

RETROSPECTIVE ECONOMIC ANALYSIS OF FRASER RIVER SOCKEYE SALMON FISHERY MANAGEMENT

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ABSTRACT

Many Fraser River sockeye salmon stocks show large cycles in abundance from year to year, but the causes of these cycles are not clear. As a result, these stocks have historically been managed under the hypothesis of cyclic dominance, i.e., maintaining the cyclic behaviour of the stocks. Biological studies and changes in management have revealed that the potential yield of the off-peak parts of the cycle could be much higher than was previously thought. We analyzed past management performance in this fishery, examining how much more profitable the fishery could have been had managers and scientists known then what we know now. We used stock-recruitment data as the basis of the biological dynamics, and used prices, fishing costs and discounting to incorporate economics. We then simulated the fishery under a variety of fisheries management regimes. We found that the fishery could have been 40-200% more profitable than it was historically if relatively simple management rules had been implemented. However, we found that there would have been relatively little increase in profit if managers had 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 parameters and finding ways to reach management goals than at predicting recruitment anomalies.

Keywords: sockeye salmon, cyclic population, fisheries management, fixed harvest rate policy, fixed escapement policy, management failure.

INTRODUCTION

Like almost all fisheries systems, sockeye salmon (*Oncorhynchus nerka*) in the Fraser River are characterized by uncertainty and variability. The abundance of a few of the largest stock complexes exhibit regular and dramatic cycles of abundance of returning spawners. In the 1800s and early 1900s there was typically one year with a large number of recruits (the 'dominant' run), followed by three years with much smaller abundances [1, 2]. The cycles of the various stocks were synchronized so that the dominant run for all stocks occurred in the 1901 cycle line (i.e., in 1901, 1905, 1909, etc.). Obstructions in the river all but destroyed these sockeye runs in 1912-1915, but once they recovered in abundance the dominant run was shifted one year later, so that the great abundances of spawners were then seen in the 1902 cycle line [1]. After this recovery, though, there appeared a 'subdominant' cycle line of in the year immediately following the dominant line in many runs. Furthermore, in recent years the dominant runs of the various stock complexes have not all occurred in the same year; for example, the peak of the Late Shuswap stock is in the 1902 line, while that of the Late Stuart and Quesnel stocks is in the 1901 line [3].

The underlying mechanism causing the cycles has been the subject of considerable debate in the biology literature. The predominant hypotheses can be roughly divided into two main lines. The first, and perhaps more prevalent, is that the ecology of the sockeye's spawning and rearing grounds generates and maintains the cycles. Suggested mechanisms have included: build-up of predator populations supported by large numbers of sockeye juveniles rearing in lakes, with

the predators then depressing populations of subsequent year-classes; cannibalism by residual or kokanee sockeye (which remain in fresh water rather than migrating to the ocean); satiation of predators at high densities of juveniles, resulting in lower mortality rates during those years; build-up of parasite populations; and depletion of food resources by strong year-classes [1, 2, 4, 5]. The second major explanation that has been put forward is the depensatory fishing mortality hypothesis, which argues that the cycles may simply be a result of historical accidents causing variation in abundance, and this variation then being amplified by differential fishing rates, since we might expect higher fishing mortality rates when abundance is lower [6].

The mechanism underlying the cycles has important management implications. If depensatory fishing mortality is responsible for the cycles, adjustments in fishing rates might 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, depending on the specific mechanism(s) at play it may be more difficult to obtain greater yields from the ‘off’ years; it may be necessary to implement more aggressive approaches, such as predator removals. Since all management approaches involve costs (foregone catch, cost of predator removals, etc.), taking an ‘incorrect’ management approach would not only leave the problem unresolved, but would be costly as well.

Previous work on the implications of this biological uncertainty for the fishery has focused on total physical yield that can be, or could have been, obtained from the fishery over the four-year cycle. This focus is consistent with federal Canadian fisheries policy which, explicitly or otherwise, 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 [7]. Some authors have incorporated discounting [8], but most have not, even when they consider monetary values [9, 10]. 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 [11]. 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 Walters, Martell and Hilborn [9], 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 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.

THE MODEL

Stock dynamics

Consider a cohort of mature sockeye salmon, numbering Q_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_t , which is some proportion u_t of the run, leaving an escapement S_t :

$$Y_t = u_t Q_t \quad (1)$$

$$S_t = Q_t - Y_t \quad (2)$$

This escapement of fish then makes its way up the river to spawn, generating some number R_t of recruits that return four (or occasionally five) years later:

$$R_t = f(S_t, \theta) \quad (3)$$

where θ is a vector of parameters and f is one of the two 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

$t + 5$, at which time they become the run (Q) of fish entering the fishing grounds. We assume that 95% of fish return in their fourth year, with the remaining 5% returning in their fifth year:

$$Q_t = 0.95R_{t-4} + 0.05R_{t-5} \quad (4)$$

Recruitment

To model the hypothesized mechanisms underlying cycles in sockeye abundance, we use two of the three stock-recruitment models used by Walters et al. [9]. The first is the classic Ricker [12] model:

$$R_t = S_t \alpha e^{b_0 S_t} \quad (5)$$

where $b_0 \leq 0$. In the current context it is best to transform the model slightly into a linear form:

$$\ln(R_t/S_t) = a + b_0 S_t + w_t \quad (6)$$

where $\ln(R_t/S_t)$ is a productivity index, $a = \ln(\alpha)$ is the maximum productivity at low spawning stock sizes, b_0 is the density-dependence parameter that determines how quickly productivity decreases with increasing escapement, and w_t is a recruitment ‘anomaly,’ i.e., the deviation from the deterministic relationship. The Ricker model corresponds to the compensatory fishing hypothesis, i.e., that cycles in sockeye abundance are purely an artifact of historical accident and fishing pressure; there is nothing inherent in the biology that causes cyclic behaviour.

The second stock-recruitment model is a variation on the Ricker model which allows for shifts in the a parameter due to interactions with previous spawning stocks:

$$\ln(R_t/S_t) = (a + b_1 S_{t-1} + b_2 S_{t-2} + b_3 S_{t-3}) + b_0 S_t + w_t \quad (7)$$

where all $b_i \leq 0$. Walters et al. [9] referred to this as the “Larkin-a” model; we will refer to it here as the Larkin model. The Larkin model corresponds to the delayed density dependence hypothesis.

In the case of Fraser River sockeye, there are nine major stock complexes that contribute to the fishery. The biological dynamics of each of these complexes are modelled separately, i.e., we estimate the stock-recruitment parameters separately for each complex.

Economics of the fishery

The commercial British Columbia salmon fishery is conducted by three types of vessel: gillnetters, seiners and trollers. The first two are small boats typically operated by a captain and, in some cases, one or two deckhands; seiners are larger boats with four to five deckhands [13].

For their analysis, Walters et al. [9] treated the exploitation rate (proportion of the run) as the control variable and calculated the catch that would have resulted from different management approaches to setting exploitation rates. In this paper we treated the fishing effort (in vessel-days) by each fleet as our control variables and examined the profit generated by the different management approaches.

We must also account for the substantial spatio-temporal overlap among the nine stock complexes, i.e., fish from some stock complexes are on the fishing grounds at the same time, so it is not practical to exert the optimal amount of fishing effort on one stock complex without affecting the other stock complexes that are running at the same time. Following Walters et al. [9] we assume that exploitation rates are set by managers for three different periods (indexed τ) during the year (called early, summer and late), and these rates apply to all stock complexes (indexed s) running during period τ .

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

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

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).

As a production function, we use a modification of the Cobb-Douglas form which allows catchability 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. Catchability for fleet f in year t is then

$$q_{f,t} = \rho_f e^{\phi_f t}$$

where ρ_f and ϕ_f are parameters specific to a given fleet. The production function is then

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

where the exponents β_f and γ_f are fleet-specific parameters. We assume that all $\beta_f = 1$, i.e., that there are constant returns to effort, and move effort to the LHS to get catch per unit effort (CPUE). When we take logarithms and expand $q_{f,t}$ we obtain

$$\ln(Y_{f,\tau,t}/E_{f,\tau,t}) = \ln(\rho_f) + \phi_f t + \gamma_f \ln(Q_{\tau,t}) \quad (8)$$

In the simulations, catch is calculated as the product of CPUE and effort.

Finally, we wish to determine the net present value (NPV) of past profits to reflect the returns to those profits (at the prevailing discount/interest rate δ) 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 profit from 1952-1998 from the perspective of a social planner looking back in time from 1998 is

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

DATA AND PARAMETER ESTIMATION

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

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. to [9].
Variable cost of fishing effort ($c_{f,t}$)		
<i>Labour</i>	1950-1984	[14]
	1986-2002	[15]
<i>Non-labour</i>	1953-1954	[16]
	1968	[17]
	1976-1995	[18]
Price ($p_{f,t}$)		
<i>By Species and Gear</i>	1976	[19]
<i>(for calculation of troll premium)</i>	1986-1990	[13]
	1996-2005	[20]
<i>Overall by Species</i>	1952-1995	[21]
	1996-2002	[20]
Production parameters (ρ_f , ϕ_f , γ_f)	1952-1995	[21]
Consumer price index	1948-2002	[22]

Biological parameters

For each of the hypothesized recruitment functions (Eq. 6 and 7), we estimated the parameters a and b_i for each of the nine major stock complexes in the Fraser River using data from 1948-2002. We used ordinary least squares to estimate the Ricker model, and a numerical search routine to estimate the Larkin model by minimizing $\sum_t w_t^2$, subject to the constraint $b_i \leq 0$. We extracted recruitment anomalies w_t as the difference between the observed and predicted $\ln(R/S)$ values for each recruitment model. These parameters provided the biological basis for our simulations.

Management parameters

The two key management parameters are u_{MSY} and S_{MSY} , the harvest rate and escapement, respectively, that produce the maximum sustainable yield. In the case of the Ricker model these are functions of a and b_0 [23], while in the Larkin model they are a more complicated function of a and b_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 in a deterministic system every year during the appropriate period τ , would yield the maximum total sustainable yield over the long term from the set of stock complexes that run 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 overlapping stock complexes in a similar way.

Economic parameters

Variable cost ($c_{f,t}$)

Since we examined the fishery from the perspective of a social planner 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.¹

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. We used several past studies of costs in this fishery over the study period [16, 18, 24] to estimate non-labour variable cost per vessel-day in 1953-54, 1968 and 1976-95 for each fleet.

The sum of labour and non-labour variable costs provided our estimate of total variable cost per vessel-day ($c_{f,t}$). Given the clear pattern in this time series of costs, we assumed that costs had increased exponentially over the entire study period, and fit an exponential curve to the raw data. For our simulations we used the raw data in years in which we had them, but for other years we interpolated by using the predicted values from the regression for our simulations.

Price ($p_{f,t}$)

Most statistics report price by gear or by species, but rarely by gear and species. Such a distinction is important because troll-caught sockeye often command a higher price. 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.

Production function parameters (ρ_f, ϕ_f, γ_f)

We used sockeye catch, fishing effort data, and run-size data to estimate the parameters of Eq. 8 using ordinary least squares. Our effort data are aggregated for the entire salmon fishery, rather than on a per-species basis. To estimate the effort that was directed at sockeye, we allocated the total fishery effort using the proportion of total salmon landed weight that was sockeye.

MANAGEMENT SIMULATIONS

We started with the assumption that either the Ricker or the Larkin model, with the parameters estimated above, represents the ‘true’ model underlying the biological system. For each assumed model, we then simulated four scenarios:

1. the historical time series, for comparison with the simulated outcomes below;
2. a fixed harvest rate policy, where the harvest is $Y_{\tau,t} = u_{MSY,\tau} Q_{\tau,t}$;
3. a fixed escapement policy, where harvest is $Y_{\tau,t} = Q_{\tau,t} - S_{MSY,\tau}$ and $S_{MSY,\tau}$ is the target escapement set by managers during period τ ; and
4. an ‘omniscient’ manager, where it is assumed that the manager knows in 1951 the value of all parameters for the entire 47-year period, and chooses a series of annual effort levels to maximize either profit (Eq. 9) or catch summed over all years.

We initialized each simulation with historical data from the first four 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 fixed 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 τ was allocated among fleets so that each fleet had a proportion of the total harvest equal to the one it obtained historically.

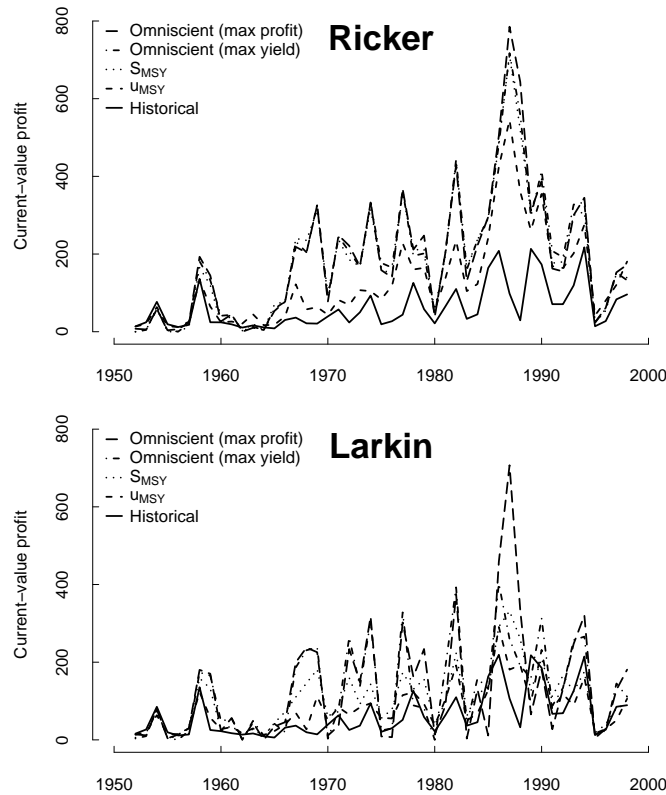


Figure 1: Time series of current-value profit (Π_t) from simulations where the Ricker (top panel) or Larkin (bottom panel) model was assumed to be the true biological model. Profit is in millions of (year 2000) Canadian dollars. The profit-maximizing omniscient simulation shown uses $\delta = 0.07$.

RESULTS

Profit obtained in different scenarios

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 sacrificing some profit in the early years (until about 1957) to allow the stocks to rebuild (Figure 1). Profits are then, on average, somewhat greater in the late 1950s and early 1960s, and much greater from the mid-1960s onward. This outcome is not very sensitive to the discount rate applied – in simulations using the Ricker model with discount rates higher than the default (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 resulted in very little rebuilding of stocks and yields 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 four 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 management approach and biological model (Figure 2). While there is great variation around the mean from year to year, this is 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, twice as much profit (relative to the historical reality) 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 each season, one during each period τ). Furthermore, three times as much profit could have been obtained if a fixed 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’

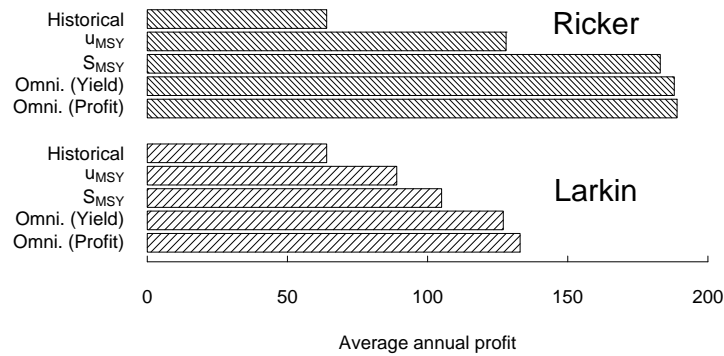


Figure 2: Mean annual current-value profit over the entire study period in different simulations when the Ricker (top) or Larkin (bottom) model was assumed to be the true model.

policy, i.e., knowing a , b_0 and all w_t parameters in advance would only yield 2-3% more profit than the S_{MSY} policy.

If the Larkin model applies, with the parameters that we estimated, the most obvious pattern is that the fishery has substantially less capacity to generate profit – depending on the management approach taken, profit under the Larkin model is 57-70% of that obtained with the same management approach under the Ricker model. This should not be surprising, since interactions between cycle lines are defined to be detrimental to productivity; in mathematical terms, the b_1 through b_3 parameters were constrained to be negative. If the Larkin model is the true model and a u_{MSY} policy had been applied, 39% more profit could have been obtained than the historical case, while 65% more profit could have been obtained with a S_{MSY} policy. Unlike with the Ricker model, though, the omniscient yield- and profit-maximizing policies do substantially better than the S_{MSY} approach, yielding 21% and 27% more profit, respectively.

Cost of management failure

Another question that might be asked is, what are the consequences of making an incorrect assumption about the underlying biology? For example, if the Ricker model is the true model but we choose the u_{MSY} 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 u_{MSY} or a S_{MSY} approach (Figure 3). If we assume that the Larkin model is the true model, we can be much more certain about the outcome of either management approach, i.e., there is a relatively small difference (11-17%) between the outcomes if we make the correct or the incorrect assumption about the underlying biology. In contrast, if we assume the Ricker model but the Larkin model is the true model, we lose 37% or 51% of total profit if we employ a u_{MSY} or S_{MSY} policy, respectively.

DISCUSSION

The results here 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 profit obtained in the fishery; the exact amount of the increase would have depended on the management target 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 [23], 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., the 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

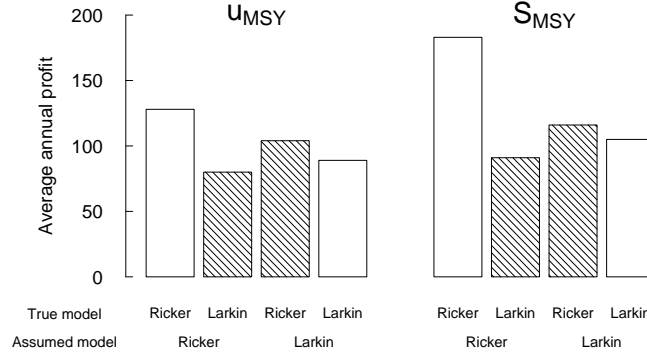


Figure 3: Average annual current-value profit obtained in simulations when the correct (open bars) or incorrect (hatched bars) policy target is used in applying a fixed harvest rate (left) or target escapement (right) policy. The “Assumed model” labels on the bottom show the model that is assumed to calculate the management parameters (u_{MSY} or S_{MSY}), while the “True model” labels just above show the model that is used in the simulation. For example, the left-most open bar shows the profit if the Ricker model is used to calculate u_{MSY} values, and these values are used in a simulation of the fishery that actually uses the Ricker model. 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.

Table 2: Estimated values of $u_{MSY,\tau}$ with few data. The $\ln(\overline{R/S})$ estimates are from taking the mean of $\ln(R/S)$ over several years, while the “intercept” estimates use the intercept of Eq. 6. Each estimate uses only the first few years of the stock-recruitment time series.

Years of data	Early (true = 0.609)		Mid (true = 0.711)		Late (true = 0.672)	
	$\ln(\overline{R/S})$	intercept	$\ln(\overline{R/S})$	intercept	$\ln(\overline{R/S})$	intercept
1948-51	0.545	0.649	0.701	0.795	0.628	0.640
1948-53	0.528	0.607	0.699	0.779	0.604	0.684
1948-55	0.528	0.655	0.680	0.789	0.616	0.673
1948-57	0.591	0.654	0.702	0.771	0.644	0.658

$\ln(R/S)$ or by estimating Eq. 6 and using the resulting a estimate. We then calculated each $u_{MSY,s}$ iteratively using $a_s = u_{MSY,s} - \ln(1 - u_{MSY,s})$ [23], and took $u_{MSY,\tau}$ as the average of $u_{MSY,s}$ weighted by the size of the stock. Mathematically,

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

where s only includes stocks running during period τ , and t includes only the years used to estimate a . As the results show (Table 2), we could have made a reasonable estimate of each $u_{MSY,\tau}$ even with only four 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_t , would have had almost no value (\$5-7 million CAD annually) if the Ricker model applied, but somewhat more (\$22-28 million CAD annually) if the Larkin model applied. The value of this information 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” [25]. Further research on sockeye fisheries management might be better directed at trying to reduce this implementation error.

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 (Figure 3) are one aspect of this. 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 [26] 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. A fixed 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 an expected outcome for each management approach.

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ENDNOTES

¹Greater detail on the data sources and estimation procedures for variable cost calculations are provided in a technical appendix, available for download at http://www.geocities.com/dale_marsden/sockeye/sockeye.html.