comm. 2012) to define the two potential values of habitat scalars. The first scalar (henceforth referred to as LH for low habitat area scalar) assumes that unfished prawn abundance in Howe Sound is 2.2 times greater than it is in the EMA habitat area (i.e., S_o =1,175,500 age-3+ female prawns). Under this LH scenario, habitat area is bounded by a 50 to 100 meter depth range (23.0 km^2 and 50.57km^2 surface area in the EMA and Howe Sound, respectively) because this is the depth range targeted by commercial prawn harvesters in Howe Sound (M. Kattilakoski, DFO, pers. comm. 2011). The second scaling estimate (henceforth HH for high habitat area scalar) reflects a prawn habitat area in Howe Sound that is 3.0 times larger than prawn habitat in the EMA (i.e., S_o = 1,602,950 age-3+ female prawns). This HH scenario reflects a wider depth range of potential prawn habitat from the intertidal up to 500 meters thereby including the entire surface area of Howe Sound (Butler 1980).

Scenarios of high and low productivity (henceforth HP and LP, respectively) are reflected by adjusting the value of steepness (h) and the associated unfished spawner level (S_o) from h = 0.40 to 0.96 and S_o = 400,130 prawns to 501,350 prawns, respectively. These parameter values are derived from the 0.025 and 0.975 quantiles of steepness from the posterior distribution in my Chapter 2 stock-recruitment analysis (Figure 12). The difference between these values and those represented in Table 7 in Chapter 2 are in how I derived the corresponding S_0 values; in this chapter I required values that represented h and S_0 that would be found together in nature. The values that were derived in Chapter 2 indicated the median and percentiles of the posterior distributions and may be less likely to be found together in nature.

Finally, I evaluated scenarios of high (0.62) and low (0.25) recruitment process error (henceforth HR and LR, respectively) because recruitment variation driving much of the variability in catch and depletion.

Management Procedures

Management procedures attempt to replicate the in-season management process for the Howe Sound fishery. Thus, each management procedure is set to open the fishery in week eight (i.e., eight weeks after the March spawning event) and to close the fishery after approximately 70 fishing days. Although there is no hard cap on the total number of fishing days per season, prawn managers tend to close the fishery after a pre-specified number days. Once Howe Sound is closed it remains closed to commercial harvest until the following May. The information collected from the fishery and analysed as part of the management procedure sub-model is set to reflect the minimum one-week lag in closure decision implemented in the current prawn fishery management strategy.

Status Quo Management Procedure

The prawn mseR model has also been modified from Kronlund et al. (2009) to reflect my interpretation of the weekly, escapement-based fishery management procedure (*see* Chapter 2). Natural mortality and the baseline spawner index value in March define how the management procedure is implemented during the commercial fishery (i.e., Equation 2). Natural mortality is assumed to be 1.33 yr^{-1}, is constant over time and across age classes, and is a separate parameter input from M in the operating model. Accounting for variability in M in the management procedure was beyond the scope of my research. As previously mentioned, the status quo procedure also includes a 25% buffer added to the baseline MMI values.

The status quo procedure is appealing because the spawner index can be measured directly from observable fishery data; however, there is no clear indication of how these in-season management values relate to estimates of population size. Nor is there any feedback mechanism that can be used to forecast stock productivity and subsequent changes to in-season management values for upcoming years. These key uncertainties in the status quo framework motivated me to consider the alternative, MSY-based procedure.

MSY-based management procedure

The MSY-based procedure estimates the March MMI value using estimates of both catchability (q) from depletion analyses and optimal escapement (S_{MSY}) from the Howe Sound stock-recruitment (SR) analysis (Chapter 2). These parameter estimates are critical for the MMI procedure for the following reasons. First, the SR relationship defines the spawning stock size at maximum sustainable yield ($\mathrm{S}_{\mathrm{MSY}}$) as well as the actual range of yield (Kronlund et al. 2012). Second, catchability (q) provides the link between prawn population size and the spawner index used in the management procedure, as well as the link between fishing effort and the exploitation rate. These two links have strong effects on season length, overall yield, and abundance relative to S_{MSY}. Third, the product of $\mathrm{S}_{\mathrm{MSY}}$ and q also defines the March MMI escapement target. Similar to the status quo, the MSY-based procedure also includes a one-week time lag to implement the closure decision. The natural mortality rate describing the in-season MMI procedure is $0.88\mathrm{yr}^{-1}$ (Boutillier and Bond 2000) and remains a separate input than M in the operating model.

Performance Measures

Because the prawn fishery does not have clearly defined management objectives, I propose a set of performance measures (objectives) that are consistent with the PA guidelines (DFO 2006). Conservation objectives aim to minimize the risk of substantial depletion of the population (FAO 1996, DFO 2006) while economic objectives aim to maximize expected yield (Butterworth 2007, Cox et al. 2008). Conservation and economic indicators are measured as the median average depletion and median average catch, respectively (Kronlund et al. 2012). Both objectives have a target value equal to one. The conservation objective of median average depletion represents the median average spawner abundance relative to S_{MSY}. I divided the median average catch output by MSY to obtain an output target equal to one (C_{MSY}). I compare both objectives across the short (years 2 to 8) and long (15 to 20) term because trade-offs amongst these objectives may change over time (Cox and Kronlund 2008). Based on preliminary simulations, I deemed 500 simulations adequate replication because the average trade-off relationships were not strongly affected as trials were increased further.

Evaluation of Performance Measures

Trade-off analyses can be used to estimate the implications that uncertainty in operating model parameters has on the performance of alternative management procedures. Evaluating these trade-offs will address DFO's three main guidelines for a precautionary approach (PA) to fisheries management by: *i*) considering alternative hypotheses about the prawn population dynamics to identify potentially undesirable outcomes, *ii*) evaluating risks (trade-offs) associated with alternative forms of the management procedure, and *iii*) demonstrating when the management procedure meets fishery management objectives, while avoiding undesirable outcomes. An ideal procedure would be one that maximizes catch while maintaining the stock at productive levels (i.e., depletion >0.4) (DFO 2006). I examined the trade-off relationship for status quo and MSY-based management procedure options over eight scenarios. I then highlight a best procedure from these candidates that is robust to uncertainties about prawn population and fishery dynamics (Cox et al. 2008). For the purposes of this project, the best procedure refers to one that meets specified objectives over a range of plausible scenarios about the resource and fishery processes based on equally weighted management objectives.

Results

Simulated management outcomes under the status quo and MSY-based management procedures are qualitatively similar to the range of historical data in the Howe Sound prawn fishery. For example, both management strategies produce a range of annual catch estimates that encompass historical catch yields of between 65,000 and 150,000 pounds per season (Figure 14, Table 3). However, neither management strategy is successful at producing a median average yield that is close to MSY (Table 12). Under low productivity (LP) scenarios, MSY is much lower than historical catch yields and the opposite is true of high productivity (HP) scenarios (Table 3 and Table 12). On average (over the 500 simulation replicates), the median yield only achieves between 10% and 20% of MSY between the short- and long-term (Table 12). As expected, high inter-annual variation in catch was a consistent feature of both escapement-based management strategies (Figure 14). Although MSY was achieved in some years, under all productivity scenarios (LP and HP) where recruitment variability was high (HR), median average catch values were consistently driven down by years of near-zero catch (Figure 14).

Both strategies successfully maintain depletion levels above 0.4 across the short- and long-term under all eight habitat area-productivity-recruitment scenarios (Table 12 and Figure 15). Therefore, I further evaluated the implications of four additional management procedures to determine if less conservative in-season escapement targets would result in stock declines. These procedures are represented by sequentially decreasing March MMI values from 1.7 to 1.0, 0.5 and 0.1 and assume a natural mortality rate of 0.88 for the in-season management procedure. Lowering the March MMI escapement value allows the fishery to continue fishing to a lower in-season management index. The least conservative procedure, MMI = 0.1, reflects a scenario that largely relies on compliance with pre-specified season length and input control regulations (i.e., control on the number of traps fished per day) versus in-season monitoring to implement the procedure.

Trade-off between catch and conservation

Low Productivity - Scenarios 1, 2, 5 and 6

In all LP scenarios, the status quo and MSY-based procedures produce similar median average catch and depletion values (Figure 16). The low catch estimates for status quo and MSY-based procedures are a result of early season closures every year (Figure 17). The less conservative management procedures (MMI = 1.7, 1.0, 0.5, 0.1) produce higher catch yields that are accompanied by decreases in depletion (Figure 16). However, all stock declines are sustainable because median depletion values remain well above 0.4. The median average catch for all low productivity scenarios (S1, 2, 5 and 8) remains below 50,000 pounds cumulative catch per season, which is approximately 20% of MSY (Table 12). In the short term, management procedures MMI = 1.0, 0.5, and 0.1 all obtain the same maximum catch as a result of the confined season length (Figure 17). While the MMI = 1.0 procedure closes the fishery early in approximately 6 years of the 20 simulated years, the more aggressive MMI = 0.5 and 0.1 procedures allow the SI to fall into the DFO critical zone yet remain open to fishing until the pre-determined end of season date (Figure 17).

Trade-offs between management procedures are more evident in the long-term where small gains in catch between procedures are associated with larger increments of depletion loss (Figure 16). Again, although losses in depletion do occur, none of the procedures result in unsustainable stock declines into the long-term. Variability in recruitment separates the performance of management procedures between the short- and long-term whereby HR scenarios (1 and 5) results in greater depletion of the stock than do LR scenarios (2 and 6).

High productivity – Scenarios 3, 4, 7, and 8

Unlike the LP scenarios, status quo and MSY-based procedures tend to produce different catch and depletion estimates under HP scenarios (Figure 16). The largest discrepancy between status quo and MSY-based procedures is in the HH-HP-LR scenario (S8) where the status quo produces greater catch yields with only slight reductions in depletion in both the short- and long-term. However, under all LH-HP scenarios the status quo and MSY-based procedures produce similar catch yield and depletion values. All of the less conservative management procedures (MMI = 1.7, 1.0, 0.5 and 0.1) produce nearly identical catch yield and depletion outputs that are constrained by the 10 week fishing season (Figure 17). Again, variability in recruitment error separates the performance of management procedures into the long term. High recruitment variability scenarios (3 and 7) result in a noticeable decline in depletion compared to the same scenarios (4 and 8) with low recruitment variability.

Sensitivity Analysis

None of the management procedures evaluated above caused notable stock declines under any of the habitat area, productivity and recruitment error scenarios. Therefore, I tested two additional assumptions about the Howe Sound prawn fishery. First, I may have underestimated fishery catchability by using the mean estimate obtained in Chapter 2. Second, the PPFA indicated interest in extending the fishing season to most of the year so, I extended the fishing season from 10 to 40 weeks. Ideally, the optimal management procedure will perform adequately under all alternative assumptions and objectives for the fishery.

Doubling the catchability estimate from $6.75e^{-6}$ to $1.35e^{-5}$ both increased the catch yields for all management procedures in all scenarios and caused larger declines in spawning stock depletion (Figure 18). All LP scenarios (1, 2, 5 and 6) produced steeper reductions in depletion and gained minimal increases in catch yield between management procedures. The stock declines below 0.4 when recruitment variability is high (HR, scenarios 1 and 5) under the more aggressive management procedures MMI = 1.0, 0.5 and 0.1 likely because these procedures keep the fishery open for the pre-determined 70-day fishing season even though the in-season spawner index values fall into the cautious and critical precautionary zones (Figure 19). The status quo and MSY-based procedures, on the other hand, generally keep the in-season spawner index values in the healthy zone (i.e., maintain spawning stock depletion above 0.4) under all eight habitat area-productivity-recruitment scenarios. Catch yields are relatively similar between all management procedures in low productivity scenarios, despite the discrepancy in season-length (Figure 18 and Figure 19). The status quo procedure closes the fishery early in approximately half of the simulated years and the MSY-based procedure consistently closes the fishery after the first week of fishing in all LP-HR scenarios (Figure 19).

In all HP scenarios (3, 4, 7 and 8), the status-quo procedure produces relatively similar catch to the less conservative MMI = 1.7, 1.0, 0.5 and 0.1 procedures (Figure 18). The MSY-based procedure again produces the lowest catch yields of all procedures evaluated, however it maintains the most conservative estimates of spawning stock depletion. Additionally, catch yield reaches a threshold based on the pre-defined season length (Figure 19). Similar to the baseline scenario (q = 6.75e^{16}), high recruitment variability drives declines in spawning stock depletion between the short- and long-term and is not accompanied by increased catch yields. Under the assumption of increased catchability, season length still appears to constrain catch yields to a range of 50% to 75% of MSY.

Increasing the season length from 10 to 40 weeks, while operating under the baseline catchability estimate of 6.75e^{16}, still did not increase total catch yields obtained by even the more aggressive management procedures (maximum yield was 60% MSY). In the short-term, all management procedures trade off catch and depletion in the same way under LP scenarios (1,2, 5 and 6) (Figure 20). Status quo and MSY-based procedures are indistinguishable, both producing low catch yields and depletion greater than 0.5 (Figure 20). Similar to before, HR scenarios tended to drive stock depletion to < 0.4 under the more aggressive management procedures (MMI = 0.5 and 0.1). Although the fishery remains open for most of the 40 week season in the MMI = 1.0, 0.5 and 0.1 procedures, the spawning stock biomass drops into the DFO cautious and critical zones and do not obtain MSY, on average (Figure 21). Management procedure MMI = 1.0 appears to performs better than the five other procedures presented in this extended season length sensitivity analysis because it rarely drops the in-season spawner index into the critical zone and because it is able to provide a longer fishing season in the majority of simulated years. Both the status quo and MSY-based procedures lose most of their catch yield as a result of consistent early-season closures and do not appear to benefit from an extended fishing season.

Discussion

Management procedure evaluation can identify the procedure that performs best under all plausible scenarios, relative to other procedures evaluated (Cox and Kronlund 2008). I found that both the status quo and MSY-based procedures demonstrate the ability to maintain sustainable stock levels of spot prawns in Howe Sound, which is likely because of successful implementation of formally adopted, pre-defined decision rules that specify actions to be taken under different circumstances (Beddington et al. 2007). However, there is a trade-off between stock conservation and catch objectives. Both the status quo and MSY-based procedures produce sub-optimal catch yield compared to the remaining four procedures, which consider lower in-season escapement thresholds. Status quo and MSY-based procedures regularly close the fishing season one week after it opens and thus, rarely produce catch that reaches 20% of MSY under any of the habitat area-productivity-recruitment scenarios. Similarly, none of the four alternative procedures (i.e., MMI = 1.7, 1.0, 0.5 and 0.1) are able to obtain MSY under any of the eight scenarios, but these alternative procedures do increase potential catch yield, especially under high productivity scenarios. Ultimately, the decision on which scenario is “best” depends on fishers and fishery managers’ willingness to accept potential losses in spawning stock for potential gains in catch yield or vice versa.

Finding a management procedure that maximizes mean annual catch without causing stock depletion requires a strategy that captures changes in recruitment variability (Breen et al. 2009, Cleary et al. 2010). I found that the MSY-based approach attempts to better characterize the relationship of the escapement target to the spawning stock biomass at MSY, but rarely allows the fishery to progress for more than one week in a season. For all other non-MSY procedures, reference points are defined independent of the productivity regime and their associated recruitment levels, thus running the risk of exploiting the stock at higher harvest rates than may be appropriate for the particular regime. Because escapement values are not set proportional to stock productivity, the escapement-based procedure may produce similar results to a constant harvest procedure (Hilborn and Walters 1992). Constant escapement strategies do not necessarily make the best use of large age-classes and can risk leaving insufficient absolute spawning biomass in weak productivity years (Garcia 1996). Thus, when the escapement value is set below surplus production, the strategy contravenes the DFO precautionary approach to fisheries management because it allows fishing to occur despite the potential to cause harm to the spawning stock. Accordingly, prawn managers and fishery stakeholders should develop a method that is responsive to changes in stock-recruitment variability, without being overly conservative to a point that penalizes the fishery (e.g., a variation of the proposed MSY-based approach) (Miller and Breen 2010).

Limitations and future work

The early in-season closures predicted by the mseR do not match the historical season lengths documented for Howe Sound. Early in-season closures occur in many of the PFMA sub-areas in coastal British Columbia, but generally at lower frequencies than those represented by the MPE. These results are likely due to model error that incorrectly characterized a high precision to detect changes in the fishery derived spawner index (i.e., a scenario of perfect catch information). In reality, uncertainty in the onboard sampling procedure often results in delays and/or missed closure signals. Adjusting the lag time in the mseR software accounts for management implementation error; however, scenarios of missed closure signals would likely end up playing out similar to the MMI = 0.1 scenario because this scenario removes the value of in-season spawner index measurement in closure decisions. Because stakeholders have clearly demonstrated interest in extending the fishing season length, it is unlikely that they will be flexible to accepting a management procedure that relies on missed closure signals (e.g., from the lag or missing in-season SI values) to avoid early closures decisions (i.e., the MSY-based procedure, and to a lesser extent the status quo). Future research could incorporate the last decade of closure decision rationale, which has been recorded by DFO prawn managers, to reduce the uncertainty around implementation error impacts on fishing season length and catch yield (Dichmont et al. 2006).

Future evaluation of the prawn management procedure could potentially reduce estimation error in the operating model by incorporating a full statistical catch-at-age model (Smith and Addison 2003, De Oliveira et al. 2007, Cox and Kronlund 2008). However, the challenge with implementing an age-based model for invertebrates is that it is difficult to quantify age classes because prawns, for example, lack bony structures that are generally used to age individuals (Xu and Mohammed 1996, Cadrin et al. 2004). Length-frequency analyses are one possible solution to characterize the age distribution of invertebrates (Schnute and Fornier 1980, Xu and Mohammed 1996). Length-frequency data is currently available for the prawn fishery (collected from DFO’s bi-annual surveys in Howe Sound) and can be used in a length-frequency program such as MULTIFAN (Fournier et al. 1991, Fournier et al. 1998). Other alternatives could extend to length- and/or growth-at-age models that have been used to manage shrimp fisheries around the world (e.g., Fu and Quinn 2000, Hansen and Aschan 2000, Franco et al. 2006). Overall, implementing a catch-at-age model would reduce estimation error and should provide more reliable estimates of escapement-based reference points for the Howe Sound prawn fishery.

The MPE represented in this report may not accurately characterize the prawn management procedure as it is implemented in Howe Sound. During the commercial season, managers add an additional buffer (of approximately 0.5) to the MMI values to reduce the risk of SI values falling below the MMI values. This buffer also offers a potential mechanism to account for observer error and/or incomplete observer coverage (i.e., missing SI data). I chose not to replicate this component of the management procedure for two reasons: 1) there was no documentation that this additional buffer has been consistently implemented since 2000, and 2) this additional buffer was not proportional to changes in the MMI escapement values and thus was computationally challenging to replicate. These buffers could be represented in the future alongside the assessment of implementation impacts recommended above.

One of the most important benefits of this management procedure evaluation is that it may prompt prawn fishers to clearly define their management objectives (Robb and Peterman 1998). While I suggested median average catch and depletion as performance metrics, fishers may be more interested in supporting a management procedure that reduces inter-annual variability in catch or one that allows for extended season lengths. Because the management procedures I evaluated tended to have high variation in season length, I would recommend that one of the management objectives be to define an acceptable range in season length. Other possibilities could follow the model of Australian fisheries, which measure fishery management success based on their ability to implement efficient, cost-effective management that is accountable to both industry and the Australian community (Punt et al. 2001). The MPE is not restricted to any specific set of conditions, management options, or quantitative objectives, therefore I encourage prawn managers to develop their own set of priorities and research items based on this study. Determination of the most relevant objectives however, will require consultation with fishery user groups whereby the MPE can help to guide these discussions (Cox and Kronlund 2008). Once fishery objectives are agreed upon, then meaningful discussions regarding which management procedure best fits the needs of the fishery can begin regarding (Smith et al. 1999, Butterworth et al. 2010).

Conclusions

Although management procedure evaluation, like any other modelling approach, cannot consider all uncertainties, factors, and processes that influence both prawn populations and fishery dynamics (Drechsler 2000), it is a useful tool to guide ideas and priorities for future research in the prawn fishery. My research clearly demonstrates that the status quo management procedure effectively avoids undesirable outcomes to prawn stocks in Howe Sound, BC. In fact, the status quo may be so risk-averse that it compromises potential economic gains for fishers. This finding should motivate prawn managers to address some of the limitations of the MPE, as mentioned above, and to apply the MPE framework to the coast-wide fishery. Extending this research to the larger spatial scale of costal BC is the next step in demonstrating that prawn management practices are sustainable and meet the precautionary approach to fisheries management (DFO 2006).

FIGURES

Figure 1 Howe Sound, BC, Pacific Fishery Management Area (PFMA). Howe Sound includes PFMA 28-1, 2, 3, 4, and 5. The experimental management area spawner-recruit data were obtained from PFMA 28-3, 4, 5 and part of 1 (East and South of Keats Island).

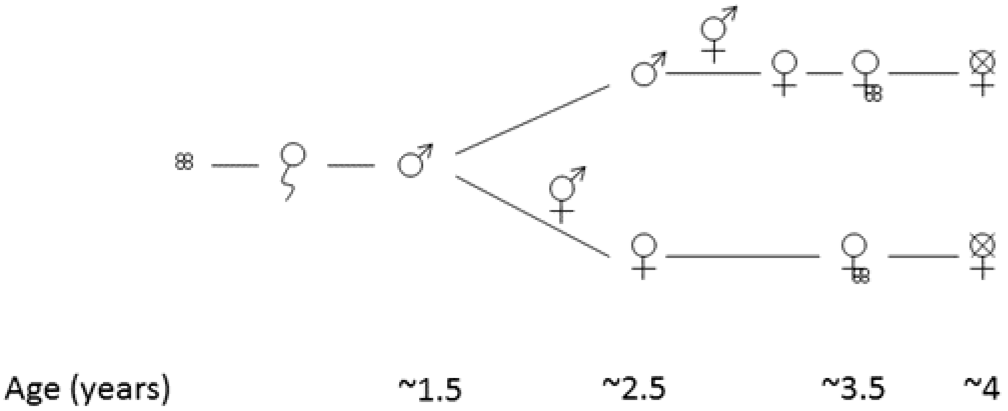

Figure 2 Life history diagram for spot prawn, *Pandalus platyceros*, in southern BC (adopted from Butler 1980 and Bergstrom 2000). Prawns settle on rocky substrate in autumn at age-1.5. Some of these prawns will function as males for another full year, while some will begin the transition to females. By age-3, all prawns should be females. These females spawn in the fall and release their eggs in March. Females die shortly after egg release between age-3.5 and age-4.

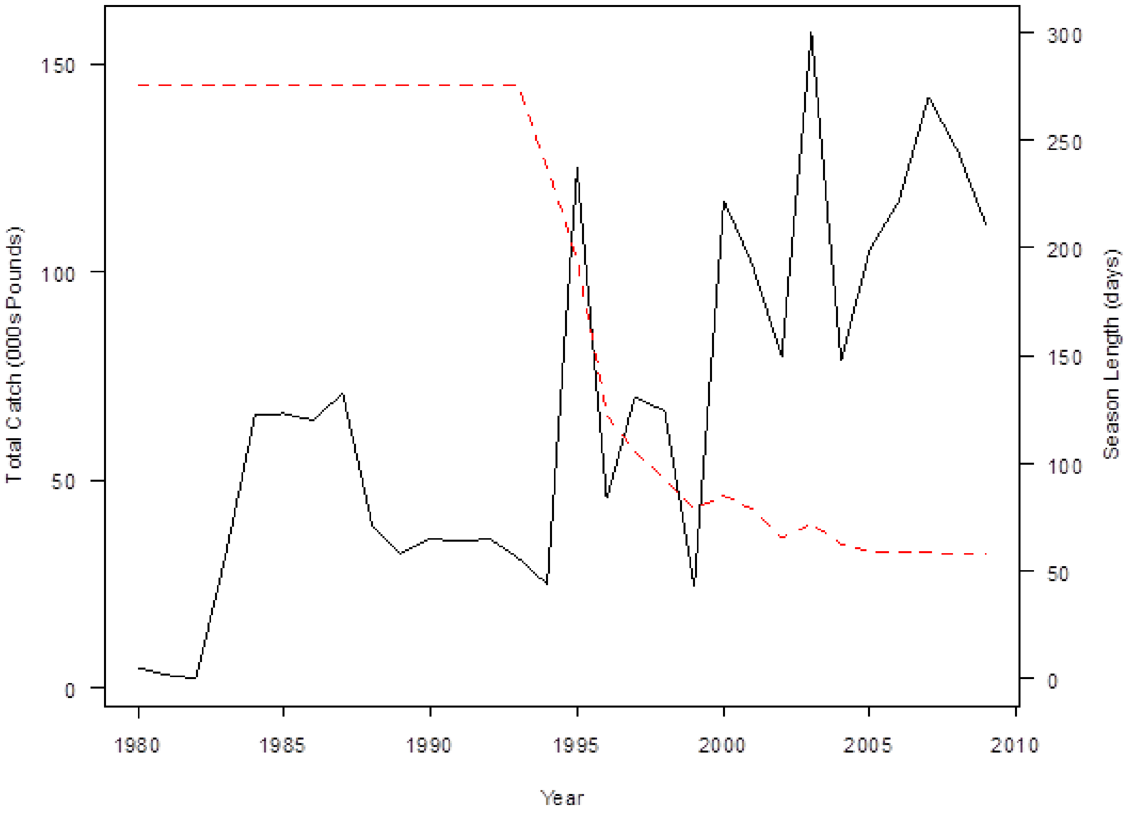

Figure 3 Commercial prawn catch per year in Howe Sound, BC and associated fishing season length (red dashed line) (1980 - 2009).

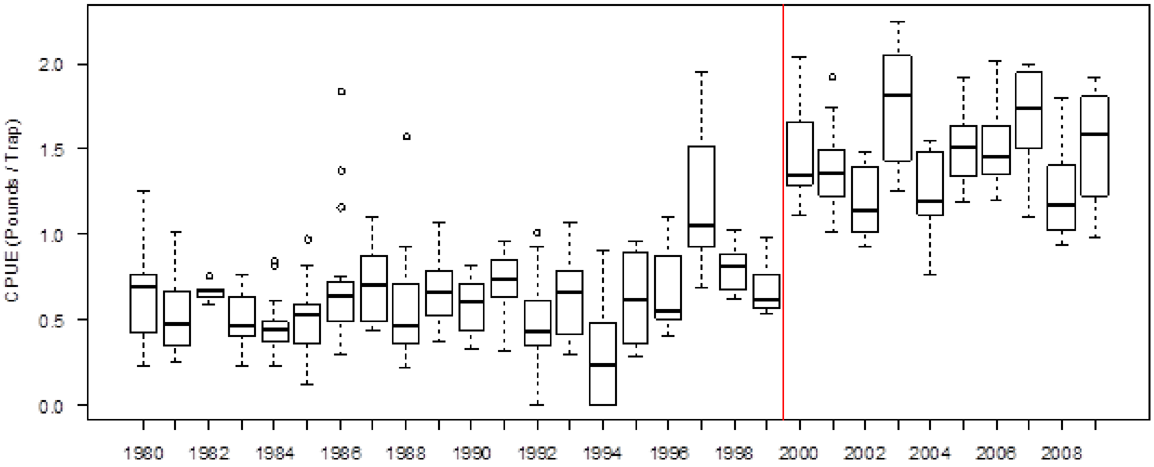

Figure 4 Commercial spot prawn fishery catch per unit effort (CPUE; 1980 - 2009) in Howe Sound, BC. Boxplots include the median CPUE value (horizontal lines), 25% and 75% interquartile ranges (box), and 1.5 times the interquartile range (whiskers). The vertical line represents a management change to the current daily single haul restriction and addition of 25% buffer to the MMI (see Table 2).

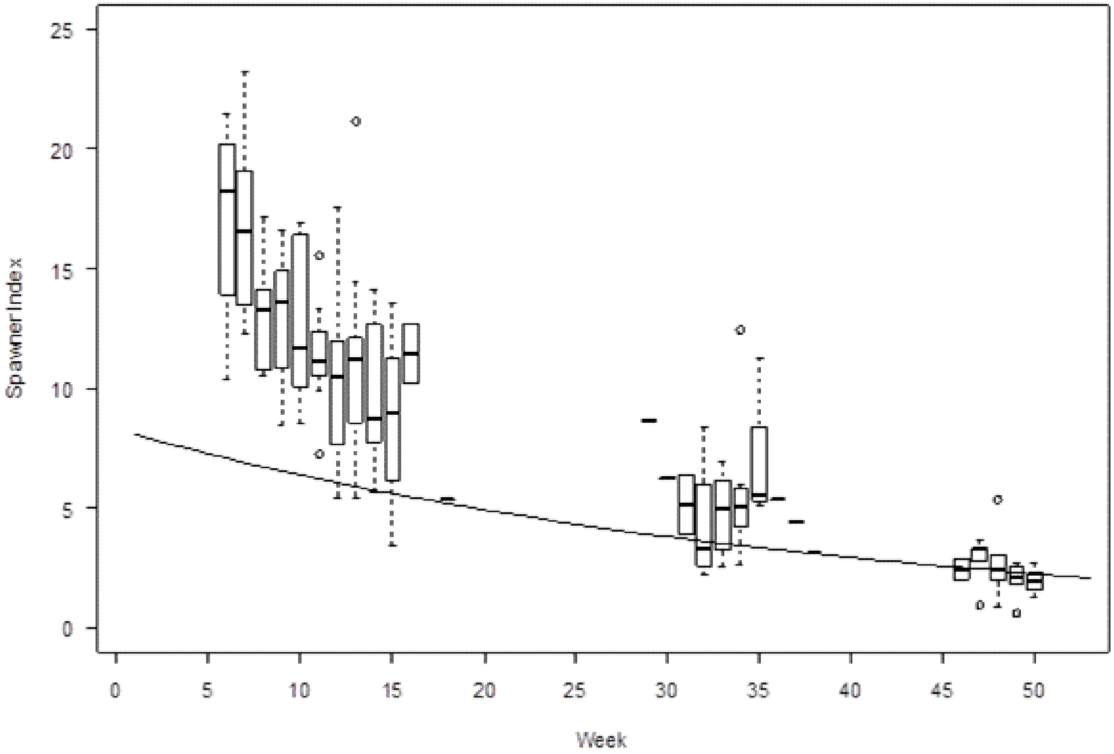

Figure 5 Weekly escapement-based management strategy (status quo) for the commercial prawn fishery in Howe Sound, B.C. (black line). Weeks are initialized such that April 1st is week one, such that the last week of March where spawning event occurs is week zero. Distribution of weekly SI data collected from the commercial fishery (May-July, weeks 6-16) and from the DFO surveys (October-November and February-March) in 2000-2010 includes median SI and interquartile (IQR) range (horizontal box-lines), full data range within 1.5*IQR (whiskers) and outliers (open circles).

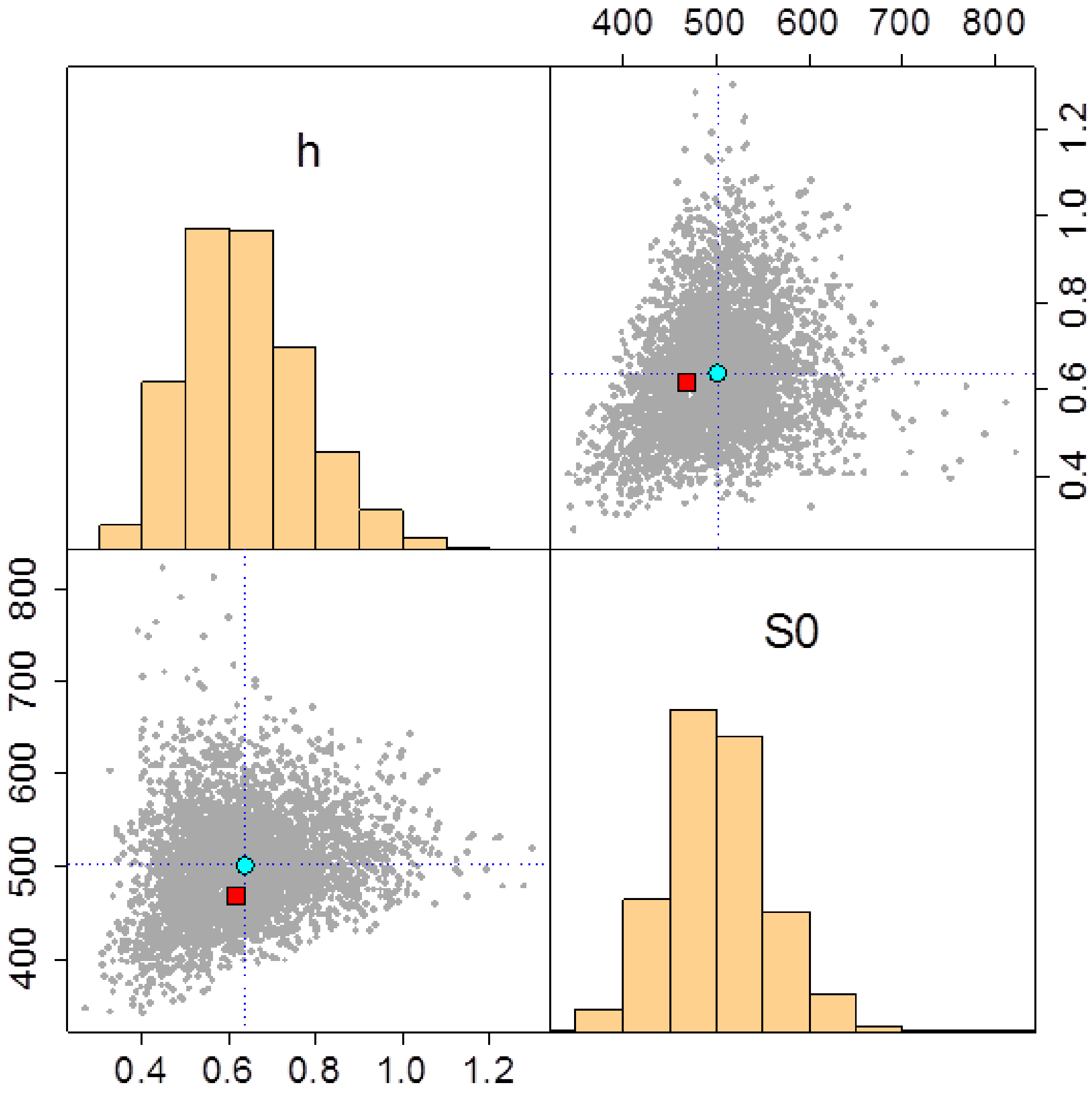

Figure 6 Marginal and pairwise posterior density samples of stock-recruitment steepness (h) and unfished spawner abundance (So) for the Howe Sound EMA spawner-recruit data. The posterior modes and means are represented by the red box and blue circle, respectively.

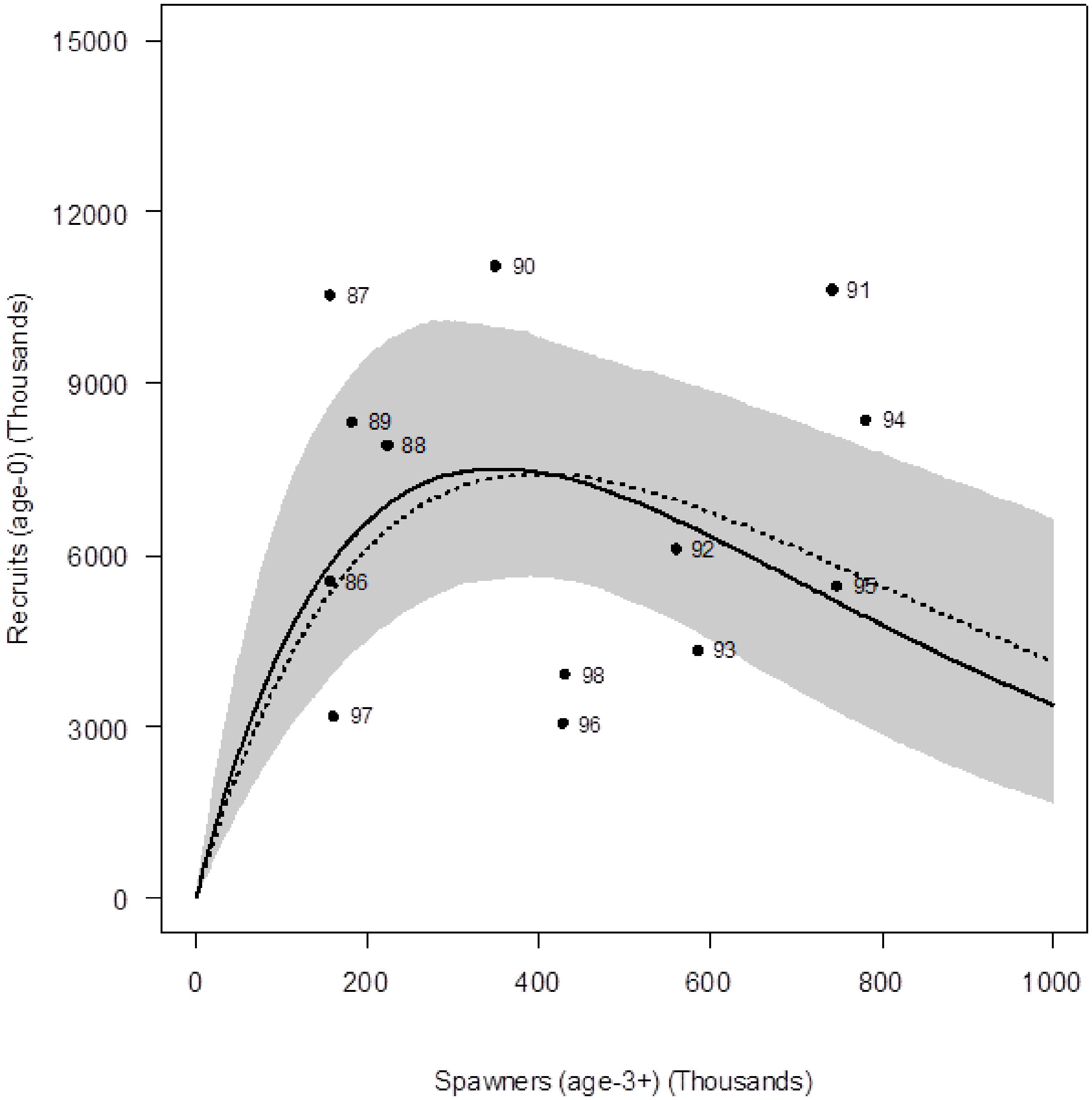

Figure 7 Posterior distribution of the Ricker stock-recruitment relationship representing uncertainty over the range of observed stock sizes. The solid black line represents the expectation of the Ricker relationship generated from the posterior means of h and So, where M = 0.88yr-1. The grey shaded area represents the 95% posterior quantile range of uncertainty in the relationship. The solid black dots represent the SR data with the numbers on the right corresponding to year of spawning events. The dotted line represents the Ricker model fit estimated by Boutillier and Bond (2000).

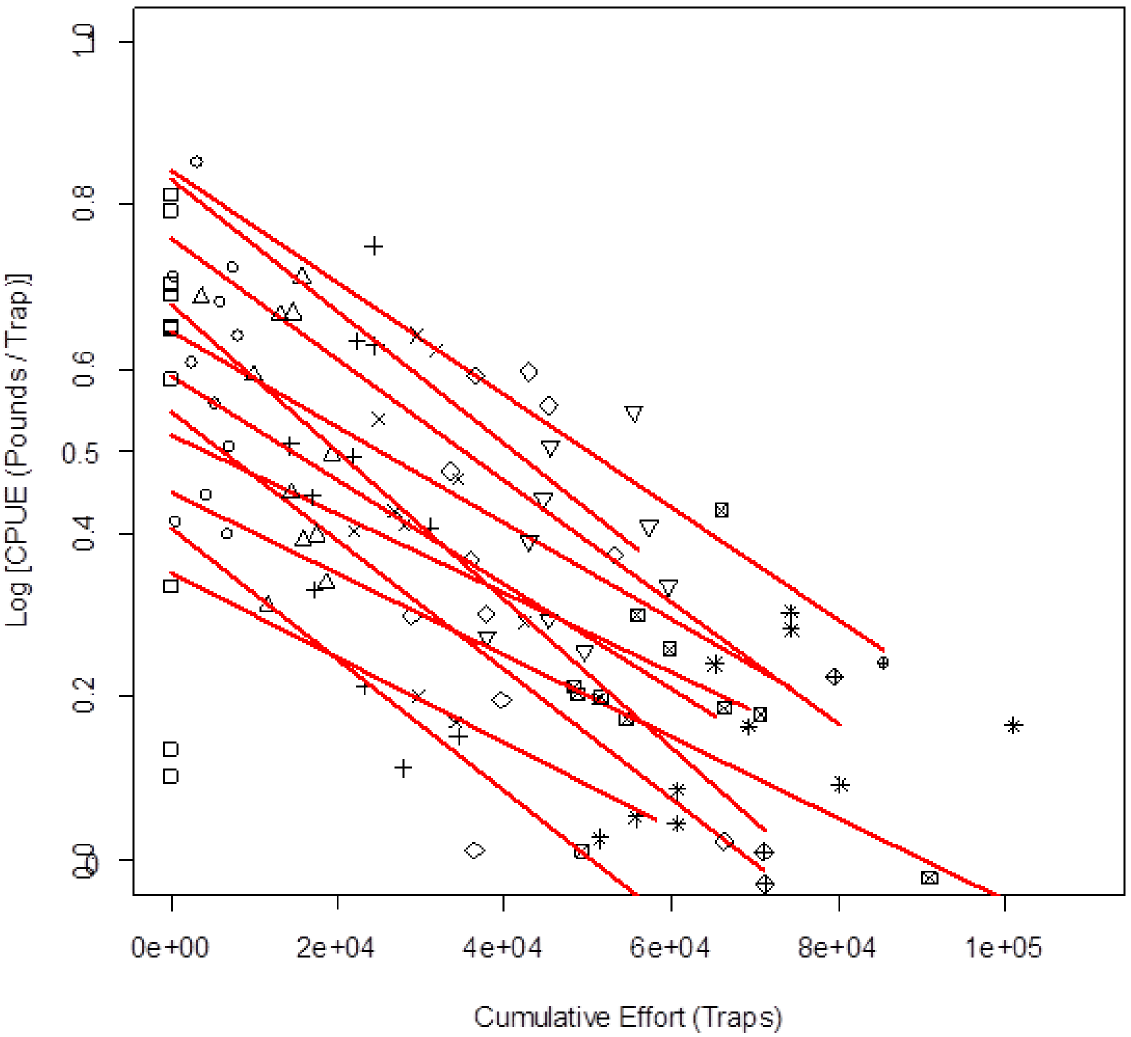

Figure 8 Depletion model fits (red lines) to observed cumulative effort and log(CPUE) for the Howe Sound commercial spot prawn fishery (2000 – 2010). Symbols correspond to years 2000-2010.

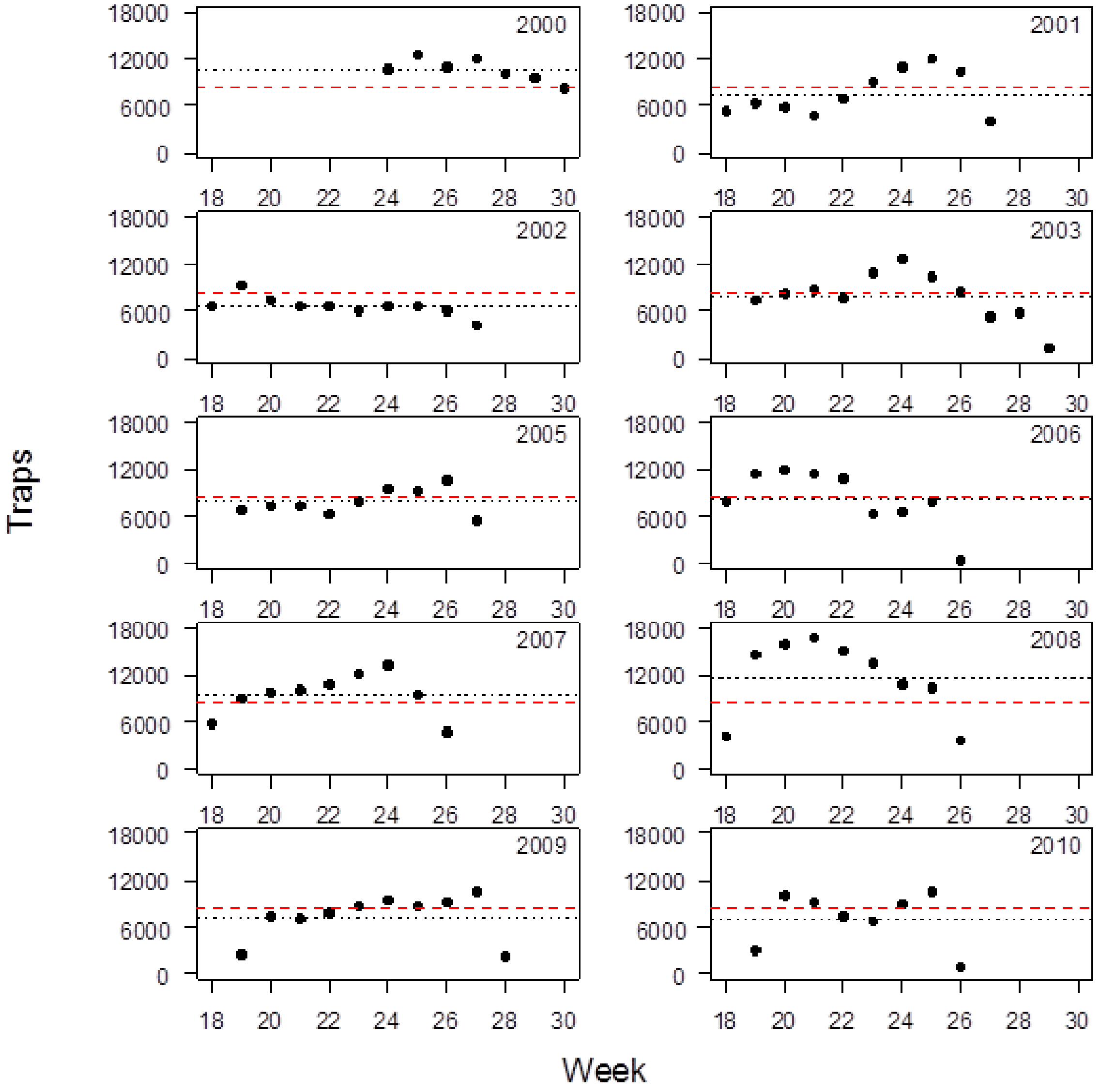

Figure 9 Weekly number of commercial prawn traps fished in years 2000 – 2010 (circles), overall mean weekly trap effort for all years (dashed line), and average year-specific weekly effort (dotted line).

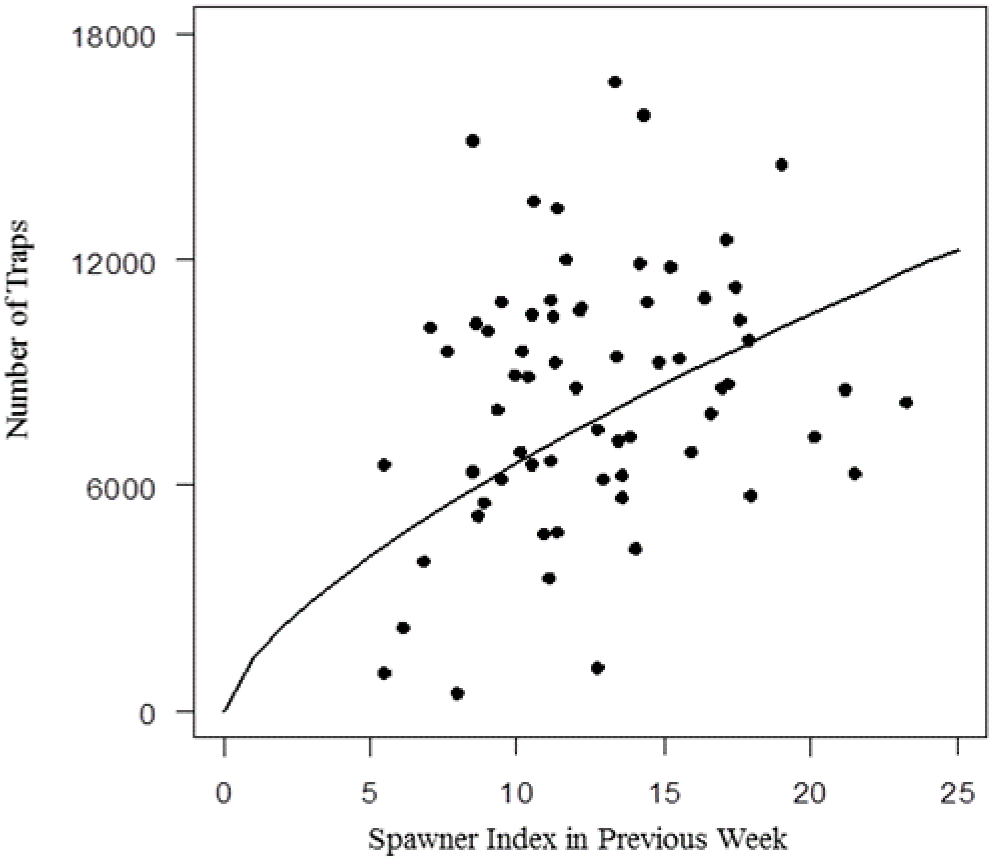

Figure 10 Relationship between the weekly trap fishing effort and the fishery-dependent spawner index values from the previous week (2000-2010) in Howe Sound, BC.

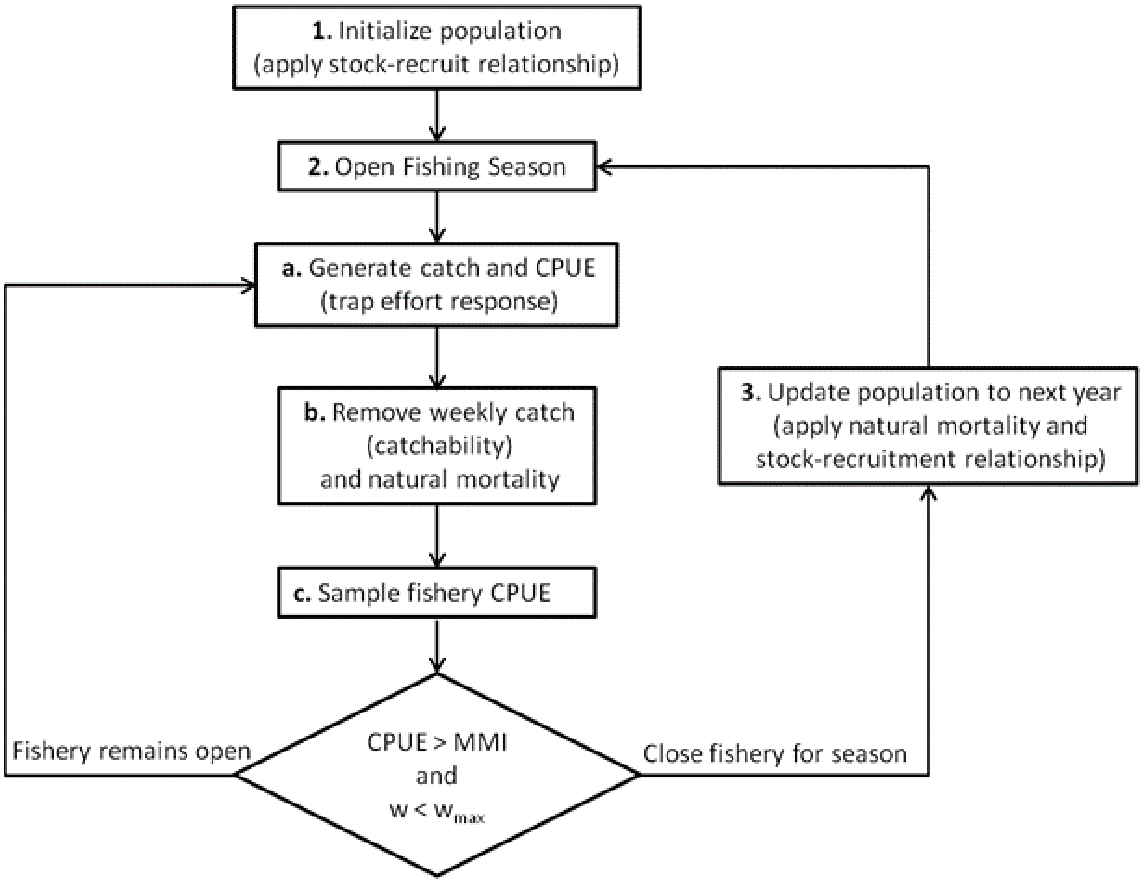

Figure 11 Generalized flow chart of the simulation model representing the prawn escapement-based management procedure in Howe Sound, BC. Whereby, MMI represents the in-season harvest control rule, and w represents the weekly decision-making time-frame with w_{max} is the last week in the pre-determined season length.

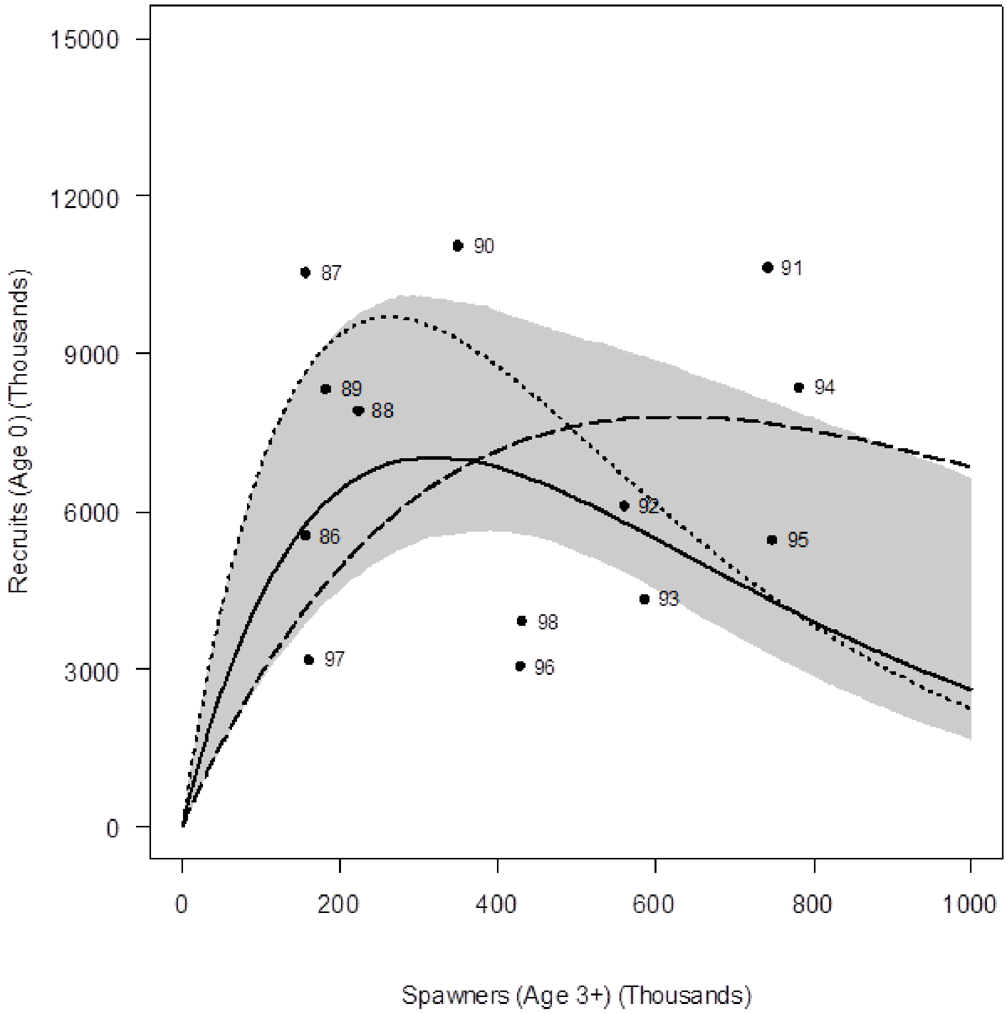

Figure 12 Bayesian posterior mean (solid line), 95% confidence range (grey shaded area), and 97.5% (dotted line) and 2.5% (dashed line) posterior quantiles of the Ricker stock-recruitment curve fitted to Howe Sound EMA spawner-recruit data (points with brood-years).

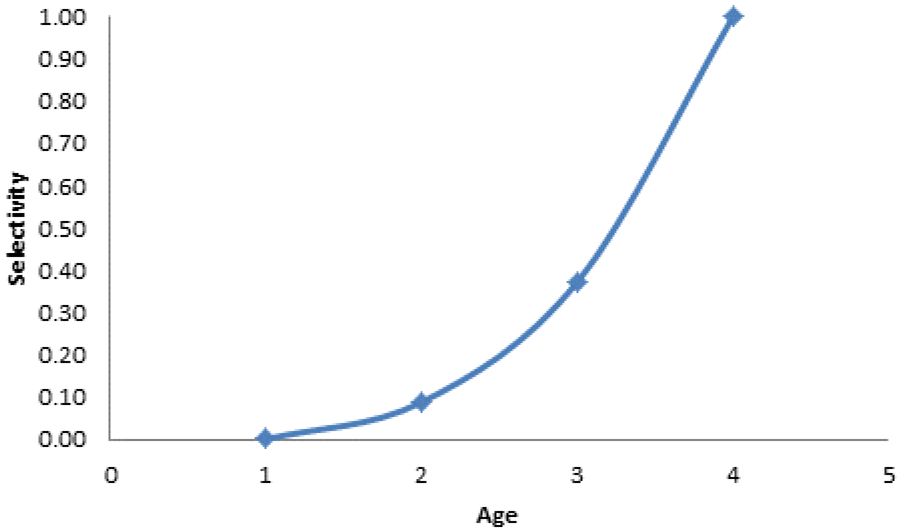

Figure 13 Age at 50% and 95% selectivity.

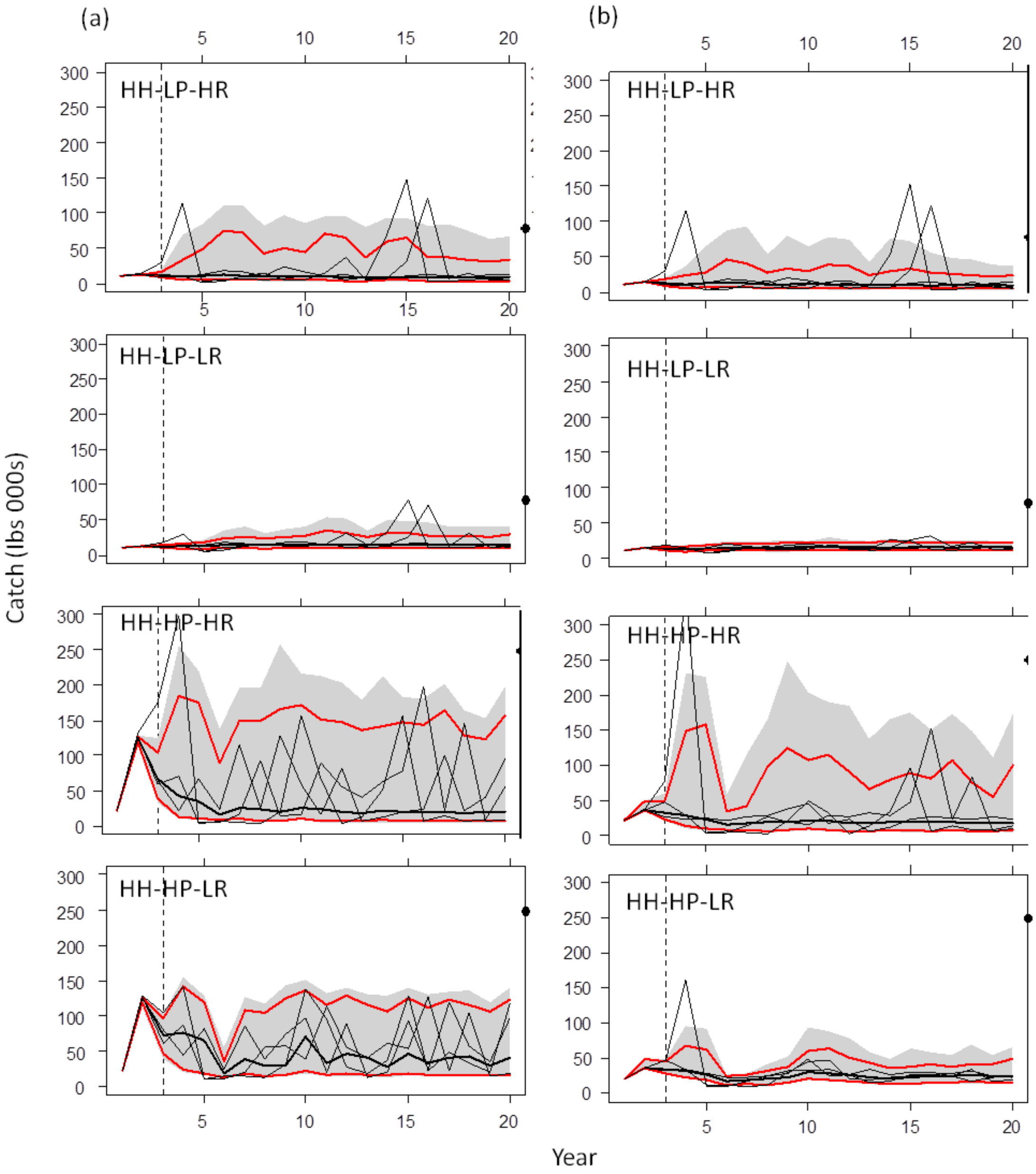

Figure 14 Trajectories of annual catch under (a) status-quo and (b) MSY-based management procedures. Panels are arranged vertically corresponding to high- and low-productivity (HP, LP) and high- and low-recruitment variability (HR, LR) scenarios; only high habitat (HH) area scenarios are displayed here. Vertical dashed lines indicate the start of the simulation trials and MSY is indicated by the filled circle. Trajectories are summarized by the median (thick black line), three individual simulation replicates (thin black lines), and the 5th to 95th percentiles (shaded area), and 10th to 90th percentiles (red lines).

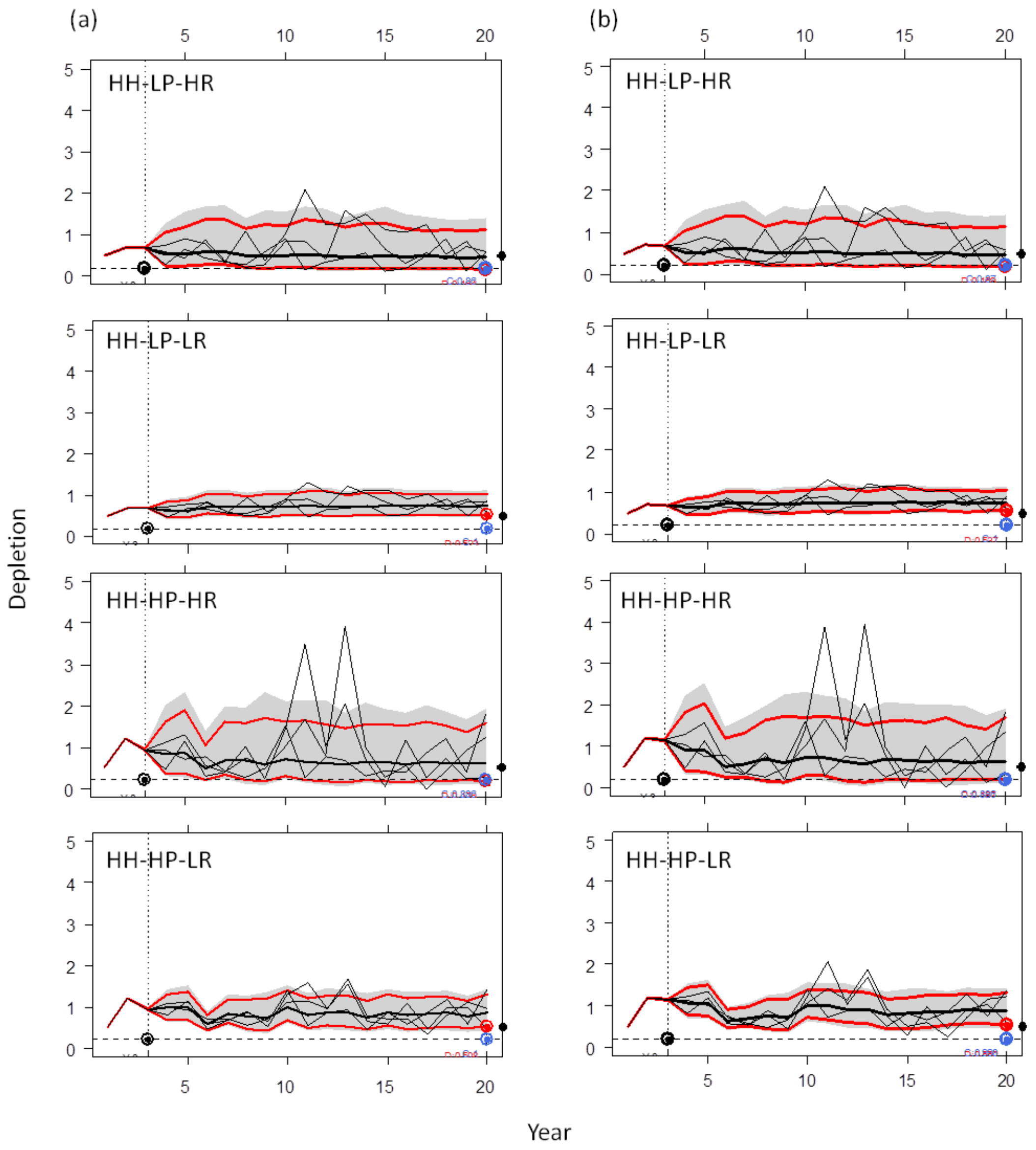

Figure 15 Trajectories of spawning stock depletion under (a) status-quo and (b) MSY-based management procedures. Panels are arranged vertically corresponding to high- and low-productivity (HP, LP) and high- and low-recruitment variability (HR, LR) scenarios; only high habitat (HH) area scenarios are displayed here. Dotted horizontal lines indicate depletion levels corresponding to the depletion objective of 0.2 and vertical dashed lines indicate the start of the simulation trials. Trajectories are summarized by the median (thick black line), three individual simulation replicates (thin black lines), and the 5th to 95th percentiles (shaded area), and 10th to 90th percentiles (red lines).

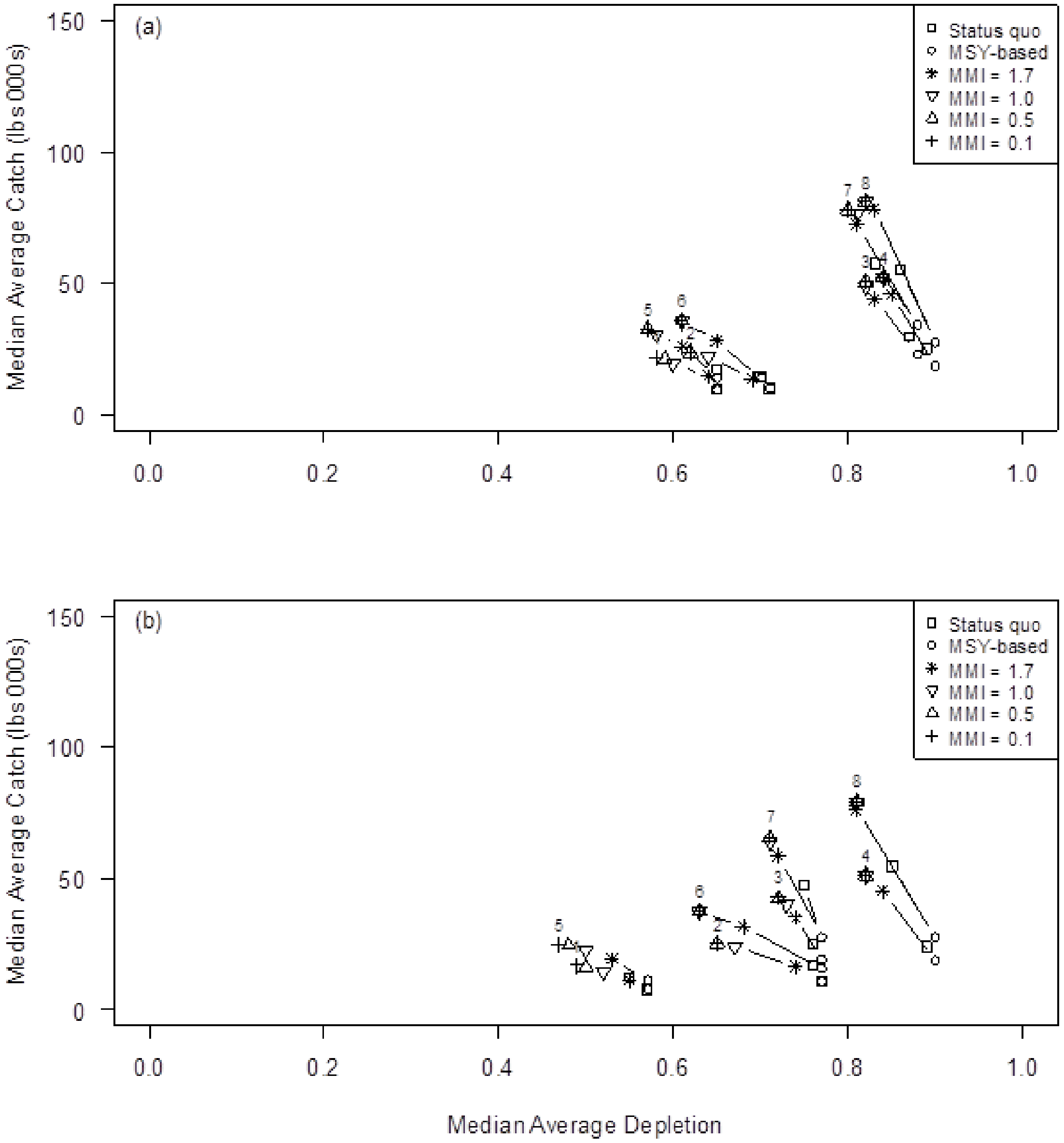

Figure 16 Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment assumptions).

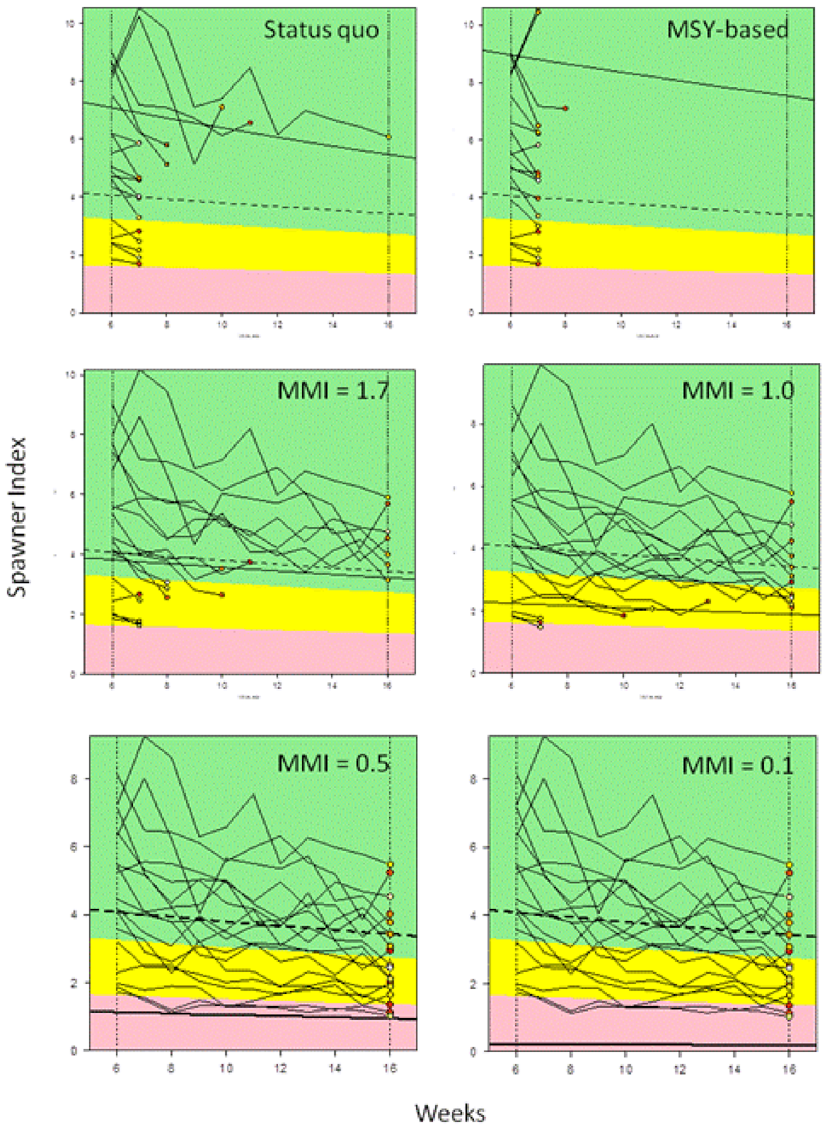

Figure 17 Harvest Control Rule traces for all management procedures under a single simulation run (1/500) of scenario HH-LP-HR. Coloured panels reflect the critical (red), cautious (yellow) and healthy (green) zones consistent with DFO`s (2006) guide to a precautionary approach for fisheries management. The minimum monthly index (MMI) management procedure is defined by the solid black line and the status quo March MMI = 2.1 with M=0.88 (versus status quo dotted line with M=1.33 in top right panel) is represented by the dotted line. Weeks are initialized such that April 1st is week 1 and the last week of March where spawning event occurs is week 52. Trace lines represent SI values generated in each simulation year. In-season closure decisions in years 1 to 20 are represented sequentially by white, yellow, orange then red filled circles.

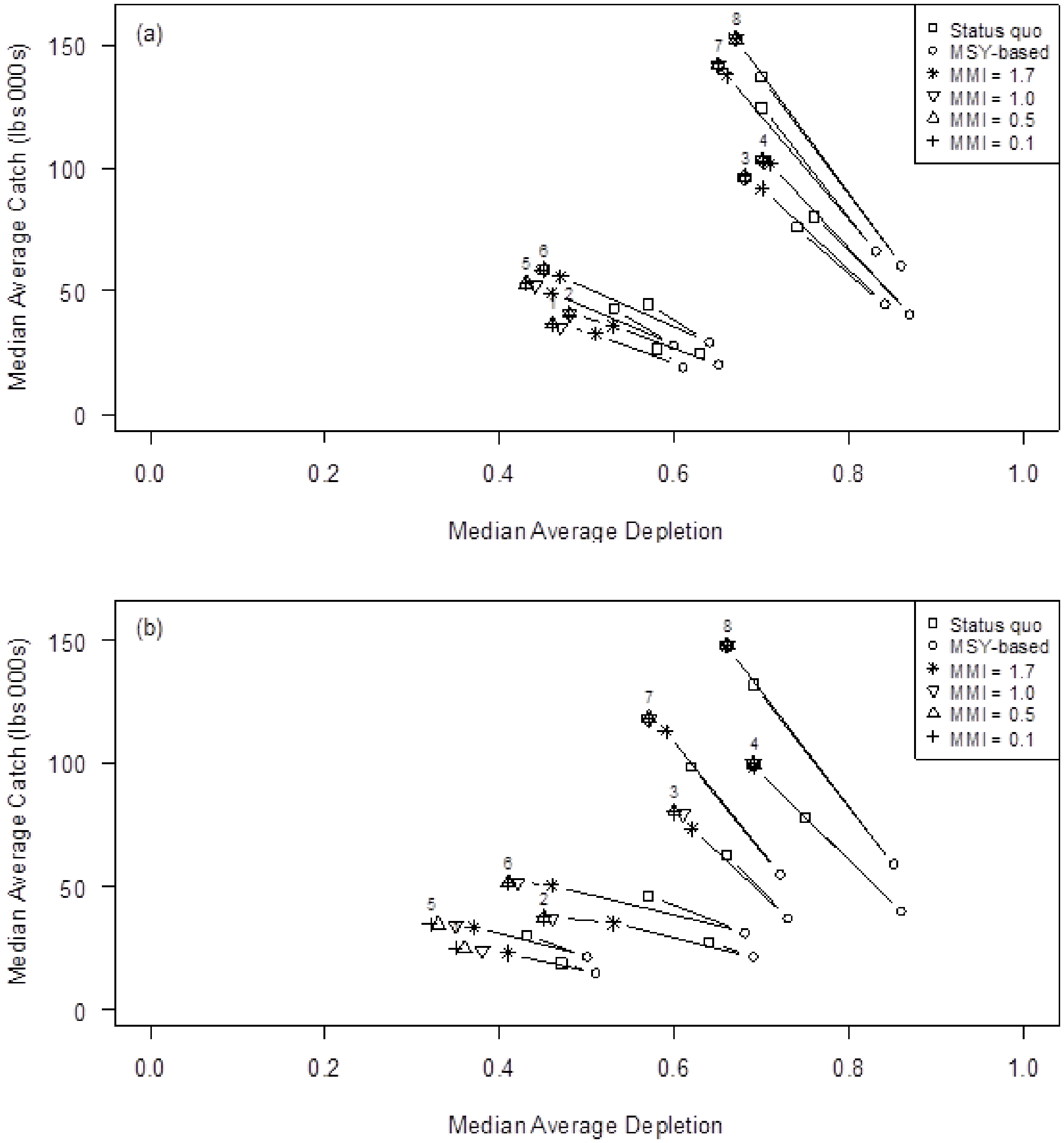

Figure 18 Sensitivity to increased catchability assumption. Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment assumptions).

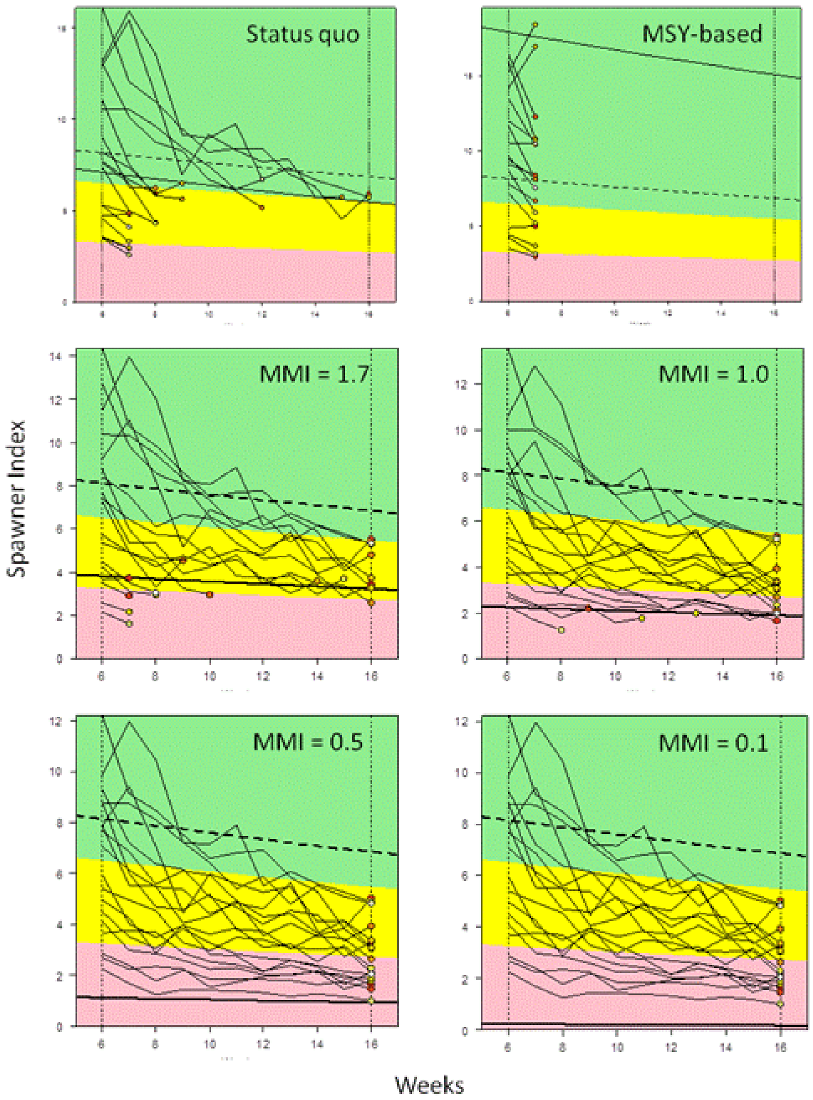

Figure 19 Harvest Control Rule traces for all management procedures under a single simulation run (1/500) of scenario HH-LP-HR (for sensitivity to increased catchability). Coloured panels reflect the critical (red), cautious (yellow) and healthy (green) zones consistent with DFO`s (2006) guide to a precautionary approach for fisheries management. The minimum monthly index (MMI) management procedure is defined by the solid black line and the status quo March MMI = 2.1 with M=0.88 (versus status quo dotted line with M=1.33 in top right panel) is represented by the dotted line. Weeks are initialized such that April 1st is week 1 and the last week of March where spawning event occurs is week 52. Trace lines represent SI values generated in each simulation year. In-season closure decisions in years 1 to 20 are represented sequentially by white, yellow, orange then red filled circles.

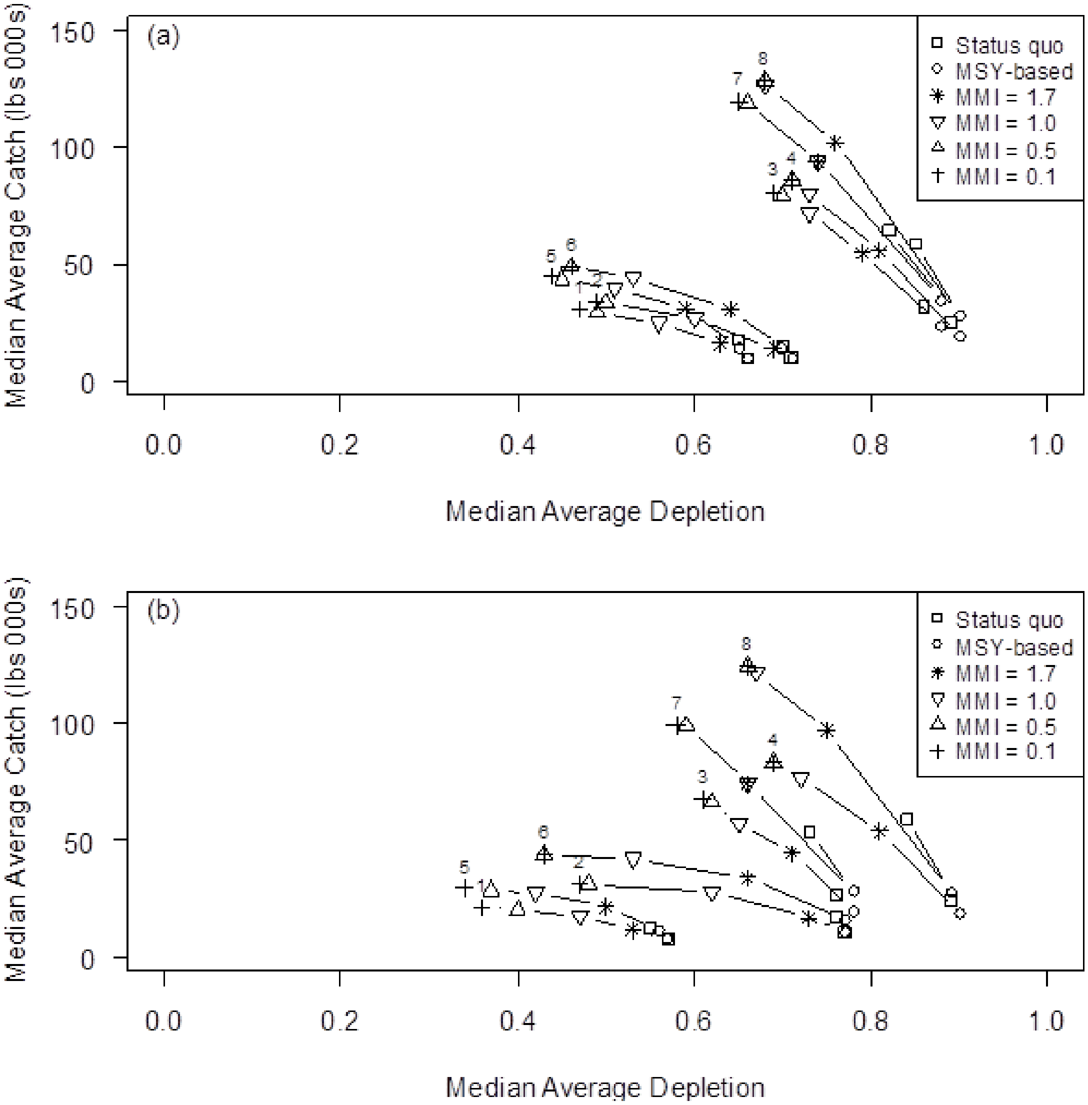

Figure 20 Sensitivity to increased season length (to 40 weeks) assumption. Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment assumptions).

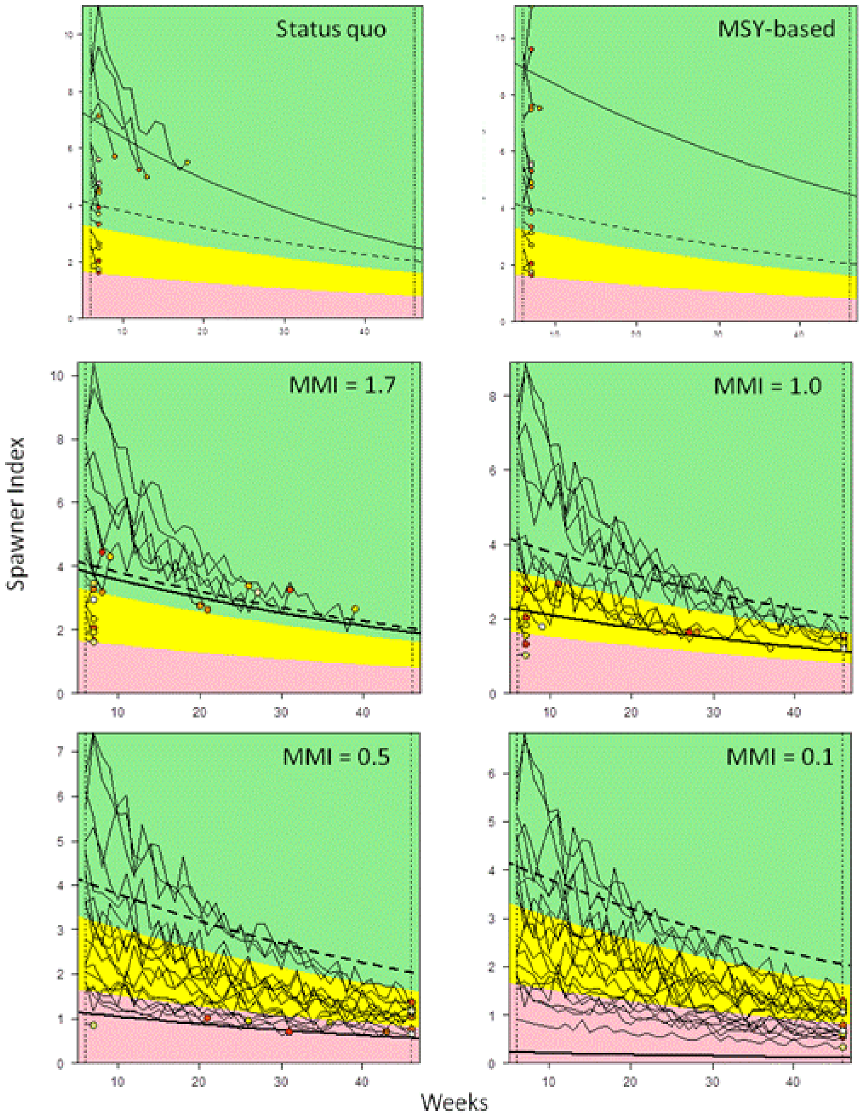

Figure 21 Harvest Control Rule traces for all management procedures under a single simulation run (1/500) of scenario HH-LP-HR (for sensitivity to increased season length). Coloured panels reflect the critical (red), cautious (yellow) and healthy (green) zones consistent with DFO`s (2006) guide to a precautionary approach for fisheries management. The minimum monthly index (MMI) management procedure is defined by the solid black line and the status quo March MMI = 2.1 with M=0.88 (versus status quo dotted line with M=1.33 in top right panel) is represented by the dotted line. Weeks are initialized such that April 1st is week 1 and the last week of March where spawning event occurs is week 52. Trace lines represent SI values generated in each simulation year. In-season closure decisions in years 1 to 20 are represented sequentially by white, yellow, orange then red filled circles.

TABLES

Table 1 History of significant management changes in the BC prawn fishery.

Year	Management Change
1979	Implementation of fixed escapement strategy using spawner index targets
1983	Harvest log books required
1985	Howe Sound pre-season (Jan-Feb) and post-season (Oct-Nov) research surveys
1988	New gear restrictions, including:
	(i) Minimum trap mesh size (38 mm for mesh traps);
	(ii) Maximum trap volume (170 L);
	(iii) Minimum size limit (30 mm carapace length)
1989	Licence limitation restricts fleet to 250 vessels
1993	Daylight fishing only
1995	2-year pilot in-season effort limitation program via:
	300 traps on six ground lines OR
	450 traps on 10 ground lines for stacked licences (max 2 licences)
1996	Minimum size limit increased to 32 mm carapace length.
1997	Effort limit, regulation, and harvest policy changes including:
	(i) In-season effort limitation program extended 1 year
	(ii) Minimum size limit increased to 33 mm carapace length;
	(iii) Release of berried females required until June 30;
	(iv) Saanich Inlet fished to 25% higher spawner index to maintain recreational fishing opportunity following the commercial fishery
1998	Effort limit, fleet, and in-season changes including:
	(i) Fishing season restricted to maximum 90 days;
	(ii) Commercial fishing season restricted May to July only
2000	SI program became operational on coast-wide basis;
	Daily single haul limit (traps hauled only once per day) in southern waters from 7 a.m. to 7 p.m;
	Trap limits increased to 500 traps for stacked licences;
	New regulations in Special Management Areas (SMAs) where recreational fisheries occur;
	(i) fished to index +25% and trap limits reduced to 150 traps on single licence or
	(ii) 250 traps on double licence
	All other coastal areas fished to index +10%;
2001	Daily single haul limit extended coast-wide
2002	Fishing season reduced to approximately 68 days per year, May 1st opening remains
2005	Bait correction factor implemented on spawner index data

Table 2 Estimated number of commercial fishing vessels in Howe Sound per week based on the assumption that each vessel fishes 150 traps per day (an assumption more valid from 2000 onward when the trap restrictions were put in place, Table 1).

Year	**Average Number of Vessels**
1980 - 1984	2.04
1985 - 1989	3.96
1990 - 1994	2.99
1995 - 1999	8.58
2000 - 2004	6.46
2005 - 2009	8.30

Table 3 Average closure dates and total catch in Howe Sound between 2000 and 2011.

Year	**Season Length (days)**	**Total Catch (pounds)**
2000	78	116,532
2001	67	92,207
2002	66	74,832
2003	72	154,531
2004*	63	65,627
2005	59	95,971
2006	59	111,141
2007	59	133,008
2008	51	119,797
2009	61	103,567
2010	46	110,093
2011	58	
Average:		107,027

*****Half of Howe Sound was closed in 42 days, the reminder stayed open for average of 61 days

Table 4 Minimum monthly index (MMI) values used as the basis of the Howe Sound in-season management procedure. MMI values represent the mean number of prawns per trap that fall into month-specific sexual stages that contribute to the March escapement value (estimated via annual natural mortality rate trajectory of 1.3 yr-1). Baseline MMI and status quo MMI values were used to implement the escapement-based management procedure from 1985 to 1999 and 2000 to present, respectively.

Month	**Baseline MMI**	**Status quo MMI**	**Sexual Stage**
April	6.4	8.1	2 & 3
May	5.9	7.4	2 & 3
June	5.4	6.8	2 & 3
July	4.9	6.1	2 & 3
August	4.4	5.5	2 & 3
September	4.1	5.1	2, 3 & 4
October	3.6	4.5	3 & 4 *
November	3.2	4.0	3 & 4 *
December	2.7	3.4	4 **
January	2.4	3.0	4 & 5
February	2.0	2.5	4 & 5
March	1.7	2.1	4 & 5

Sexual Stage: (1) mature males, (2) transitions, (3) females with no eggs, (4) females with eggs (berries), (5) spent females

* stage 2 individuals have grown to class 3

** stage 3 individuals have developed into stage 4 berried females

Table 5 Analysis of covariance (ANCOVA) used to determine the minimal adequate linear model to describe the relationship between weekly catch per unit effort (CPUE) and cumulative fishery effort (EW) each year (Y).

Model	**Equation**	**Res. Df**	**RSS**	**Df**	**SS**	**F**	**Pr(>F)**
3	log(CPUE) ~ E_W + Y + E_W * Y	88	1.03				
2	log(CPUE) ~ E_W + Y	99	1.23	11	0.20	1.58	0.12
1	log(CPUE) ~ E_W	110	9.16	11	7.93	61.64	<2e-16***

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 6 ANCOVA for alternative linear model fits between the weekly (w) number of traps (T) fished and the fishery-dependent spawner index (SI) derived in the previous week. Data years (Y) examined include 2000-2010.Significance is measured at the $p \leq 0.05$ level.

Model	**Equation**	**Res. DF**	**RSS**	**DF**	**SSQ**	**F**	**Pr(>F)**
3	$\log(T_w) \sim \log(SI_{(w-1)}) + Y + \log(SI_{(w-1)}) * Y$	46	13.79				
2	$\log(T_w) \sim \log(SI_{(w-1)}) + Y$	55	17.87	9	4.08	1.51	0.17
1	$\log(T_w) \sim \log(SI_{(w-1)})$	64	22.01	9	4.14	1.53	0.16

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 7 Summary of posterior distributions for Ricker stock-recruitment model parameters, steepness (*h*) and unfished spawner abundance (S_o). MCMC control parameters used a burn-in of 10000, total sample size of 4,000,000, and chain thinning of 1000.

Parameter	**Quantile**			**Mean**	**Mode**
	2.5%	50%	97.5%		
h	0.40	0.62	0.96	0.64	0.62
S_o (pounds)	400,130	498,240	621,490	501,351	499,330

Table 8 DeLury depletion model estimates of initial prawn abundance (N_o), CPUE and catchability (q) based on Howe Sound commercial catch and cumulative trap effort data (2000-2010) where q is estimated as the slope of the linear regression. Significance is measured at the $p \leq 0.05$ level separately for each year.

Year	No* (pounds)	CPUE	q	SE_q	p-value	
2000	349049.9	1.68	4.82 e-06	2.54 e-06	9.94 e-02	.
2001	220563.5	1.73	7.84 e-06	1.06 e-06	7.66 e-05	***
2002	186724.2	1.50	8.03 e-06	1.34 e-06	3.26 e-04	***
2003	338630	2.32	6.85 e-06	6.05 e-06	1.26 e-06	***
2004	275885.7	1.42	5.15 e-06	3.14 e-06	1.39 e-01	
2005	284510.3	1.80	6.34 e-06	8.33 e-06	1.25 e-04	***
2006	326219.9	1.91	5.85 e-06	9.82 e-07	5.68 e-04	***
2007	290003.2	2.13	7.36 e-06	9.47 e-07	1.09 e-04	***
2008	316586.8	1.57	4.95 e-06	1.16 e-06	3.66 e-03	**
2009	219233.8	1.97	8.99 e-06	9.76 e-07	1.55 e-05	***
2010	284206.8	2.30	8.08 e-06	1.12 e-06	3.62 e-04	***
Overall Mean	281056	1.85	6.75e-06			

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

*N_o is calculated as CPUE/q

Table 9 Summary table for effort dynamics Model 1 (log(Tw) ~ log(SI(w-1))) selected from ANCOVA analysis. The residual SE is 0.59 on 64 degrees of freedom, multiple R-squared is 0.13, adjusted R-squared is 0.11, F-statistic is 9.21 on 64 DF, and p-value is 0.0038.

	Estimate	SE	t value	Pr(>|t|)
Intercept	7.23	0.56	12.93	< 2e-16 ***
log(SpawnInd)	0.68	0.22	3.04	0.0035 **

Significance codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 10 Notation for the hermaphroditic prawn population, survey and fishery operating model. The “Symbol” column gives notation used in subsequent equation tables and “Names” provide the actual variable names used in the R computer code. Values are derived from Chapter 2 analyses, operating model conditioning, or best available information and are fixed in the operating model and management procedure unless specified otherwise.

Description	**Value**
Age-at-50% maturity	3.5
Age-at-95% maturity	3.6
Age-at-50% selectivity	2.9
Age-at-95% selectivity	3.6
Number of age-classes	5
Instantaneous natural mortality rate (/yr)	0.88
Error in natural mortality rate	0
Carapace length-at-age 1 (mm)	10.0
Asymptotic carapace length (mm)	60.0
von Bertalanffy growth constant	0.30
Length-weight slope	4.1e-06
Length-weight power	2.77
Fishery catchability coefficient	6.75e-06
Hyperstability	1.0
Index error	0.11
Effort	7.23
Effort power	0.68
Effort error	0.15

Table 11 Summary of operating model characteristics that define the scenarios for the management procedure simulations. A scenario is defined by three variables; for example, the scenario of low habitat area, low productivity (*h*), and low recruitment error (σ_R) is LH-LP-LR. The unfished spawning stock biomass (S_0) is associated with h but does not define the scenario.

Scenario	Label	Habitat Area	h	S_0	σ_R
S1	LH-LP-HR	2.2	0.4	1,208,550	0.62
S2	LH-LP-LR	2.2	0.4	1,208,550	0.25
S3	LH-HP-HR	2.2	0.96	1,135,780	0.62
S4	LH-HP-LR	2.2	0.96	1,135,780	0.25
S5	HH-LP-HR	3	0.4	1,648,030	0.62
S6	HH-LP-LR	3	0.4	1,648,030	0.25
S7	HH-HP-HR	3	0.96	1,548,790	0.62
S8	HH-HP-LR	3	0.96	1,548,790	0.25

Table 12 Performance of status quo and MSY-based management procedures for each operating model scenario. Table values represent the median performance outcome over 500 replicates in short- (2 to 8 years) and long-term (15 to 20 years) projection periods. MSY and catch are reported as thousands of pounds.

	Scenario	Procedure	MSY	Short term			Long term		
				$\overline{C}$	C_{MSY}	$\overline{D}$	$\overline{C}$	C_{MSY}	$\overline{D}$
1	LH-LP-HR	Status quo	57.44	9.45	0.16	0.65	7.63	0.13	0.57
		MSY-based	57.44	9.77	0.17	0.65	7.76	0.14	0.57
2	LH-LP-LR	Status quo	57.44	9.80	0.17	0.71	10.72	0.19	0.77
		MSY-based	57.44	9.82	0.17	0.71	10.77	0.19	0.77
3	LH-HP-HR	Status quo	182.60	29.90	0.16	0.87	25.00	0.14	0.76
		MSY-based	182.60	23.17	0.13	0.88	19.03	0.10	0.77
4	LH-HP-LR	Status quo	182.60	24.95	0.14	0.89	23.89	0.13	0.89
		MSY-based	182.60	18.64	0.10	0.90	18.52	0.10	0.90
5	HH-LP-HR	Status quo	78.33	17.47	0.22	0.65	12.19	0.16	0.55
		MSY-based	78.33	14.15	0.18	0.65	11.12	0.14	0.57
6	HH-LP-LR	Status quo	78.33	14.68	0.19	0.70	16.68	0.21	0.76
		MSY-based	78.33	14.19	0.18	0.70	15.58	0.20	0.77
7	HH-HP-HR	Status quo	249.00	57.50	0.23	0.83	47.24	0.19	0.75
		MSY-based	249.00	34.32	0.14	0.88	27.53	0.11	0.77
8	HH-HP-LR	Status quo	249.00	55.42	0.22	0.86	54.60	0.22	0.85
		MSY-based	249.00	27.54	0.11	0.90	27.28	0.11	0.90

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