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ARTICLE

Balancing Biological Sustainability with the Economic Needs of Alaska's Sockeye Salmon Fisheries

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Abstract
Total revenue in the Bristol Bay, Alaska, fishery for sockeye salmon *Oncorhynchus nerka* has declined by 80% over the past two decades. In contrast to other fisheries where declining revenues are a consequence of declining catches, Bristol Bay sockeye salmon landings have remained high and the revenue decline is a result of falling prices, which in turn are a consequence of competition from increased production of rainbow trout/steelhead *O. mykiss* (hereafter, rainbow trout) and coho salmon *O. kisutch* farmed in Chile. This paper explores possible changes to current management strategies that would continue to ensure biological sustainability while enhancing economic returns. We simulate three management strategies for Bristol Bay sockeye salmon: fixed escapement range, conditional fixed harvest, and conditional fixed harvest rate. Yields from these simulations are combined with a forecast of Chilean rainbow trout and coho salmon production and a model of international trade flows for Alaskan sockeye salmon and Chilean coho salmon and rainbow trout to generate forecasts of exvessel price and total revenue for 2010 under each management strategy. The simulations suggest that a change from the current fixed escapement range management strategy could improve the economic health of the fishery without compromising biological sustainability.

Alaskan salmon fisheries have been managed under a system of region- and gear-specific limited entry permits since the mid-1970s (Adasiak 1979; Rogers 1979; Rettig 1984). The Bristol Bay fishery for sockeye salmon *Oncorhynchus nerka* is the largest high-value salmon fishery in North America. High-value salmonids include wild-caught Chinook salmon *O. tshawytscha*, sockeye salmon, and coho salmon *O. kisutch* and farmed Chinook salmon, coho salmon, rainbow trout/steelhead *O. mykiss* (hereafter, rainbow trout), and Atlantic salmon *Salmo salar* (Knapp et al. 2007). The Bristol Bay sockeye salmon fishery is managed by the Alaska Department of Fish and Game (ADFG) to achieve escapement within a range selected to maintain a sustainable yield on average (Policy for the Management of Sustainable Salmon Fisheries 2001). Escapement goal ranges are established for each of nine major drainages within the five management districts that comprise the Bristol Bay watershed (Figure 1; Minard and Meacham 1987; Baker et al. 2006). Under current management practice, the fisheries are not opened unless it is estimated that run strength will be sufficient to meet the escapement goal; when estimated run strength exceeds the escapement goal, the entire surplus is allocated to harvest (Eggers 1992; Hilborn 2006).

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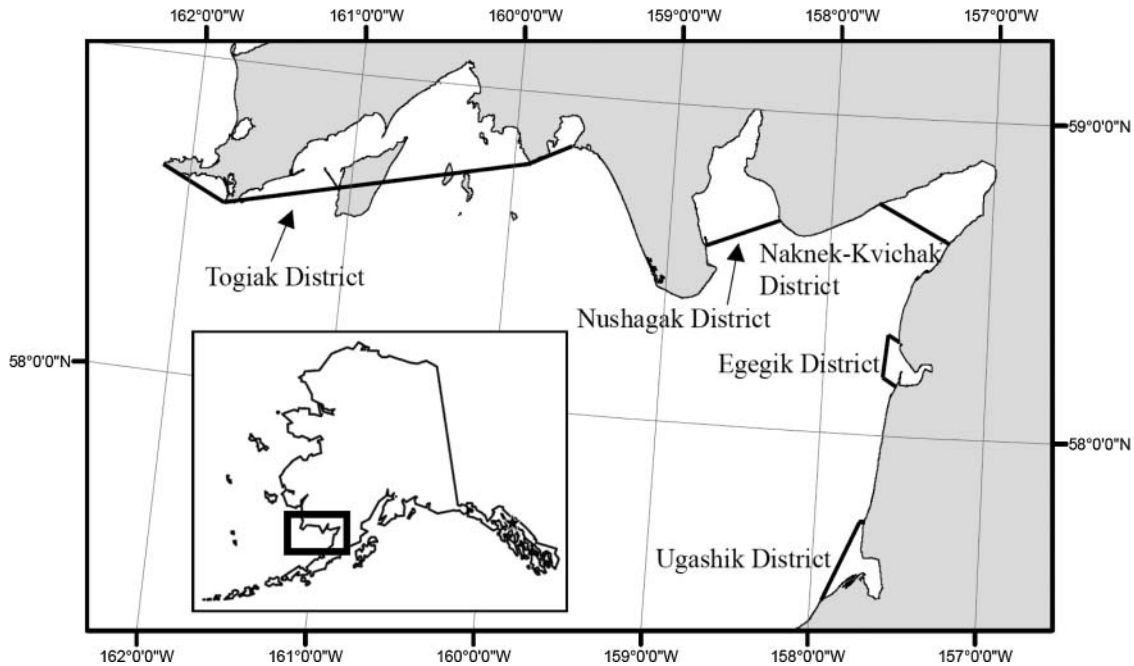

FIGURE 1. Fishing districts of Bristol Bay, Alaska (source: Bristol Bay Area Districts, Subdistricts, and Sections 2004).

Biological sustainability has not protected the Bristol Bay sockeye salmon fishery from economic failure (Hilborn 2006). The fishery dropped in total exvessel value (the product of annual landings and price paid to fishermen) from a record high of US$210 million in 1990 to an all-time low of $32 million in 2002, primarily from a decline in average exvessel prices (Figure 2; Clark et al. 2006). Bristol Bay set-net permits experienced a more than fivefold decline in value between 1990 and 2002, and drift-net permits experienced more than a 10-fold decline in the same period (Tide 2008). Economic failure in the Bristol Bay sockeye salmon fishery and similar failures in biologically sustainable salmon fisheries across the state of Alaska have been attributed to marketplace competition induced by increased Chilean exports of farmed Atlantic salmon, coho salmon, and rainbow trout (Herrmann 1993, 1994; Asche 1997; Asche et al. 1998, 1999; Gilbertsen 2003; Link et al. 2003; Asche and Tveterås 2004; Knapp et al. 2007).

Japan is the primary market for Alaskan fresh or frozen sockeye salmon as well as Chilean farmed coho salmon and rainbow trout and is also an important market for farmed rainbow trout from Norway (Asche et al. 1998, 2005; Knapp 2004; Knapp et al. 2007; Williams et al. 2009). In the late 1980s, Alaskan sockeye salmon comprised 90% of Japanese imports of high-value salmonids (Figure 3). By 2005, Alaskan sockeye salmon represented less than one-fifth of the Japanese high-value salmonid imports. The decline in market share has resulted not only from increases in Japanese imports of farmed coho salmon and rainbow trout but also from a decrease in the proportion of Alaskan sockeye salmon exported to Japan annually. It is unlikely that Alaskan salmon harvests will ever again dominate the world market as they did in the 1980s.

Crutchfield and Pontecorvo (1969), Hilborn (2006), and Bue et al. (2008), among others, have suggested that alternatives to maximum sustainable yield-based management strategies could improve the economic viability of salmon fisheries. In an attempt to find a practical solution with straightforward implementation, this study contrasted the current management strategy with two alternative strategies that could be adopted without substantive changes to state or federal regulations. The strategies differ in

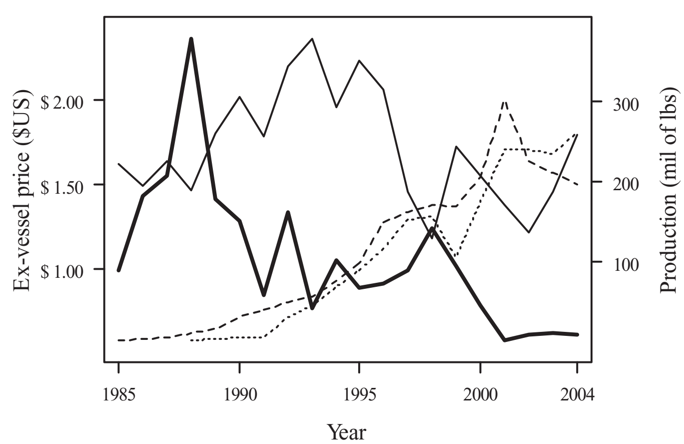

FIGURE 2. Exvessel price (bold solid line; expressed in real 2004 U.S. dollars) and landings (solid line; millions of lb) of sockeye salmon in Alaska between 1985 and 2004, presented with total production (millions of lb) of Chilean farmed coho salmon (dashed line) and Chilean farmed rainbow trout (dotted line).

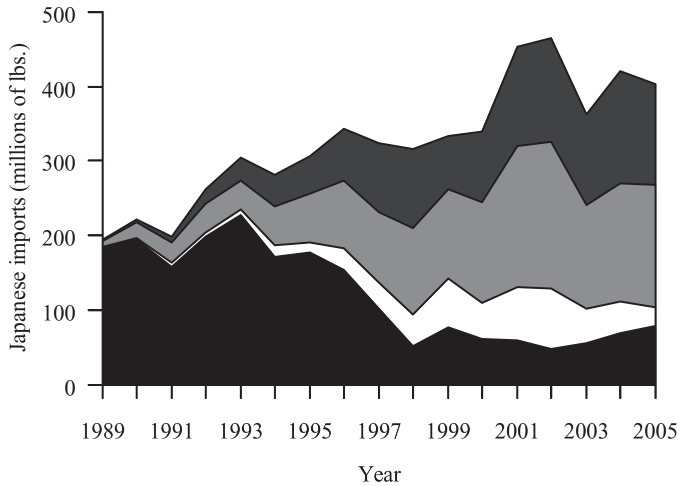

FIGURE 3. Japanese imports (millions of lb) of Alaskan sockeye salmon (black), Norwegian farmed rainbow trout (white), Chilean farmed coho salmon (light gray), and Chilean farmed rainbow trout (dark gray) from 1989 to 2005 (data sources: Skolbekken 2008; National Marine Fisheries Service, Fisheries Statistics Division, personal communication; A. Gertosio Ramirez, Chilean Undersecretary of Fisheries, personal communication).

how they distribute the inherent variability of run strength between harvest and escapement. We focus on finding tools to reduce the variability in catch in order to reduce the mismatch between processing capacity and magnitude of harvests. In addition, reduction of the variability in yield could partially dampen the costly tendency to ramp up fishing capacity, which is characteristic of high-variability fisheries (Caddy and Gulland 1983; Ludwig et al. 1993; Hjerne and Hansson 2001).

The objectives of this study were threefold. The first objective involved the use of Bristol Bay sockeye salmon recruitment models to determine whether the current management plan for Bristol Bay sockeye salmon could be modified without sacrificing biological sustainability. The second objective was to develop a model describing the costs of and potential for increases in Chilean production of coho salmon and rainbow trout; this model was used to explore the future potential of Chilean production to affect Alaskan sockeye salmon prices. The final objective was to determine which of the alternative management strategies yielded the greatest average exvessel revenues. To address the final objective, we conducted stochastic simulations that combined the Bristol Bay sockeye salmon recruitment models and the Chilean production models with the Williams et al. (2009) model of international trade flows in import and export markets for Alaskan sockeye salmon and Chilean coho salmon and rainbow trout. The international market model was designed to illustrate the forces that have led to and may continue to lead to the development of new markets, new product forms, new marketing strategies, or a combination of these. The simulations produced probability density functions for escapements and exvessel revenues under each of the alternative management strategies.

METHODS

Bristol Bay Sockeye Salmon Management

Biological model.—Return-per-spawner and age-class proportion data for each of the nine drainages (Alagnak, Egegik, Igushik, Kvichak, Naknek, Nushagak, Togiak, Ugashik, and Wood rivers) were obtained from the Bristol Bay brood tables for 1979–1998. Historical catch data from the same time period were obtained from ADFG and were incorporated into the model simulations. Data prior to 1979 were not used because the method of counting escapement in the Nushagak River drainage was changed, resulting in incompatible time series; partial counts were conducted from a tower at an upriver location until 1978, whereas a main-stem sonar counter was used after 1978 (Clark et al. 2006).

The first step in modeling the biological systems was to model the return-per-spawner relationship,

$$R_{jt} = S_{j,t-k}\exp(\alpha_j + \beta_j S_{j,t-k}) \times \left\{\sigma_j^2(1\ S_{j0})\left[\begin{pmatrix}\mathbf{1}\\ \mathbf{S}_j\end{pmatrix}(\mathbf{1}\,\mathbf{S}_j)\begin{pmatrix}1\\ S_{j0}\end{pmatrix}\right]\right\} + \varepsilon_{jt}, \quad (1)$$

for each drainage j. The first part of equation (1) is a traditional Ricker return-per-spawner relationship, where R_{jt} represents the number of recruits, the parameter α represents productivity, and the β parameter is related to density dependence. The number of spawners in year $t-k$ is denoted S_{t-k}, where k is the lag time between spawning and the return of progeny to spawn (time t). To ensure biological plausibility, the model parameters for each drainage were constrained to be positive (Ricker 1954). The second part of the equation corrects the bias introduced by fitting the Ricker model in log space and exponentiating the resulting estimates (Kennedy 1983). The Ricker model was fitted in log space, and the bias-corrected parameters are reported in levels. The variance of the residuals is represented as σ^2, $\mathbf{S}$ is a vector of observed escapement, and S_0 is the observed escapement for which an estimate of recruitment is desired.

A maximum likelihood procedure was used to fit a Dirichlet distribution to the observed age-class proportions (Evans et al. 2000; Bue et al. 2008),

$$f(\theta|\alpha_1,\ldots,\alpha_k) = \frac{\Gamma(\alpha_1+\ldots+\alpha_k)\theta_1^{\alpha_1-1}\ldots\theta_k^{\alpha_k-1}}{\Gamma(\alpha_1)\ldots\Gamma(\alpha_k)} + \upsilon_i, \quad (2)$$

where the distribution is parameterized by α_k and the θ_k parameters correspond to the relative proportions expected to return at each age, subject to the constraints that $\theta_1, \ldots, \theta_k$ are greater than or equal to 0 and $\sum_{k=1}^{n}\theta_k$ is equal to 1. Γ is the standard notation for a gamma distribution and υ_i represents the process error. Random draws from the Dirichlet distribution described in equation (2) were generated by the methods of van den Boogaart and Tolosana-Delgado (2008).

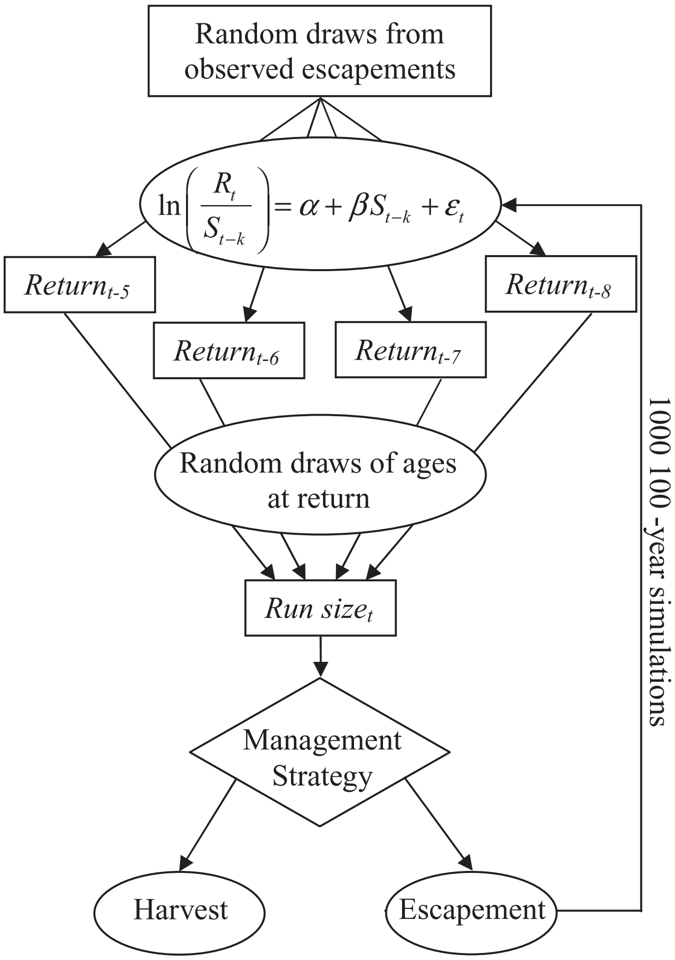

FIGURE 4. Flow chart for model simulation of Bristol Bay sockeye salmon run size, to which three management strategies were applied (see Methods for definition of symbols).

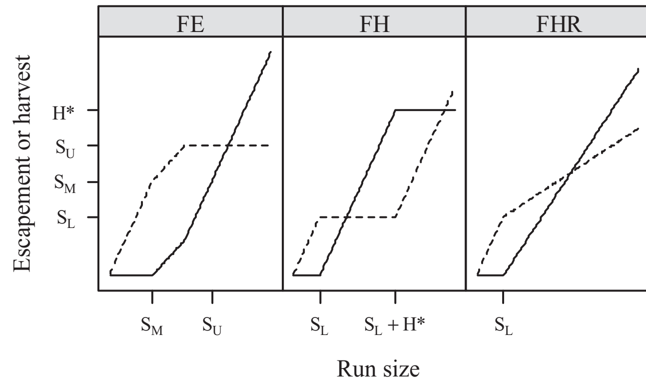

FIGURE 5. Graphical characterization of three sockeye salmon management strategies: fixed escapement (FE), fixed harvest (FH), and fixed harvest rate (FHR). Escapement (dashed lines) and harvest (solid lines) are plotted as functions of run size for each management strategy and in relation to lower (S_L), midpoint (S_M), and upper (S_U) escapement goals and a harvest goal (H^*).

The simulations were initialized with a random draw from past observed returns. Run sizes were generated by inserting this random value into equation (1), which produced a mean for a distribution from which a random draw could be taken (Figure 4). This value (i.e., the return size) was then redistributed to year of return by taking random draws from the Dirichlet distributions (equation 2). The portions of the redistributed return sizes could then be summed together to create a run size that would be available for harvest if the escapement level was reached for each year. Each of the three management strategies was then applied to generate an escapement value and a harvest value. The process was repeated over a 100-year trajectory, and the entire simulation was repeated 1,000 times (Figure 4). The first 25 years of each 100-year trajectory were used to initialize and stabilize the simulation and were not used for analysis of the management strategies.

Alternative management strategies.—Three alternative management strategies for Bristol Bay sockeye salmon were explored: a fixed escapement range (FE), a conditional fixed harvest (FH), and a conditional fixed harvest rate (FHR). The essential features of these strategies are depicted in Figure 5. The FE strategy approximates the current ADFG management practice of maintaining escapement within a range around a midpoint goal, which is selected to produce a sustainable yield. Under the FE strategy, harvesting is not allowed when the simulated run size is below the midpoint escapement goal. When the simulated run size exceeds the midpoint escapement goal, the surplus is evenly apportioned between escapement and harvest until escapement reaches the maximum escapement goal, after which all additional fish are allocated to harvest. Thus, under the FE strategy, all variability associated with runs that exceed the escapement goal is absorbed by the harvest sector.

Under the FH strategy, harvesting is not allowed if the simulated run size is below the minimum escapement goal. When the simulated run size exceeds the minimum escapement goal, surplus fish are allocated to harvest until the harvest goal is achieved, after which all additional fish are allowed to escape; in other words, all variability associated with run sizes larger than the harvest goal is borne by the stock. This strategy gives deference to economic objectives as long as the simulated run size exceeds the minimum escapement goal.

The FHR strategy distributes the variability associated with large run sizes between the escapement and harvest. Under the FHR strategy, harvest is not allowed if the simulated run size is below the minimum escapement goal; when the run size exceeds the minimum escapement goal, a fixed rate of harvest is applied. Following the work of Bue et al. (2008), we applied a harvest rate of 0.7. This strategy represents a hybrid of the FE and FH strategies and applies no hard caps on escapement or harvest; escapements may exceed escapement goals, and harvests may exceed harvest goals. These three strategies are intended to be illustrative of the range of management strategies that would be largely consistent with current regulations in the state of Alaska.

TABLE 1. Escapement and harvest goals (millions of fish) for the Bristol Bay sockeye salmon fishery.

		Escapement goal range[a]			Harvest goal[b]	
District	Drainage	Lower limit	Midpoint	Upper limit	Mean	SD
Egegik	Egegik River	0.80	1.10	1.40	7.22	4.53
Ugashik	Ugashik River	0.50	0.85	1.20	2.50	1.54
Togiak	Togiak River	0.10	0.15	0.30	0.49	0.22
Naknek–Kvichak	Naknek River	0.80	1.10	1.40	8.84	5.68
	Kvichak River	2.00	6.00	10.00		
	Alagnak River	0.17	0.19	0.20		
Nushagak	Nushagak River	0.34	0.55	0.76	4.63	2.35
	Igushik River	0.15	0.23	0.30		
	Wood River	0.70	1.10	1.50		

[a]Source: Lloyd et al. (2007).
[b]Harvest goals were generated by taking random draws from historically observed harvests.

The escapement goals used in the simulations are based on the current ADFG goals for each of the nine Bristol Bay drainages (Table 1). Baker et al. (2006) provide a detailed discussion and description of current escapement goals. For the Kvichak River, ADFG has identified a cyclic production trend and accordingly implements two escapement goal ranges (Fair 2003). Rather than model this additional complexity, we used the broader of the two goal ranges. Depending on the management strategy being modeled, the simulations used the lower, midpoint, or upper escapement goal.

Harvest goals were designed to emulate the actual operation of the fishery. The current management strategy anticipates that fishermen will harvest all surplus production in excess of the midpoint escapement goal; however, this only occurs when there are willing buyers and willing sellers. In practice, fishermen have been known to refrain from fishing when exvessel prices are low and when processors have limited their daily and overall season purchases based on plant capacity and market considerations. Because these choices by harvesters and processors are independent of biological management goals and because the basis for these choices is known only to the fishermen and processors, we treat harvest goals as random variables drawn from the empirical distribution of historical harvests. Although these goals are arbitrary, they nonetheless represent the recent range of harvest levels imposed on the fishing fleet by the processing sector. Harvest goals were kept constant over each 100-year simulation trajectory but were allowed to vary between simulations. For the Egegik, Ugashik, and Togiak districts (Table 1), the harvest goals were applied directly. The Nushagak and Naknek–Kvichak districts report catch records that are pooled across districts; therefore, the harvest goal was drawn for the combined district and catches were apportioned between the districts based on random draws from a Dirichlet distribution fitted to historic proportions of total escapement.

Chilean Salmon Production

To better understand the economic future of the Alaskan sockeye salmon fishery, a model of Chilean coho salmon and rainbow trout production was constructed. Chilean production was the focus of this study because it has the greatest potential for expansion (Asche et al. 1999; Bjørndal and Aarland 1999) and because it is the largest source of coho salmon and rainbow trout that compete directly in primary markets for Alaskan sockeye salmon (Williams et al. 2009). Although the costs of labor and other nonfeed inputs are important and have varied over time, feed is the largest component of production costs (Asche 1997). Thus, the costs of production for marine-reared salmon and trout are directly related to the prices of primary feed inputs: fish meal, soy meal, fish oil, and vegetable oil. Because production costs drive the price of salmon (Asche 1997), we can expect changes in fish meal and soy meal prices to be strongly related to changes in the quantity of salmon produced from aquaculture.

Production model.—The model of Chilean coho salmon and rainbow trout production emphasized dynamic linkages between the quantity of farmed salmon production and the associated costs. The model consisted of a stacked vector of Chilean coho salmon and rainbow trout production as a function of lagged production, the fractional differences of adjusted fish meal and soy meal prices, and a linear time trend. Conventional time series assume that the time interval in which the observations were collected matches the exact periodicity of the dynamic relationship (Shumway and Stoffer 2006). Estimation of fractional differences avoids this assumption by instead estimating the proper time interval. Fish meal and soy meal prices acted as proxies for production costs. The linear time trend was used to reflect observed increases in demand for Chilean coho salmon and rainbow trout. The use of feed prices as proxies for production costs is supported by Guttormsen (2002), who demonstrated that the price of feed inputs is the primary driver of finished-product prices in the current production environment. The production forecast equation is represented as

$$\begin{pmatrix} {}^{\text{coho}}Q_t^{\text{Chile}} \\ {}^{\text{rt}}Q_t^{\text{Chile}} \end{pmatrix} = d \begin{pmatrix} {}^{\text{coho}}Q_{t-1}^{\text{Chile}} \\ {}^{\text{rt}}Q_{t-1}^{\text{Chile}} \end{pmatrix} + \gamma_0(1-d) + \gamma_1\left[eP_t^{\text{fishmeal}} - d\left(eP_{t-1}^{\text{fishmeal}}\right)\right] + \gamma_2\left[P_t^{\text{soymeal}} - d\left(P_{t-1}^{\text{soymeal}}\right)\right] + \gamma_3 t + \begin{pmatrix} \xi_{1t} \\ \xi_{2t} \end{pmatrix}, \tag{3}$$

where ${}^{\text{coho}}Q_t^{\text{Chile}}$ is the annual quantity of coho salmon production, ${}^{\text{rt}}Q_t^{\text{Chile}}$ is the annual quantity of rainbow trout production, eP_t^{fishmeal} is the inflation-adjusted annual average effective price of fish meal, P_t^{soymeal} is the inflation-adjusted annual average price of soymeal, t is a monotonic time trend, and d is the fractional difference. A seemingly unrelated regression structure was used to represent relationships between the errors (ξ_{it}) of the two series. Estimates of the coefficients (γ) and d parameter were obtained by using nonlinear least-squares methods. Historical production and export data were obtained from the Chilean Undersecretary of Fisheries (A. Gertosio Ramirez, personal communication).

Meal price forecasts.—While the real (inflation-adjusted) price of soy meal has remained relatively constant over time, fish meal has exhibited substantial price increases in addition to increased volatility over time (Figure 6). Global monthly average nominal prices for fish meal and soy meal during 1989–2005 were obtained from the GLOBEFISH unit of the Food and Agriculture Organization of the United Nations (H. Josupeit, personal communication). The prices were adjusted for inflation to a 2006 basis and were also adjusted to reflect changes in the fish meal inclusion ratio (FIR) and the economic feed conversion rate (eFCR),

$$eP_t^{\text{fishmeal}} = (\text{eFCR}_t)(\text{FIR}_t)\left(P_t^{\text{fishmeal}}\right), \tag{4}$$

where changes in the FIR (lb of fish meal per lb of feed) reflect substitution of soy meal and other lower-priced proteins for increasingly expensive fish meal (Glencross et al. 2007). Improvements in the eFCR (lb of feed per lb of finished weight) have resulted from two factors. First, increases in the price of fish feed have motivated farmers to more carefully match feed application to feed demand to avoid profligate losses of unconsumed feed into the benthos. This more responsible application of feed has also been encouraged by government agencies that are responsible for regulation of environmental impacts. Second, feed producers have adjusted feed formulations to increase nutrient uptake efficiency, thereby producing more growth per pound of food consumed.

Tangential time trends were fitted to point estimates of the FIR (Vial 2006) and eFCR (Larraín 2002) by using a Gauss–Newton algorithm (Bates and Chambers 1992). These

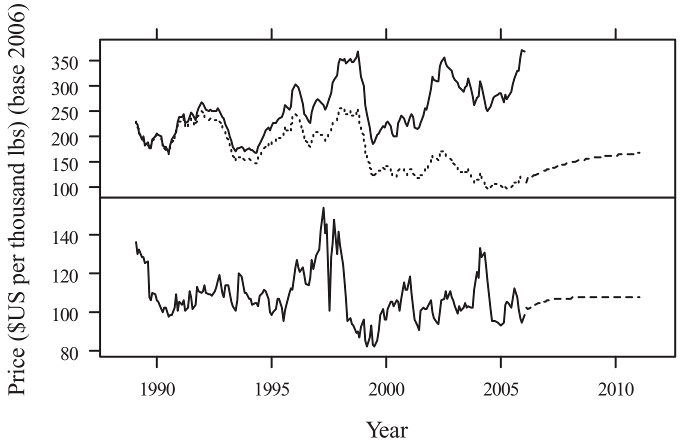

FIGURE 6. Real (2006 base year) prices of fish meal (upper panel) and soy meal (lower panel), with observed values represented as solid lines (H. Josupeit, GLOBEFISH, personal communication). The effective price of fish meal is represented as a dotted line; model forecasts of effective fish meal price and soy meal price are represented as dashed lines.

functional forms were selected to allow for parsimonious nonlinear relationships that could be bounded from above or below to reflect natural biological and physical constraints,

$$\text{eFCR} = (1/\lambda_1)\left[-\arctan\left(\frac{t-\bar{t}}{\lambda_2}\right) + 1.5\right] + 1 \tag{5}$$

and

$$\text{FIR} = \lambda_3\left[-\arctan\left(\frac{t-\bar{t}}{\lambda_4}\right) + 1.5\right], \tag{6}$$

where the eFCR was determined by two parameters. The first parameter, λ_1, reflected the upper bound for the eFCR; the second parameter, λ_2, acted as a scaling parameter for the observed time period. To assure biological plausibility, estimates of eFCR were constrained to be greater than or equal to 1. The FIR was also determined by two parameters, λ_3 and λ_4, and was bounded above 0 because a negative FIR is implausible.

Estimates of the eP_t^{fishmeal} and P_t^{soymeal} series were modeled jointly by using a multivariate state space time series (SSTS) model,

$$\left(P_t^{\text{soymeal}}\ eP_t^{\text{fishmeal}}\right)' = \mathbf{C}\mathbf{z}_t + \mathbf{e}_t \tag{7}$$

and

$$\mathbf{z}_{t+1} = \mathbf{A}\mathbf{z}_t + \mathbf{B}\mathbf{e}_t, \tag{8}$$

where equation (7) maps the observed series (eP_t^{fishmeal} and P_t^{soymeal}) into a vector of latent state variables, $\mathbf{z}_t$, and a set of innovations, $\mathbf{e}_t$. Equation (8) represents dynamic relationships among the state variables. Although the state variables are unobservable, they can be determined after the model parameters have been estimated and they are constructed as minimum sufficient statistics for the past realizations of the observation series. The number of state variables depends on the degree to which the series are correlated and on the complexity of the underlying dynamics. Methods for estimating the coefficient matrices (**A**, **B**, and **C**) and solving for the latent state variables are described by Aoki and Havenner (1991).

The model fitting procedure for the SSTS model (equations 7 and 8) involves a joint choice of the system lag and the number of state variables. The process of specifying the system lag and state variables is largely subjective; therefore, to guard against spurious fits to the observations, we used a sample of the time series (180 monthly observations corresponding to January 1989–December 2003) for model estimation and we reserved 24 monthly observations (corresponding to January 2004–December 2005) for ex-post validation.

Production projections.—Annual averages of the monthly forecasts of eP_t^{fishmeal} and P_t^{soymeal} from the SSTS model (equations 7 and 8) were entered into the model for Chilean coho salmon and rainbow trout production (equation 3). The production of Chilean coho salmon and rainbow trout was scaled to export quantities by using a simple linear relationship based on historic values,

$$\begin{pmatrix} {}^{\text{rt}}X_t^{\text{Chile}} \\ {}^{\text{coho}}X_t^{\text{Chile}} \end{pmatrix} = \omega_0 + \begin{pmatrix} {}^{\text{rt}}Q_t^{\text{Chile}} & 0 \\ 0 & {}^{\text{coho}}Q_t^{\text{Chile}} \end{pmatrix} \omega_1 + \varepsilon_t, \quad (9)$$

where the ω_i are coefficient vectors to be estimated, ${}^{\text{rt}}X_t^{\text{Chile}}$ is the quantity of rainbow trout exported from Chile to Japan, and ${}^{\text{coho}}X_t^{\text{Chile}}$ is the quantity of coho salmon exported from Chile to Japan. Stochasticity was incorporated into the projections by taking random draws from normal distributions of the annual price forecasts.

Exvessel price forecasts.—To use the international market model, the simulated numbers of sockeye salmon landed in Bristol Bay (${}^{\text{sock}}Q^{\text{BBfish}}$) had to be expanded into estimates of statewide total round weight of landings in pounds (${}^{\text{sock}}L^{\text{AKlb}}$). To do this, we exploited a simple linear relationship based on historical data,

$${}^{\text{sock}}L_t^{\text{AKlb}} = \phi_0 + \phi_1\left({}^{\text{sock}}Q_t^{\text{BBfish}}\right) + \eta_t, \quad (10)$$

and the simulated values for Chilean exports of coho salmon and rainbow trout (equation 9) and simulated landings of Alaskan sockeye salmon (equation 10) were used as inputs into the international market model. Where ϕ represents the estimated coefficients and η the error term. The international market model consisted of eight simultaneous equations: four inverse-demand equations and four allocation equations. The demand equations included Japanese demand for (1) Chilean-reared coho salmon, (2) Chilean-reared rainbow trout, (3) Norwegian-reared rainbow trout, and (4) Alaskan harvests of sockeye salmon. The allocation equations included Chilean exports of coho salmon to Japan, Chilean exports of rainbow trout to Japan, Norwegian exports of rainbow trout to Japan, and exports of Alaskan sockeye salmon to Japan. These equations and their estimates are a subset of the equation system reported by Williams et al. (2009). Variables (e.g., national population sizes, inflation rates, fuel prices, and exchange rates) that were not perturbed in the simulations were held at constant 2005 levels throughout the simulations.

Incorporating Stochasticity

Alaskan sockeye salmon landings were generated as random draws of 5-year harvest trajectories from 100-year alternative management strategy simulations for Bristol Bay and were expanded to simulated statewide total landings by using equation (10). Stochasticity was incorporated by randomly drawing from a normal distribution in which the total landings obtained from equation (10) were treated as a conditional mean and the SD from the regression was treated as the random perturbation. This process was iterated 500 times for each management strategy under each of three production scenarios: prefarming (conditions that antedated the development of Chilean aquaculture of coho salmon and rainbow trout; i.e., 1990 conditions), current (conditions characteristic of 2005 levels), and forecast (conditions based on a 5-year forecast; i.e., 2010 conditions).

For the future production scenario, stochasticity was incorporated into projections of Chilean coho salmon and rainbow trout production at three stages. First, stochasticity was integrated into the price forecasts by drawing from a normal distribution with the conditional mean from the forecasts generated by the SSTS model (equations 7 and 8) and the SD obtained from the model fit. These variables were then incorporated into equation (3) to generate 5-year forecasts for Chilean coho salmon and rainbow trout production. Second, the quantity of production from equation (3) served as the conditional mean for a normal distribution (with SD obtained from the model fit) from which a random draw was taken to generate a production forecast for the production forecast trajectory. Third, by using the methods of Salkever (1976), the production forecasts were converted into export forecasts by drawing from another normal distribution with the conditional mean obtained from equation (9) and the SD obtained from the same model fits. This process was repeated 500 times for each production scenario × management strategy combination.

Once all of the random variables were generated, the exports of Chilean coho salmon and rainbow trout and the statewide total round weight of landings were entered into the international market model (Williams et al. 2009). The system of equations was solved by using a Newton algorithm in the Statistical Analysis System (SAS 2007). This process was iterated 500 times over each 5-year trajectory for each production scenario × management strategy combination.

RESULTS

Bristol Bay Sockeye Salmon Management

Coefficient (α and β) estimates and goodness-of-fit statistics for the nine sockeye salmon recruits-per-spawner models

TABLE 2. Coefficient of determination (R^2) and parameter estimates for Ricker recruits-per-spawner models for sockeye salmon in each of the nine Bristol Bay-area drainages. The models were fitted in log space. Bias-corrected parameter estimates are reported in exponentiated terms rather than log space.

Drainage	R^2	SD	α Estimate	α P	β Estimate	β P
Alagnak River	0.32	0.43	1.84	< 0.001	−1.58	0.007
Egegik River	0.07	0.61	2.35	< 0.001	−0.33	0.235
Igushik River	0.52	0.67	1.66	< 0.001	−1.69	0.000
Kvichak River	0.33	0.81	0.33	0.290	0.00	1.000
Naknek River	0.10	0.52	1.43	< 0.001	−0.26	0.157
Nushagak River	0.63	0.38	1.44	< 0.001	−0.76	0.000
Togiak River	0.31	0.58	1.88	< 0.001	−4.20	0.008
Ugashik River	0.23	0.72	1.88	< 0.001	−0.54	0.027
Wood River	0.30	0.48	1.74	< 0.001	−0.62	0.010

(equation 1) are reported in Table 2. The R^2 values for the models are reported in levels rather than in log space. Forecasts based on estimates of the coefficients of Ricker recruitment models accounted for 7% (Egegik River) to 63% (Nushagak River) of the observed variability in the natural logarithm of recruits per spawner. The highest β estimate was 0 for the Kvichak River—the only drainage for which it was necessary to constrain the β estimate. The lowest β estimate was −4.20 for the Togiak River. The range in β for the remaining drainages was smaller: −0.26 to −1.69. Estimates of α ranged from 0.33 (Kvichak River) to 2.35 (Egegik River). The model performance was similar to that reported in previous studies indicating high variability in the recruits-per-spawner relationship at lower levels of escapement and little information at high levels of escapement (Gibson and Myers 2004; Martell et al. 2008). The observations and fitted models are represented in Figure 7.

All management strategies appeared to be biologically sustainable because no strategy drove a sockeye salmon population to extinction or into uncontrolled population growth. Although this is implicit in the shape of the Ricker model for deterministic simulations, it is not assured during stochastic simulations. This outcome is important because it indicates that all of the combinations of management strategies and biological models were able to maintain run size equilibria, which is particularly crucial for implementing a fixed-harvest strategy. All drainages reached equilibrium in sockeye salmon run size within 25 years of the start of the simulation under all three management strategies. The one exception was the Kvichak River, which only reached equilibrium after approximately 75 years under the FH strategy. Under the other two strategies, the Kvichak River reached equilibrium just as quickly as the other drainages.

Although the management strategies varied in their effects on run size across drainages, the FE strategy consistently produced the highest harvests and the FH strategy consistently produced the lowest harvests. In addition, the FE strategy maintained constant escapement levels and produced the lowest escapement levels observed in each drainage, while the FH strategy produced the highest escapement levels across all drainages.

At a baywide scale, the FE strategy generated the highest variability in harvest and intermediate levels of variability in run size (Figure 8). As would be expected with a fixed-escapement policy, the FE strategy yielded the lowest variability in escapement. The FH strategy also performed as expected, yielding the lowest variability in harvest (Figure 8). The FHR strategy produced the lowest variability in run size and intermediate variability in harvest and escapement levels.

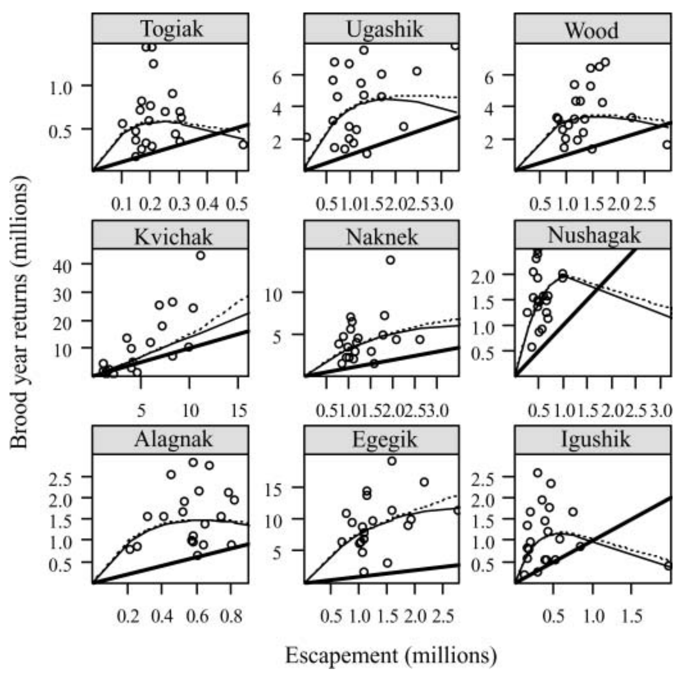

FIGURE 7. Sockeye salmon brood year return versus escapement for the nine Bristol Bay-area drainages (open circles = observed returns; solid lines = unadjusted fits of returns; dashed lines = bias-corrected fits of returns; bold lines = one-to-one replacement lines). Note that the scale for both escapement and brood year returns varies among drainages.

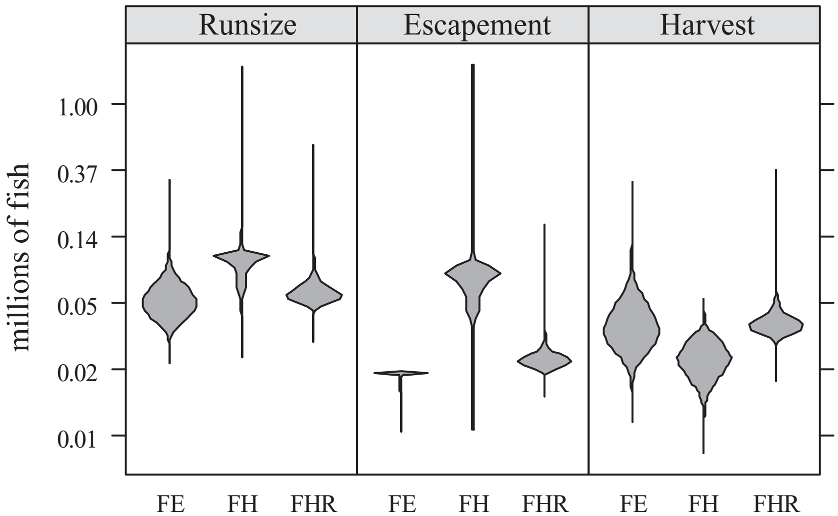

FIGURE 8. Distribution of simulated sockeye salmon run size, escapement, and harvest (millions of fish) for Bristol Bay as a whole (n = 56,250 iterations in the simulation) under three management strategies: fixed escapement (FE), fixed harvest (FH), and fixed harvest rate (FHR). The violin plots represent the kernel density estimates.

Chilean Salmon Production

Estimates of Chilean coho salmon and rainbow trout production (equation 3) are conditional on the estimates of eP_t^{fishmeal} and P_t^{soymeal} (equations 7 and 8), which are in turn conditional on estimates of the eFCR (equation 5) and FIR (equation 6). The eFCR model accounted for 97% of the variation observed in the time series of eFCRs, and the FIR model accounted for 90% of the variation in the FIR time series. The estimates for the four parameters (λ_1–λ_4) were all significant ($P < 0.0001$; Table 3).

A model with a system lag of 1 month and two state variables was selected to model the eP_t^{fishmeal} and P_t^{soymeal} time series. This was based on consideration of model performance in-sample by using R^2 and Akaike's information criterion adjusted for small sample sizes (AIC_c; Burnham and Anderson 2002). Note that a system lag of 1 month allows for lags of up to 2 months on the individual time series. The R^2 value for the in-sample observations and P_t^{soymeal} was 0.758, and the corresponding AIC_c was 6.352; the R^2 value for the in-sample observations and eP_t^{fishmeal} was 0.966, and the AIC_c was 6.743. The R^2 values over the observations reserved for ex-post validation were 0.767 for P_t^{soymeal} and 0.994 for eP_t^{fishmeal}, and the corresponding AIC_c values were 6.270 and 6.239. The increase in R^2 and decrease in AIC_c indicate that model performance did not deteriorate over the observations reserved for model validation. This outcome is particularly striking because the observations reserved for model validation correspond to a period of increased volatility in fish meal prices (Figure 6). The re-estimation of the model with the full set of observations (n = 204) yielded R^2 values equal to 0.760 for P_t^{soymeal} and 0.974 for eP_t^{fishmeal}, which were higher than the R^2 values for the in-sample model fit,

$$\begin{pmatrix} P_t^{\text{soymeal}} \\ eP_t^{\text{fishmeal}} \end{pmatrix} = \begin{pmatrix} -19.625 & 17.028 \\ -87.268 & -49.695 \end{pmatrix} \mathbf{z}_t + \mathbf{e}_t$$

$$\mathbf{z}_{t+1} = \begin{pmatrix} 0.932 & 0.033 \\ 0.060 & 0.901 \end{pmatrix} \mathbf{z}_t + \begin{pmatrix} -0.015 & -0.010 \\ 0.028 & -0.008 \end{pmatrix} \mathbf{e}_t .$$

The model's ability to accurately predict turning points in the time series was statistically significant (Henriksson–Merton turning point test: $P < 0.001$; Henriksson and Merton 1981).

Annual averages of the P_t^{soymeal} and eP_t^{fishmeal} were used to estimate the coefficients of the Chilean salmon production model. The value of d was estimated as 0.418 (SE = 0.197). The values of the remaining coefficients are shown below (SEs are given in parentheses below the corresponding coefficients):

$$\begin{pmatrix} {}^{\text{coho}}Q_t^{\text{Chile}} \\ {}^{\text{rt}}Q_t^{\text{Chile}} \end{pmatrix} - d \begin{pmatrix} {}^{\text{coho}}Q_{t-1}^{\text{Chile}} \\ {}^{\text{rt}}Q_{t-1}^{\text{Chile}} \end{pmatrix} = \underset{(4.82\times 10^{3})}{(-3.73 \times 10^{4})}(1-d)$$
$$+ \underset{(9.49 \times 10^{-2})}{(9.22 \times 10^{-2})} \left[eP_t^{\text{fishmeal}} - d\left(eP_{t-1}^{\text{fishmeal}}\right) \right]$$
$$+ \underset{(0.195)}{0.225} \left[P_t^{\text{soymeal}} - d\left(P_{t-1}^{\text{soymeal}}\right) \right] + \underset{(4.15)}{10.9}t .$$

TABLE 3. Parameter estimates and SEs for models of economic feed conversion rate (eFCR) and fish meal inclusion ratio (FIR). Asymptotic t-tests were significant for all parameters (all $P < 0.0001$).

Model	Parameter	Estimate	SE
eFCR	λ_1	3.59	9.65×10^{-2}
	λ_2	2,190	2.43×10^{2}
FIR	λ_3	23.0	5.20×10^{-1}
	λ_4	3,040	4.78×10^{2}

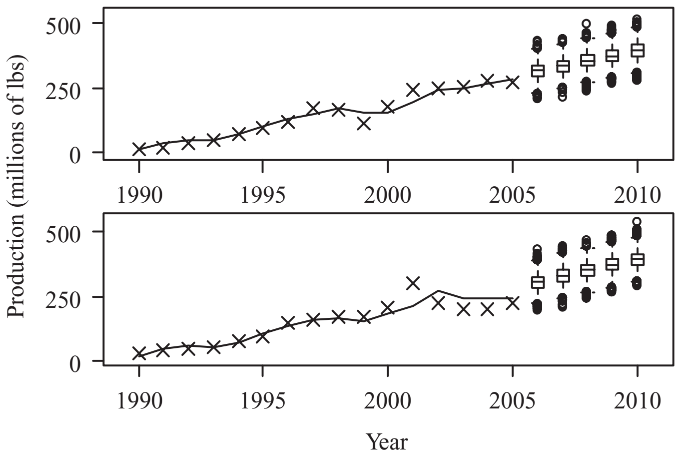

FIGURE 9. Chilean production of rainbow trout (upper panel) and coho salmon (lower panel) during 1990–2010 (crosses = observed production; solid lines = model estimates). The box-and-whisker plots represent production projections (box = interquartile range; solid line within box = median; whiskers = most extreme points that are within 1.5 times the box length; open circles = points lying beyond 1.5 times the box length).

The production model accounted for 85% of past variation in the time series for Chilean coho salmon production and 95% of past variation in the time series for Chilean rainbow trout production. The observations, model estimates, and 5-year projections for Chilean salmon production are depicted in Figure 9. The projections represent a steadily increasing trend.

The coefficients and SEs (in parentheses below the coefficients) for the linear relationships used to map Chilean coho salmon and rainbow trout production into export quantities are

$$^{\text{coho}}X_t^{\text{Chile}} = \underset{(7.50)}{0.19} + \underset{(0.05)}{0.73}\left(^{\text{coho}}Q_t^{\text{Chile}}\right)$$

and

$$^{\text{rt}}X_t^{\text{Chile}} = \underset{(3.17)}{3.56} + \underset{(0.02)}{0.62}\left(^{\text{rt}}Q_t^{\text{Chile}}\right),$$

The coho salmon equation had an R^2 of 0.944, and the rainbow trout equation had an R^2 of 0.986.

Exvessel Price Forecasts

Simulated numbers of sockeye salmon landed in Bristol Bay (i.e., $^{\text{sock}}Q^{\text{BBfish}}$) were expanded into estimates of $^{\text{sock}}L^{\text{AKlb}}$ by using equation (10). When fitted to historic data, equation (10) accounted for 90% of the past variation in statewide landings. The coefficients and SEs (in parentheses below the coefficients) for equation (10) are

$$^{\text{sock}}L_t^{\text{AKlb}} = \underset{(13.10\times 10^6)}{(85.22\times 10^6)} + \underset{(0.51)}{6.64}\left(^{\text{sock}}Q_t^{\text{BBfish}}\right).$$

The direction of the effect of the alternative management strategies on exvessel price was consistent across the three production scenarios (Figure 10a). The FH strategy produced the highest median exvessel price, the FE strategy produced the lowest exvessel price, and the FHR strategy generated an intermediate exvessel price. As expected, simulations that were designed to reflect the conditions predating large-scale salmon aquaculture in Chile (i.e., the prefarming [1990] scenario) resulted in the highest median exvessel price. Although the average difference in exvessel price was statistically significant for each pairwise combination of management strategies ($P < 0.001$), the only practical differences were that exvessel prices were substantially larger in the prefarming scenario than in the other two scenarios.

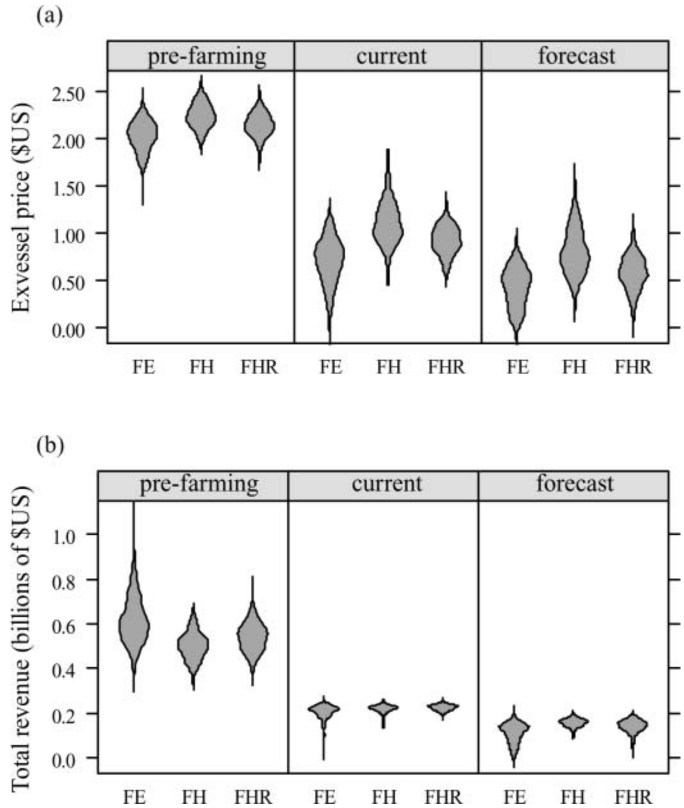

FIGURE 10. Alaskan sockeye salmon **(a)** exvessel price and **(b)** total revenue for three management strategies (FE = fixed escapement; FH = fixed harvest; FHR = fixed harvest rate) under three production scenarios: prefarming (conditions that antedated the development of Chilean aquaculture of coho salmon and rainbow trout; i.e., 1990 levels), current (conditions characteristic of 2005 levels), and forecast (based on a 5-year forecast). The violin plots represent the kernel density estimates.

Unlike the effect on exvessel price, the effect of management strategy on total revenue varied in magnitude and direction across production scenarios (Figure 10b). Under the prefarming scenario, the FE strategy produced the highest median total revenue and the FH strategy produced the lowest. Under the current (2005) and 5-year-forecast (2010) production scenarios, the FH strategy produced the highest median total revenue and the FE strategy produced the lowest. The total revenue was highest under the prefarming scenario and lowest under the

5-year-forecast scenario. Again, differences in mean total revenue were statistically significant ($P < 0.001$) across all production scenario × management strategy combinations, but the only meaningful differences were between total revenues under the prefarming production scenario and the other two scenarios.

DISCUSSION

For each Bristol Bay-area drainage, all three management strategies maintained sockeye salmon run size equilibria under all three production scenarios, with the exception of the FH strategy applied to the Kvichak River drainage. Failure in the Kvichak River simulations probably resulted from the poor fit of the recruits-per-spawner relationship rather than a failure of the FH strategy (Fair 2003). The FHR strategy produced the lowest variability in run size, while the FH strategy produced the highest variability. None of the strategies drove a population into extinction. The FH strategy reduced the variability in yield and long-term average yield relative to the other strategies. This is consistent with previous research on applying a constant harvest strategy to Atlantic herring *Clupea harengus* (Hall et al. 1988), Atlantic mackerel *Scomber scombrus* (Overholtz 1993), Atlantic menhaden *Brevoortia tyrannus* (Ruppert et al. 1985), and Pacific hake *Merluccius productus* (Swartzman et al. 1983; see also Murawski and Idoine 1989). Sockeye salmon differ from these species because they are semelparous and cannot be "saved" for harvest in future years. Nevertheless, there can be ecological advantages to allowing more fish to escape by increasing the spawning biomass and in turn increasing the availability of marine-derived nutrients to juvenile salmon (Schmidt et al. 1998; Uchiyama et al. 2008).

The FHR strategy produced the lowest run size and intermediate levels of escapement in comparison with the other two strategies. Although the shift in distribution of variability from yield to escapement has the potential to exacerbate variability in run size, this did not occur in our simulations. Moreover, higher variability in escapement may more closely mimic the natural variability in escapement that occurs in unexploited river systems (Walters and Parma 1996; Schindler et al. 2006).

The effects of the three management strategies on exvessel price were consistent across the three production scenarios for Chilean coho salmon and rainbow trout. Under all three scenarios, the FH strategy resulted in the highest median exvessel price and the FE strategy resulted in the lowest. This supports the continued existence of an inverse relationship between exvessel price and landed quantities of wild Alaskan sockeye salmon: lower harvests lead to higher exvessel prices once there has been a proper accounting for the effect of changes in Japanese imports of Chilean-reared coho salmon and rainbow trout and Norwegian-reared rainbow trout. It is unsurprising that an inverse price–quantity relationship for exvessel prices was clearly evident under conditions that predated the rapid expansion of salmon aquaculture, as this was a period when Alaska accounted for over 50% of the world production of high-value salmon. However, we identified two unanticipated but welcome outcomes for Alaska's salmon industry: (1) the same inverse price–quantity relationship remained evident under current market conditions in which Alaska accounted for less that 10% of the world production of high-value salmon and (2) this relationship was expected to persist even under simulations that anticipated the continued expansion of salmon aquaculture capacity. These outcomes are welcome because they mean that the economic effects of alternative escapement management strategies are not solely determined by the vagaries of international markets but are also endogenous to the choice of management strategy.

The effect of management strategy on exvessel revenues varied according to production scenario. Under the prefarming scenario, the FE strategy produced the highest median exvessel revenue and the FH strategy produced the lowest; under the current and 5-year-forecast scenarios, the FH strategy produced the highest median exvessel revenue and the FE strategy produced the lowest. Thus, when Alaska led the world in production of high-value salmon, it was economically sensible to pursue a management strategy that was designed to maximize run strength, whereas given the emergence of competition from Chilean production of salmon and trout it is more economically sensible to pursue a fixed-harvest strategy once the escapement objectives have been satisfied. Although Figures 8 and 10 indicate overlap in the performance of the three management strategies, in the current and forecast production scenarios the FE strategy is stochastically dominated by the FHR strategy, which is in turn stochastically dominated by the FH strategy in terms of median exvessel price, median exvessel revenue, median run strength, and median escapement.

In addition to unknowns associated with salmon production outside of Alaska, there are many factors that could also have an effect on future production of coho salmon and rainbow trout in Chile. One such factor is the changing world market for vegetable-derived oils; for example, the nascent biodiesel sector could stimulate an increase in the supply of soy meal as a byproduct of soy oil production, thus generating a concomitant decrease in soy meal prices. On the other hand, increased demand for corn from the ethanol industry could result in increased demand for soy meal from the pork and poultry producers, thereby leading to upward pressure on soy meal prices. Labor unions and environmental advocacy groups could also have unpredictable impacts on the Chilean aquaculture industry. Lastly, as retailers and consumers have developed increased interest in accreditation attributes such as Marine Stewardship Council (MSC) certification, price premiums for already MSC-labeled products may rise to the advantage of Alaskan salmon fisheries, which are MSC certified.

One other factor that could have a dramatic effect on the rate of expansion of Chilean salmon aquaculture is the infectious salmon anemia virus (ISAV), a disease that previously was only known to occur in the Northern Hemisphere. In winter 2007, unprecedented mortality of Chilean farmed Atlantic salmon was attributed to this virus (Godoy et al. 2008).

Mortality rates for infected Atlantic salmon can exceed 50% (Kibenge 2006; MacWilliams et al. 2007). Although ISAV has not been associated with high levels of mortality in coho salmon or rainbow trout, the emergence of ISAV in Chile could have a range of effects—both positive and negative—on Alaskan sockeye salmon prices. For example, if the high mortality rate of farmed Atlantic salmon leads to a decrease in the Atlantic salmon supply, there could be an opportunity for increased sales of Alaskan sockeye salmon in the United States market. Alternatively, a shift in resources and facilities from the production of Atlantic salmon to the production of rainbow trout and coho salmon, which are largely unaffected by ISAV, could cause a downward pressure on exvessel prices of Alaskan sockeye salmon in the Japanese market.

The effects of the three management strategies and three production scenarios on total revenue reflect changes in global markets for salmon. The combined aquaculture and capture-fishery supply of sockeye salmon, coho salmon, and Chinook salmon and marine-reared rainbow trout under the prefarming scenario was less than 65% of the current (2005) production levels. Under those conditions, even though the FE strategy resulted in marginal increases in quantity relative to the FH strategy, the total revenues increased; in other words, modest average increases in Alaskan landings more than offset any modest decreases in exvessel price. In contrast, at the production levels characterized by the current and forecast simulations, marginal increases in average quantity harvested under the FE strategy relative to the FH strategy caused both exvessel price and total revenue to decline. The FH strategy provides the opportunity to focus on quality by reducing the tendency to catch as many fish as time will allow. If international demand for sockeye salmon, coho salmon, Chinook salmon, and rainbow trout remains inelastic, Alaska's sockeye salmon fishery would benefit from management strategies that discourage maximum harvests in years with large runs and that instead focus on maximizing the quality of the sockeye salmon that are produced.

There are many plausible variations on the three management strategies we have explored in this paper. For example, the fraction of runs allocated to harvest under the FE and FHR strategies could be varied from the 50:50 and 70:30 proportions we modeled. Similarly, the FH and FHR strategies could be hybridized to create a strategy with a continuously variable harvest rate that asymptotically approaches a harvest goal. Although the Ricker models used to represent recruits-per-spawner relationships indicate that escapements above the midpoint escapement goal could adversely affect future returns, the simulations suggest that this is unlikely when overescapement events are infrequent. Moreover, the lackluster fit of the estimated recruits-per-spawner relationships does not evoke confidence in particular point estimates of escapement levels that maximize sustainable yields.

The simulated harvest strategies and production scenarios indicate that a fixed-harvest strategy could increase the total value of the Bristol Bay sockeye salmon fishery due to the fundamental change in the international salmon market caused by the introduction of large quantities of farmed salmon; however, there are several other reasons to consider implementing this strategy. One example is that the weak recruits-per-spawner relationship modeled for the Bristol Bay drainages strengthens the case for adopting a management strategy that maintains current lower bounds on escapement and stabilizes the upper bound for harvests. The relationship between Chilean production of coho salmon and rainbow trout and the exvessel price of Alaskan sockeye salmon suggests that the FH strategy could benefit from setting a dynamic harvest goal that can be adjusted based on near-term forecasts of Chilean production. Lastly, the benefit of choosing a fixed-harvest strategy over a fixed-escapement or fixed harvest rate strategy could be further amplified both by taking advantage of the lower harvests to improve the quality of fish delivered, thus obtaining a high exvessel price per pound, and by providing increased opportunity for improving the efficiency of the processor operations because the harvest levels will be known at the beginning of the season. This change in relationship between total quantity landed and total revenue could be used to encourage fishermen to dedicate more time to improving product quality rather than focusing on increasing total harvest.

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