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

by

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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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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 (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

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 catel01 0 0 1 482.17 227.03 Tmg spike in ospikescapement agreed 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

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

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

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.

Depletion Analysis to Parameterize Catchability

Catchability (

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) $$T_w \qquad SI_{w-1} \qquad {}^{w}$$

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

(14) $$\log\ T_w \qquad \log \qquad\qquad \log\ SI_{w-1} \qquad {}_{w}.$$

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

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 and parameters from the best-fit model were 7.23 and 0.68, respectively.

Discussion

Stock-Recruitment Parameterization

Understanding the stock-

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).

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

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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-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 ab (cc5s067 Tm[(E)-e1u gr TJETBpt)5(he)-5(expe)5

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

es 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 decis3(for)-8(th)3(e)] TJETst policy t 5350JE42in613>JET5(t)3(co[(sim)12(u)-7(la)5(t)-4(ed da)5(

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 4^{th} year represents the spawning population. Prawn death after spawning is implemented through a 5^{th} 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 ${}_{M}$ as the estimated standard deviation in log *M* residuals around their expected values as per the following equation:

(15) $$M_t \quad M_0 \exp \quad {}_{M} \; {}_{t} \quad {}^{2}_{M} / 2$$

where

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., $_M$); 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 spa

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 (S_{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 S_{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 $0.88 yr^{-1}$ (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 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 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 length (Figure 19). Similar to the baseline scenario (q = 6.75e^{16}

Limitations and future work

The

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-effec Tm[(effe)4(c)2vient,

FIGURES

Figure 1 Howe Sound, BC, Pacific Fishery Management Area (PFMA). Howe Sound

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

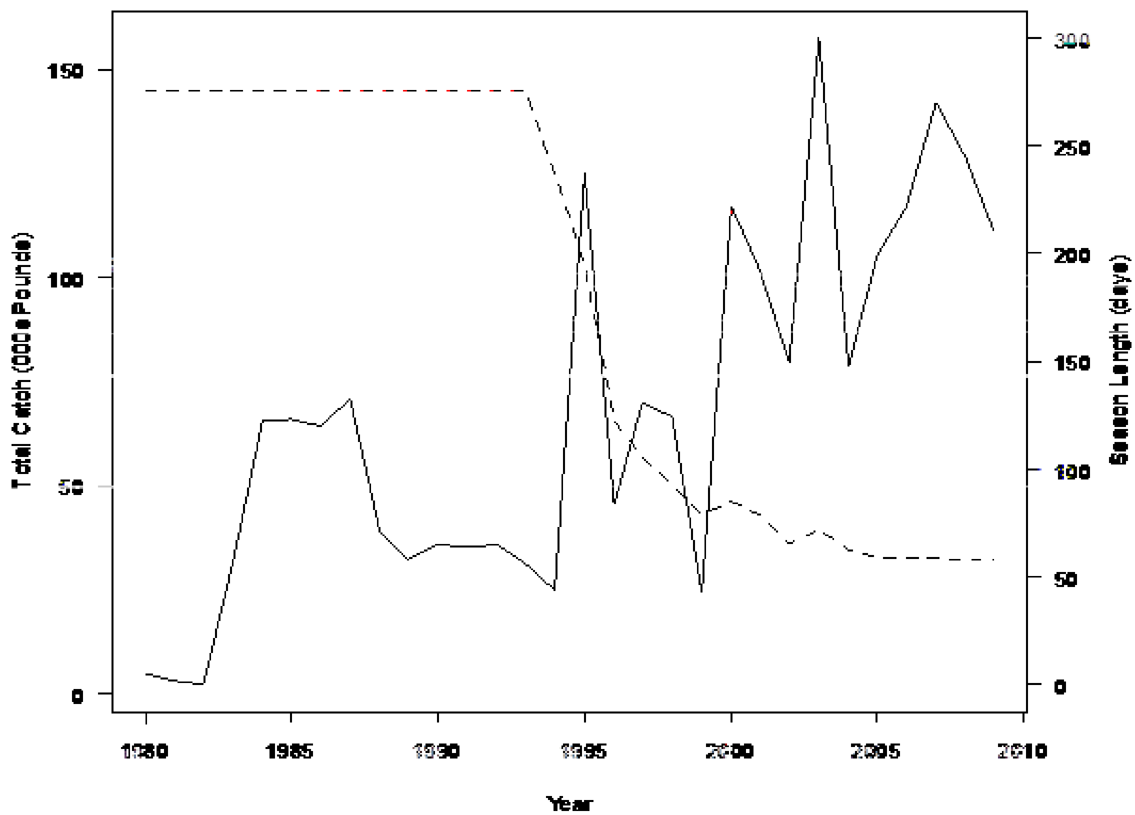

Figure 3 Commercial prawn catch per year in Howe Sound, BC and associated fishing season length (red dashed line) (1980 - 2009).

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

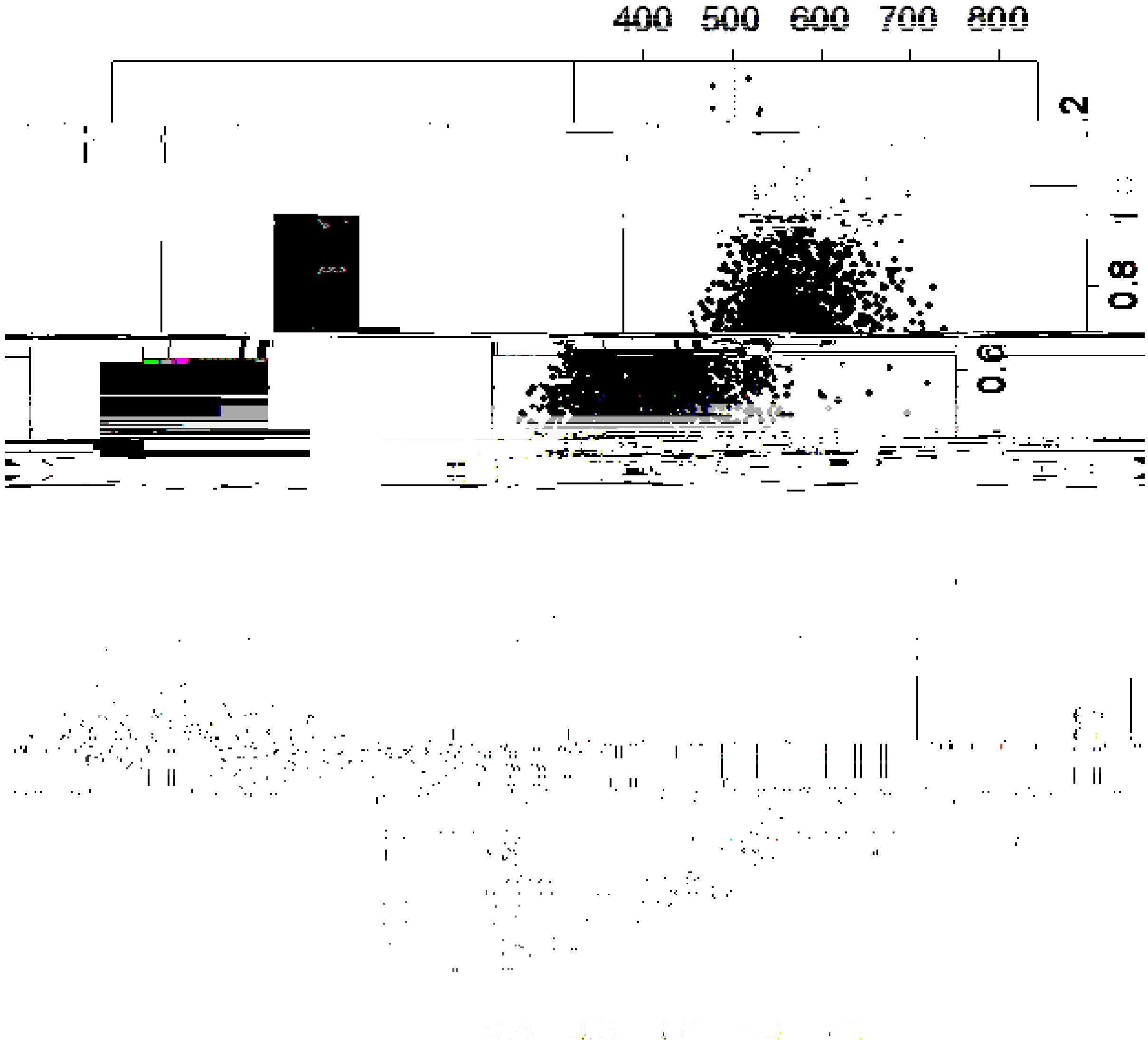

Figure 6 Marginal and pairwise posterior density samples of stock-recruitment steepness (h) and unfished spawner abundance (So) for the Howe Sound EMA spawner-recruit data. The posterior modes and means are represented by the red box and blue circle, respectively.

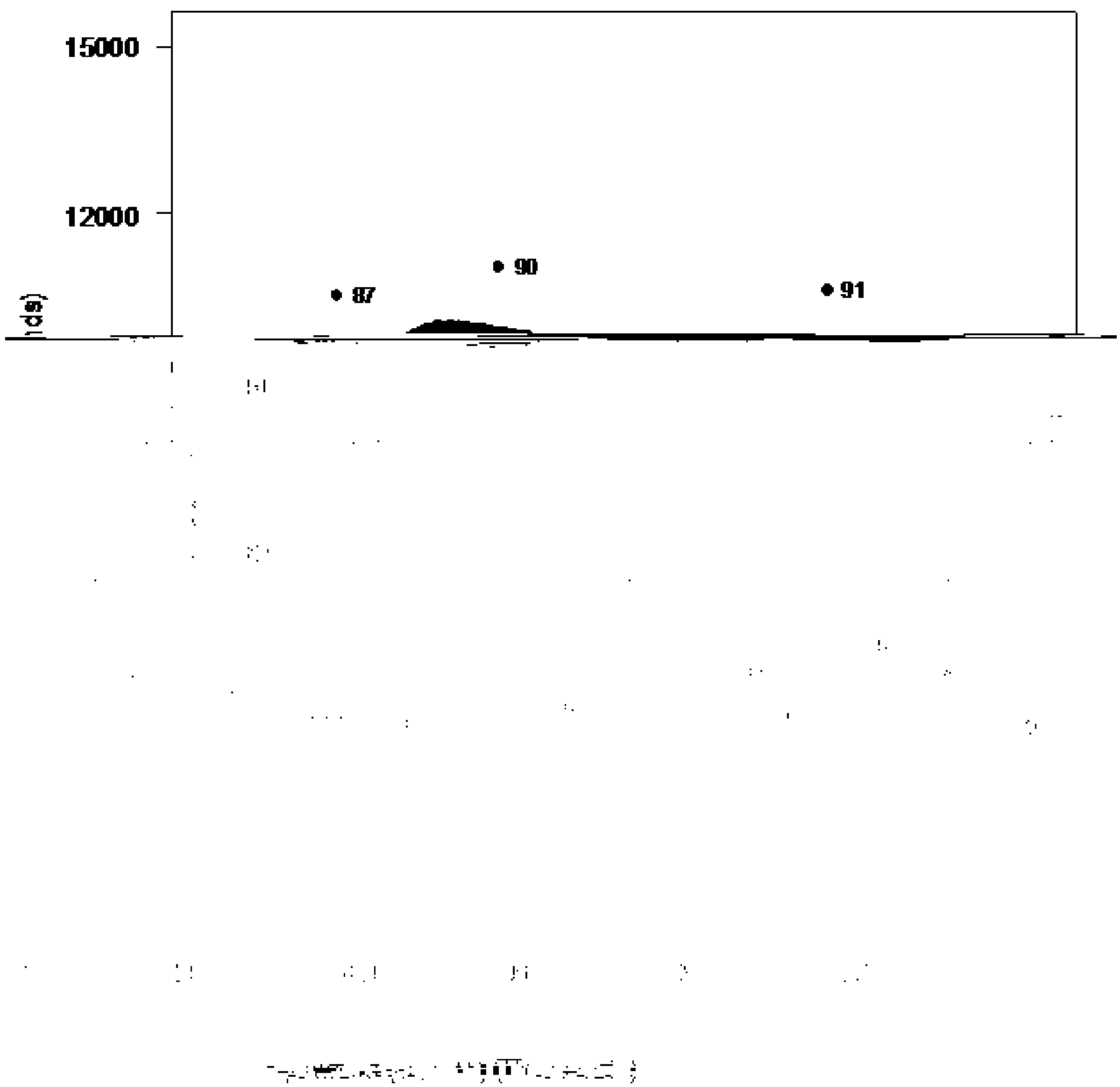

Figure 7 Posterior distribution of the Ricker stock-recruitment relationship representing uncertainty over the range of observed stock sizes. The solid black line represents the expectation of the Ricker relationship generated from the posterior means of h and So, where M = 0.88yr-1. The grey shaded 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).

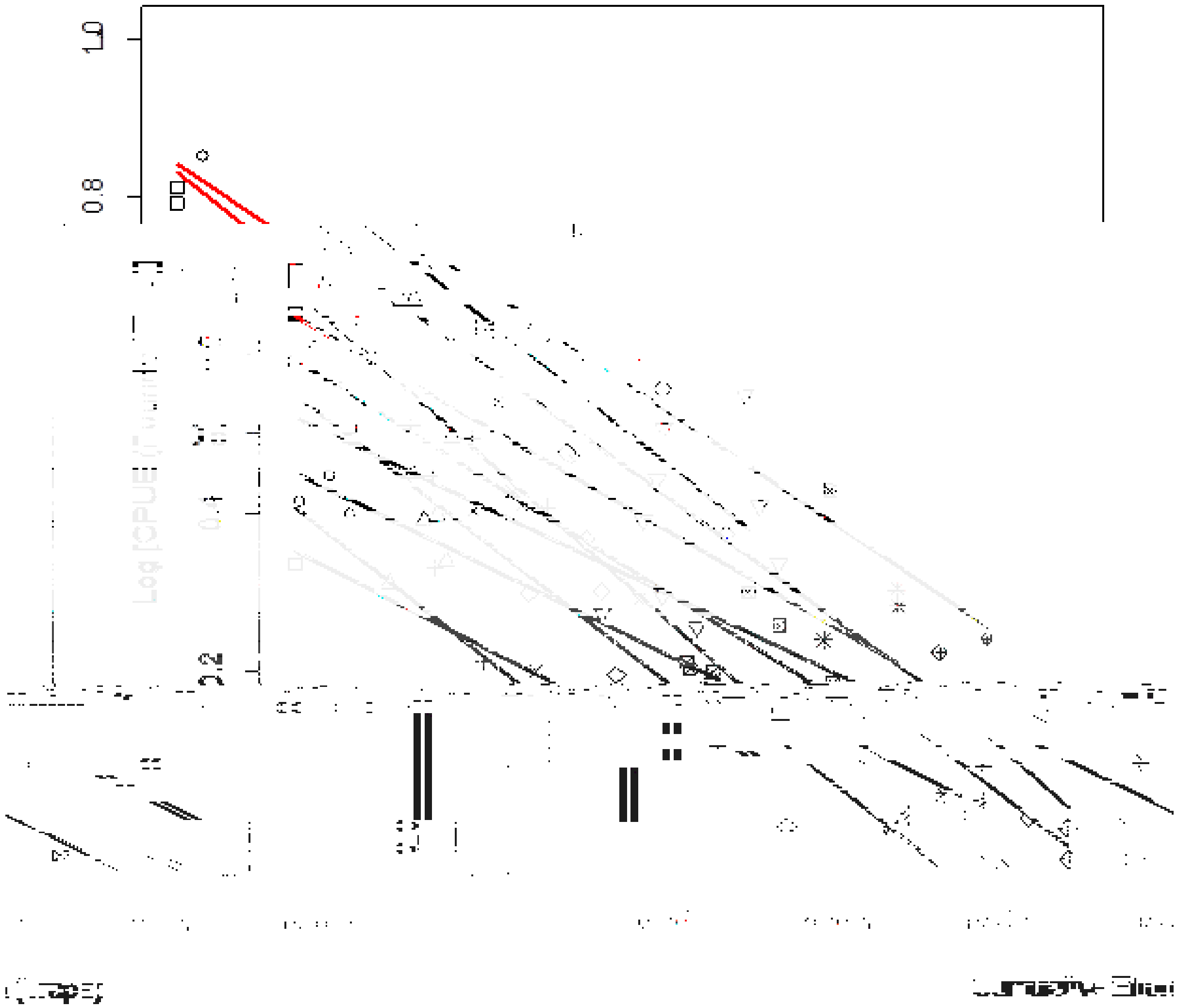

Figure 8 Depletion model fits (red lines) to observed cumulative effort and log(CPUE) for the Howe Sound commercial spot prawn fishery (2000 2010). Symbols correspond to years 2000-2010.

Figure 10 Relationship between the weekly trap fishing effort and the fiweeween--weeweeng effort and tha

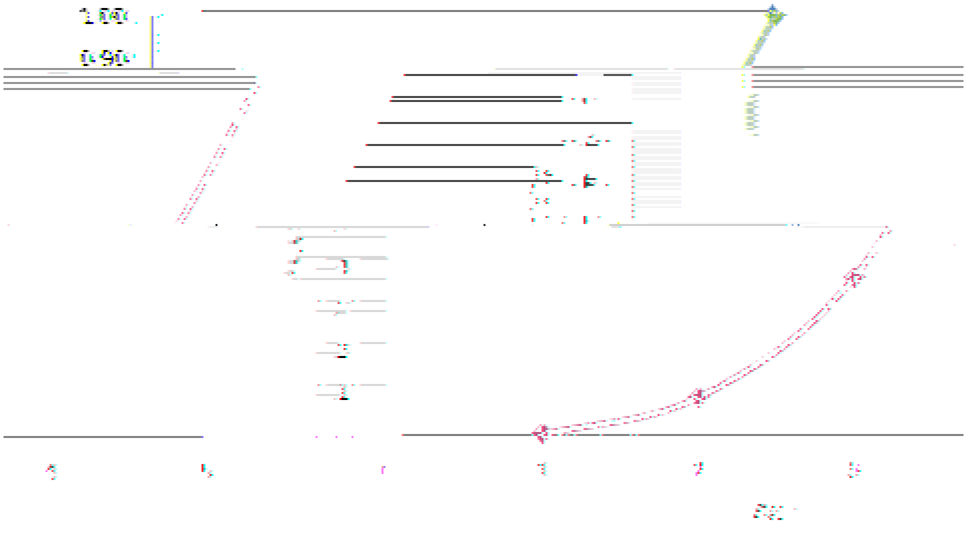

Figure 13 Age at 50% and 95% selectivity.

Figure 14   Trajectories of annual catch under (a) s

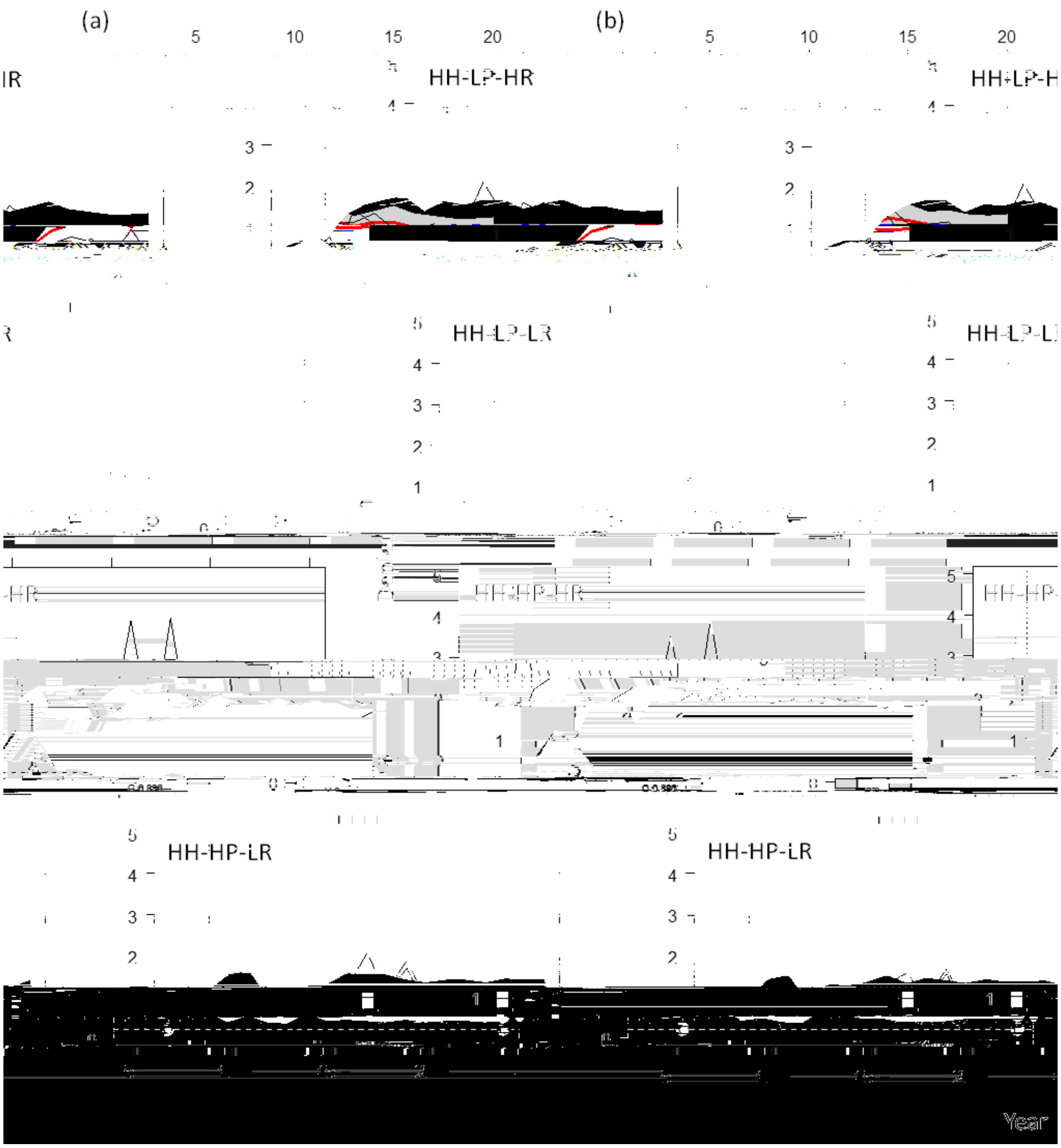

Figure 15 Trajectories of spawning stock depletion under (a) status-quo and (b) MSY-based management procedures. Panels are arranged vertically corresponding to high- and low-productivity (HP, LP) and high- and low-recruitment variability (HR, LR) scenarios; only high habitat (HH) area scenarios are 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).

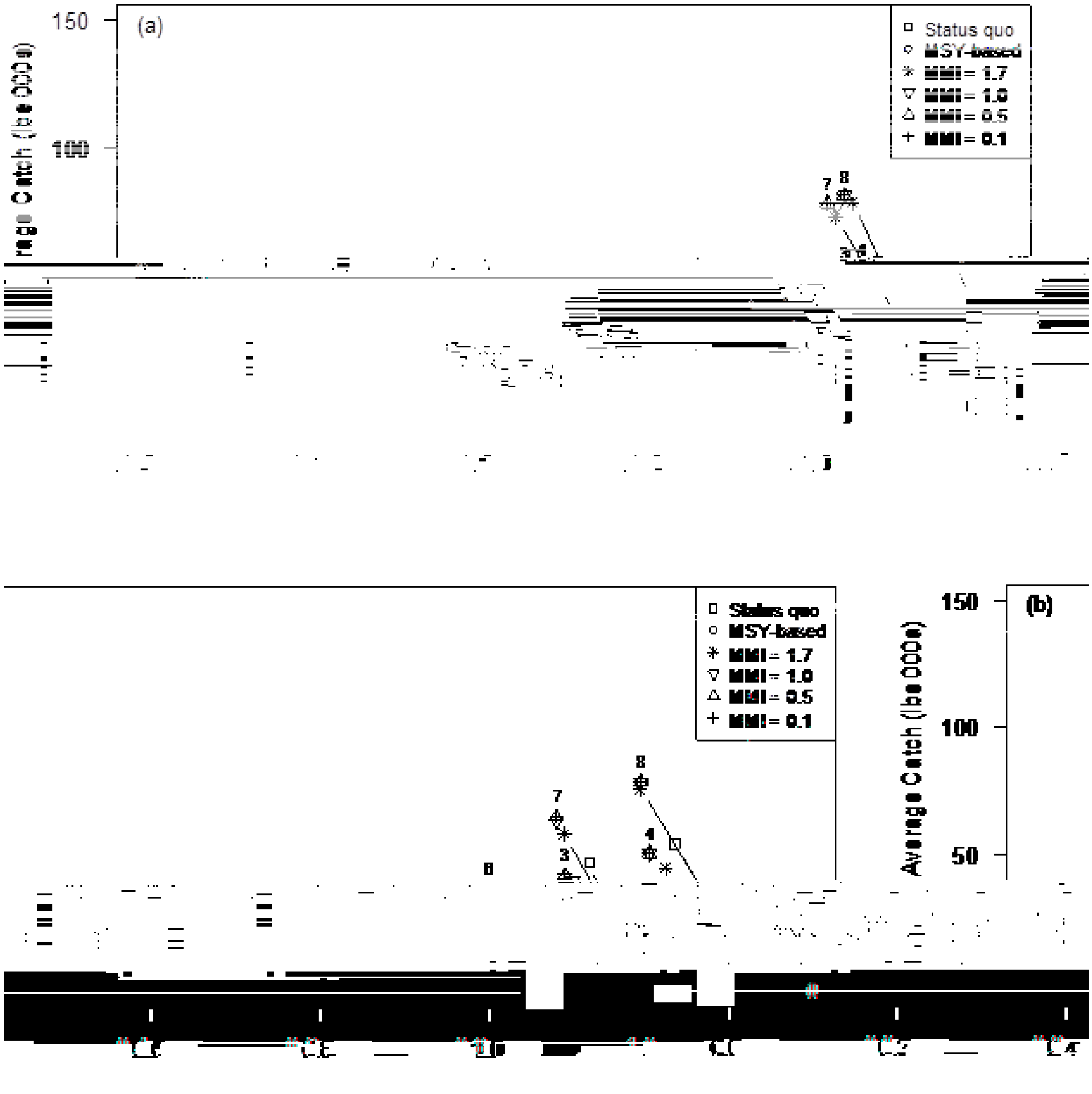

Figure 16 Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment assumptions).

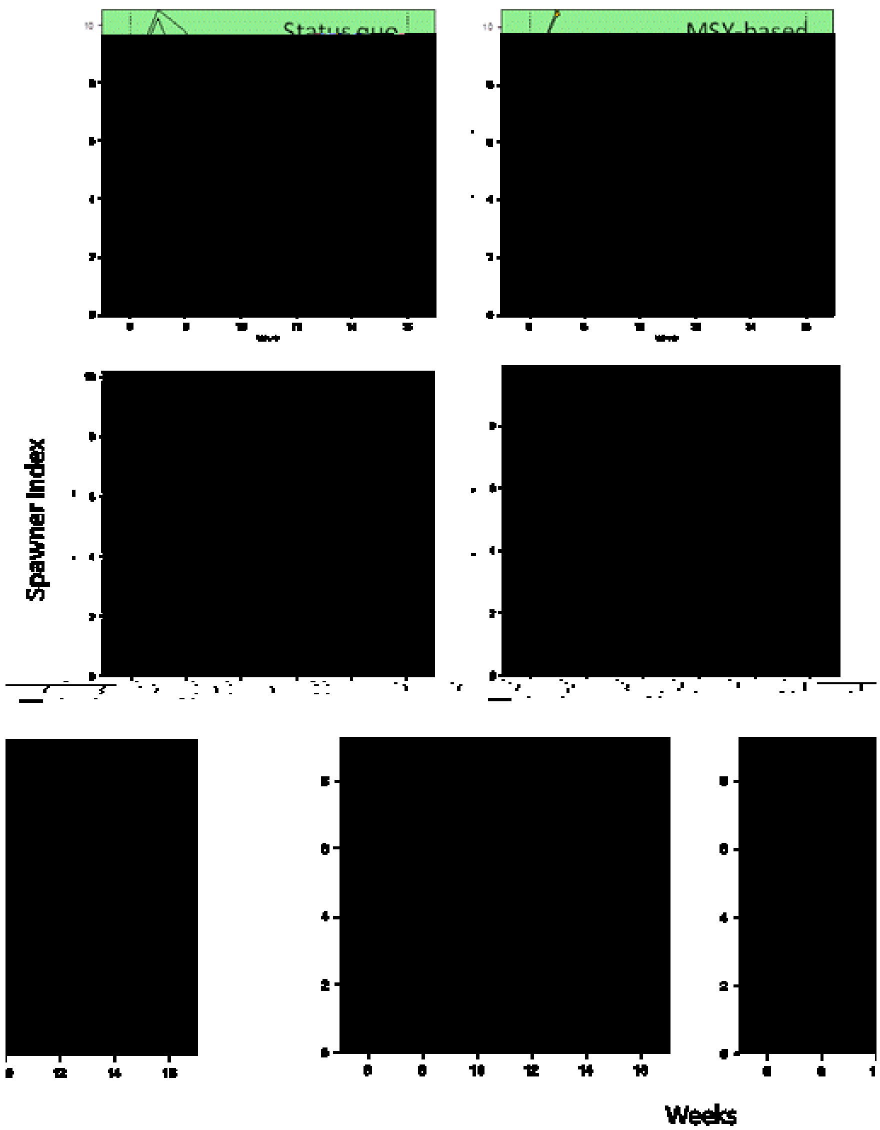

Figure 17 Harvest Control Rule traces for all management procedures under a single simulation run (1/500) of scenario HH-LP-HR. Coloured panels reflect the critical (red), cautious (yellow) and healthy (green) zones consistent with DFO`s (2006) guide to a precautionary approach for fisheries management. 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.

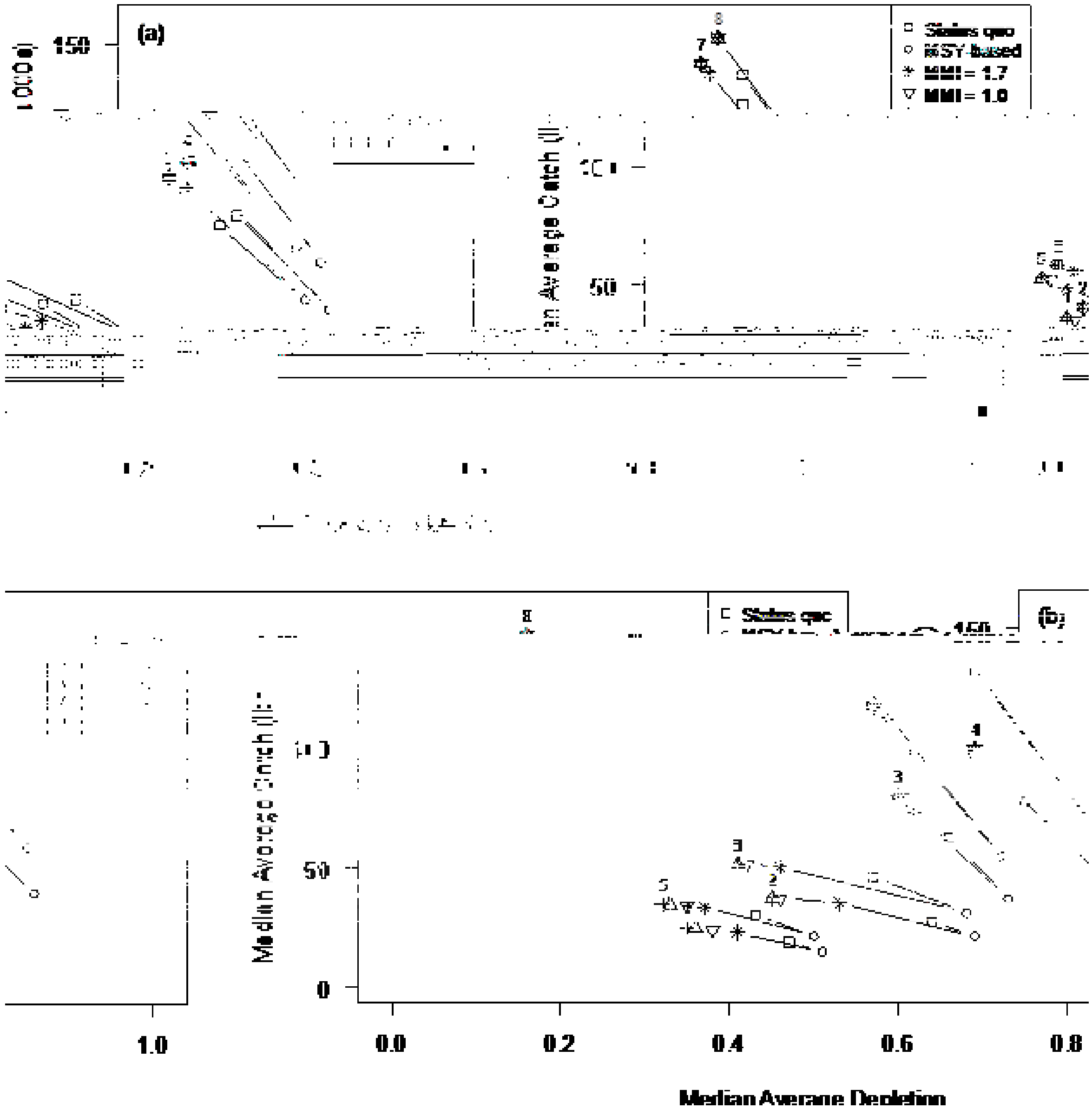

Figure 18 Sensitivity to increased catchability assumption. Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment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

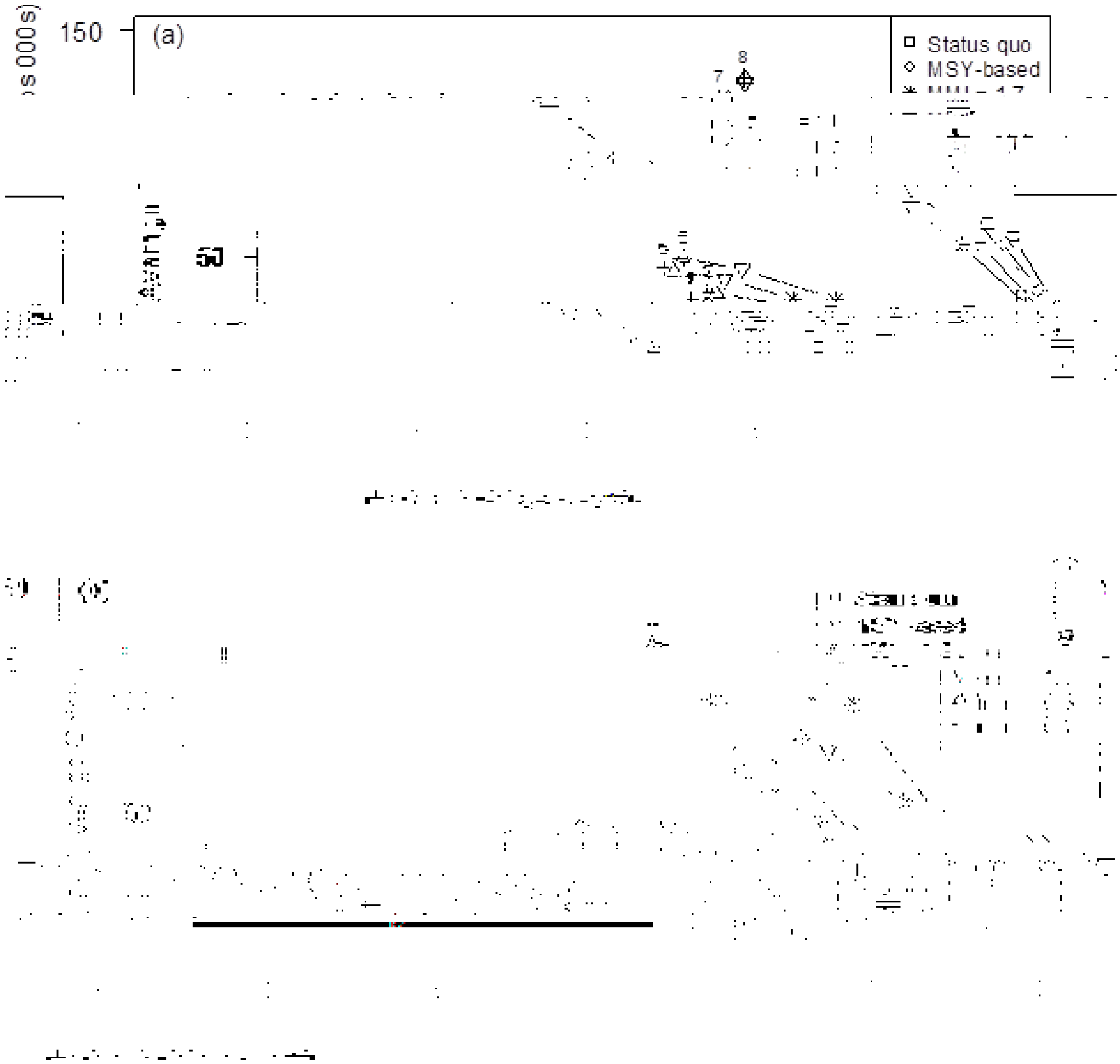

Figure 20 Sensitivity to increased season length (to 40 weeks) assumption. Trade-off relationships between median average catch and median average spawning biomass depletion in the short- (a) and long-term (b) for operating model scenarios S1 to S8 (combinations of high and low habitat area-productivity-recruitment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

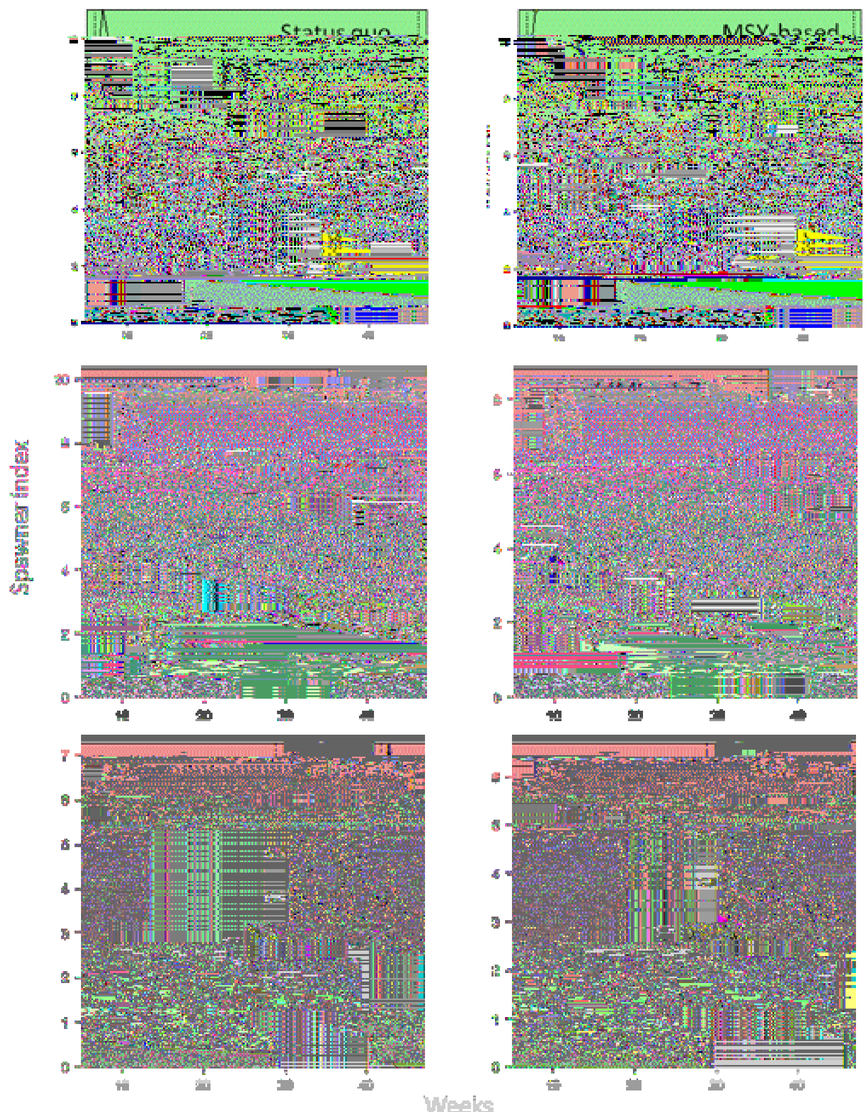

Figure 21 Harvest Control Rule traces for all management procedures under a single simulation run (1/500) of scenario HH-LP-HR (for sensitivity to increased season length). Coloured panels reflect the critical (red), cautious (yellow) and healthy (green) zones consistent with DFO`s (2006) guide to a 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	

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. 58

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	

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

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				

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

year.

Year	No* (pounds)	CPUE	q	SE_q	p-value

Table 10 Notation for the hermaphroditic prawn population, survey and fishery ubsequent

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 ($_{R}$) is LH-LP-LR. The unfished spawning stock biomass

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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