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Analyses of Harvest Strategies for Pandalid Shrimp Populations

by

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Abstract

In general, dynamics of a population are governed by natural mortality (M) and a spawner-recruit relationship (S-R). Two models of M (constant and increasing M both with lognormal error of CV of 20%) and recruitment (R) (constant and Beverton-Holt (B-H) R both with lognormal error of CV of 50%) were examined for a simulated population with population parameters identical to those estimated for the pink shrimp population in Kachemak Bay. Fishing was simulated with 6 levels of constant harvest rates (0.0 to 0.9) and 3 levels of threshold (0 to 40% of virgin spawning stock biomass (SSB_0)). With constant $M \leq 0.4$, no threshold management was necessary under optimal harvesting. For a population of constant R, threshold management only resulted in lower yield, but had little effect on population sustainability. But threshold management was essential to prevent a population with B-H R from crashing.

In light of the importance of the M and S-R relationships, pre-season management was conducted with M and R higher than, lower than, or equal to their true levels. Survey sampling was assumed to occur once every 1 to 3 years. A too low specification of M resulted in higher cumulative yield and risk regardless of sampling frequency. But more frequent sampling helped reduce the risk. On the other hand, mis-specification of R had very little effect on forecasting population abundance if the population was sampled annually. Less frequent sampling induced higher risk if R was specified too high, but it had little effect if R was specified too low. In conclusion, frequent sampling and good understanding of M are most important for sound management of the shrimp fishery.

Introduction

Harvest strategies for exploited fish populations depend on the goals and objectives to be achieved (Quinn and Deriso, 1999). Fisheries scientists define goals primarily as maximizing yield while maintaining the population at a sustainable level. For fish populations with deterministic dynamics, it is easy to define the optimal harvesting. Biological reference points such as $F_{0.1}$ and $F_{35\%}$ have been determined for many fisheries based on per-recruit analyses. They provide an answer for optimal harvesting under the special case of constant recruitment and constant

harvest rate. These reference points are useful for management when very little information on the population is available, but they largely neglect the inherent properties of dynamic systems.

Uncertainties penetrate every process of fish population dynamics: recruitment, natural death, maturity and growth. Introduction of stochasticity into these processes and the overall assessment process as well is necessary for achieving realistic management strategies, but it considerably complicates the mathematics. Most problems of determining optimal harvesting strategies under stochasticity must be solved numerically. In light of this obvious problem, our primary goal of evaluating harvest strategies would not be mathematical refinement, but rather finding robust self-correcting strategies that can operate with only fuzzy knowledge about stock levels and recruitment curves (May *et al.*,. 1978). Therefore, Monte Carlo simulations with a length-based population model modified from Quinn *et al.*, (1998) were employed to evaluate harvest strategies.

Patterns of recruitment, maturity and growth affect optimal harvesting (Clark, 1991), and harvest strategies should be explored on a species basis rather than relying on general results (Sigler and Fujioka 1993). Therefore, in this paper, we examined harvest strategies for pink shrimp (*Pandalus borealis*) based on population parameters and some features in recruitment and natural death obtained for the Kachemak Bay population (Fu *et al.*, in press).

Pink shrimp in Kachemak Bay were harvested intermittently with small landings in the 1950s and 1960s. Since 1970, the catch increased dramatically to about 2000 *t* and remained near that level until the early-*1*980s (Davis, 1982) (Figure 1). Since 1971, annual trawl surveys were carried out to obtain population biomass estimates upon which guideline harvest levels (catch quotas) were set. A low population biomass estimate from the survey resulted in partial closure of the fishery in 1983. The fishery was totally closed in the fall of 1986 due to continued low stock size (Gustafson, 1994), and since then surveys have not indicated any stock recovery.

The depletion of pink shrimp population in Kachemak Bay seemed to be part of the serial depletion experienced by many other crustacean populations in Alaskan waters in the early-*1*980s, for instance red king crab on the shelf around Kodiak Island (Orensanz *et al.*, 1998). Pink shrimp is a major diet source for cod (Albers and Anderson, 1985). The consistently high level of cod and other groundfish populations since the early-1980s may have prevented the pink shrimp population from recovering (Bechtol, 1997). Annual recruitment (defined as all shrimp at age 1) estimates were low during the late-1970s and early-1980s, but there was some rebound in the mid-1980s (Fu *et al.*, in press, Figure 1). On the other hand, natural mortality displayed a sharp increasing trend since the early-1980s. Simulation of this population indicated no alternative harvest policies could have altered the population's fate of collapse (Fu *et al.*, in press).

However, natural mortality is commonly assumed constant over time when evaluating harvest strategies. In this paper, we specifically compared optimal harvest strategies under different assumptions of natural mortality for assessing the potential impact of natural mortality on the population responses to exploitation. In addition, we also examined two types of recruitment variability in regard to management strategies.

The ultimate goal of analyzing harvest strategies is to determine an optimal harvesting policy prior to actual fishing (i.e. pre-season management). The determination of optimal harvesting is dependent on three major factors: recruitment, natural mortality prior to fishing, and pre-season assessment of population status through some type of survey. The first two factors are beyond human control and are usually subject to high variation and uncertainty. Using simulations, we examined the effects of the mis-specification of natural mortality and recruitment on average yield and population sustainability. Our objective was not to develop optimal exploitation for specific situations, but rather to seek ways that pre-season management can be robust to uncertainties in natural mortality and recruitment.

Methods

*Length-based population model

The simulation for evaluating harvest strategies for pandalid shrimp is based on a length- based population model that follows each cohort throughout its life history (Quinn *et al.*, 1998). The model follows the population from recruitment age, assuming that the length frequency at recruitment is a simple discrete normal distribution (N_D). The probability density function (PDF) for the lengths x at recruiting age r and at the start of time t is:

$$f_{r,t}(x) \sim N_D(\boldsymbol{m}_{r,t}, \boldsymbol{s}_r^2) = e^{-\frac{1}{2\boldsymbol{s}_r^2}(x-\boldsymbol{d}_{r,t})^2} \Big/ \boldsymbol{x}_{r,t} \, , \quad \text{where} \, \boldsymbol{x}_{r,t} = \sum_x e^{-\frac{1}{2\boldsymbol{s}_r^2}(x-\boldsymbol{d}_{r,t})^2} .$$

$\delta_{r,t}$ is the mean length at age r and time t, and σ_r is the deviation of the length frequency normal distribution at age r. The abundance of the newly recruited shrimp at length x is:

$$R_t \equiv N_{r,t}(x) = N_{r,t} \cdot f_{r,t}(x).$$

The recruited shrimp and those at older ages are modeled to go through a growth and natural death process before they are exposed to fishing. The standard von Bertalanffy growth model is utilized to express the growth pattern from one age to next, assuming that growth is constant over time: $L_{a+1} = L_\infty(1-\boldsymbol{r}) + \boldsymbol{r}L_a + \boldsymbol{e}$, where $\boldsymbol{r} = e^{-k}$ is the Brody coefficient, and $\boldsymbol{e} \sim N(0, \boldsymbol{s}^2)$. $L_¥$ is the asymptotic length, and κ is a curvature parameter, governing the speed to approach $L_¥$.

The expected variance at age $a+$ after growth for an individual of length x at age a is:
$$\boldsymbol{s}_{a+} = \boldsymbol{s}^2 \frac{1 - \boldsymbol{r}^{2(a+1-r)}}{1 - \boldsymbol{r}^2} + \boldsymbol{r}^{2(a+1-r)}\boldsymbol{s}_r^2 .$$

After one growth increment, the relative distribution of lengths $p_{a+,t+}(L)$ is:

$$p_{a+,t+}(L) = \sum_x f_{a,t}(x)e^{-\frac{1}{2\boldsymbol{s}_{a+1}^2}(L-\boldsymbol{m}_{a+1,t+1}(x))^2} .$$

After growth and natural death during the specific time t period, the abundance of age a shrimp at length x and at time t $N_{a,t}(x)$ (starting at age r) has become $N_{a+,t+}(x)$:

$$N_{a+,t+}(x) = N_{a,t}p_{a+,t+}(x)e^{-M_t} .$$

Given instantaneous full recruitment exploitation rate $\boldsymbol{m}$, the abundance at age $a+1$ and at the start of time $t+1$, $N_{a+1,t+1}(x)$, after the growth, natural death and fishing mortality is:

$$N_{a+1,t+1}(x) = N_{a+,t+}(x)(1 - \boldsymbol{m}S_x),$$

where S_x is the selectivity function that follows the common logistic curve: $S_x = \dfrac{1}{1 + e^{-\boldsymbol{g}(x-L_{50})}}$, where $\boldsymbol{g}$ is the shape parameter, and L_{50} is the length at which 50% of the individuals are vulnerable to fishing.

Catch at age a and during time t, $C_{a,t}(x)$, is: $C_{a,t}(x) = N_{a+,t+}\boldsymbol{m}S_x$.

Population biomass and yield are obtained from the sum of abundance and catches across all ages multiplied by weight at length, which has a relation of $W_x = a_w x^{b_w}$. Exploitable biomass and yield are expressed as:

$$B_{t,x} = \sum_x \sum_a N_{a,t}(x)W_x S_x,$$
$$Y_{t,x} = \sum_x \sum_a C_{a,t}(x)W_x.$$

For simplicity, maturity is assumed as length-independent within the same age. Female spawning stock biomass (SSB) at time t is defined as:

$$SB_t = \sum_x \sum_a \lambda_a N_{a,t}(x)W_x,$$

where λ_a is the proportion of females at age a. We assume pink shrimp in Kachemak Bay are males at ages 1 to 3 and transform into females afterwards, i.e., λ_1, λ_2 and $\lambda_3 = 0.0$, λ_4, λ_5 and $\lambda_6 =1.0$.

* Stochastic simulation

A population with a maximum age of 6 was simulated to be like the pink shrimp population in Kachemak Bay, Alaska (Fu *et al*., in press). Parameters of spawner-recruit relationship, growth, gear selectivity and weight-at-length relationship were obtained from Fu *et al*., (in press, Table 1). The simulation started from year 1978 when an environmental regime shift took place (Albers and Anderson 1985) and extended to 2001 with 1000 replications. The simulation model incorporated process errors associated with recruitment, natural mortality, and growth variability. Measurement errors in SSB were also implemented, so that when the estimated SSB dropped below a threshold level (see below), the fishery was closed. These errors were assumed to have a coefficient of variation (CV) of 20% based on the average historical variability for survey biomass estimates (Gustafson, 1994). Fishing mortality was assumed to be implemented without error, so that the effects of mis-specification in recruitment and natural mortality can be better evaluated.

To investigate effects of harvest strategies on populations of different features, two sets of recruitment (*R*) model were examined, including constant *R* at the historical average value (608 million) and Beverton-Holt with auto-correlation (simply called B-H). Both *R* models included lognormal process errors with CV of 50% (Figure 2). The B-H model parameters were obtained from Fu *et al*., in press (Table 1). Growth variability is reflected from the mean length at recruitment ($\delta_{r,t}$), which has a normal distribution with mean of 9.0 mm and standard deviation of 1.0 mm. Similarly, two sets of natural mortality (*M*) were used. Because *M* is commonly assumed to be constant in either stock assessment or evaluation of management strategies, annual *M* was set at 0.4 with a lognormal variation (CV = 20%). To align with the actual *M* estimates from the Kachemak Bay pink shrimp stock, a second *M* model with a steady increasing rate of 0.03 from 1983 to 1998 was employed (Figure 2). In order not to let *M* increase to unreasonable level, *M* was assumed to decrease steadily at the same rate after 1998. Similarly, variation with a CV of 20% was imposed.

* Comparisons of harvest strategies and threshold levels

SSB has been frequently used as an indicator of stock size and population health. A level of 20% of pristine SSB (SSB_0) has been considered useful as a threshold for recruitment overfishing (Beddington and Cooke, 1983, Quinn *et al*., 1990, Francis 1993, Thompson 1993). We used constant harvest rates ranging from 0.0 to 0.9. In addition to the common threshold of 20% of SSB_0, threshold levels of 0% (no threshold) and 40% of SSB_0 were also explored.

For each harvest level, annual average risk is calculated as the percentage out of the 1000 replicates that the population falls below 20% of SSB_0. Optimal harvest level was defined as the value that maximized yield while minimizing the risk of population decline (Hollowed and Megrey, 1993). Therefore the following objective function was employed for obtaining the optimal harvest level μ:

$$Max\left\{\frac{Y_m}{MaxY} - RISK_m\right\},$$

where Y_m is the cumulative yield in the last year at a given harvest level averaged over the 1000 replicates; MaxY is the maximum among Y_m; and $RISK_m$ equals the average risk over the entire time period at a given harvest level. If a strategy produces maximum yield but always drives the population below 20% of SSB_0, then the objective function has a value of 0.0. The worst case would have a value approaching -1 and the best case would have a value approaching 1.

* Sensitivity analyses

Simple sensitivity analyses with regard to gear selectivity and female maturity at age 4 were conducted to examine their effect on a simulated population. The population was assumed to have random variable M with mean of 0.4 and lognormal error with CV of 20%. In order to allow the population to decline at low SSB level, the B-H R model with lognormal error of CV of 50% was used. The sensitivity was inspected with respect to the optimal harvesting assessment.

*Pre-season management

Analyzing harvest strategies is mainly for directing fishery management prior to actual fishing. The main idea of pre-season management is to find an optimal harvest rate based on our knowledge about the present population abundance, R and annual M. The annual length-based population assessment model was applied and the same objective function was used for determining optimal harvesting. To demonstrate the effect of mis-specification of R and M, we applied the optimal harvest rate to the simulated population with true parameters of R and M (R_{true} and M_{true}), from where true yield and risk were obtained. A flow chart is used to illustrate the pre-season management (Figure 3). Depending on whether a survey takes place, the population abundance estimate is renewed using R_{true} and M_{true} or derived from previous year's assessment based on specified R and M. For simplicity, no measurement errors in survey biomass estimates were imposed. Therefore, when a survey takes place, the true biomass is known. The results from the simulation are the most optimistic that can be obtained.

R_{true} and M_{true} were generated in the same way as above: B-H R with CV of 50% and constant M (mean = 0.4, CV = 20%). Two sets of R were specified with two constant means of $\exp(5.0)$, below the true average, and $\exp(8.0)$, above the true average, and lognormal errors (CV = 50%). The specified R was independent of SSB if SSB was above 10% of SSB_0, otherwise R was set to be 0.0. For annual M, three sets of values were specified: 0.2 less than each annual M_{true} (M_{true} - 0.2); constant value of 0.4 with no variation; and 0.2 more than each annual M_{true} (M_{true}+ 0.2). The simulated population was surveyed once every 1 to 3 years for comparisons.

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Results

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* Effects of constant exploitation rate

Because exploitation was assumed to take place before the starting year 1978, the population biomass in 1978 becomes smaller for a higher exploitation rate (Figure 4). With the constant R and M model, population biomass stayed at a certain stable level corresponding to a certain exploitation level when no threshold was imposed upon management (Figure 4). Cumulative yield steadily increased, and the risk of the spawning biomass going below the threshold level (20% SSB_0) was high for exploitation rates of 0.5 and above. With a threshold of 20% SSB_0, biomass levels zigzagged at exploitation rates above 0.5 due to fishery closures. Consequently, annual risk at high exploitation rates varied greatly between high and none. On the other hand, as M increased steadily from 0.4 to 0.82, population biomass dropped down to low levels even with no exploitation (Figure 5). Threshold management helped to reduce the risk, but the resultant fishery closures greatly reduced the total yield. In addition, because R was independent of SSB as long as SSB was above 10% of SSB_0, the population was sustainable below 20% of SSB_0 even under high exploitation without threshold management. Therefore, no threshold is needed to sustain a population with constant R, which is of course highly unlikely in reality.

When recruitment is a function of spawning biomass with the B-H model, high exploitation rates such as 0.7 and 0.9 without a threshold wiped out the population completely under either constant M (Figure 6) or increasing M (Figure 7). Management with a threshold is critical to keep the population from extinction. At a low exploitation rate of 0.1, constant M kept the population biomass at a stable and high level and there was no need for threshold management (Figure 6). However, as M increased over time, population biomass declined dramatically to below the threshold level under any exploitation rate. Threshold management prevented complete extinction under high exploitation (Figure 7). Under all cases, cumulative yield curves for an exploitation rate of 0.1 were distinctively below other yield curves. This low level of exploitation did not seem to be profitable under any case in terms of fishery yield, and it did not stop population from crashing when the M level was high.

* Optimal constant exploitation rate

Optimal harvesting is not only related to the natural process of recruitment and death, but also related to the management action, such as previous harvesting level and management threshold. Table 2 shows the results for optimal harvesting as a function of the spawner-recruit model, natural mortality, and measurement error in SSB. Because the measurement error was used to determine fishery closures when a threshold was imposed, there are no results given for that situation when a threshold was not used. When $M = 0.6$, measurement error resulted in negative SSB, so no results were available. With no measurement error in SSB under the constant R model, the scenarios of constant M (0.4) and increasing M (Table 2) provided interesting contrasts. When no threshold was imposed, increasing M caused the optimal exploitation rate to decline from 0.50 to 0.39 and the risk of population collapse to increase from 0.01 to 0.41. However, imposing a threshold level of 20% SSB greatly reduced the risk to 0.03. Though optimal exploitation rate increased to 0.46, cumulative yield dropped from 11435 down to 8530. Fishery closures reduced total yield, but prevented the population from going below the threshold when M increased to a high level. Further increasing the threshold level to 40% was not necessary when the population had small risk of collapse (< 0.05); instead it greatly reduced the total yield by executing more fishery closures. If we allow the population to endure a risk of collapse of 0.05, scenarios with constant M equal to 0.4 do not need threshold management under either constant R or B-H R model when the population is exploited at the optimal level.

Optimal harvesting was also examined for $M = 0.2$ and 0.6. Comparing $M = 0.4$ to $M = 0.2$, we noted that the optimal harvest rate and yield increased from 0.29 to 0.38 and from 8408 to 22083 respectively when there was no threshold. Both M models had very low risk of population collapse. However, as constant M increased up to 0.6, the population had very high risk of collapse (about 0.96), and the optimal harvesting would be to harvest the population heavily at the beginning before the population dies out from high natural death. In this case, a threshold would not help to prevent population collapse.

With the B-H R model, increasing M resulted in high risk of population collapse (0.54) under the optimal harvest rate of 0.31. This harvest rate is higher than that under the constant M assumption (0.29). However, the high risk of population collapse under increasing M suggested that we had no better way of protecting the population. Threshold management made little difference to the population risk of collapse.

Optimal exploitation rate varied not only across scenarios with different R and M models, but also across different threshold levels. Optimal exploitation rate generally increased with threshold levels that were examined. No general rules regarding optimal harvest rate were found. For example, with constant R, the optimal harvest rate decreased from 0.5 to 0.39 as M changed from constant to increasing over time, but the optimal harvest became equivalent as threshold level increased from 0 to 20 to 40%.

When SSB was measured lower than the actual level, there were more chances to close the fishery, which resulted in under-exploitation of the population. When SSB had positive measurement error, the population was overexploited by continuing to fish when there was a need to stop. Under any type of R and M models, measurement error in SSB resulted in either decreased yield or increased risk of population collapse.

* Sensitivity of optimal harvesting to selectivity and maturity

When M was constant with a value of 0.4, there was no need for threshold management under the optimal harvesting level. This feature provides convenience for examining sensitivity of optimal harvesting, because threshold management complicates the determination of optimal harvest rate. When the selectivity curve shape parameter γ was fixed at the estimated value of 0.57, the optimal exploitation rate increased steadily from 0.22 to 0.28 as L_{50} increased from 14 to 16.5, but the resultant total yield decreased steadily from 9072 to 8439 (Table 3). However, corresponding risk of collapse was variable and the lowest risk was at $L_{50} = 16.0$. We fixed L_{50} at 16.0, and varied γ from 0.52 to 0.72. As γ increased, total yield decreased slightly and the optimal exploitation stayed at nearly the same level. Risk of collapse had its lowest value when γ was equal to the estimated value (0.57). Nevertheless, the difference in risk among all the scenarios was very small, because the population was under favorable conditions.

Population reproduction is closely related to female abundance at age. With $M = 0.4$ and the B-H recruitment model, the population was not sustained with only a small portion of age 4 shrimp as females. The risk of collapse was 0.88 when only 20% of age 4 shrimp were females (Table 4). The optimal harvesting under this

situation was to catch them at the beginning before they die out naturally. The optimal exploitation rate was estimated to be 0.57. As age 4 female proportion increased to 40%, the risk was reduced to 0.10, and the optimal harvest rate was very small, 0.1, which resulted in small yield at the end. As the female proportion further increased to 0.8, optimal exploitation rate increased to 0.23; total yield increased to 7087 and risk of collapse decreased greatly to 0.03.

* Pre-season management

Under the situation of true spawner-recruitment relationship, the effectiveness of pre-season management is determined by the level of M specified and survey sampling frequency as well (Figure 8). When annual M was specified at 0.2 lower than M_{true}, and the population was sampled once every year, the cumulative yield was consistently higher than those obtained from scenarios with higher levels of M. Nevertheless, cumulative risk was also consistently higher. Despite the danger of falling below threshold, the spawning biomass did not show any declining trend. When annual M was fixed at the constant and true value of 0.4, cumulative yield was very close to that from the scenario of M_{true}; however, risk was much higher in comparison. Risk from the scenario of M_{true} was 0.0. On the other hand, specifying M by a value of 0.2 higher than the true value reduced the cumulative yield, but kept the population under very low or no risk of collapse.

Sampling frequency had no effect on management and population response to exploitation if M is accurately known, but it played an important role when M was mis-specified, and especially when M was specified too low. Under the scenario in which M was 0.2 lower than the true value, the risk of population collapse greatly increased when the population was sampled only once every 2 or 3 years. Compared with sampling once every 2 years, sampling once every 3 years resulted in lower yield as well as higher risk. The population was gradually wiped out as time progressed.

Under the situation of M_{true}, the effectiveness of pre-season management is more dependent on the survey sampling frequency than on the R levels assumed (Figure 9). If the population was sampled once every year, setting recruitment at either exp(5.0) or exp(8.0) level resulted in the similar yield and risk levels. However, when population was sampled once every 3 years, specifying R too high produced much higher yield and risk as well. Spawning biomass was quickly depleted and remained at very low level for several decades. Nevertheless, fishery closures and a period of favorable recruitment (despite low spawning biomass) brought the population back to relatively high levels for a few years (years 70 to 85). In contrast, when R was at exp(5.0) level, sampling once every 3 years did not produce a bad effect on yield and risk, although the spawning biomass became quite variable.

Discussion

Based on examinations of biological reference points using various levels of mean annual M with random variation, steepness of the B-H relationship (the mean recruitment at SSB = 20% SSB_0) and recruitment variability, Francis (1993) demonstrated that acceptable harvesting levels depended strongly on the steepness of the S-R relationship, and less strongly on M. However, random variable natural death may not be adequate to describe M for some populations, for instance, red king crab population in Bristol Bay, Alaska (Zheng *et al*., 1997), whose abundance fluctuated periodically. In this paper, we have shown that with a constant mean M of 0.4 the pink shrimp population was sustained under the optimal harvesting level, but with an increasing trend in M, high risk of collapse resulted under B-H S-R relationship. On the other hand, when the constant mean M increased to 0.6, the population was quickly depleted. Therefore, Francis's conclusion that M was a less important source of uncertainty in estimating long-term productivity of a fishery than the S-R relationship could also be due to the fact that the annual M was relatively small (from 0.05 to 0.3) for all the populations he examined. Under relatively small M, the importance of M was concealed.

A threshold is a level of female spawning biomass (or total biomass), below which there may not be enough recruitment to sustain a population. Therefore, for a certain population, the appropriate threshold depends on its S-R relationship, particularly that at low population abundance levels. However, for mere comparisons, we designated the same threshold level when we were comparing the effect of harvesting levels on populations of constant and B-H R. With constant R model, the R level is independent of SSB, so the threshold management loses its meaning. Even under high exploitation rates and its SSB is consistently below its defined threshold, the population can be sustained. Although threshold management helps the population remain at some biomass level

higher than the threshold, it greatly reduces the yield, and therefore is not desirable, at least with respect to the objective function chosen (which balances fishery yield against population risk).

With the B-H R model and constant M, the shrimp population is sustained above its threshold when fished at an optimal harvesting level, so no threshold may be necessary.

Zheng *et al*., (1997) illustrated that a threshold had little effect on yield and spawning biomass variability when a fishery had small handling mortality of 20% or less, but a threshold was important to protect the population when handling mortality rate was 50%. Haist *et al*., (1993) also concluded from simulation studies that there was no requirement for a threshold spawning stock biomass for exploitation rates below 0.4 under the assumption of constant M. Nevertheless, as M increases, threshold management helps prevent the population from crashing, so a threshold may be desirable when unknown changes in the ecosystem occur.

Sensitivity analysis with gear selectivity implied that with the assumed logistic selectivity model, optimal harvesting was robust to reasonable changes in selectivity parameters. However, female maturity at age 4 seemed to play an important role in sustaining a shrimp population.

Pre-season management is essential for putting forward an optimal harvesting level. Its validity is dependent upon the estimation of present population abundance status and that of M and R in the following year. When population abundance is estimated every year without measurement error, mis-specification of R has very little effect on the forecast, but under-estimation of M can increase population risk of collapse. Therefore, good understanding of M is more important than that of R. When sampling frequency reduces to once every 2 or 3 years, over-estimation of R or under-estimation of M deteriorates the pre-season management in terms of conservation. Similarly, measurement error in population abundance estimates can degrade the ability to forecasting and managing. Therefore, we propose that more effort in fishery management should go to research survey for obtaining better population abundance estimates.

Finally, when we presented our research results in the International Pandalid Shrimp Symposium, September 8-10, Halifax, our simulation with seasonal considerations in harvest strategies was well welcome. Encouraged by the great need to take a further step in investigating harvest strategies with seasonal mortality, growth and maturity incorporated, we took out the seasonal simulation from the original paper, and expended it into a more complete work. We hope to have the work published soon.

Acknowledgments

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Table 1. Parameters of spawner-recruit relationship, growth, selectivity and weight-at-length relationship for the simulations.

Parameters	Estimates
$S\text{-}R\ \alpha$	1.826
$S\text{-}R\ b$	0.002
$S\text{-}R\ f$	0.267
$L_{\yen}$	24.698
k	0.367
s	0.529
s_r	1.127
L_{50}	16.720
g	0.572
a_W	0.00055
b_W	3.06818

Table 2. Optimal exploitation rate (μ), objective function value (f), maximum yield (MaxY) and risk of population decline averaged over the entire time period corresponding to different R and M models and threshold levels under constant μ.

S-R	M	T (%)	μ E[5]=0%	E=20%	f E=0%	E=20%	MaxY E=0%	E=20%	Risk E=0%	E=20%
C-R[1]	$M_{0.4}$[3]	0	0.50	—	0.72	—	18565	—	0.01	—
C-R	$M_{0.4}$	20	0.46	0.65	0.91	0.97	16964	15045	0.00	0.03
C-R	$M_{0.4}$	40	0.56	0.90	0.94	0.95	12487	9766	0.0	0.05
C-R	M_a[4]	0	0.39	—	0.18	—	11435	—	0.41	—
C-R	M_a	20	0.46	0.42	0.78	0.88	8530	8077	0.03	0.02
C-R	M_a	40	0.56	0.85	0.99	0.96	6227	5480	0.01	0.04
B-H	$M_{0.2}$	0	0.38	—	0.96	—	22083	—	0.01	—
B-H	$M_{0.2}$	20	0.42	0.53	0.99	0.99	21558	20644	0.01	0.01
B-H	$M_{0.2}$	40	0.56	0.85	0.92	0.94	16097	16100	0.0	0.07
B-H[2]	$M_{0.4}$	0	0.29	—	0.92	—	8408	—	0.02	—
B-H	$M_{0.4}$	20	0.39	0.42	0.96	0.99	8187	7904	0.01	0.01
B-H	$M_{0.4}$	40	0.57	0.90	0.89	0.88	6675	5631	0.00	0.12
B-H	$M_{0.6}$	0	0.75	—	0.04	—	4771	—	0.96	—
B-H	$M_{0.6}$	20	0.75	—	0.05	—	2907	—	0.95	—
B-H	$M_{0.6}$	40	0.90	—	0.04	—	2430	—	0.97	—
B-H	M_a	0	0.31	—	0.36	—	5945	—	0.54	—
B-H	M_a	20	0.41	0.37	0.56	0.61	4695	4572	0.32	0.34
B-H	M_a	40	0.60	0.48	0.728	0.748	3953	3179	0.26	0.25

Notes for Table 2:
[1] Constant recruitment model with a value of the historical average of 608 million.
[2] Beverton-Holt spawner-recruitment relationship with autocorrelation.
[3] $M_{0.2}$, $M_{0.4}$ and $M_{0.6}$ denote constant average M with a value of 0.2, 0.4 and 0.6.
[4] Annual natural mortality increases at the rate of 0.03 per year after 1983 (M=0.4), and decreases at the rate of 0.03 per year after 1998 (M=0.82).
[5] E denotes measurement errors for SSB with CV equal to 0 and 20% respectively.

Table 3. Optimal harvest rates (μ), objective function value (*f*), maximum yield (MaxY) and risk of population decline averaged over the entire period corresponding to different selectivity parameters under the assumptions of B-H spawner-recruitment relationship and constant *M* of 0.4.

g	*L₅₀*	*m*	*f*	MaxY	Risk
0.57	14.0	0.22	0.91	9072	0.026
0.57	14.5	0.23	0.92	8970	0.028
0.57	15.0	0.24	0.92	8841	0.027
0.57	15.5	0.25	0.92	8689	0.023
0.57	16.0	0.26	0.92	8515	0.018
0.57	16.5	0.28	0.92	8439	0.020
0.52	16.0	0.27	0.92	8661	0.026
0.62	16.0	0.26	0.92	8495	0.019
0.67	16.0	0.26	0.92	8475	0.022
0.72	16.0	0.26	0.92	8456	0.025

Table 4. Optimal harvest rates (μ), objective function value (*f*), maximum yield and risk of population declines averaged over the entire period corresponding to different age 4 female ratios under the assumptions of B-H spawner-recruitment relationship, constant *M* of 0.4, L_{50} of 16.0 mm and λ of 0.57.

λ_4	μ	*f*	MaxY	Risk
0.2	0.57	0.04	3670	0.875
0.4	0.1	0.47	2624	0.103
0.6	0.18	0.79	5190	0.048
0.8	0.23	0.88	7087	0.031
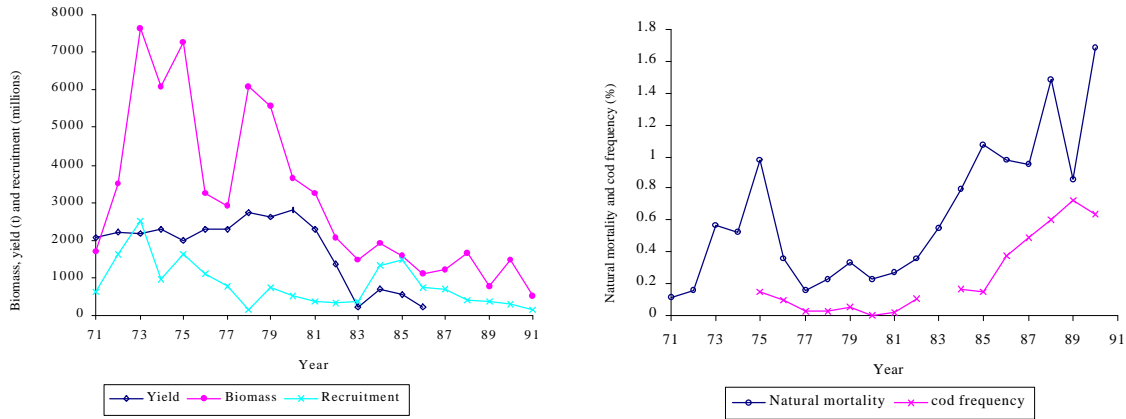
Figure 1. Observed yield, survey biomass estimates and estimated recruitment for the pink shrimp population in Kachemak Bay (left panel) and estimated natural mortality and cod occurrence frequency obtained from the same surveys (right panel).
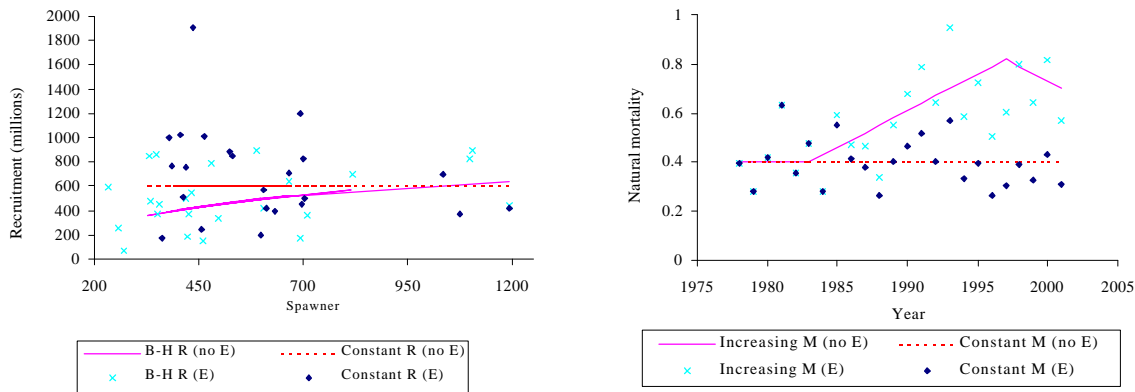

Figure 2. Constant (608 million) and B-H recruitment with auto-correlation with and without lognormal error ("E" and "no E") (CV = 50%) (left panel), and constant and increasing M with and without lognormal error ("E" and "no E") (CV = 20%) (right panel).
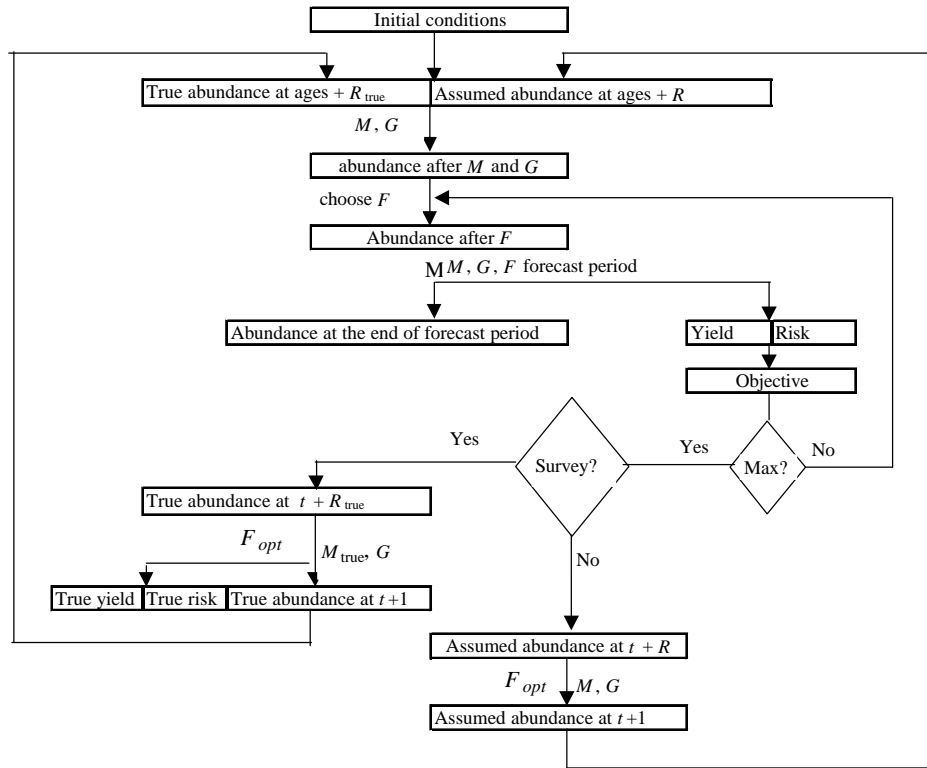
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Figure 3. Flow chart illustrating the pre-season management; growth *G* was assumed to be true; *R*, *M* and *F* denote assumed annual recruitment, natural mortality and fishing mortality respectively; F_{opt} is the optimal harvesting level, and R_{true} and M_{true} are the true *R* and *M* levels.
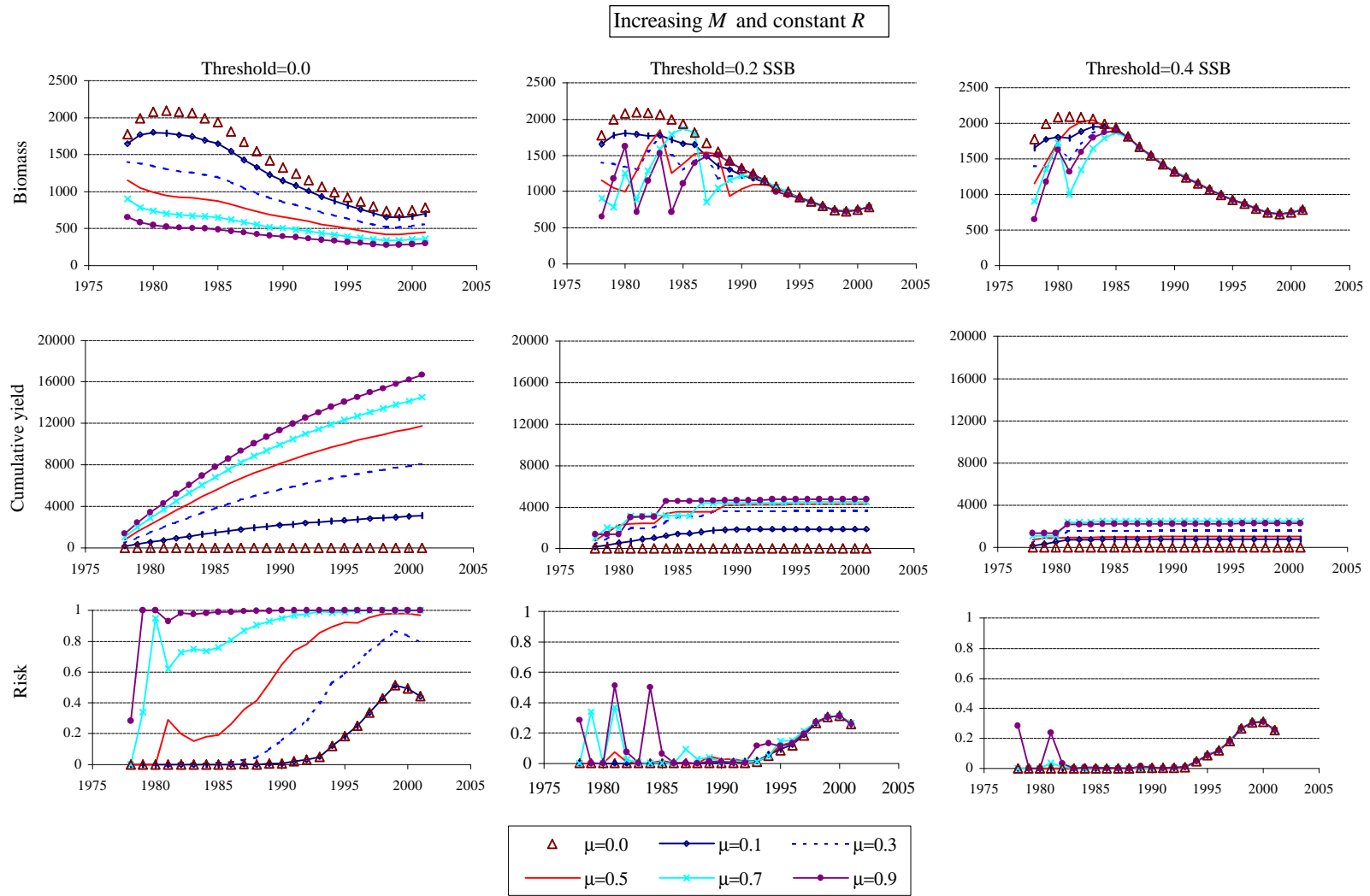
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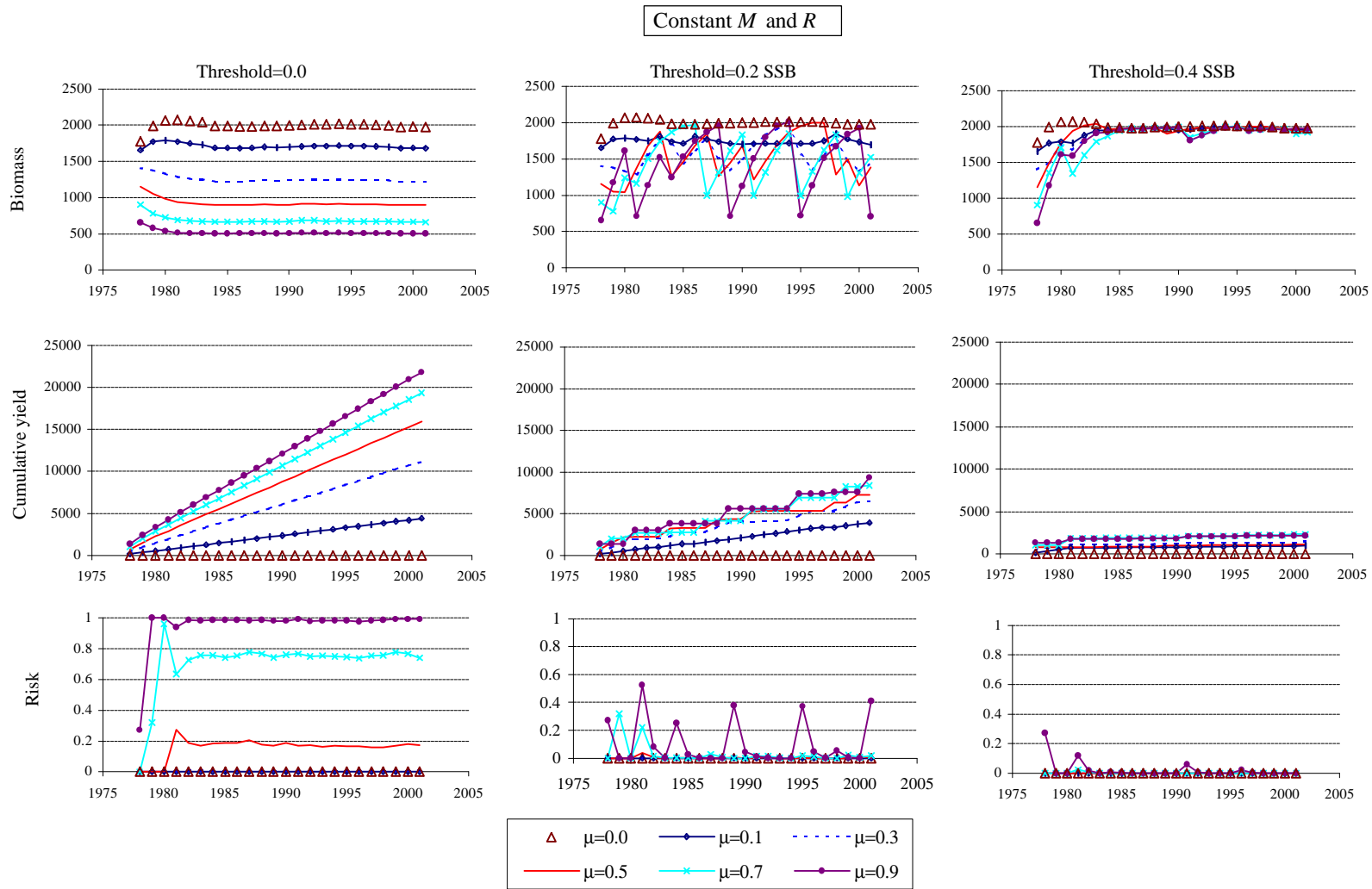
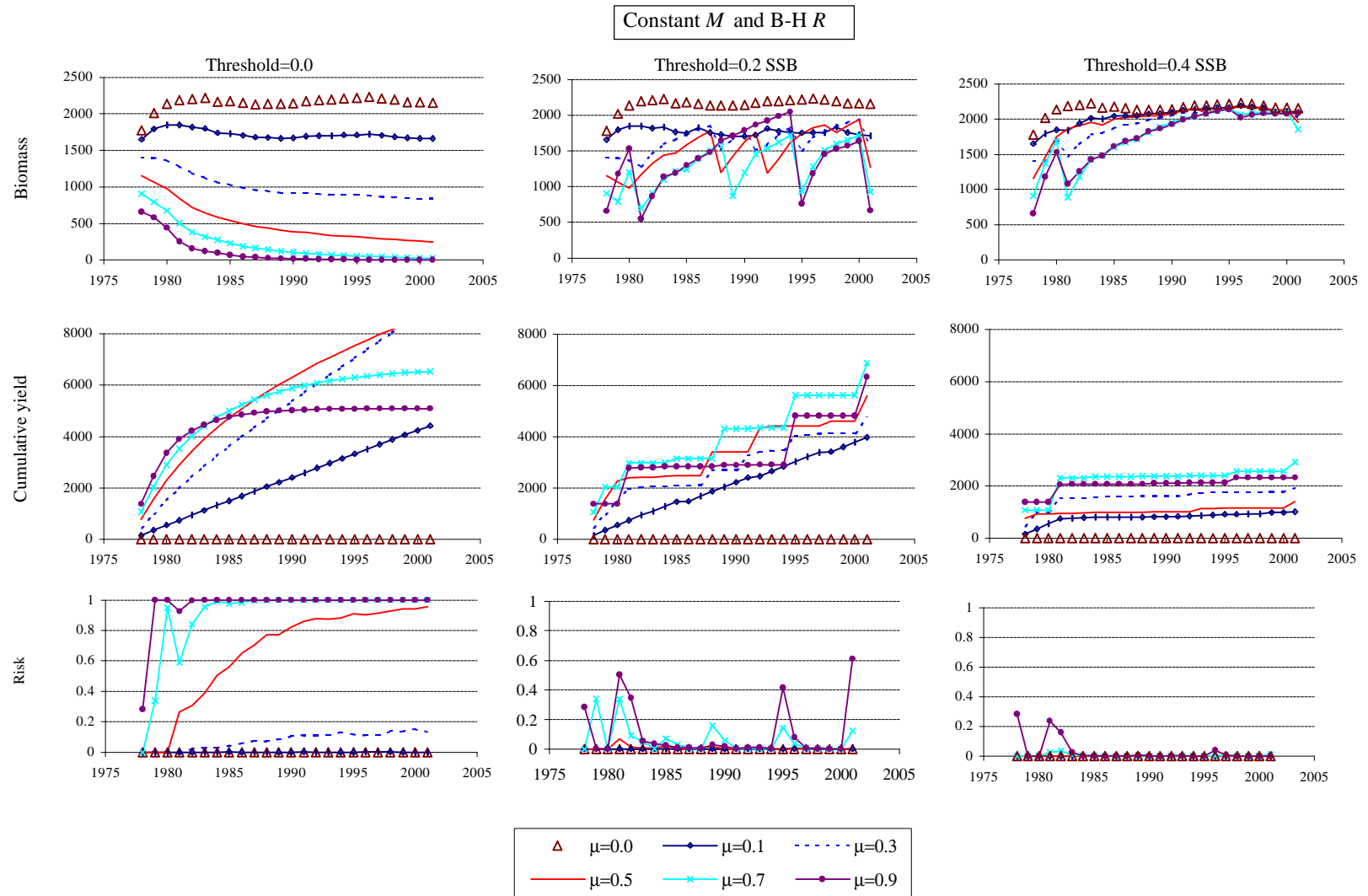Figure 4. Comparisons of biomass, cumulative yield and risk over time from 6 levels of exploitation rates (μ) (within panel) and 3 levels of threshold (between column) under the situation of constant *R* and *M*.

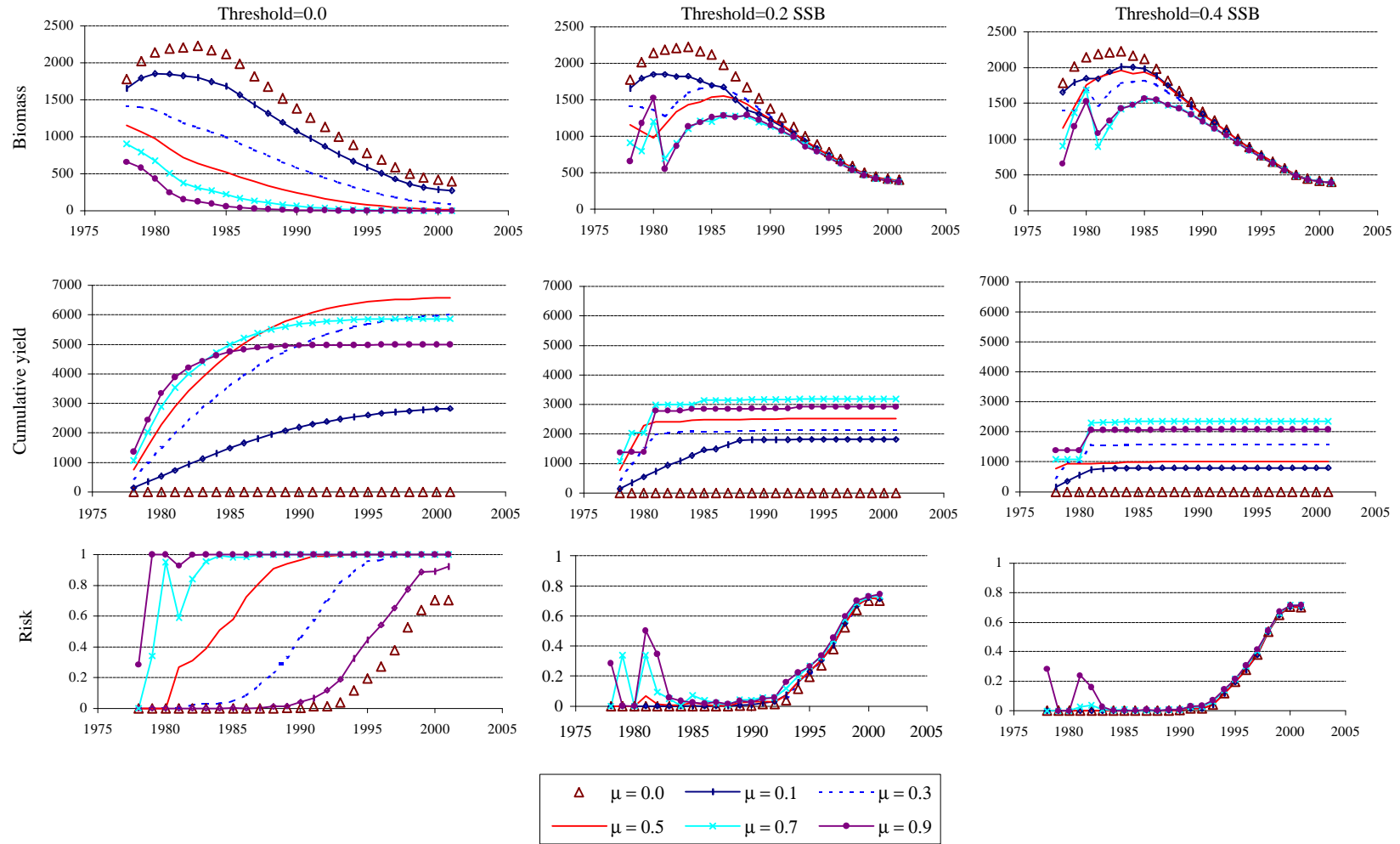Figure 5. Comparisons of biomass, cumulative yield and risk over time from 6 levels of exploitation rates (μ) (within panel) and 3 levels of threshold (between column) under the situation of constant *R* and increasing *M*.

Constant *M* and B-H *R*

Figure 6. Comparisons of biomass, cumulative yield and risk over time from 6 levels of exploitation rates (µ) (within panel) and 3 levels of threshold (between column) under the situation of B-H *R* and constant *M*.

Figure 7. Comparisons of biomass, cumulative yield and risk over time from 6 levels of exploitation rates (μ) (within panel) and 3 levels of threshold (between column) under the situation of B-H *R* and increasing *M*.
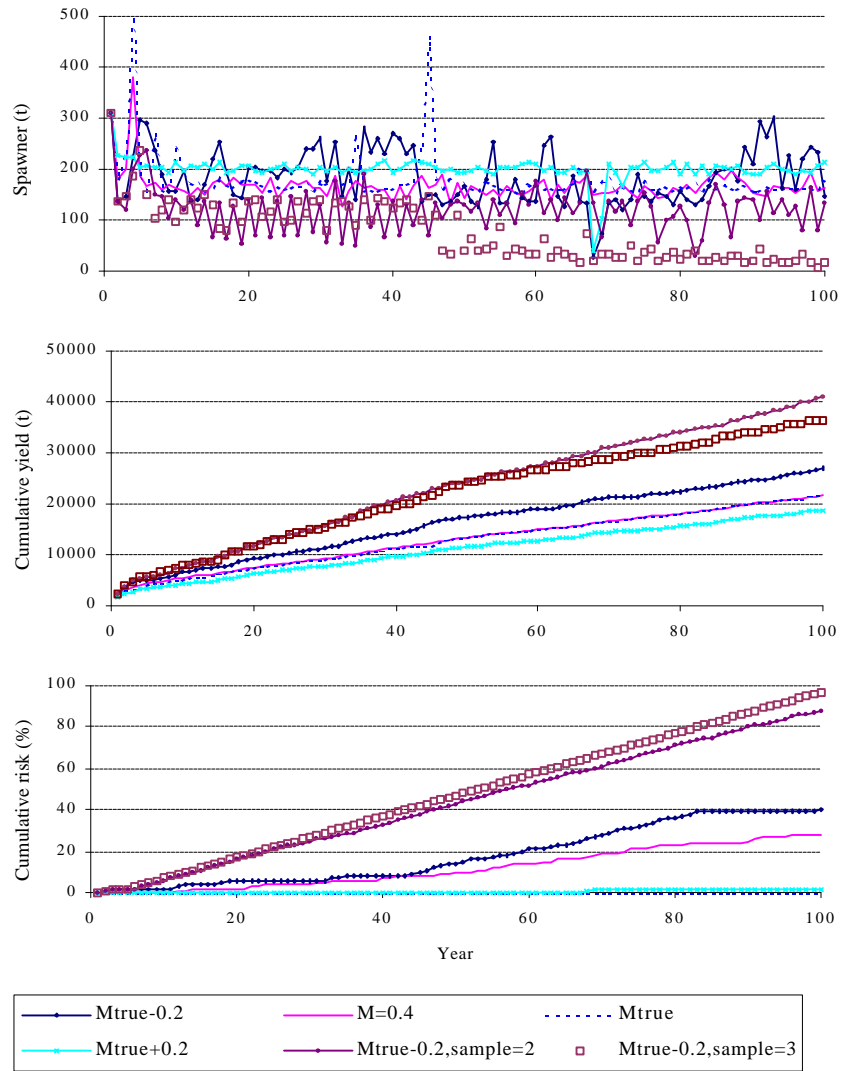
Figure 8. Comparisons of biomass, cumulative yield and risk from various pre-season management given R_{true}, four levels of M (0.2 less than M_{true}, constant at 0.4, M_{true}, 0.2 more than M_{true}) and two additional sampling frequencies (sampling once every 2 and 3 years) with M_{true} - 0.2.
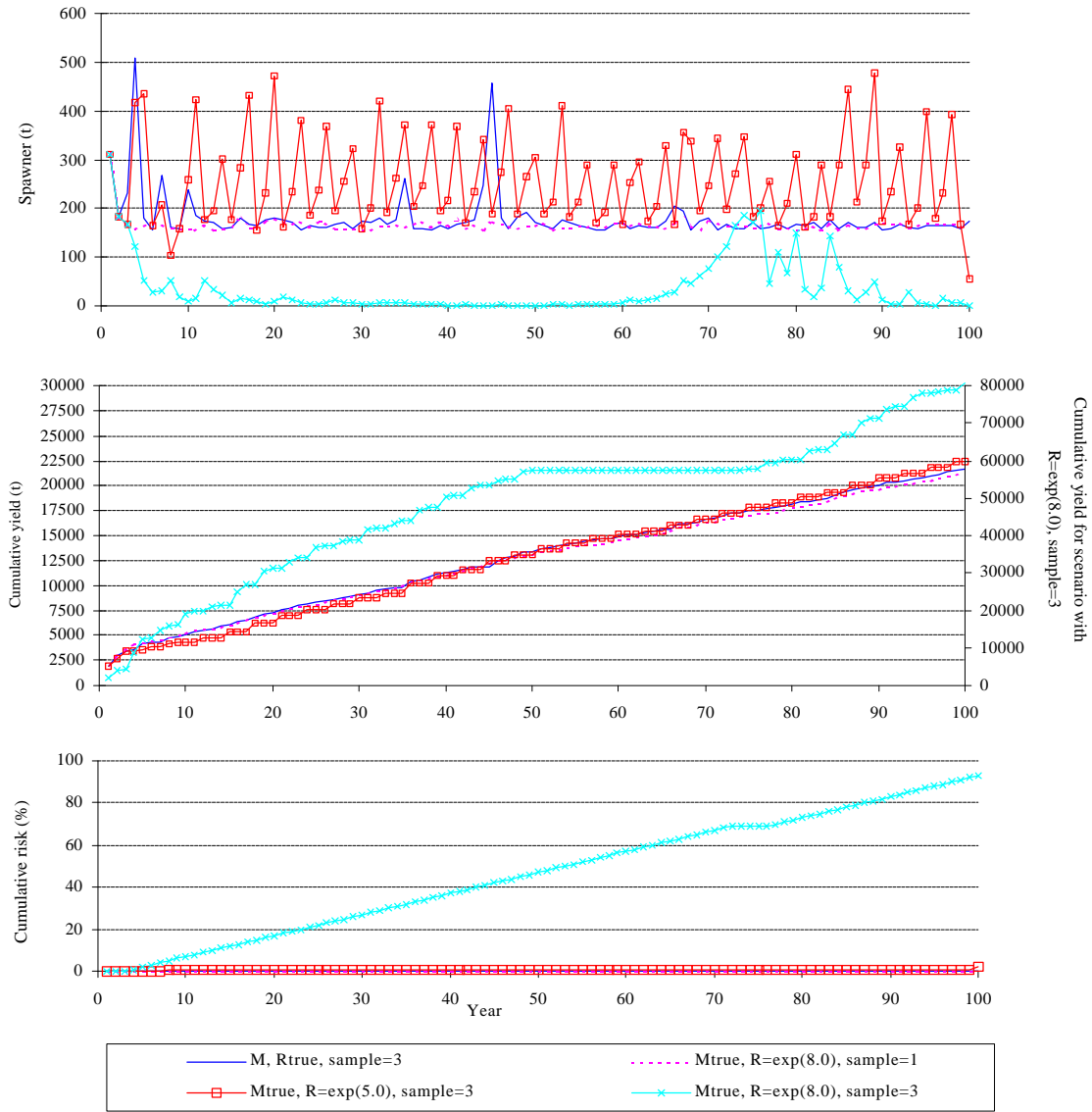
Figure 9. Comparisons of biomass, cumulative yield and from various pre-season management given M_{true}, three levels of R (exp(5.0), R_{true}, exp(8.0)) and one additional sampling frequency (sampling 3 years) with R of exp(8.0).