



# Retrospective bioeconomic analysis of Fraser River sockeye salmon fishery management

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## ABSTRACT

We analyzed past management performance in the Fraser River sockeye salmon fishery, examining how much more profitable the fishery could have been under different harvest rules than those that were applied historically. There has been uncertainty about what management regime would be optimal because of (1) large cycles in the abundance of the stocks, the cause(s) of which are unknown, and (2) past underestimates of the capacity of the ecosystem to produce sockeye. We used historical stock-recruitment data and variation in productivity as the basis for retrospective biological dynamics using two different biological models, each model corresponding to a hypothesized cause of the cyclic population dynamics. We then used prices, fishing costs and discounting to incorporate the economics of the fishery, and simulated the fishery under several different harvest rules. We found that the fishery could have been 20–200% more profitable than it was historically if relatively simple harvest rules (fixed exploitation rate or target escapement) had been implemented. However, we found that there would have been relatively little increase in profit above the level attained by these simple rules if managers had also known in advance the so-called recruitment anomalies, i.e., the deviation of actual recruitment from that predicted by the deterministic model. The results suggest that, if this fishery is to be managed to maximize long-term profit given conservation constraints, research would be better directed at discovering management-related parameters (optimal exploitation rate and optimal escapement) and finding ways to reach management goals than at predicting recruitment anomalies.

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## 1. Introduction

Salmon in the Fraser River have been an important part of British Columbia's economy and culture for millennia. Aboriginal people traditionally caught salmon as the fish were returning to spawn, with the fish being consumed locally as well as traded with other groups. Commercial fisheries by non-natives began in the 1860s and rapidly expanded over the following five decades. Sockeye salmon (*Oncorhynchus nerka*) in the Fraser River were a major focus of these fisheries, which in the early days focused on producing canned product for export (Henderson and Graham, 1998). Disaster struck the Fraser sockeye stocks in 1912–1915 when obstructions in the river prevented the sockeye from reaching the spawning grounds (Ricker, 1950). Since then many stocks have gradually recovered so that they produced record catches in the 1980s and 1990s (Henderson and Graham, 1998), while others have declined to the point of being declared endangered (COSEWIC, 2003). Sock-

eye salmon comprised about one third of the total commercial salmon catch in British Columbia in the 1950s and 1960s, but this proportion increased to about two thirds by the late 1990s, due to increases in sockeye catch as well as decreases in catch of other species. Recent years have again seen decreases in abundance of some stocks, to the point that the commercial fishery for Fraser sockeye was closed in 2005 and 2007 to allow enough returning fish to reach the spawning grounds to ensure that conservation goals would be met.

Like almost all fished species, Fraser sockeye pose management problems because of uncertainty about stock dynamics and variability in the stock size. The abundance of a few of the largest stocks have exhibited regular and dramatic cycles of abundance of returning spawners, varying in some stocks by two to four orders of magnitude in any 4-year period (Schnute et al., 2000). The underlying mechanism causing the cycles has been the subject of considerable debate in the biology literature (reviewed by Levy and Wood, 1992). The predominant hypotheses are: that the ecology of the sockeye's spawning and rearing grounds generates and maintains the cycles through some form of delayed density-dependence (Ricker, 1950; Ward and Larkin, 1964; Larkin, 1971; Levy and Wood, 1992; Walters and Woodey, 1992); and the compensatory fishing mortality

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hypothesis, which suggests that the cycles may simply be a result of historical accidents causing variation in abundance, and this variation then being amplified by higher exploitation rates on smaller cycle lines (Walters and Staley, 1987). A recent workshop that examined the phenomenon of cycles in Fraser sockeye (Cass and Grout, 2006) produced a consensus that delayed density-dependent interactions are “a biological reality,” but to varying degrees across the different systems, and that high fishing pressure is required to establish and maintain cycles. Thus there is still considerable uncertainty about what causes the observed abundance cycles.

Another important type of uncertainty in the Fraser sockeye fishery concerns the potential productivity of the system. There are two distinct but related aspects of this limitation. First, sockeye stocks are limited to some extent by the total productive capacity of the system as a whole, in particular their rearing lakes, but the degree and nature of this limitation is not known. There have been attempts to assess these limits indirectly (e.g., Hume et al., 1996; Shortreed et al., 2001), but it has been argued that the only way to minimize this uncertainty is through adaptive management experiments, where stocks would intentionally be allowed to rebuild to clarify limits (Walters and Hilborn, 1976; Walters, 1981). Such experiments were begun in the late 1980s once it became more apparent that many stocks were actually over-exploited, and because Canada, under the 1985 Pacific Salmon Treaty, was entitled to most of the increased catch that might arise from a stock rebuilding program (Welch and Noakes, 1991; Huppert, 1995). These experiments have indeed revealed that the capacity of the system is significantly higher than was previously thought.

The second type of uncertainty about productive capacity is closely related to that about cyclic dominance: if density-dependent interactions among cycle lines actually exist in the forms hypothesized, they will reduce total potential productivity. If these interactions do not exist, however, total production could be substantially increased by allowing rebuilding of off-cycle lines (Walters and Staley, 1987; Welch and Noakes, 1990, 1991). Some such rebuilding of off-cycle lines has been attempted in the Fraser River, and in some cases has caused the cyclic patterns in returns to begin breaking down (Cass and Grout, 2006). There is still some question, though, of whether this pattern will be repeated on other stocks that have not yet rebuilt, and whether productivity might still be somewhat suppressed by weak cycle-line interactions.

The various types of uncertainty and the cyclic variability in stocks present numerous management questions. First, if compensatory fishing mortality alone is responsible for the cycles, adjustments in fishing rates should allow the ‘off’ years to rebound and, in the long run, allow greater and/or more stable yields. However, if delayed density-dependence on rearing grounds causes the cycles, it might be substantially more difficult to obtain significantly greater yields since growth in abundance in the off years might depress the dominant and/or sub-dominant years, possibly resulting in a net loss of yield. It is useful to assess what benefits might have been obtained from the fishery under each of these hypotheses about stock dynamics. Second, the historical assumption that the system was less productive than it in fact was has most likely led to substantial long-term catches and profits being foregone because the potential net gains from a stock rebuilding program were not fully understood. How much additional benefit might have been obtained if we had had more information about the true productivity of the system? Finally, the extreme variability from year to year in stock sizes available for fishing raise the question of how best to determine the catch that might be taken each year. For example, should a fixed exploitation rate be applied each year, or should a target escapement be allowed onto the spawning grounds whenever possible (Walters and Parma, 1996)? And how do the implications of the harvest policy depend on the underlying stock dynamics model?

Previous work on the implications of uncertainty and variability for the fishery has focused on total physical yield that can be, or could have been, obtained from the fishery given the 4-year cycles. This focus is consistent with federal Canadian fisheries policy which, explicitly or otherwise, often tends to try to maximize yield. However, there are two respects in which an economic analysis could contribute to management. First, to ensure consistency with other public policy decisions and to allow proper accounting of costs and benefits of time-variant policies, some type of discounting of future benefits should be incorporated into the models (Clark, 1990). Some authors have incorporated discounting (Collie and Walters, 1987), but most have not, even when they consider monetary values (Martell et al., 2008; Welch and Noakes, 1990). Second, assessing costs and benefits to society requires consideration of factors other than physical yield; profit obtained from the fishery can be argued to be a better overall indicator of net social benefits (Clark, 1985). This requires consideration of fish prices and fishing costs, both of which vary over time.

In this paper we examine the Fraser River sockeye fishery from an economic perspective. We extend an analysis conducted by Martell et al. (2008), who evaluated retrospectively the performance of management from 1952 until 1998, asking how much ‘extra’ catch could have been obtained from the various stocks given the information available today, and under different assumptions about the causes of the cyclic nature of some stocks. We build economics onto their model, incorporating information about prices of fish, costs of fishing, and discounting. The paper is best seen as a thought experiment that examines what might have happened if different management approaches had been taken and if we had known then what we know now about the productive capacity of the stock, all conditioned on different hypotheses about the underlying stock dynamics.

The next section describes our bioeconomic model. The following two sections describe the data used and how we estimated the parameters necessary for our simulations. We then describe our results and discuss some implications in the final section.

## 2. Model

### 2.1. Stock dynamics

We begin with a cohort of mature sockeye salmon from stock  $s$ , numbering  $Q_{s,t}$ , entering the fishing grounds in year  $t$  on the way from ocean feeding grounds to their spawning stream. The fishery takes a catch numbering  $Y_{s,t}$ , which is some proportion  $u_{s,t}$  of the run, leaving an escapement  $S_{s,t}$

$$Y_{s,t} = u_{s,t} Q_{s,t} \quad (1)$$

$$S_{s,t} = Q_{s,t} - Y_{s,t} \quad (2)$$

This escapement of fish then makes its way up the river to spawn, generating some number  $R_{s,t}$  of recruits that return 4 (or occasionally 5) years later

$$R_{s,t} = f(S_{s,t}) \quad (3)$$

where  $f$  is one of the two recruitment functions described below. Note that the time subscript refers to the brood year (i.e., the year in which the fish spawn); recruits subscripted  $t$  do not actually recruit until  $t + 4$  or  $t + 5$  (or, very rarely,  $t + 3$  or  $t + 6$ ), at which time they become the run ( $Q$ ) of fish entering the fishing grounds. The size of the run of fish will be

$$Q_{s,t} = \sum_{a=3}^6 \kappa_{a,s,t-a} R_{s,t-a} \quad (4)$$

where  $\kappa_{a,s,t}$  is the proportion of recruits from stock  $s$  and brood year  $t$  that return at age  $a$ . Because  $\kappa_3$  and  $\kappa_6$  have typically been  $<0.01$ , we simplified our simulations by using  $\kappa_5 = \kappa_3 + \kappa_5 + \kappa_6$ .

## 2.2. Recruitment

We use two different stock-recruitment functions to model the hypothesized mechanisms underlying cycles in sockeye abundance. The first, corresponding to the depensatory fishing hypothesis, is the classic [Ricker \(1954\)](#) model:

$$R_{s,t} = S_{s,t} \alpha_s \exp(b_{s,0} S_{s,t} + w_{s,t}) \quad (5)$$

where  $b_{s,0} \leq 0$ . In the current context it is best to transform the model to a linear form:

$$\ln(R_{s,t}/S_{s,t}) = a_s + b_{s,0} S_{s,t} + w_{s,t} \quad (6)$$

where  $\ln(R_{s,t}/S_{s,t})$  can be thought of as a productivity index,  $a_s = \ln(\alpha_s)$  is the maximum productivity at low spawning stock sizes,  $b_{s,0}$  is the density-dependence parameter that determines how quickly productivity decreases with increasing escapement, and  $w_{s,t}$  is a recruitment ‘anomaly,’ i.e., the deviation from the deterministic relationship. Note that with the Ricker model there is nothing inherent in the stock-recruitment function to cause cyclic behaviour.

The second stock-recruitment model corresponds to the delayed density dependence hypothesis, and is often referred to as the [Larkin \(1971\)](#) model. This is a variation on the Ricker model that allows for decreases in  $\ln(R/S)$  due to interactions with previous spawning stocks  $S_{s,t-i}$ , where  $i = 1-3$ :

$$\ln\left(\frac{R_{s,t}}{S_{s,t}}\right) = a_s + b_{s,0} S_{s,t} + b_{s,1} S_{s,t-1} + b_{s,2} S_{s,t-2} + b_{s,3} S_{s,t-3} + w_{s,t} \quad (7)$$

where all  $b_{s,i} \leq 0$ . The  $b_{s,i}$  are parameters for density dependence operating at lags of  $i$  years; if  $b_{s,i} < 0$ , spawners in year  $t - i$  will have a negative impact on productivity in year  $t$ .

In the case of Fraser River sockeye, there are nine major stock complexes (Early Stuart, Late Stuart, Stellako, Quesnel, Chilko, Seymour, Late Shuswap, Birkenhead and Weaver) that comprise the bulk of the fishery. We modeled the biological dynamics of each of these complexes separately, i.e., we estimated the stock-recruitment parameters separately for each complex.

## 2.3. Catch function

To model catch in the fishery, we must account for the substantial spatio-temporal overlap among the nine stock complexes on the fishing grounds: fish from some stock complexes migrate at the same time, so it is not practical to exert the optimal amount of fishing effort on one stock complex without affecting other stock complexes. Following [Martell et al. \(2008\)](#) we assume in our model that exploitation rates  $u$  are set by managers for three different periods (indexed  $\tau$ ) during the year (called early, summer and late), and these rates apply to all stock complexes (indexed  $s$ ) migrating during period  $\tau$ .

As a catch function, we use a modification of the Cobb-Douglas form that allows catchability (the constant of proportionality between inputs and catch) to vary over time, which is necessary given the long time scale of our study. We assume, given technological changes in the fishery, that catchability has increased exponentially over the study period, and that catchability varies independently in the three fleets that target sockeye, gillnetters, seiners and trollers. Catchability for fleet  $f$  in year  $t$  is then

$$q_{f,t} = \rho_f \exp(\phi_f t)$$

where the parameters are specific to a given fleet:  $\rho_f$  is catchability in the first year of the study and  $\phi_f$  is the percentage increase in catchability each year. The catch function is then

$$Y_{f,\tau,t} = q_{f,t} E_{f,\tau,t}^{\beta_f} Q_{\tau,t}^{\gamma_f} \quad (8)$$

where the exponents  $\beta_f$  and  $\gamma_f$  are fleet-specific elasticities reflecting the percentage increase in catch with a 1% increase in effort or stock size, respectively, and are assumed to be  $\geq 0$ .  $\beta > 1$  or  $\gamma > 1$  would indicate increasing returns to effort or stock size, respectively;  $\beta = 1$  or  $\gamma = 1$  would indicate constant returns to the respective factors, while  $\beta < 1$  or  $\gamma < 1$  would indicate diminishing returns.

Finally, to drive the stock dynamics, we must include catch that is taken not only by the Canadian commercial fleet, but also by US fishers and aboriginal Canadian fishers. US fishers have been allocated varying proportions of the total Fraser sockeye catch at different points in history, and aboriginal fishers along the banks of the river have also taken significant catches. In the simulation model, catch by US and aboriginal fishers in any given year is estimated using the historical proportion of the total run each group took in that year, i.e.,  $Y_{\tau,t}^{\text{US}} = u_{\tau,t}^{\text{US}} Q_{\tau,t}$ , and similar for aboriginal catch. The total catch taken from each run-timing group is then calculated as

$$Y_{\tau,t}^{\text{Total}} = (u_{\tau,t}^{\text{US}} + u_{\tau,t}^{\text{A}}) Q_{\tau,t} + \sum_{f=1}^3 Y_{f,\tau,t}$$

This catch  $Y_{\tau,t}^{\text{Total}}$  is assigned to the stock complexes within each run-timing group in proportion to each complex's abundance in year  $t$ , and these removals from the population then drive the stock dynamics as in Eq. (2).

## 2.4. Economics of the fishery

With fleet  $f$  exerting  $E_{f,\tau,t}$  vessel-days of effort during period  $\tau$  in year  $t$ , the cost of fishing in a given year is

$$C_t = \sum_{f=1}^3 \sum_{\tau=1}^3 c_{f,t} E_{f,\tau,t}$$

where  $c_{f,t}$  is the variable cost of fishing per vessel-day. Note that this cost function does not include any fixed costs or capital costs. We assume that the Fraser River sockeye fishery has played a relatively small role in decisions about investment in the BC salmon fleet, on the following basis: (1) the fleet exploits five species of Pacific salmon, with Fraser River sockeye salmon accounting for a varying proportion of the total annual BC salmon catch over the study period, averaging 30%; and (2) at various times in the history of the fishery, many salmon vessels have obtained a substantial portion of their revenue from species other than salmon (e.g., seiners catch herring). Since we infer that most investment decisions are based primarily on factors outside the Fraser River sockeye fishery, it is reasonable to ignore fixed and capital costs when assessing the profitability of this particular fishery.

The total revenue generated in year  $t$  is

$$V_t = \sum_{f=1}^3 \sum_{\tau=1}^3 p_{f,t} Y_{f,\tau,t} g_t$$

where  $p_{f,t}$  is the price per kg received by fleet  $f$  for sockeye in year  $t$ , and  $g_t$  is the average weight (in kg) of sockeye caught in year  $t$ . We assume that price in any given year is perfectly elastic with respect to quantity, since most BC salmon is exported, and comprises a relatively small portion of global salmon production ([DFO, 1992](#)).

**Table 1**

Data sources for parameter estimation and simulations.

Variable/parameter	Year(s)	Source
Run size ( $Q_t$ ), recruitment ( $R_t$ ), escapement ( $S_t$ )	1948–2002	A. Cass, Fisheries and Oceans Canada, pers. comm. Described by Schnute et al. (2000).
Catch function parameters ( $\rho_f$ , $\phi_f$ , $\gamma_f$ )	1952–1996	DFO (1952–1995)
	2000–2006	B. Patten, Fisheries and Oceans Canada, pers. comm.
Variable cost of fishing effort ( $c_{f,t}$ )		
Labour	1950–1984	Government of Canada (1952–1986)
	1986–2002	Statistics Canada (2006)
Non-labour	1953–1954	Buchanan and Campbell (1957)
	1968	Campbell (1969)
	1976–1995	Gislason (1997)
Price ( $p_{f,t}$ )		
By Species	1952–1995	DFO (1952–1995)
	1996–2002	DFO (2006)
By Species and Gear (for calculation of troll premium)	1976	Shaffer (1979)
	1986–1990	DFO (1992)
	1996–2005	DFO (2006)
Consumer price index	1948–2002	IMF (2005)

Finally, we wish to determine the net present value (NPV) of past profits to reflect the returns to those profits (at the prevailing discount rate  $\delta$ ) had they been invested elsewhere in the economy. The current value of profit is

$$\Pi_t = V_t - C_t$$

and the present value of the stream of profits from 1952 to 1998 from the perspective of a social planner looking back in time from 1998 is

$$\pi = \sum_{t=1952}^{1998} \Pi_t (1 + \delta)^{1998-t} \quad (9)$$

### 3. Parameter estimation and simulations

We obtained the raw data (sources in Table 1) necessary for parameter estimation from the literature, and estimated parameters as described below. All economic data are in Canadian dollars (CAD) and were adjusted to real 2000 dollar values using the Consumer Price Index (CPI).

#### 3.1. Stock-recruitment parameters

For each of the hypothesized recruitment functions (Eqs. (6) and (7)), we estimated the parameters  $a_s$  and  $b_{s,i}$  for each of the nine major stock complexes in the Fraser River using data from 1948 to 2002. We used ordinary least squares (OLS) to estimate the parameters of the Ricker and Larkin models as shown in Eqs. (6) and (7) (Tables 2 and 3). We used a numerical search routine (“optim” in R; <http://www.r-project.org>) to estimate the Schnute and Kronlund (1996) non-linear formulation of the Larkin model by minimizing  $\sum_t w_{s,t}^2$ , subject to the constraint  $b_{s,i} \leq 0$ . We extracted recruitment anomalies,  $w_{s,t}$ , as the difference between the observed and predicted  $\ln(R/S)$  values for each recruitment model, i.e., the residuals from the regressions. We used the OLS Ricker estimates and non-linear Larkin estimates as the biological basis for our simulations, but provide the linearly estimated Larkin parameters for their comparability to the Ricker parameters. Note that there is likely to be some correlation in the  $w_{s,t}$  values across stocks as all stocks spend several years in overlapping areas in the ocean, and migrate through some of the same river and ocean waters. However, Peterman et al. (1998) found that these correlations are for the most part small in the stocks that we are modelling (median correlation coefficient for 36 pairwise correlations = 0.19), so we chose to disregard this correlation in our estimations. We also examined the residuals for temporal autocorrelation by regressing  $w_{s,t}$  on  $w_{s,t-1}$  for each stock

**Table 2**

Stock-recruitment and management parameter estimates for the Ricker model.  $S_{MSY}$  values are in millions of fish. For each  $a$  and  $b$  value we show the coefficient estimate with the standard error below it. Asterisks indicate statistical significance at  $\alpha = 0.05$  (one asterisk) and 0.01 (two asterisks).

Stock complex	$a_s$	$b_{0,s}$	$u_{MSY,s}$	$S_{MSY,s}$	$u_{MSY,\tau}$	$S_{MSY,\tau}$
Early Stuart	1.55 0.14**	−1.96 0.80*	0.61	0.31	0.61	0.31
Late Stuart	1.99 0.20**	−1.45 0.70*	0.72	0.49	0.71	3.45
Stellako	1.96 0.13**	−3.46 1.09**	0.71	0.21		
Quesnel	1.94 0.13**	−0.30 0.22	0.71	2.35		
Chilko	2.17 0.15**	−1.90 0.35**	0.76	0.40		
Seymour	1.66 0.15**	−6.38 2.65*	0.64	0.10	0.67	2.31
Late Shuswap	1.77 0.15**	−0.34 0.13*	0.67	1.93		
Birkenhead	2.14 0.17**	−6.89 1.55**	0.75	0.11		
Weaver	1.93 0.21**	−4.19 3.54	0.71	0.17		

**Table 3**

Stock-recruitment and management parameter estimates for the linear Larkin model (Eq. (7)).  $S_{MSY}$  values are in millions of fish. Standard errors are shown below the parameter estimates. Asterisks indicate statistical significance at  $\alpha = 0.05$  (one asterisk) and 0.01 (two asterisks).

Stock complex	$a_s$	$b_{0,s}$	$b_{1,s}$	$b_{2,s}$	$b_{3,s}$	$u_{MSY,\tau}$	$S_{MSY,\tau}$
Early Stuart	2.11 0.18**	−2.14 0.79**	−3.26 0.80**	−1.59 0.70*	−0.91 0.70	0.75	0.09
Late Stuart	2.29 0.28**	−1.72 0.71*	−1.55 0.71*	−1.10 0.80	0.33 0.79	0.76	1.20
Stellako	2.14 0.22**	−3.03 1.10**	−1.20 1.15	0.83 1.14	−2.15 1.28		
Quesnel	2.13 0.16**	−0.31 0.22	−0.09 0.22	−0.48 0.24	−0.39 0.24		
Chilko	2.30 0.22**	−1.61 0.40**	−0.85 0.42*	−0.14 0.42	0.24 0.43		
Seymour	2.09 0.19**	−5.71 2.77*	−5.54 2.86	−4.31 2.88	−4.78 2.76	0.77	0.86
Late Shuswap	2.35 0.31**	−0.58 0.16**	−0.32 0.16*	−0.40 0.16*	−0.04 0.16		
Birkenhead	2.22 0.22**	−6.68 1.77**	−1.37 2.08	1.04 2.11	−0.60 2.00		
Weaver	1.84 0.30**	−5.45 3.95	2.07 3.96	3.70 3.96	−2.18 4.03		



**Table 4**  
Estimates of parameters of two CPUE models, model A (Eq. (11)) and model B (same as A, but without  $\ln(Q)$ ). Parameter estimates are given as mean  $\pm$  standard error, with asterisks indicating statistical significance at  $\alpha = 0.05$  (one asterisk) or 0.01 (two asterisks). AIC is the Akaike information criterion.

Fleet	Model	$\phi_f$	$\gamma_f$	$n$	$R^2$	$F$	AIC
Gillnetters	A	$0.025 \pm 0.004^{**}$	$0.114 \pm 0.075$	145	0.285	31.5	276
	B	$0.028 \pm 0.004^{**}$	–	145	0.275	29.9	277
Seiners	A	$0.0043 \pm 0.0078$	$0.657 \pm 0.149^{**}$	101	0.233	14.1	255
	B	$0.020 \pm 0.008^{**}$	–	101	0.073	3.63	272
Trollers	A	$0.057 \pm 0.016^{**}$	$0.045 \pm 0.179$	42	0.332	6.95	58.1
	B	$0.058 \pm 0.015^{**}$	–	42	0.330	6.90	56.2

(Wooldridge, 2003). We found statistically significant (at  $\alpha = 0.05$ ) autocorrelation for two stocks when we used the Ricker model, and only one stock when we used the Larkin model. Thus, autocorrelation does not appear to be an overly common problem in this data set, and we proceed without correcting for its effects. In general, our parameter estimates are similar to those of the last official stock assessment of Fraser River sockeye (Cass et al., 2000).

These stock-recruitment parameters then allow calculation of two key management parameters:  $u_{MSY,s}$  and  $S_{MSY,s}$ , the exploitation rate and escapement, respectively, that produce the maximum sustainable yield (MSY). In the case of the Ricker model these are functions of  $a_s$  and  $b_{s,0}$  (Schnute and Kronlund, 1996), while in the Larkin model they are a more complicated function of  $a_s$  and  $b_{s,i}$ . Given the mixed stock nature of the fishery, though, it is not possible to fish individual stocks at rates that will produce MSY, no matter which biological model is used. We therefore used a numerical search to find a set of exploitation rates ( $u_{MSY,\tau}$ ,  $\tau = 1, 2, 3$ ) or target escapements ( $S_{MSY,\tau}$ ,  $\tau = 1, 2, 3$ ) that, when applied every year in a deterministic system with no recruitment variability, would yield the maximum total sustainable yield over the long-term from the set of stock complexes that migrate during that period. We used a numerical approach to find  $u_{MSY,\tau}$  and  $S_{MSY,\tau}$  under the Larkin model for each set of stock complexes in a similar way (Tables 2 and 3).

It is worth noting that the use of the Larkin model in simulations does not impose cycle-line interactions on the simulated population. If there is no evidence of interactions in the data, the  $b_{s,i}$  ( $i > 0$ ) parameters will be estimated to be very small or even zero, in which case the Larkin model reduces to the Ricker model. This allows for variation among stocks in both the existence and the strength of cycle-line interactions.

### 3.2. Catch function parameters

Our catch and effort data are broken down by year, month, fleet, and statistical area. Most of our monthly data provide effort for the entire salmon fleet without differentiating by target species. To obtain data for sockeye only, we selected those catch-effort records for which sockeye comprised  $> 80\%$  of the total catch in that month and area for the gear type in question. The resulting data set contained 145 records for gillnets, 101 records for seiners, and 42 records for trollers.

A key component of the catch function (Eq. (8)) that is missing from this data set is the stock size  $Q$ . While we have data on the annual stock sizes of each of the nine stock complexes that we model, we cannot match these stock sizes temporally with our catch data to allow estimation of the stock effect on catch (i.e., the  $\gamma_f$  parameters). To try to crudely assess the stock effect, we used data on the total stock size in the year in question, i.e.,  $Q_t^{\text{total}} = \sum_{s=1}^9 Q_{s,t}$ . We modified the catch function by taking logarithms to obtain

$$\ln(Y_{i,t}) = \ln(\rho_f) + \phi_f t + \beta_f \ln(E_{i,t}) + \gamma_f \ln(Q_t^{\text{total}}) \quad (10)$$

Least-squares estimations of the parameters for each fleet using Eq. (10) found roughly constant returns to effort: the mean estimates ( $\pm$  standard error) of  $\beta_f$  were  $0.92 \pm 0.03$  for gillnetters,  $0.81 \pm 0.07$  for seiners, and  $0.94 \pm 0.12$  for trollers. We therefore assumed for the

actual estimations that  $\beta_f = 1$  for all fleets, and instead estimated two catch per unit effort (CPUE) functions

$$\ln\left(\frac{Y_{i,t}}{E_{i,t}}\right) = \ln(\rho_f) + \phi_f t + \gamma_f \ln(Q_t^{\text{total}}) \quad (11)$$

which we call model A; and a similar function with  $\ln(Q)$  omitted, model B. The estimates of these parameters produced mixed results (Table 4). For gillnetters and trollers the estimate of  $\gamma_f$  is quite small, and omitting this variable from the model appears to make little difference to the fit; indeed, for trollers, the Akaike Information Criterion (AIC) is lower (i.e., the fit is better) when we omit  $Q$ . For seiners it appears that the model including  $Q$  fits better, and that the stock effect on CPUE is substantial. Fitting a single model for all gears and including dummy variables for the different gears yielded an estimate of  $\gamma = 0.300 \pm 0.070$ . Given this ambiguity among fleets, the relatively modest effect of stock size on CPUE, and the unavailability of data that would allow us to accurately estimate or simulate this stock effect, we decided to use model B for our simulations, i.e., we assumed that there is no effect of stock size on CPUE. Note that this assumption of catch per unit effort being independent of stock size is often made in bioeconomic studies of schooling pelagic species (Mackinson et al., 1997).

To correct for bias introduced by our logarithmic estimation (Kennedy, 1983), we predict the catch per unit effort values for each year,  $CPUE_{f,t}^*$ , as

$$CPUE_{f,t}^* = \widehat{CPUE}_{f,t} \cdot \exp\left[-\frac{\sigma^2}{2}(1 - \mathbf{z}'(\mathbf{Z}'\mathbf{Z})^{-1}\mathbf{z})\right]$$

where  $\widehat{CPUE}$  is the CPUE value predicted by the OLS parameters,  $\sigma^2$  is the variance of the residuals,  $\mathbf{z} = (1, t)$ , and  $\mathbf{Z}$  is the variance-covariance matrix from the regression for model B. The resulting annual estimates of CPUE are shown in Fig. 1.

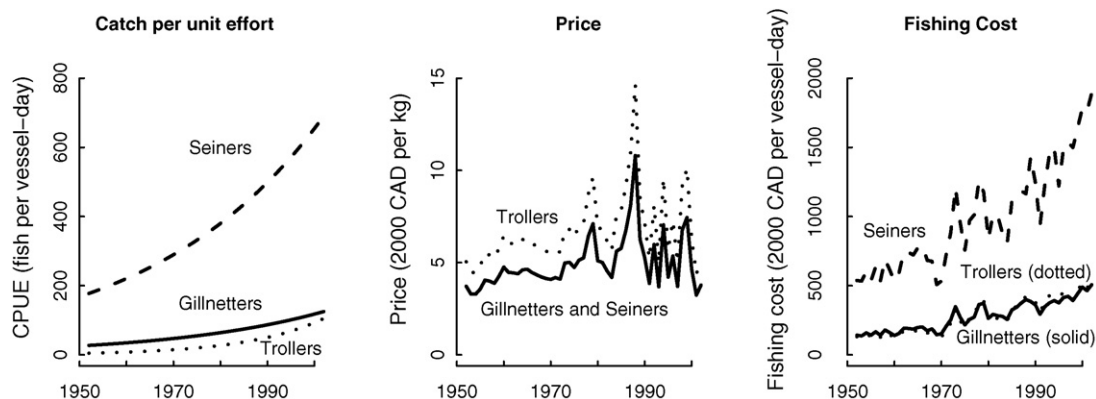
### 3.3. Economic parameters

#### 3.3.1. Variable cost

Since we examined the fishery from the perspective of a fishery manager trying to maximize aggregate profit, we took variable cost to be the opportunity cost of labour, plus any other costs associated with running the vessel on a daily basis. Capital costs, as well as fixed costs such as insurance, maintenance, etc. were omitted for reasons discussed above.

To estimate labour costs, we obtained average annual incomes for BC fishermen (1950–1984) and workers in BC resource industries (1986–2002), and then adjusted these values using census data to account for higher earnings by captains compared to deckhands (Table 1). Average crew sizes were then used to estimate total labour cost per vessel-day of effort for each fleet. The single year with missing data (1985) was estimated as the average for 1982–1984 and 1986–1988.

We used several studies of costs in this fishery over the study period (Buchanan and Campbell, 1957; Gislason, 1997; Sinclair, 1960) to estimate non-labour variable cost per vessel-day in 1953–1954, 1968 and 1976–1995 for each fleet. In general, these



**Fig. 1.** Estimates of time-variant parameters for simulation models: catch per unit effort (CPUE), landing price for sockeye, and fishing cost. Note that costs for trollers and gillnetters are quite similar and overlap substantially.

reports gave cost data as an average per vessel for the fishing season, or for the entire fleet along with the number of vessels in the fleet. It was then straightforward to calculate average cost per vessel-day of fishing. This left us with a data set with many gaps, i.e., years without estimates of costs. To fill these gaps, we assumed, given the clear pattern in the time series, that non-labour costs had increased exponentially over the study period, and fit an exponential curve to the raw data. For the simulations, we used raw data for the years in which we have them, and the interpolated values for the rest of the years. Finally, the sum of labour and non-labour variable costs provided our estimates of total variable cost per vessel-day ( $c_{f,t}$ ; Fig. 1).

### 3.3.2. Price

Most statistics report price by fleet or by species, but rarely by gear and species. Such a distinction is important because troll-caught sockeye often command a higher price than net-caught sockeye. Where possible (see Table 1), we obtained prices for sockeye for each gear. We found that there was no trend in the price premium for troll-caught sockeye, so we used the average of this premium (the ratio of troll-caught to net-caught sockeye) as the premium obtained in all years. We used the overall average sockeye price as the price for gillnet- and seine-caught sockeye, and this average multiplied by the troll premium as the price for troll-caught sockeye (Fig. 1).

### 3.4. Management simulations

To evaluate the consequences of various harvest rules we started with the assumption that either the Ricker or the Larkin model, with the parameters ( $a_s$ ,  $b_{s,i}$ ,  $w_{s,t}$  for all  $s$  and  $t$ ) estimated above, accurately represents the underlying biological system. For each assumed model, we then simulated four scenarios:

- (1) application of the historical time series of exploitation rates,  $u_{\tau,t}$ , for comparison with the simulated outcomes below;
- (2) application of a fixed harvest rate policy in every year, where the harvest is  $Y_{\tau,t} = u_{MSY,\tau} Q_{\tau,t}$ ;
- (3) application of a target escapement policy, where harvest is  $Y_{\tau,t} = \max\{0, Q_{\tau,t} - S_{MSY,\tau}\}$  and  $S_{MSY,\tau}$  is the target escapement set by managers for period  $\tau$ ; and
- (4) application of an 'omniscient manager' routine, as described by Martell et al. (2008). For these simulations, we assume that the manager knows in 1951 the value of all parameters, including the annual recruitment anomalies  $w_{s,t}$ , for the entire 47-year period. We then use a numerical search routine (again "optim" in R) to find the time-series of annual effort levels that will maximize either discounted profits (Eq. (9)) or catch summed over all

years. This approach is sometimes referred to as an "open-loop" policy simulation (Walters and Martell, 2004).

We initialized each simulation with historical data from the first 4 years of our data set (1948–1951). For the simulation of the historical time series, effort levels were set for 1952–1998 to produce annual catches equal to the historical ones. For the fixed harvest rate and target escapement policies, effort levels were set so that the resulting harvest rate or escapement was equal to the target level. For the omniscient manager scenario, a numerical search was used to find the time series of effort levels that maximized the total discounted profit (Eq. (9)) with a range of discount rates (0.03, 0.07, 0.11, 0.25, 0.50 and 1.0). For all simulations, total effort for each period  $\tau$  was allocated among fleets so that each fleet had a proportion of the total harvest equal to the one it obtained historically. These effort levels were then combined with our CPUE, price and cost estimates to calculate profits over the study period.

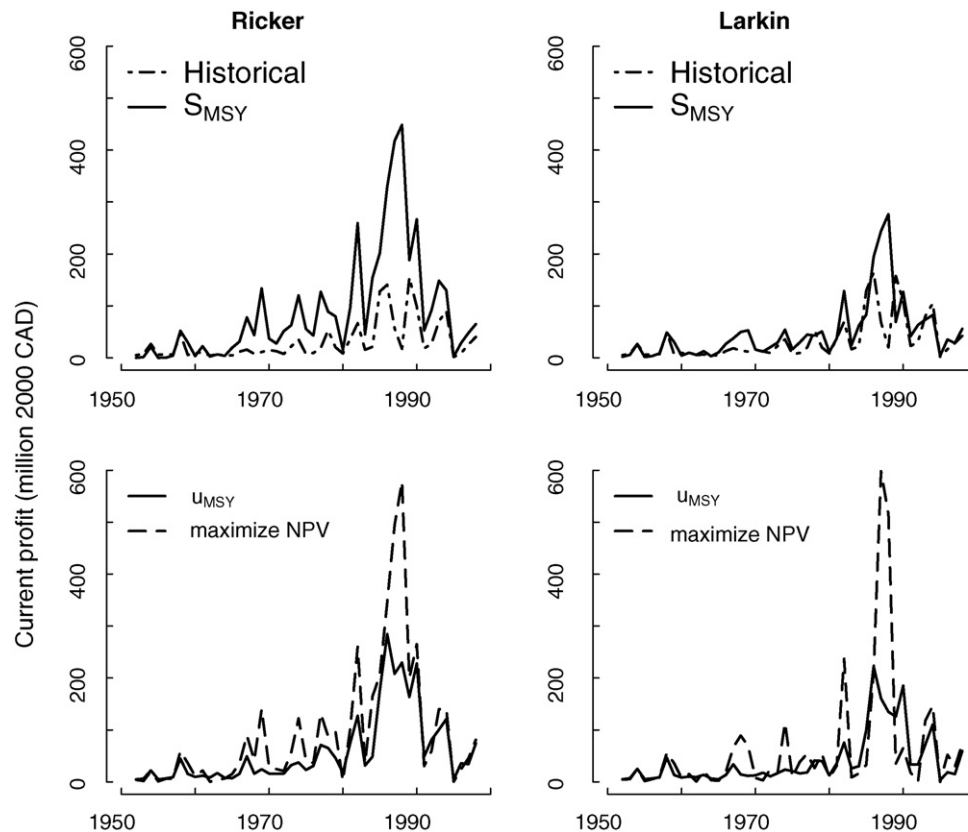
Note that we include no stochastic elements in our simulations, e.g., in the implementation of harvest strategies, which can sometimes be problematic (Holt and Peterman, 2006). We recognize that this deterministic approach glosses over some potentially important implementation difficulties. However, we can still examine the overall issue of long-term profitability in the fishery with our relatively simple model.

## 4. Results and discussion

The general pattern seen when comparing any of the simulated policies to the historical series is similar under both the Ricker and the Larkin models: all policies call for forgoing some profit in the very early years (until about 1957) to allow the stocks to rebuild (Fig. 2). Profits are then, on average, somewhat greater in the late 1950s and early 1960s, and much greater from the mid-1960s onward when compared to the historical values.

For the NPV maximization scenario, this temporal pattern is mildly sensitive to moderate variations in the discount rate: in simulations using the Ricker model with discount rates higher than the default ( $\delta = 0.07$ ), discounting at 0.25 produced only a small deviation from the trajectory obtained with lower rates, and a loss of 9% of current-value profit over the study period. A discount rate of 0.50, however, resulted in very little rebuilding of stocks and yielded a total 47-year profit only slightly greater than the historical scenario, while a discount rate of 1.0 resulted in almost complete elimination of all stocks within 4 years. The rest of the results presented were obtained in simulations where the discount rate was set to 0.07, the standard federal government of Canada rate.

We averaged the current-value profit over the 47-year period for each scenario to examine the overall result of each manage-



**Fig. 2.** Time series of current-value profit ( $\Pi_t$ ) from simulations where the Ricker (left panels) or Larkin (right panels) model was assumed to be the true biological model. The top panels show a simulation of the historical fishery, and a fishery managed using a target escapement policy ( $S_{MSY}$ ), while bottom panels show simulations of a fishery managed using a fixed harvest rate ( $u_{MSY}$ ) and a NPV-maximizing omniscient manager with  $\delta = 0.07$ . The catch-maximizing omniscient manager is omitted for the sake of clarity, and because the pattern is quite similar to that for the NPV maximization.

ment approach and biological model (Table 5). While there is great variation around the mean from year to year, the mean is nevertheless useful in providing an intuitive benchmark to discuss the relative benefits in each scenario. Assuming the Ricker model is the 'true' model underlying the biological dynamics, almost twice as much profit (relative to the historical outcome) could have been obtained from the fishery if a simple fixed exploitation rate harvest policy had been applied (i.e., three different exploitation rates,  $u_{MSY,\tau}$ , applied every year, one during each period  $\tau$ ). Furthermore, almost three times as much profit could have been obtained if a target escapement policy had been applied, with target escapement in each period set to the value of  $S_{MSY,\tau}$  as calculated above. However, under the Ricker model, using an 'omniscient' policy (i.e., knowing  $a_s$ ,  $b_{s,0}$  and all  $w_{s,\tau}$  parameters in advance) would produce only about 3–4% more profit than the target escapement policy.

If the Larkin model, with the parameters that we estimated, is the 'true' model underlying the stock dynamics, the most apparent difference from the Ricker model is that the fishery has substantially less capacity to generate profit: depending on the management

approach taken, profit under the Larkin model is 56–70% of that obtained with the same management approach under the Ricker model (Table 5). This should not be surprising, since interactions between cycle lines are defined to be detrimental to productivity, since the  $b_{s,1}$ ,  $b_{s,2}$  and  $b_{s,3}$  parameters were constrained to be negative. If the Larkin model is the 'true' model and a fixed exploitation rate policy had been applied, 24% more profit could have been obtained than the historical case, while 48% more profit could have been obtained with a target escapement policy.

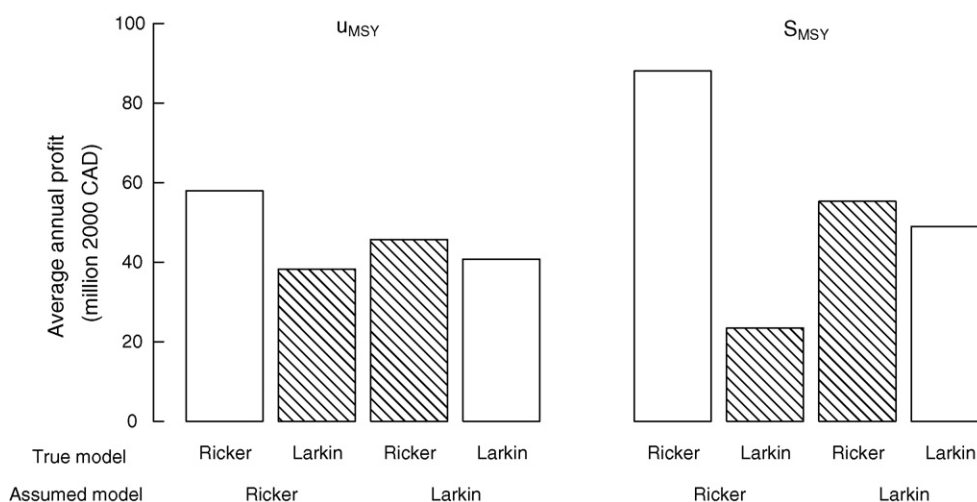
In a substantial divergence from the results obtained with the Ricker model, the omniscient yield- and profit-maximizing policies applied under the Larkin model yield 27% and 30% more profit, respectively, than the target escapement approach, and produced almost twice as much profit as the historical case (Table 5). This greater improvement in performance obtained with omniscient manager policies under Larkin relative to Ricker occurs because of the cyclic nature of populations under the Larkin model, and the fact that the cycles are not synchronized. Under the Ricker model, each  $S_{MSY,\tau}$  is the optimal escapement every year, while under the Larkin model each  $S_{MSY,\tau}$  represents a compromise between four different optimal escapements, each one applicable during a different year in the 4-year cycle. The omniscient manager is not constrained in this manner and can therefore set escapements closer to an optimum level. An additional difference between results with the Ricker and Larkin models is that profits generated under the Larkin model are generally more variable, with higher coefficients of variation in the fixed harvest rate and omniscient manager simulations. This variability arises from the cyclic behaviour of stocks under the Larkin model.

Another question that might be asked is, what are the consequences of making an incorrect assumption about the underlying

**Table 5**

The mean, standard deviation (S.D.) and coefficient of variation (CV) of annual current-value profit over the entire study period in different simulations. Scalar values are in millions of CAD.

Simulation	Ricker model			Larkin model		
	mean	S.D.	CV	mean	S.D.	CV
Historical	30	37	1.22	33	40	1.22
Fixed harvest rate	58	69	1.19	41	51	1.25
Target escapement	88	106	1.20	49	59	1.20
Maximize yield	91	114	1.26	62	94	1.52
Maximize NPV	92	124	1.35	63	117	1.85



**Fig. 3.** Average annual current-value profit obtained in simulations when the 'correct' (open bars) or 'incorrect' (hatched bars) management parameter ( $u_{MSY}$  or  $S_{MSY}$ ) is used in applying a fixed harvest rate (left) or target escapement (right) policy. The "assumed model" labels on the bottom denote the model that is assumed to calculate the management parameters, while the "true model" labels just above denote the model that is actually used to run the simulation. For example, the left-most open bar shows the profit if the Ricker model is used to calculate  $u_{MSY}$  values (assumed model = Ricker), and these values are used in a simulation of the fishery that actually uses the Ricker model (true model = Ricker). In contrast, the left-most hatched bar shows the result if the Ricker model is assumed and the  $u_{MSY}$  values are calculated using it, but we simulate the fishery using the Larkin model.

biology? For example, if the Ricker model is the 'correct' model but we choose the  $u_{MSY,\tau}$  values that are appropriate under the Larkin model, how much profit is lost? The consequences of a management error are qualitatively similar whether we are taking a fixed exploitation rate or a target escapement approach (Fig. 3). If we assume that the Larkin model is correct, we can be much more certain about the outcome of either management approach: if we are mistaken in our choice of model, the fishery would make 12–13% more profit. In contrast, if we assume the Ricker model to be correct but the Larkin model is in fact the correct model, we lose 34% or 73% of total profit if we employ a fixed exploitation rate or target escapement policy, respectively.

The results here, like those of Martell et al. (2008), suggest that better knowledge of the biology of the system, i.e., the degree of knowledge that we have today about the parameters of the stock recruitment relationships, could have substantially increased the benefits obtained in the fishery; the exact amount of the increase would have depended on the harvest rule employed, and the true biological model (Ricker or Larkin) underlying the system. Of course, a substantial data set would have been required before it would have been possible to estimate all parameters with any degree of certainty. Since the value of  $S_{MSY}$  is a function of the  $a$  and  $b_i$  parameters (Schnute and Kronlund, 1996), application of this target would have required a long time series of stock-recruitment data. However,  $u_{MSY}$  is a function of  $a$  only, i.e., of productivity at low stock sizes. Since the stocks were actually quite small in the early 1950s, it would have been possible to roughly estimate  $u_{MSY}$  at that time. To demonstrate this, we estimated, using only the first few years of data, the  $a$  parameter for each stock ( $a_s$ ), either as the average of  $\ln(R/S)$  or by estimating Eq. (6) and using the resulting  $a$  estimate. We then calculated each  $u_{MSY,s}$  iteratively using  $a_s = u_{MSY,s} - \ln(1 - u_{MSY,s})$  (Schnute and Kronlund, 1996), and took  $u_{MSY,\tau}$  as the average of  $u_{MSY,s}$  weighted by the size of the stock. Mathematically,

$$u_{MSY,\tau} = \frac{\sum_s u_{MSY,s} \sum_t Q_{s,t}}{\sum_s \sum_t Q_{s,t}}$$

where  $s$  only includes stocks running during period  $\tau$ , and  $t$  includes only the years used to estimate  $a$ . As the results show (Table 6), we could have made a reasonable estimate of each  $u_{MSY,\tau}$  even with only 4 years of data.

In contrast with the great value of knowledge of the  $a$  and  $b_i$  parameters, the ability to predict recruitment anomalies,  $w_{s,t}$ , would have had almost no value (3–4 million CAD annually) if the Ricker model applied, but somewhat more (13–14 million CAD annually) if the Larkin model applied. This finding is similar to that of Walters and Parma (1996), who found that there was little to be lost in a wide variety of fisheries by applying a fixed exploitation rate policy as opposed to trying to take advantage of recruitment variability. The value of the information about recruitment anomalies must be compared to the cost of gathering the information, and it is questionable whether the gains possible with the information, given the uncertainty about the biological model, would be worth the necessary research expenditure, or whether those resources might be better spent in other areas of research. For example, it is not possible to implement the simple harvest policies simulated here exactly as intended—there is always some implementation error (Holt and Peterman, 2006). Further work on sockeye fisheries management might be better directed at finding ways to reduce this implementation error.

Our findings in the current study agree largely with those of Martell et al. (2008). In the current case, incorporation of economic considerations has not resulted in qualitatively different conclusions from those obtained when considering physical yield alone. This lack of a difference might result partly from our simple linear

**Table 6**

Values of  $u_{MSY,\tau}$  estimated using few data, by (1) taking the mean of  $\ln(R/S)$  over several years and (2) using the intercept of Eq. (6). Each estimate uses only the first few years of the stock-recruitment time series as specified in the first column.

Years of data	Early (true=0.609)		Mid (true=0.711)		Late (true=0.672)	
	$\ln(R/S)$	intercept	$\ln(R/S)$	intercept	$\ln(R/S)$	intercept
1948–1951	0.545	0.649	0.701	0.795	0.628	0.640
1948–1953	0.528	0.607	0.699	0.779	0.604	0.684
1948–1955	0.528	0.655	0.680	0.789	0.616	0.673
1948–1957	0.591	0.654	0.702	0.771	0.644	0.658



cost and catch models, which unlike many economic models of fisheries do not include increasing costs of fishing as stocks decrease. Nevertheless, as discussed in the introduction, it is desirable to incorporate economic considerations into quantitative analyses of fisheries policy whenever possible.

An issue that we do not tackle directly, but which is relevant in all cases that we consider, is the relative costs and risks associated with each management approach. The costs of management failure (Fig. 3) are one aspect of this, and our analysis suggests that, at least for the harvest policies simulated here, assuming that the Larkin model is the true model can be seen to be a precautionary approach to management. Indeed, this is consistent with the current approach of setting escapement strategies based on simulations with the Larkin model (Cass and Grout, 2006). However, the implementation of each management approach has direct costs as well as the benefits shown here. A fixed harvest rate policy yields more stable profit over time (Hannesson, 1993) and is relatively easy for managers to implement because it is relatively independent of the total returns. There are, however, conservation risks associated, since there is a fishery even in years with very small runs—given other uncertainties not modeled here, this policy might result in a higher probability of stock collapse due to overfishing. A target escapement policy, in contrast, yields more variable profit but is safer from a conservation perspective, since in years with runs smaller than  $S_{MSY}$  there is no fishery. However, such a policy is more difficult to implement than the  $u_{MSY}$  policy because it is heavily dependent on knowing how many fish will be running in a given year. A more complete analysis of this management problem, then, would consider not only the potential benefits of management approaches, but also the costs and risks associated, and try to estimate the probabilities of various possible outcomes for each management approach. It would also be helpful to consider implementation error and other stochastic factors in the analysis. These improvements would help provide a more sound basis for informed decision-making.

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