Optimal harvesting considering biological and economic objectives

Brian G. Bue, Ray Hilborn, and Michael R. Link

Abstract: Most examinations of optimal harvesting policies have considered only biological objectives, yet it is increasingly recognized that a primary objective of many fisheries is economic profitability. Using Bayesian risk analysis, we compare policies that combine fish harvesting, the revenue brought in by fish sales, the cost of harvesting and processing, and processing and fishing capacity to find policies that maximize biological yield and economic profit to the processing and harvesting sectors for a major Pacific salmon (*Oncorhynchus* spp.) fishery in Bristol Bay, Alaska. We show that although average catch is maximized by a fixed escapement policy, total revenue is maximized by a policy that includes some harvesting at stock sizes below that required to produce maximum average catch. In addition, there is a wide range of policies that provide 90% of the maximum for any of the biological and economic objectives considered. Economic profitability is enhanced by limitations on processing and harvesting capacity.

Résumé : La plupart des examens des politiques optimales de récolte ne tiennent compte que des objectifs biologiques, bien qu'il soit de plus en plus reconnu que l'un des buts principaux visés par de nombreuses pêches commerciales est la rentabilité économique. À l'aide d'une analyse bayésienne des risques, nous comparons des politiques qui combinent la récolte des poissons, les revenus générés par les ventes de poissons, les coûts de la récolte et de la transformation, ainsi que les capacités de pêche et de transformation, afin de trouver des politiques qui maximisent le rendement biologique et le profit économique aux secteurs de la pêche et de la transformation, dans le cas d'une importante pêche commerciale de saumons du Pacifique (*Oncorhynchus* spp.) dans la baie de Bristol, Alaska. Nous montrons qu'alors que la capture moyenne est maximisée par une politique d'échappement fixe, le revenu total est maximisé par une politique qui inclut certaines récoltes à des tailles de stocks qui sont inférieures à celles nécessaires pour produire des captures moyennes maximales. De plus, il existe une gamme étendue de politiques qui permettent d'atteindre 90 % du maximum de chacun des objectifs biologiques et économiques considérés. Des restrictions sur la capacité de pêche et de transformation augmentent la rentabilité économique.

[Traduit par la Rédaction]

Introduction

The theory of optimal harvesting suggests that maximization of biological yield is achieved by holding the spawning population at a constant level (Clark 1976). This population size is commonly referred to as the biomass that produces maximum sustainable yield (B_{MSY}), and the escapement goal and harvest policies that hold spawning stock constant are referred to as fixed escapement policies (Hilborn and Walters 1992). Among the few commercial fisheries that are theoretically managed for fixed escapement are most of Alaska's terminal Pacific salmon (*Oncorhynchus* spp.) fisheries. For these fisheries, the annual harvest is manipulated by in-season regulation in an attempt to hold the spawning stock size within a range close to the calculated B_{MSY} (Minard and Meacham 1987; Fair 2003).

Alaskan salmon fisheries have been biologically successful, with record catches occurring in many areas since the late 1970s (Eggers 1992). It is not clear how much of this success can be attributed to either the escapement policies or favorable environmental conditions (Hilborn 2006). However, the economic success of the fisheries in the 1980s and 1990s has evaporated as salmon prices have declined dramatically because of increasing competition with farmed salmon from Chile and wild salmon from Russia (Asche et al. 1999; Hilborn 2006; Knapp et al. 2007). Coincidental with the decline in the price of salmon, the value of fishing permits collapsed and fishermen are struggling to stay in business, with many unable to operate (Link et al. 2003; Schelle et al. 2004). The decline in value of fishing permits reflects the decline in expected future earnings in the fishery (Karpoff 1984, 1989; Huppert et al. 1996).

Although the average economic profit for drift gillnet vessels in Bristol Bay from 1982 to 1996 was between US$13 000 and US$47 000, the fishery now operates at a net loss (Schelle et al. 2004), with average profit negative for all

Received 22 January 2007. Accepted 1 October 2007. Published on the NRC Research Press Web site at cjfas.nrc.ca on 13 March 2008.
J19780

B.G. Bue.[1] Bue Consulting LLC, P.O. Box 641, Palmer, AK 99645, USA.
R. Hilborn. School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98195, USA.
M.R. Link. LGL Alaska Research Associates, Inc., 1101 East 76th Avenue, Suite B, Anchorage, AK 99518, USA.

[1]Corresponding author (e-mail: bbue@mtaonline.net).

 doi:10.1139/F08-009

years between 1997 and 2003 except 1999. Link et al. (2003) reported that in 2001, permit holders averaged US$4 000 in income after operating costs, but before debt service on permits and vessels. Given the large number of unused permits in other Alaskan salmon fisheries and the low market value of limited entry permits, the economic results in Bristol Bay are likely typical of most Alaskan salmon fisheries. Economic returns to fish processors have paralleled those of the fishermen.

The traditional assumption of Alaskan fisheries management has been that if the resource was managed to produce maximum sustained yield, the economics would take care of itself. In contrast, economists have long recognized that the economically optimal harvesting policy is not the same as the policy that maximizes sustainable biological yield (Gordon 1953; Scott 1955; Clark 1976). The Bristol Bay sockeye salmon (*Oncorhynchus nerka*) fishery contributes such a large volume of catch to the world market that it affects the worldwide price. Knapp (2004) has estimated (under specific assumptions about the price of farmed fish in Japan) that when the Bristol Bay catch is 10 million fish, the price would be US$1.43·kg^{-1} ex-vessel, and if the catch was 30 million fish, the price would be US$0.79·kg^{-1}. This has clear implications on the selection of a harvest policy. The basic logic of the fixed escapement policy is that if the expected production of one additional fish in the spawning stock produces one or more fish in the future, then that fish should be added to the spawning stock, whereas if the expected production of one additional fish in the spawning stock is less than one, then that fish should be harvested now. If the objective is to maximize the economic value of the catch, then the optimum number of fish in the escapement or catch will depend on the size of the return. When the salmon run is small and little catch is expected, the economic value of a fish in the catch is above average, and the expected number of fish produced by an additional spawner will need to be large enough to offset the differential in price between the present and future salmon returns. A priori, we would expect that maximization of revenue would suggest some harvesting at total salmon returns lower than the traditional optimum biological escapement.

The economic profitability of the harvesting sector depends on the size and efficiency of the fishing fleet. It has been estimated that the optimal number of drift net licenses for the Bristol Bay sockeye salmon fishery is about 800–1200 rather than the current 1858 (Schelle et al. 2004). A considerably smaller fishing fleet operating under the present vessel and gear restrictions would most likely be unable to harvest large catches. Charles (1983) has shown for marine fisheries that revenues are maximized by a combination of harvesting and investment strategies and that there is a maximum level of harvesting capacity. Similarly, there is presumably a maximum optimum processing capacity; the fixed costs in maintaining large processing plants that might only be fully utilized for a week every few years would far outweigh the profit from the additional fish processed.

We expect that maximization of revenue will suggest some harvesting at total salmon returns lower than the traditional optimum escapement and a maximum level of harvest constrained by the fixed costs of harvesting and processing. In this paper, we will present a methodology for evaluating a wide range of harvest policies taking into account biological and economic factors and illustrate the use of these methods for the sockeye salmon return to the Egegik River, Bristol Bay, Alaska.

Materials and methods

Model formulation

We examined a wide range of harvest policies to determine where both biological and economic objectives are optimized through a modeling process. The model was made up of three distinct components: (*i*) a salmon production submodel in which historic catch, escapement, and age data were combined to simulate the escapement to total salmon return relationship and evaluate the uncertainty in such relationships using Bayesian analysis; (*ii*) a harvest policy submodel in which a wide range of harvest policies was applied to each year's simulated salmon return to generate catches; and (*iii*) an economic submodel in which revenue and costs for both fishing and fish processing were combined with the simulated harvests to estimate net present value to the harvesting and processing sectors.

Salmon production submodel

A spawner–recruit relationship was used to drive the population dynamics of the modeled salmon returns. The relationship was estimated from historical catch and escapement data, which had been tabulated into brood tables (Hilborn and Walters 1992). Although several different models can be used, we present the formulation for the Beverton–Holt model:

$$(1) \qquad R_t = \frac{S_t}{\dfrac{1}{\alpha} + \dfrac{S_t}{\beta}} \exp(w_t)$$

where S_t and R_t are the spawning stock and subsequent salmon return for brood year t, respectively, and w_t is the process error in brood year t. Autocorrelation in the process error associated with the fit of the model to the historic data was accounted for by

$$(2) \qquad w_t = z w_{t-1} + \sigma_{w*} w_t^* \sqrt{1 - z^2}$$

where w_t^* is the white noise random error at brood year t with mean 0 and standard deviation 1, z is the autocorrelation term, and σ_{w*} is the standard deviation of the random process error component (Morris and Doak 2002). The value for w_t^* can be found by

$$(3) \qquad w_t^* = \frac{w_t - z w_{t-1}}{\sigma_{w*}\sqrt{1 - z^2}}$$

The likelihood for the Beverton–Holt spawner–recruit model that incorporates autocorrelation in the process error can be written as

$$(4) \qquad L[R \mid \alpha, \beta, \sigma_{w*}, z] = \prod_t \frac{1}{\sigma_{w*}\sqrt{2\pi}} \exp\left(\frac{-(w_t^*)^2}{2\sigma_{w*}^2}\right)$$

The above equations are sufficient to find the maximum likelihood estimates of the parameters. However, when evaluating the consequences of any harvest policy for Pacific salmon, particularly the interannual variability in catch or spawning stock, it is important to incorporate age at salmon return information rather than simply considering brood-year salmon returns. For this application, age structure was modeled using the Dirichlet distribution and the methods developed by Evans et al. (2000). The Dirichlet distribution is the multivariate form of the beta distribution, which is sometimes used to model the Bernoulli parameter defining the probability in a success–failure situation. This distribution generalizes the beta in that it can be used to model more than one "yes" or "no" parameter at once. Random numbers generated from both the beta and Dirichlet distributions lie between zero and unity, making them suitable for generation of proportions.

The form of the Dirichlet distribution is

$$(5)\qquad f(\theta|\alpha_1,\ldots,\alpha_K)=\frac{\Gamma(\alpha_1+\ldots+\alpha_K)\,\theta_1^{\alpha_1-1}\ldots\theta_K^{\alpha_K-1}}{\Gamma(\alpha_1)\ldots\Gamma(\alpha_K)}$$

where α_k are parameters of the Dirichlet distribution and θ_k is the proportion of age class k subject to the constraints θ_1, …, $\theta_k \geq 0$ and $\Sigma_{k=1}^{K}\theta_k = 1$. A Dirichlet distribution was fitted to m years of historical age-class data using maximum likelihood. The log likelihood for m years of observations is

$$(6)\qquad \ln[L(\alpha|\theta_m)]=\sum_{m=1}^{M}\left[\ln\Gamma(\alpha_0)-\sum_{k=1}^{K}\ln\Gamma(\alpha_k)+\sum_{k=1}^{K}(\alpha_k-1)\ln(\theta_{km})\right]$$

with

$$\alpha_0=\sum_{k=1}^{K}\alpha_k$$

A multivariate random vector was sampled from the fitted Dirichlet distribution for each brood year with the resulting vector defining the nature of the age class for that simulated brood-year return.

Harvest strategy submodel

A wide range of harvest policies including constant escapement, constant harvest rate, and constant catch can be simulated using a simple linear model in which catch is a linear function of total salmon return. Catch for this model is constrained to be less than the total salmon return and greater than or equal to zero (Hilborn and Walters 1992). For example, a constant harvest rate policy can be simulated by a linear function with intercept zero and slope equal to the harvest rate, a constant escapement policy can be simulated using a linear function with a slope of 1.0 and an intercept of negative the escapement goal, and a constant catch policy has a slope of zero and an intercept equal to the constant catch. We can further modify this submodel by capping the catch at a maximum. We call this type of policy a "floor–ceiling model" in which "floor" is the size of the salmon return at which harvesting begins, "harvest rate" is the slope of the line, and "ceiling" is the maximum harvest. Note that the "harvest rate" in this terminology is only the fraction of all salmon returns harvested if the "floor" is zero. It could more properly be called the "marginal harvest rate", i.e., the fraction of the salmon return that would be harvested. This harvest strategy model has the potential of identifying the combination of escapement goal, harvest rate, and catch ceiling that has the greatest potential of maximizing parameters such as yield or net present value. The model can be written as

$$(7)\qquad \hat{C}_y=\begin{cases}C_{\max} & \text{if } -E+\mu\hat{T}_y>C_{\max}\\ -E+u\,\hat{T}_y & \text{if } \hat{T}_y>E\\ 0 & \text{if } \hat{T}_y<E\end{cases}$$

where $\hat{T}_y$ is the estimated total salmon return in year y, $\hat{C}_y$ is the estimated catch for year y, $C_{\max}$ is the ceiling or maximum allowable catch, E is the escapement floor, and u is the marginal harvest rate subject to the constraint $0 \leq u \leq 1.0$. We can use this generalized harvest strategy to identify the combination of E, u, and $C_{\max}$ that maximizes a desired outcome (e.g., catch and economic profits).

Economic submodel

An economic submodel was developed to characterize how the economic value of the catch from a single fishery changes across harvest policies. Income to the processors and fishermen was modeled using the August Japanese wholesale and ex-vessel price for Bristol Bay sockeye salmon, whereas the cost of processing the catch and harvesting the fish was estimated using previously developed models for the Bristol Bay sockeye salmon fishery (Link et al. 2003). Combining the production, harvest, and economic models into a single simulation allows for the estimation of the long-term value of the catch or net present value (NPV) for a wide range of harvest policies.

August Japanese wholesale price for Bristol Bay sockeye salmon and the magnitude of the catch were used to estimate revenue to the fish processors. Knapp (2004) estimated ex-vessel price for Bristol Bay sockeye salmon using the volume of the Bristol Bay sockeye salmon harvest and the wholesale price of farmed Coho salmon (*Oncorhynchus kisutch*) in Japan. In addition, Knapp (2004) and Holzinger (2007) implied that the Japanese wholesale price for Bristol Bay sockeye salmon was directly related to the ex-vessel price. We assumed that the August wholesale and ex-vessel prices were linearly related and developed a relationship based on the findings of Knapp (2004) to calculate the August Japanese wholesale price for Bristol Bay sockeye salmon in 2003 dollars per kilogram that would be paid in year y of our simulation using

$$(8)\qquad P_{\text{whole},y}=\exp[4.82+(-0.35\ln B_y)+(0.96\ln P_{\text{coho},y})+\varepsilon_{\text{whole},y}]$$

where $P_{\text{whole},y}$ is the August Japanese wholesale price of Bristol Bay sockeye salmon, B_y is the biomass of the Bristol Bay sockeye salmon harvest in metric tons, $P_{\text{coho},y}$ is the wholesale price of farmed coho salmon in Japan, and $\varepsilon_{\text{whole},y}$ is the process error. The data came from Knapp (2004) for the years 1991–2003 and from G. Knapp (personal communication, 2007) for the years 2004–2006. Because we had no means of estimating $P_{\text{coho},y}$ for our simulations without de-

Table 1. Parameters used to simulate operating costs for shore-based and floating salmon processors in Bristol Bay, Alaska (Link et al. 2003).

	Processor type	
	Shore-based	Floating
Operating parameters		
Processor capacity (in no. of fish)	1 600 000	800 000
Product recovery rate	0.77	0.80
Fixed costs (facility overhead)	$1 900 000	$1 500 000
Variable costs for raw fish		
Cost for fish (ex-vessel price)[a]	$P_{\text{ex},y}$	$P_{\text{ex},y}$
Tendering cost	$0.37	$0.29
Fish tax	$0.04	$0.07
Variable costs for processing fish		
Cost purchased for labor	$0.44	$0.46
Cost purchased for packaging	$0.22	$0.11
Cost purchased for miscellaneous	$0.02	$0.02
Cost purchased for utilities (fuel, water, etc.)	$0.09	$0.18
Carrying cost	$0.02	
Freight cost	$0.09	
Total variable cost purchased[b]	$1.29 + $P_{\text{ex},y}$	$1.13 + $P_{\text{ex},y}$

Note: Costs (including taxes) are per kilogram in US dollars.
[a]From eq. 9.
[b]Total variable cost is the sum of the raw fish and processing variable costs.

veloping another model for worldwide farmed coho production, we assumed that $P_{\text{coho},y}$ would be the average price paid for the years 2000–2006 (US$4.25·kg^{-1} in 2003 dollars) for all years in the simulation. It was also assumed that the average weight of sockeye salmon was 2.68 kg for the conversion of numbers of fish obtained from the harvest policy model into biomass. Process error was simulated by drawing a random normal deviate with a mean of zero and a standard deviation of 0.124, calculated from the variability of the data. Revenue to the processors was then calculated by multiplying the harvest volume by the price.

Revenue to both drift and set gillnet fishermen was estimated using the ex-vessel price and the magnitude of the catch. Ex-vessel price in dollars per kilogram that would be paid in year y ($P_{\text{ex},y}$) was estimated using the historic relationship between August Japanese wholesale price and ex-vessel price for the years 1991–2006 (data from Knapp (2004) and G. Knapp, Institute of Social and Economic Research, University of Alaska, Anchorage, AK 99508, USA, personal communication, 2007):

$$(9) \qquad P_{\text{ex},y} = -0.19 + 0.34 P_{\text{whole},y} + \varepsilon_{\text{ex},y}$$

Process error ($\varepsilon_{\text{ex},y}$) was assumed to be normally distributed and was simulated by drawing a random normal deviate with a mean of zero and a standard deviation of 0.095 estimated from the data. Again, the average weight of sockeye salmon was assumed to be 2.68 kg and revenue to the fishermen was calculated by multiplying the harvest volume by the ex-vessel price.

The information used for determining the cost of processing and catching fish was obtained directly from appendix F of Link et al. (2003). For their analysis, Link et al. (2003) developed hypothetical processing plants, both shore-based and floating, using information gathered through interviews with plant managers and owners. The floating processor was designed to process crab and Pacific cod, as well as salmon. Because of this, we felt it inappropriate to charge all of the fixed or overhead cost for floating processors to the salmon fishery and subsequently made the assumption that half of the total annual overhead cost would be charged to the Bristol Bay salmon fishery. All other costs for processing salmon described by Link et al. (2003) were included in our model (Table 1).

The operating parameters for the drift and set gillnet fleets were estimated by Link et al. (2003) using information acquired by the State of Alaska Commercial Fisheries Entry Commission for a study designed to determine the optimum number of permits holders for Bristol Bay (Schelle et al. 2004). This information was divided into three groups based on residency: (*i*) residents of the immediate Bristol Bay area, (*ii*) other Alaskan residents, and (*iii*) non-Alaskan residents. Each residency group was further divided into three subgroups based on revenue rankings. We simplified our model by averaging the costs for each revenue group within a residency group, while maintaining the residency stratification (Table 2). For the purpose of simplicity, we elected to use the average residencies by gear group presented by Link et al. (2003). Uncertainty about the cost estimates for both processing and catching fish was not estimated by Link et al. (2003) and consequently was not incorporated into our model.

Gross revenue to the fish processors in year y ($I_{\text{proc},y}$) is a function of the magnitude of the catch (C_y), the August Japanese wholesale price ($P_{\text{whole},y}$), and the recovery rate or percentage of the catch converted to marketable product (r):

$$(10) \qquad I_{\text{proc},y} = C_y P_{\text{whole},y}\, r$$

Table 2. Parameters used to simulate costs for each permit fished in the drift and set gillnet fisheries (Link et al. 2003).

	Drift gillnet			Set gillnet		
	Local	Other Alaskan	Non-Alaskan	Local	Other Alaskan	Non-Alaskan
Crew parameters						
Average number of paid crew	1.4	1.7	1.7	2.0	2.0	2.0
Average crew share (prop of gross)	0.14	0.13	0.13	0.05	0.05	0.05
Fixed costs						
Fuel, oil, lubricants	$1 451	$1 192	$1 325	$346	$328	$291
Maintenance	$2 360	$1 944	$2 008	$838	$824	$796
Nets	$1 474	$1 218	$1 205	$573	$563	$545
Miscellaneous gear and supplies	$600	$634	$586	$1 092	$1 074	$1 038
Administrative services	$408	$537	$734	$179	$170	$151
Transportation	$1 054	$1 423	$2 296	$0	$501	$1 000
Food	$1 383	$1 009	$1 259	$626	$621	$613
Insurance	$1 608	$1 643	$1 802	$175	$174	$171
Moorage, gear storage, boat haulout	$652	$1 478	$1 477	$165	$160	$150
Property tax	$369	$568	$515			
Vessel license fees	$48	$47	$48	$100	$100	$100
Permit renewal fees	$188	$202	$572	$312	$312	$312
Total fixed cost[a]	$11 595	$11 895	$13 829	$4 406	$4 827	$5 167
Variable costs						
Total crew share (proportion of gross)	0.196	0.221	0.221	0.100	0.100	0.100
Raw fish tax (proportion of gross)	0.020	0.029	0.030	0.050	0.050	0.050
Total variable costs (proportion of gross)[b]	0.216	0.250	0.251	0.150	0.150	0.150

Note: Costs are in US dollars.
[a]Total fixed cost is the sum of all fixed costs.
[b]Total variable cost is expressed as the proportion of gross revenue and is the sum of the proportions for the variable costs.

Total cost to process the catch for a year ($H_{\text{proc},y}$) is a function of the magnitude of the catch and the variable ($V_{\text{proc},y}$) and fixed (F_{proc}) costs of processing, which differ between shore-based ($V_{\text{shore},y}$, F_{shore}) and floating ($V_{\text{float},y}$, F_{float}) processors. Variable cost for processing the catch for year y was estimated by

$$(11)\qquad V_{\text{proc},y} = V_{\text{shore},y}\, p_s + V_{\text{float},y}\,(1 - p_{\text{s}})$$

where p_{s} is the proportion of the catch processed by shore-based plants. Fixed costs were estimated by

$$(12)\qquad F_{\text{proc}} = \frac{G_{\text{tot}}\, p_{\text{s}}}{G_{\text{shore}}}\, F_{\text{shore}} + \frac{G_{\text{tot}}(1 - p_{\text{s}})}{G_{\text{float}}}\, F_{\text{float}}$$

where G_{tot} is the total processing capacity and G_{shore} and G_{float} are the capacities of the modeled shore-based and floating processors, respectively. The total cost to process the catch for year y was then

$$(13)\qquad H_{\text{proc},y} = V_{\text{proc},y}\, B_y + F_{\text{proc}}$$

Net present value to the fish processors (NPV_{proc}) for a time period n years in length is

$$(15)\qquad \text{NPV}_{\text{proc}} = \sum_{y=1}^{n} \frac{I_{\text{proc},y} - H_{\text{proc},y}}{(1 + d)^{y}}$$

where d is the discount rate.

The calculation of net present value to the drift ($\text{NPV}_{\text{drift}}$) and set ($\text{NPV}_{\text{set}}$) gillnet fishermen was similar to the calculations for the fish processors. The differences were (*i*) the use of ex-vessel price in the place of August Japanese wholesale price in the calculation of gross revenue, (*ii*) the determination of both variable and fixed costs using the proportions of local residents, other Alaskan residents, and non-Alaskans rather than the proportion of catch processed by shore-based operations, (*iii*) the inclusion of an average annual capacity estimate for each drift and set gillnet permit in place of processing capacity, and (*iv*) an accounting for the allocation of catch between drift and set gillnet fisheries.

Application to the sockeye salmon fishery of the Egegik District, Bristol Bay, Alaska

Catch and escapement data for sockeye salmon returning to the Egegik District, Bristol Bay, Alaska, were used to illustrate this model. Escapement data were collected annually using counting towers, catch numbers were obtained from fish ticket data, and age data were collected from both the catch and escapement (West 2003).

Data from the 1974 through 2000 brood years were used to estimate the Beverton–Holt spawner–recruit model (eq. 1) using both the more traditional maximum likelihood methodology and a Bayesian model that incorporated the Metropolis algorithm for Markov chain Monte Carlo simulation (MCMC; Gelman et al. 1995; Carlin and Louis 1996). For the MCMC simulation, 500 samples of the model parameters were collected from a 205 000 sample chain. The first 155 000 samples were discarded to allow the model to stabilize and every 100th sample after the first 155 000 was collected, producing 500 MCMC draws of the model param-

Table 3. Priors used to initialize and constrain the Markov chain Monte Carlo used to estimate the Beverton–Holt spawner–recruit model for sockeye salmon, Egegik River, Bristol Bay, Alaska.

Parameter	Prior	Minimum; maximum	Prior σ
α	4.0	0.1; 20.0	10.0
β[a]	30 000	2000; 50 000	50 000
σ	1.0	0.0; 2.0	10.0
z	0.20	0.05; 0.90	10.0

[a]β is in terms of thousands of fish.

eters. The priors used (Table 3) reflected our general thoughts for sockeye salmon production in the Egegik system, as well as Bristol Bay as a whole. The standard deviation for the priors was selected to reflect our uncertainty in the model parameters and to allow the MCMC model to search a wide range of possible parameter values. Minimum and maximum limits were used to keep the parameters within a reasonable range.

The Dirichlet distribution fit to the observed age composition for the Egegik District (Table 4) was used to randomly generate 500 age distributions. Variation in age composition for the simulated salmon returns was modeled by randomly drawing with replacement from the generated age compositions and applying it to a salmon return.

Average yield or catch for a given harvest policy ($\overline{C}_i$) was estimated as the average for a 100-year simulation (k) of the population exposed to the harvest policy for each of the MCMC draws (j),

$$(16)\qquad \overline{C}_i = \frac{\sum_{j=1}^{500}\sum_{k=1}^{100} C^*_{ijk}}{50\ 000}$$

Fourteen percent of the catch for each simulated year was allocated to the set gillnet fishermen, with the remaining 84% going to the drift gillnet fishermen. This allocation is consistent with the present management plan for the Egegik District.

The approximate size of the catch of the other Bristol Bay Districts is required to obtain reasonable estimates of the wholesale and ex-vessel price (eqs. 8 and 9). Our revenue models were constructed using metric tons of sockeye salmon sold from all of Bristol Bay, and the effect of catches from other districts will have a large effect on the expected price for the Egegik catch. We assumed that the catch of the other Districts would remain at approximately the previous 20-year average (16 million fish) and added the simulated Egegik catch for the estimation of revenue to the processors and fishermen. The biomass of the total Bristol Bay catch used for the estimation of salmon prices for each simulated catch was then

$$(17)\qquad B_y = (C_y + 16\ 000\ 000) \times 2.68$$

in which the average weight of Bristol Bay sockeye salmon is assumed to be 2.68 kg.

It was assumed that 75% of the catch for each simulated year would be processed by shore-based processors and that the residency of the fishermen would be the same as that reported in Link et al. (2003). For drift gillnet fishermen, the proportion of local residents was 0.25, other Alaskan residents, 0.25, and non-Alaskan residents, 0.50. For set gillnet fishermen, the proportion of local residents was 0.43, other Alaskan residents, 0.31, and non-Alaskan residents, 0.26.

Table 4. Statistics reflecting the fit of the Dirichlet distribution to the age composition data for sockeye salmon, Egegik River, Bristol Bay, Alaska.

	Age classes			
	1.2	1.3	2.2	2.3
Observed mean	0.078	0.147	0.454	0.295
Theoretical mean	0.099	0.147	0.444	0.310
Observed variance	0.0052	0.0156	0.0306	0.0129
Theoretical variance	0.0089	0.0125	0.0246	0.0214

Net present value for a given harvest policy by processor and fisherman type (i) was estimated by calculating NPV for each 100-year simulation (k) and then averaging across the MCMC draws (j):

$$(18)\qquad \mathrm{NPV}_i = \frac{1}{500}\sum_{j=1}^{500}\sum_{k=1}^{100}\frac{(I_{ijk} - H_{ijk})}{(1+d)^k}$$

where the discount rate (d) was 0.07. Although a formal economic analysis would have examined a wide range of discount rates, we elected to simplify our analysis by examining just one, leaving the more indepth analysis to future researchers. The United States Office of Management and Budget (Circular No. A-94) recommends a discount rate of 0.07 as it approximates the marginal pretax rate of return on an average investment in the private sector in recent years. A 100-year simulation allowed the biological models to approach equilibrium while capturing the vast majority of the net present value.

Results

The Beverton–Holt model was fit to the Egegik River spawner–recruit data using both the traditional maximum likelihood method and a Bayesian model (Fig. 1*a*). The estimated average yield for the Bayesian model was greater for any level of escapement than the maximum likelihood model and suggested that the highest average yields would occur at higher levels of escapement (Fig. 1*b*). The high expected yields obtained from the Bayesian model are due to the uncertainty in the spawner–recruit data set. The data are reasonably consistent with the hypothesis of no density dependence (Fig. 1*a*), and only our maximum prior for β (50 million fish; Table 3) keeps the Bayesian model from including significant weight for this possibility. The maximum likelihood method did not fully account for uncertainty in the data and suggested more evidence for density dependence. A lack of density dependence implies much higher potential yields at all spawning stock sizes.

Evaluation of harvest policies for optimum biological yield

One important model output was the estimation of the range of harvest policies that produce large, sustained catches. Although the maximum average yield for any harvest control

Fig. 1. (*a*) The fit of the Beverton–Holt escapement–recruit curve and (*b*) a comparison of the resulting yield curves using a traditional maximum likelihood fit (broken line) and a Bayesian model (solid line) for sockeye salmon (*Oncorhynchus nerka*), Egegik River, Bristol Bay, Alaska.

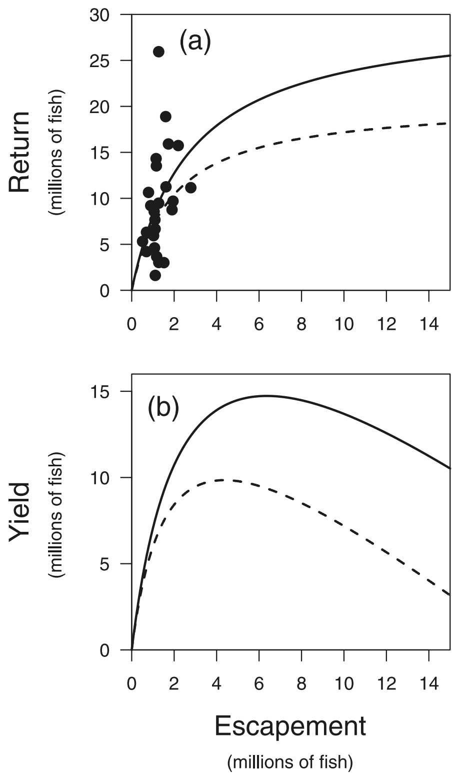
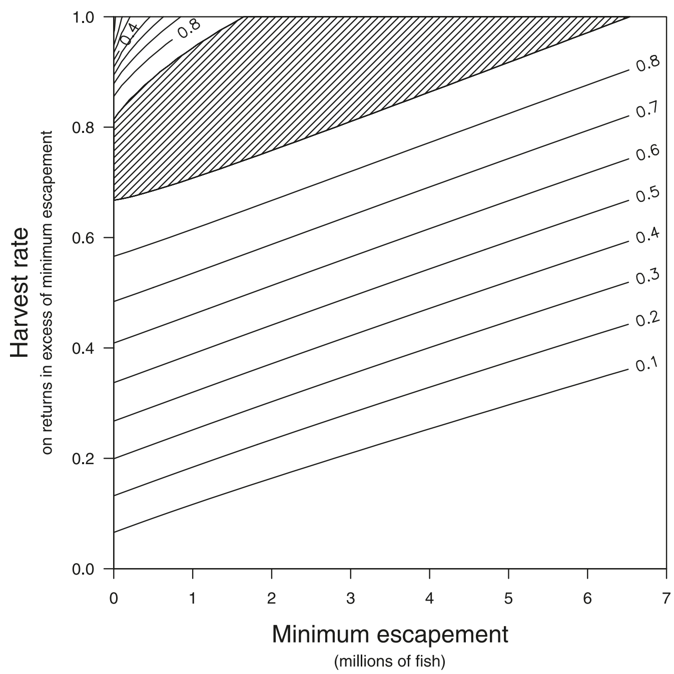


Fig. 2. Estimated proportion of the maximum average biological yield obtained from a wide range of harvest policies for sockeye salmon (*Oncorhynchus nerka*) returning to the Egegik River, Bristol Bay, Alaska. Hatched region represents 90% and greater of the maximum biological yield.



rule examined was just over 12.1 million fish, we found that large sustained catches in excess of 11.0 million fish could be expected for a wide range of control rules.

Biological escapement goals in Alaska are often expressed as the range of escapements most likely to produce a catch that is 90% or greater of the maximum sustained yield or the maximum average catch. In Bristol Bay, this goal is generally obtained using a fixed escapement rule, which is represented in our control rule by setting $u = 1$ (eq. 7). Another commonly used harvest policy is the management for a fixed exploitation rate, which can be viewed as a fixed harvest rate without a minimum escapement goal. Our simulation results indicate that a fixed escapement goal policy with a range of 1.6 to 6.6 million fish or a fixed harvest rate policy with exploitation rates of 0.67 to 0.82 will produce, on average, catches within 90% or greater of the maximum sustained yield (Fig. 2). In addition, there is a wide range of other harvest policies that will produce average yields within 90% of the maximum.

Evaluation of harvest policies for optimum economic yield

We calculated the maximum net present value for the processing sector and the drift and set gillnet fleets by fixing the capacity of those segments of the industry and then searching for the harvest control rule that maximizes the net present value (Fig. 3). For all industry components examined, there is a capacity that maximizes net present value, roughly 10 million fish for processors, 12 million fish for drift gillnetters, and 2.1 million fish for set gillnetters. Capacity is directly related to the size of the processing plant or the magnitude of the individual fishing operation and ultimately reflects the level of fixed costs required to process or harvest fish. In general, processors and fishermen are undercapitalized and unable to catch or process the available catch for the ascending or left side of the curve, while they are overcapitalized and do not make efficient use of their investment in capacity for the right side or descending limb. The number of processors or the number of fishermen that optimize NPV can be estimated by finding the capacity for which NPV is maximized and dividing it by the average processor size or average drift or set gillnet capacity.

We explored a range of minimum escapements and harvest rates along with optimum capacity of the processors and fishing fleets for economic yield to see how economic performance varied with the control rule. As with the biological yield analysis, we found a wide range of harvest policies likely to produce high, sustained economic returns (Fig. 4).

Comparison of harvest policies for optimizing biological and economic yield

A comparison of the harvest policies that optimized biological and economic yield was performed by combining the results of the biological and economic evaluations and visually comparing them (Fig. 5). Net present value was optimized for harvest policies that could be considered more aggressive than those that optimized biological yield. Portions of the range of minimum escapements that optimized NPV were lower than those that optimized biological yield. Likewise, the range of harvest rates that optimized NPV was wider and completely encompassed the range that optimized biological yield.

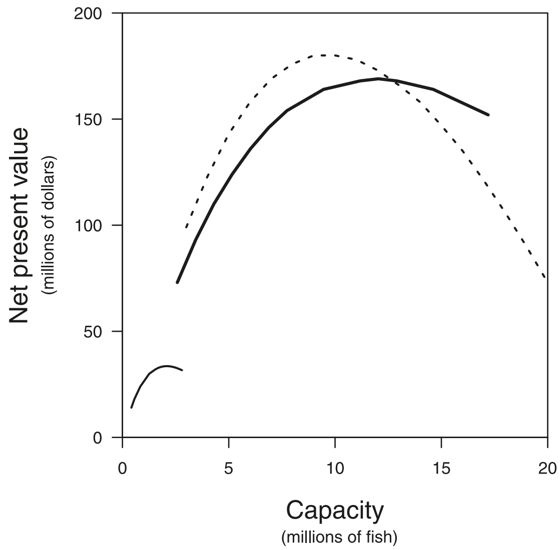


Fig. 3. Estimated relationship between net present value and maximum capacity for the processors (broken line) and the drift (thick solid line) and set (thin solid line) gillnet fleets, Egegik River, Bristol Bay, Alaska.

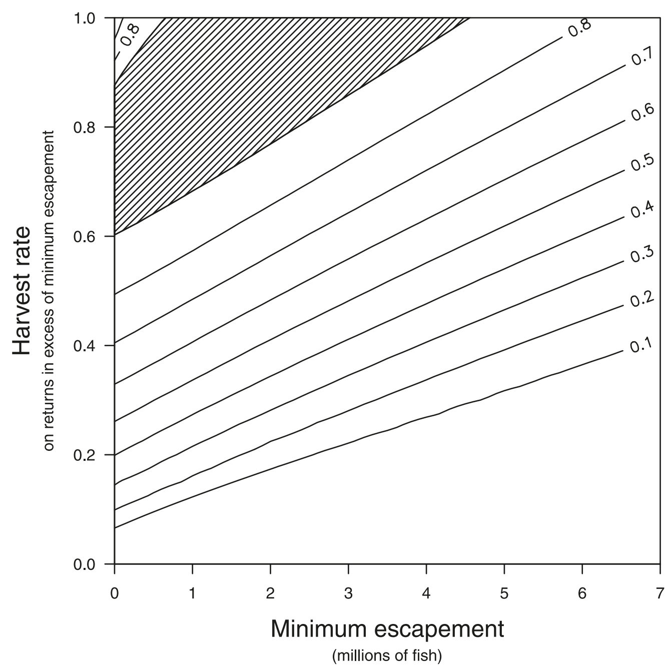


Fig. 4. Estimated proportion of the maximum average net present value for the drift gillnet fleet obtained from a wide range of harvest policies for sockeye salmon (*Oncorhynchus nerka*) returning to the Egegik River, Bristol Bay, Alaska. Hatched region represents 90% and greater of the maximum net present value.

Discussion

Our method of computing the escapement goal range that maximizes biological yield (also known as the biological escapement goal or BEG) adds a number of factors that have not been considered in past Bristol Bay BEG analyses, but it does not provide a qualitatively different picture of optimum biological management. In general, the range of escapements that would emerge as the formal escapement range under the 90% of MSY rule would be broader and, in particular, go to higher values of escapement than the traditional Beverton–Holt fitting. The broader range is partially due to considering parameter uncertainty in the Bayesian analysis. For these methods, large escapements tend to produce larger than average salmon returns because of the assumption of a lognormal error structure. If you have a large escapement and unusually good recruits per spawner, then you will get a very large salmon return, which greatly affects the overall average.

Consideration of salmon price, the cost of harvesting and processing fish, and processing and harvesting capacity provides a very different view of "optimal" management. The most striking effect was the importance of capping capacity; it simply does not pay to have a large fishing fleet or processing capacity that is only used every few years. This has been recognized by the Commercial Fisheries Entry Commission in its recommendations for a much smaller fleet, and the processing industry has certainly reduced its capacity in recent years. It would seem appropriate for the official harvesting policy to recognize that the economic viability of the industry may be enhanced if there was a maximum catch limit for the Bay. The August Japanese wholesale and ex-vessel price relationships are sensitive to changes in the worldwide demand for wild Bristol Bay sockeye salmon. Accurate estimates of these price relationships are critical for determining of the optimal management policy and capacity cap to maximize future economic benefits.

Capping catch implies that in years of large salmon returns, there will be some large escapements to individual river systems. Although the Kvichak River has had escapements in excess of 20 million fish, there are concerns that an escapement of 3–10 million fish in any of the other Bristol Bay River systems might have an impact on future spawning success and juvenile fish growth. Before formally adopting harvest strategies that incorporate a maximum catch component, a biological evaluation that examines both the risks of large escapements on future salmon production and the benefits of large escapements to a wide range of other ecosystem components such as nutrient inputs, primary production, resident freshwater fish species, and terrestrial animals should be considered (Cederholm et al. 1999; Hilderbrand et al. 1999; Schindler et al. 2005). The recent large escapements in the Alagnak River and Wood River systems of Bristol Bay will provide useful information for this evaluation (Schindler et al. 2006; Quinn et al. 2007).

The impact of volume on price appears to primarily affect the harvesting strategy at low run sizes, and our analysis suggests that the bottom end of the escapement range should be a "soft landing" rather than a "hard floor". When salmon returns are low and the price is high, it is economically optimal to allow some harvesting, even at low stock sizes. It is important to note that this applies only to Bristol Bay wide catch. If an individual district has a poor salmon return but the other districts have good salmon returns, then the total Bristol Bay wide production will not be low, the price will not be particularly high, and there will be no economic ben-

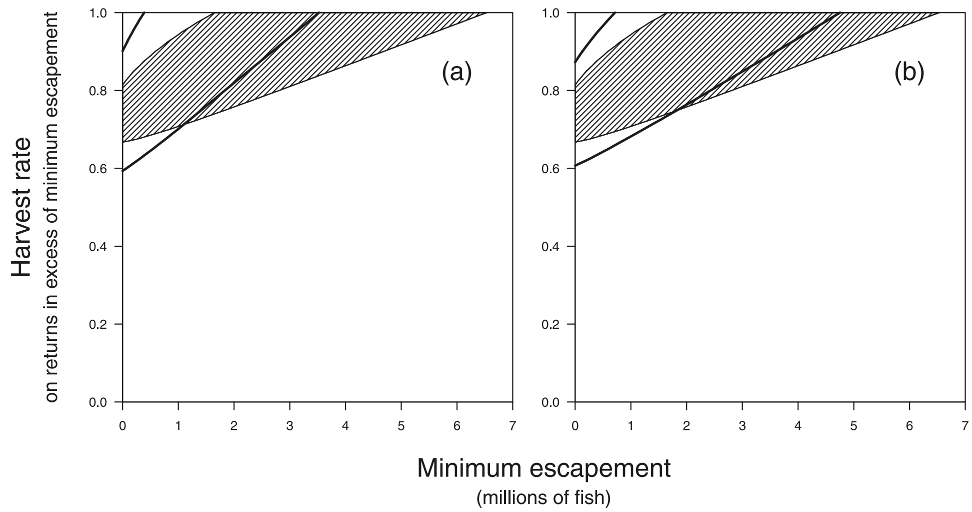


Fig. 5. Estimated biological yield (hatched area) and net present value (heavy lines) for (*a*) the fish processors and (*b*) the set gillnet fishermen obtained from a wide range of harvest policies for sockeye salmon (*Oncorhynchus nerka*) returning to the Egegik River, Bristol Bay, Alaska. The hatched area indicates the region of 90% and greater of the maximum biological yield; the solid lines indicate the outline for the region in which 90% and greater of the maximum net present value was obtained.

efit for harvesting below the escapement floor in the weak district.

Although all of our analyses are built on the assumption of a single annual harvest decision, in practice these stocks are managed in-season, and the harvesting and processing capacities are daily limits rather than annual limits. It would be useful to evaluate the in-season implementation of harvest strategies to determine if there are ways to provide for more early-season harvest. Early-season harvest has the potential of improving the economics by allowing a fixed capacity in both the harvesting and processing sectors to handle more fish through a single season. Bristol Bay managers are traditionally reluctant to provide much fishing opportunity until they are confident that they will reach their escapement goals. The results of the economic analysis suggest that some harvesting below traditional escapement floors is economically optimal, thus the economic performance of the fishery may be enhanced by more aggressive fishing early in the season.

We see several avenues for further work on harvest strategies. We have shown that the optimal harvest strategy with economic objectives can differ significantly from the biological escapement goal. We used published economic data but suggest that an updating of the data is in order, and a more in-depth economic analysis, including a detailed examination of our assumption regarding the economic discount factor, should be made. Although the cost of fishing and fish processing have most likely been affected by the recent increase in the price of petroleum products, it is also highly likely that the salmon price-to-volume relationships are in flux because of changing world markets. The integration of the annual harvest strategy with the reality of in-season management is a high priority. A major limitation of the methods used here is the use of brood tables to summarize the life history of the fish. The biology of sockeye salmon has shown great changes in survival over different life history stages, and it seems likely that an analysis based on a life history model, including freshwater and marine survival, would provide a better understanding of the role of density dependence in these stocks and, indeed, in almost all salmon.

Finally, it would be useful to calculate the optimal harvest strategies simultaneously for all fishing districts. Bristol Bay harvest strategies have traditionally been evaluated on a district-by-district basis, but the harvesting and processing capacity and impacts of volume on price are a Bristol Bay wide phenomena. Although this is not a trivial task, we suspect that it is now possible with modern computational methods and should be pursued.

Acknowledgements

Funding for this work came primarily from the Bristol Bay Science and Research Institute. RH had additional support from the National Science Foundation, The Gordon and Betty Moore Foundation, and Bristol Bay salmon processors. The staff of the Alaska Department of Fish and Game provided data, as well as valuable insight and discussions. Pamela Mace and an anonymous reviewer provided valuable comments that greatly improved the paper.

References

Asche, F., Bremnes, H., and Wessells, C.R. 1999. Product aggregation, market integration, and relationships between prices: an application to world salmon markets. Am. J. Agr. Econ. **81**: 568–581.

Carlin, B.P., and Louis, T.A. 1996. Bayes and empirical Bayes methods for data analysis. Chapman and Hall, London, UK.

Cederholm, C.J., Kunze, M.D., Murota, T., and Sibatani, A. 1999. Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. Fisheries, **24**: 6–15.

Charles, A.T. 1983. Optimal fisheries investment under uncertainty. Can. J. Fish. Aquat. Sci. **40**: 2080–2091.

Clark, C.W. 1976. Mathematical bioeconomics: the optimal management of renewable resources. Wiley-Interscience, New York.

Eggers, D.M. 1992. The benefits and costs of the management program for natural sockeye-salmon stocks in Bristol Bay, Alaska. Fish. Res. **14**: 159–177.

Evans, D.G., Browning, J.B., and Bue, B.G. 2000. A simulation model for sockeye salmon in the Wood and Nushagak rivers: a tool for evaluating escapement and harvest levels. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage, Alaska, Regional Information Rep. No. 2A00-40.

Fair, L.F. 2003. Critical elements of Kvichak river sockeye salmon management. Alaska Fish. Res. Bull. **10**: 95–103.

Gelman, A., Carlin, J.B., Stern, H.S., and Rubin, D.B. 1995. Bayesian data analysis. Chapman and Hall, London, UK.

Gordon, H.S. 1953. An economic approach to the optimum utilization of fishery resources. J. Fish. Res. Board Can. **10**: 442–456.

Hilborn, R. 2006. Fisheries success and failure: the case of the Bristol Bay salmon fishery. Bull. Mar. Sci. **78**: 487–498.

Hilborn, R., and Walters, C.J. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Hilderbrand, G.V., Schwartz, C.C., Robbins, C.T., Jacoby, M.E., Hanley, T.A., Arthur, S.M., and Servheen, C. 1999. The importance of meat, particularly salmon, to body size, population productivity, and conservation of North American brown bears. Can. J. Zool. **77**: 132–138.

Holzinger, A. 2007. An econometric analysis of global salmon market prices and their implications for the Alaska wild salmon industry. M.Sc. thesis, Department of Economics, University of Alaska, Fairbanks, Alaska.

Huppert, D.D., Ellis, G.M., and Noble, B. 1996. Do permit prices reflect the discounted value of fishing? Evidence from Alaska's commercial salmon fisheries. Can. J. Fish. Aquat. Sci. **53**: 761–768.

Karpoff, J. 1984. Insights from the markets for limited entry permits in Alaska. Can. J. Fish. Aquat. Sci. **41**: 1160–1166.

Karpoff, J. 1989. Characteristics of limited entry fisheries and the option component of entry licenses. Landsc. Econ. **65**: 386–393.

Knapp, G. 2004. Projections of future Bristol Bay salmon prices. Prepared for the Alaska Commercial Fisheries Entry Commission. Institute of Social and Economic Research, University of Alaska, Anchorage. Available online at cfec.state.ak.us/pita/mnu_BBOptNum.htm.

Knapp, G., Roheim, C.A., and Anderson, J.L. 2007. The great salmon run: competition between wild and farmed salmon. TRAFFIC North America. World Wildlife Fund, Washington, D.C. Available online at traffic.org/content/849.pdf.

Link, M.R., Hartley, M.L., Miller, S.A., Waldrop, B., Wilen, J., and Barnett, A. 2003. An analysis of options to restructure the Bristol Bay salmon fishery. Bristol Bay Economic Development Corporation, Dillingham, Alaska. Available online at bbsalmon.com/FinalReport.pdf

Minard, R.E., and Meacham, C.P. 1987. Sockeye salmon (*Oncorhynchus nerka*) management in Bristol Bay, Alaska. *In* Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. *Edited by* H.D. Smith, L. Margolis, and C.C. Wood. Can. Spec. Publ. Fish. Aquat. Sci. No. 96. pp. 336–342.

Morris, W.F., and Doak, D.F. 2002. Quantitative conservation biology: theory and practice of population viability analysis. Sinauer Associates Inc., Sunderland, Massachusetts.

Quinn, T.P., Eggers, D.M., Clark, J.H., and Rich, H.B. 2007. Density, climate, and processes of prespawning mortality and egg retention in Pacific salmon (*Oncorhynchus* spp.). Can J. Fish. Aquat. Sci. **64**: 574–582.

Schelle, K., Iverson, K., Free-Sloan, N., and Carlson, S. 2004. Bristol Bay salmon drift gillnet fishery optimum number report. Alaska Commercial Fisheries Entry Commission, Juneau, Alaska, Rep. No. 04-3N.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D. 2005. Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska. Ecology, **86**: 3225–3231.

Schindler, D.E., Leavitt, P.R., Johnson, S.P., and Brock, C.S. 2006. A 500-year context for the recent surge in sockeye salmon (*Oncorhynchus nerka*) abundance in the Alagnak River, Alaska. Can. J. Fish. Aquat. Sci. **63**: 1439–1444.

Scott, A. 1955. The fishery: the objectives of sole ownership. J. Pol. Econ. **63**: 116–124.

West, F.W. 2003. Abundance, age, sex, and size statistics for Pacific salmon in Bristol Bay, 2002. Alaska Department of Fish and Game, Division of Commercial Fisheries, Anchorage, Alaska, Regional Information Rep. No. 2A03-23.