The Value of El Niño Forecasts in the Management of Salmon: A Stochastic Dynamic Assessment

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The El Niño-Southern Oscillation (ENSO) is the largest source of interannual variability in global climate. Variability in climate has been linked to variability in fisheries, specifically salmon stocks of the Pacific Northwest. The ability to forecast El Niño events already exists and is likely to improve in coming years. An accurate prediction may have value because it allows for better management decisions. In this article, we develop a bioeconomic model of the coho salmon fishery and derive the value of information from improved El Niño forecasting ability. We find that a perfect El Niño forecast results in an annual welfare gain of approximately $1 million, while imperfect forecasts lead to smaller gains. Results also suggest that optimal management in the face of uncertainty involves a "conservative" management strategy, resulting in lower harvest, higher wild fish escapement, and lower hatchery releases than management in the absence of such uncertainty.

Key words: coho salmon, economic analysis, El Niño, value of information.

The El Niño-Southern Oscillation (ENSO) is the largest source of interannual variability in the global climate system. Strong ENSO phases in the Pacific Ocean, known as El Niño events, are characterized by changes in water temperature and a reduction in intensity of trade winds, affecting biological and climatological functions in North America (Pearcy and Schoener, Barber and Chavez). Ocean and inland climate effects associated with El Niño have large economic consequences in sectors such as agriculture, energy, and fisheries. Pelagic fish species are susceptible to the extreme interannual variability of ocean conditions that accompanies an El Niño event. For example, the collapse of the Peruvian anchovetta fishery in 1972 was attributed, in part, to El Niño.

The intensity of an El Niño event is defined by atmospheric pressure changes in the South Pacific, which eventually translate into changes in oceanic and weather conditions off the Pacific Northwest coast. El Niño events increase water temperature and reduce ocean upwelling, which in turn disrupts the food chain, upon which salmon depend. In addition, El Niño events alter rainfall patterns, which may have adverse consequences for the instream environment critical to salmon reproduction.

Pacific Northwest coho salmon numbers were sharply reduced in 1982–83 by the most severe El Niño event this century (Pearcy and Schoener). In 1983, the number of wild coho returning to their natural streams was only 42% of preseason predictions (S.L. Johnson). Subsequent year returns indicated that mortality of all age classes increased under El Niño conditions. Over the past decade, salmon stocks in the Pacific Northwest have been very low relative to historical averages. The explanation for the low stocks includes several anthropogenic factors; however, oceanographic conditions such as El Niño and longer-term decadal shifts in ocean climate regimes are also responsible (Nickelson). Low

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stocks resulted in the closure of the recreational and commercial coho salmon fisheries off California, Oregon, and Washington in 1994 and closure of the commercial coho fishery off California and Oregon in 1995, 1996, and 1997 [Pacific Marine Fishery Council (PFMC)].

Prior to 1995, stock predictors used by the PFMC, the primary salmon management agency along the Pacific Coast, did not include ocean conditions as an explanatory variable. Since 1995, the predictor for wild coho returns has included current ocean conditions but not forecast of future ocean conditions (PFMC). Given that fishery managers must commit to various management actions before the season starts, and that management takes place in a dynamic setting (where management in one year relies on predictions of uncertain conditions in future years), accurate forecasts of ocean conditions are potentially valuable.

The ability to predict El Niño is already in place and forecast accuracy is likely to improve in coming years (Adams et al. 1995, Barber and Chavez). El Niño forecasts have economic value insofar as they are incorporated into management strategies that mitigate adverse consequences. Examples of management controls that may be affected by improved forecasts include harvest levels and operations of fish hatcheries. Some of the potential benefits from accurate El Niño and other climate forecasts have been assessed (see Adams et al. 1995 for the value of El Niño forecasts to agriculture; Mjelde, Sonka, and Peel for a comprehensive review of value of climate forecast studies).[1]

To date, no systematic analysis has been conducted on the value of improved climate forecasts to an ocean fishery. Changes in fish stocks have economic consequences to recreational users, commercial fishers, and indirect users of the salmon resource. The purpose of this article is to develop a method to assess the value of climate information in a fishery and to apply this method to the case of the coho salmon fishery. We combine models and data from several disciplines in a stochastic dynamic framework. Quantitative estimates of the value of El Niño forecasts under alternative information states are provided. The estimates are intended to be illustrative, rather than assessments of specific policy prescriptions. The analysis also compares the value of more accurate forecasts with that of extending the time frame of such forecasts.

The article begins with a discussion of optimal decision making under uncertainty as it applies to management of a fishery. We then describe the bioeconomic decision model, combining biology, climatology, and economics into a statistical model to determine optimal management. Several levels of forecast ability are evaluated, and the corresponding value of optimal management under each information structure is compared. Finally, implications of the research are discussed, including optimal management under various ENSO scenarios.

Optimal Decision Making in a Stochastic Dynamic Model

Calculating the value of improved El Niño forecasts to a fishery requires the development and combination of models and data from biology, climatology, and economics into a composite bioeconomic model. This section describes the framework for optimal decision making in a dynamic stochastic fishery.

The literature on fisheries management under uncertainty focuses on simple stochastic models (Getz, Francis, and Swartzman; Reed; others). Reed analyzes a model with stochastic growth, constant price, and per unit harvest costs that depend only on the level of stock. In this model, Reed shows that the optimal harvest strategy requires managing for a constant spawning stock escaping the fishery. All variability in growth is absorbed by current harvest. Getz, Francis, and Swartzman consider cases where payoffs are not linear in the current harvest rate. More recently, Lande, Engenand, and Soothor have shown that very conservative management may be optimal in a stochastic fishery with threat of extinction. All of these models exclude at least some of the following complications: hatchery and wild-mixed stock factors, density dependence, and cost or demand considerations that make the relationship between harvest and payoffs complex. Further, none of these models considers the opportunity for reducing uncertainty about future stock conditions and the consequent increase in value from improved de-

[1] Other studies of the value of improved forecasts include applications in raisin crop management and prices (Lave), frost forecasting (Baquet, Halter, and Conklin), irrigation (Glantz), air pollution (Adams, Crocker, and Katz), agriculture (Adams et al. 1995), and other economic activities.

cision making, which is the focus of this study.

If efficiency is a social objective, then fishery managers seek to maximize the present value of welfare derived from the fishery. Assuming risk neutrality, the objective is equivalent to maximizing the sum of expected discounted net value (NEV). Solving for the optimal management path yields the expected net present value (NPV) from time t, which can be expressed as

$$(1)\quad \mathrm{E}\{NPV_t(y_t)\} = \mathrm{E}\{\max \sum_{s=t}^{T} NEV(\mathbf{u}_s, \mathbf{y}_s)\delta^s\},$$

$$\text{subject to } y_{s+1} = f(\mathbf{u}_s, \mathbf{y}_s, \varepsilon_s\{x_s\}),$$

$$y_t \text{ given}, \qquad \mathbf{y}_s \geq 0 \quad \text{for all } s$$

where $\mathbf{u}_s$ is a vector of control variables (harvest, hatchery production, and hatchery releases); $\mathbf{y}_s$ is a vector of populations in each age class (young, smolts, and adults); $\epsilon_s\{x_s\}$ is a random variable whose distribution depends on the El Niño phase, x_s; $f(\mathbf{u}_s, \mathbf{y}_s, \epsilon_s\{x_s\})$ is net growth; and δ is the discount factor. Uncertainty enters the bioeconomic model via the state equation where stochastic El Niño events affect coho growth and survival. Using Bellman's principle of optimality, we can rewrite the maximization problem as

$$(2)\quad PV_t(y_t) = \max_{u_t} NEV(u_t, y_t) + \delta \cdot \mathrm{E}[NPV_{t+1}(y_{t+1})].$$

Dynamic programming is used to solve for an optimal solution, given the information structure. The value of information arises from allowing decision makers to reduce uncertainty prior to making a decision. We use Bayesian decision theory to solve for the value of information. The effect of water temperature (El Niño condition) on salmon survival is a continuous function. However, to accommodate available data and for ease of computation, we model El Niño as having discrete phases: normal (N), weak (W), and strong (S), the probabilities of which are constant through time. Specifically, this rules out serial correlation. We use N, W, and S to refer to discrete intensities of El Niño, affecting mortality and fecundity of coho salmon off the west coast of North America. Let z_t represent the forecast El Niño phase at time t. According to Bayes's Theorem, the posterior probability of the true phase, $x \in X$, given a forecast phase, z, is

$$(3)\quad \mathrm{prob}(x|z) = \frac{\mathrm{prob}(z|x) \cdot \pi(x)}{\sum_{x \in X} \mathrm{prob}(z|x) \cdot \pi(x)}.$$

The prior probability $\pi(x)$ is the historical frequency of true El Niño phase, x. An appropriate measure of forecast accuracy is the likelihood function, $\mathrm{prob}(z|x)$, or the probability of a particular phase forecast given the true phase. Realizations of forecast accuracy, described by the likelihood function, are employed, along with the prior distribution, to determine the posterior probabilities. This information is necessary for determining the probability that any particular phase will occur given a forecast.

If no forecast information is available, but the manager recognizes historical frequencies of occurrence, then decisions will be based solely on the prior distribution. By "updating" prior information with the likelihood function, the accuracy (or expected value) of the decision is increased. The value of information is a relative assessment, which must be judged against a "base case." The value of improved information is a random variable with distribution determined by the form of the objective function and error structure representing the uncertainty. In this analysis, the statistic of interest is the expected value of information, which is defined as the difference between the expected value of the objective function with and without the improved information:

$$(4)\quad \mathrm{E}\{VOI\} = \mathrm{E}\left\{\sum_{t=0}^{\infty} NPV(\cdot)\delta^t\right\}_{\phi} - \mathrm{E}\left\{\sum_{t=0}^{\infty} NPV(\cdot)\delta^t\right\}_{\psi}$$

where ϕ and ψ represent different information structures, completely defined by their respective posterior distributions.

Bioeconomic Model of the Coho Salmon Fishery

We now describe the bioeconomic environment in which stochastic dynamic programming takes place. Given our empirical em-

Table 1. Parameters of the Biological Growth Function under Various ENSO Phases

ENSO Phase	M_1	M_2	M_3	ρ	γ	θ	κ	ω	$\pi(x)$
Normal	0.25	0.15	0.1	30	0.2	6,821	3.5587	5.49	0.61
Weak	0.275	0.165	0.11	30	0.2	6,253	3.5587	4.45	0.25
Strong	0.3	0.18	0.12	30	0.2	5,684	3.5587	3.8	0.14

Source: Sampson 1995.

phasis on a fishery, this framework combines models and data from biology and economics. This section develops the biological and economic relationships necessary to evaluate welfare changes associated with alternative fishery management strategies.

Biological Model

The biological component of the stochastic model was developed by Sampson. This section describes the elements of the Ricker spawner-recruit model, as modified to accommodate the biological manifestations of El Niño events on coho salmon in the Pacific Northwest. Mortality, fecundity, and average weight for coho are modeled as random variables determined by the El Niño phase. This information is contained in several relationships and is needed to implement the biological growth function constraint specified in equation (1).

This cohort model employs a discrete-time approach that tracks each of the three age classes through time. Specifically, coho survival to a given month, τ, in their life cycle is modeled as an exponential function of time and natural mortality coefficients.[2]

$$(5) \quad S_1 = \exp(-M_1 \cdot \tau)$$

$$(6) \quad S_2 = \exp[-M_2 \cdot (\tau - 12)]$$

$$(7) \quad S_3 = \exp[-M_3 \cdot (\tau - 24)]$$

where S_i is the survival of coho and M_i is a random variable describing the natural mortality rate in year $i = 1, 2, 3$. For example, the percentage of coho surviving to month twelve of their life is $\exp(-12M_1)$, or between 2.7% and 4.9% depending on the El Niño phase (see table 1). An additional factor potentially limiting ocean survival of coho salmon is density dependence (Nickelson). Density-dependent mortality is reflected in the analysis by the following relationship:

$$(8) \quad dd(t) = \frac{1}{1 + \exp[\gamma(smolts(t) - \rho)]}$$

where $dd(t)$ is the density dependent survival at time t. At age eighteen months, the total stock of coho is multiplied by $dd(t)$, which is near 1 for low populations, and near 0 for very high populations. The parameters γ and ρ reflect the relative magnitude of the effect and the critical population at which density-dependent effects become significant, and smolts are the number of coho entering the ocean at eighteen months of age. The density dependence effect, which reflects the limited carrying capacity of the environment, is combined with natural mortality to determine the fraction of smolts that survive at eighteen months.

Wild coho that survive natural mortality all three years of their life, density dependence as they enter the ocean, and harvest while they are adults enter their natal streams to reproduce. Recruitment effectiveness is governed by the Ricker spawner-recruit model. The number of young coho salmon produced in a given year (t) is a nonlinear function of the number of adults that survived to spawn the previous year with two exogenously determined shifters, θ and κ, according to the following relationship:

$$(9) \quad young(t + 1) = \theta \cdot adults(t) \exp[-\kappa \cdot adults(t)]$$

where θ represents the initial slope of the recruit function (a measure of the number of young produced before any crowding takes place) and is treated as a random variable determined by the El Niño phase; and κ is the inverse of the number of adults (in millions) that maximizes the number of young produced. In the preceding cohort model, survival in each year is governed by equations

[2] The biological model uses a monthly time step. However, the economic benefits are measured annually. Therefore, in linking the biological and economic models, only the annual values are important.

(5)–(7), density-dependent mortality is described by equation (8), and spawning success is modeled by equation (9).

Average weight of adult fish, ω (in pounds), affects biological functioning indirectly via its influence on fecundity. It is possible that reduced weight during an El Niño event could carry through into future years. We did not find any evidence in the literature on this linkage between present weight and future survival. Therefore, we assume that fish whose weight is reduced during an El Niño event but also survive the event are able to recover in future non–El Niño years. However, average weight directly affects the economic decision model by influencing the ex-vessel revenue per fish since fishers are paid on a price per pound basis. Table 1 gives the values for each biological growth function parameter under the three possible El Niño phases that are used in the empirical analysis.

Economic Model

The economic model accounts for welfare impacts of management, including changes in consumer surplus and producer quasi-rents. This section describes the variables and general structure of the objective function of the optimization model. An explanation of the implementation of the benefits transfer approach, and calculation of each variable with citations for the source is provided.

Welfare measurement: components of value. Analysis of welfare changes in the commercial fishery includes both consumer and producer components. Profit is the most obvious measure of welfare to commercial fishers. Change in profit associated with a price change is an exact measure of both compensating and equivalent variation (Just, Hueth, and Schmitz). However, in the case of the effects of El Niño, welfare changes usually arise from changes in management rather than from changes in prices.

In the short-run, it is assumed that fixed inputs, such as boats, cannot be costlessly transferred to other activities. When a firm is faced with restrictive management that curtails production (harvest), it faces a loss associated with shutting down equal to quasi-rent (QR) (Just, Hueth, and Schmitz). Since profit underestimates the benefits accruing to a firm from staying in business, producer surplus and quasi-rent are more useful measures for use in economic welfare analyses. Because coho salmon from this region comprise a relatively small percentage of the world market for fresh salmon, prices are assumed to be unaffected by the onset of an El Niño event.[3] Thus, consumers are unaffected by year-to-year management changes in the Pacific Northwest coho salmon fishery.

Altered management and stock abundance also affects recreational anglers. Since income spent on recreational fishing likely comprises a small proportion of the total budget, welfare of recreational fishers is estimated as Marshallian consumer surplus. In the recreational fishery, consumer surplus is a measure of the net benefits to anglers from participating in the recreational fishery (beyond what they must pay to participate). The demand function for in-stream harvest takes the same general form as the ocean recreational demand, where total economic surplus is estimated with the consumer surplus resulting from changes in fishing success rates. The above welfare changes apply to use values. In the Pacific coho fishery, there is a social goal of maintaining viable wild (non-hatchery) populations of fish. Specifically, nonusers of the resource are assumed to derive satisfaction from knowing the wild salmon are sustained in viable, "healthy" populations. Such passive-use values have been measured for Pacific Northwest salmon by other researchers using hypothetical valuation methods (e.g., Olsen, Richards, and Scott). The resultant demand functions provide an estimate of changes in passive-use values associated with different population levels of returning adults. Finally, costs of producing fish for all of the above cases must be considered and should be subtracted from the economic components of value described above.

The benefits transfer approach (utilization of an existing valuation estimate from one study site to estimate benefits in an alternative setting) is employed to obtain estimates of these welfare components (Berrens, Brookshire and Neill).[4] The recreational coho salm-

[3] Because they are sold in fresh form, coho and chinook may occupy a niche market where large changes in harvest affect price. However, because the literature does not suggest a significant effect of El Niño on commercial species other than coho in the Pacific Northwest (most notably chinook), we model ex-vessel price as independent of the El Niño phase.

[4] The low cost and expedient nature of this approach make it attractive for use in prototypical analyses such as this. Errors created in the transfer of benefit estimates from one site to another are a function of the uncertainty in the differences between demand functions for recreation at the two sites.

on fishery is divided into three "use" components for the purposes of demand estimation: in-stream, ocean-charter, and ocean-private angling. Demand functions for each of these categories are derived from published literature for the Pacific Northwest region. Extant estimates are also used to formulate a demand curve reflecting the existence value of wild coho salmon. Similarly, producer quasi-rents accruing to charter boat operators and commercial harvesters are estimated using secondary cost and revenue data from the literature. Through optimization, the model chooses total harvest, which is allocated between various user groups according to current management guidelines.[5]

Objective function. The optimization criterion is to maximize the expected net present value (NPV) of the future stream of benefits from the commercial and recreational coho fishery subject to biological production function constraints, managerial constraints, and biological parameters which depend on the El Niño phase. That is, expected NPV is maximized over a discrete distribution of possible future events and other information. Undiscounted net economic value is expressed as follows:

$$(10)\quad NEV(t) = freshCS(t) + charCS(t) + privCS(t) + charQR(t) + comQR(t) + exist(t) - hsCOST(t)$$

where $freshCS(t)$ is consumer surplus from river recreational (freshwater) fishing in year t, $charCS(t)$ is consumer surplus from ocean recreational charter boat fishing, $privCS(t)$ is consumer surplus from ocean recreational private boat fishing, $charQR(t)$ is the producer quasi-rents (TR-TVC) generated in ocean recreational charter fishery, $comQR(t)$ is the producer quasi-rents (TR-TVC) generated in commercial coho fishery, $exist(t)$ is the existence value of wild coho, and $hsCOST(t)$ is the hatchery production cost.

Variable estimation. Numerous studies have analyzed the economic value of fisheries-based recreation and commercial fisheries (see Freeman and R.L. Johnson for reviews). However, few focus on coho salmon. Similarly, there are few studies that estimate costs of operating commercial fishing vessels and charter boats; of these, most derive point estimates for a few selected years. However, the literature does provide suggestions for estimating fishers' costs when data are scarce. Commercial and recreational surplus estimates are derived using published findings, historical data, and current management constraints.

Consumer surplus from in-stream angling. The demand for freshwater salmon angling in the region, expressed either on a per fish or per trip basis, has been estimated by several researchers (e.g., Meyer, Brown, and Hsiao; Loomis; Olson, Richards, and Scott; Adams et al. 1993). Estimated marginal values per fish ranges from \$7.50 to \$78. This wide range of marginal values is due, in part, to the different catch and population levels found in the cited studies. The estimate of demand for freshwater angling used here is based primarily on the results from Olsen, Richards, and Scott. An affine function approximates the demand curve for freshwater angling, as the data were inadequate for using a more complex functional form.[6] Using freshwater harvest of coho salmon from Columbia River tributaries and coastal streams, the following consumer surplus for freshwater angling results:

$$(11)\quad freshCS(t) = 52.64 \cdot freshH(t) - 133.27 \cdot [freshH(t)]^2$$

where $freshH(t)$ is the freshwater harvest of coho salmon (in millions).

Consumer surplus from ocean recreational angling. Some of the above studies also calculate consumer surplus in the ocean recreational fishery. In addition, Abdullah uses the travel cost method to value Oregon ocean sport-caught salmon. As with the studies estimating values from in-stream angling, ocean recreational angling models implicitly assume that anglers place more emphasis on quantity than weight of fish caught. None distinguish between private trips and charter trips, or, for

[5] Approximately 88% of total allowable catch is assumed to be harvested in the ocean, of which 80% is commercially harvested and 20% is taken by recreational anglers. See Costello or PFMC for further description of allocation guidelines and recent trends.

[6] Estimation of this demand curve and those that follow involves locating two points on the (assumed affine) demand curve using data on marginal values associated with certain catch levels (from the studies cited in the text).

the most part, between chinook and coho recreational angling. As with the estimates for freshwater angling, marginal values differ, from $21 to $65 per fish. The estimate of consumer surplus in the ocean recreational fishery again relies heavily on results from Olsen, Richards, and Scott. The following consumer surplus for ocean recreational charter angling is estimated:

$$(12) \quad charCS(t) = 56.30 \cdot charH(t) - 53.0 \cdot [charH(t)]^2$$

where $charH(t)$ is the charter catch of coho salmon (in millions).

Consumer surplus from private ocean recreational angling is estimated using the same average and marginal valuation estimate as the charter consumer surplus. However, the number of fish harvested each year is different, resulting in slightly different marginal values. This results in the following estimate of consumer surplus for ocean private angling:

$$(13) \quad privCS(t) = 56.29 \cdot privH(t) - 28.56 \cdot [privH(t)]^2$$

where $privH(t)$ is the private (i.e., noncharter, noncommercial) ocean catch of coho (in millions).

Consumer surplus from passive use of coho salmon. Current management of Pacific coho salmon includes managing the stock of wild fish for constant escapement. Wild fish provide ecological services, including enhancing biodiversity, adding nutrients to streams with decaying bodies, and providing an indicator of general aquatic ecosystem health. Thus, wild coho salmon likely have value beyond their traditional use-values. Legislation, including the Endangered Species Act (ESA), and current public sentiment appear to confirm this hypothesis. Olsen, Richards, and Scott included passive-use value questions for nonusers in a (CVM) survey. They estimate a passive-use value of approximately $17 per adult that returns to its natal stream (for a doubling of 1988 Columbia River salmon stocks). Adjusting this to 1995 dollars, 800,000 wild coho adults have a estimated marginal value of $20 per fish. The following exponential decay function for consumer surplus for wild spawners is used:

$$(14) \quad existCS(t) = 69.93 \cdot \{1 - \exp[-2.86 \cdot spawn(t)]\}$$

where $spawn(t)$ is the number of wild spawning coho salmon (in millions).

Quasi-rents to charter boat operators. Modeling quasi-rents accruing to charter boat operators requires an estimate of total revenue (TR) and total variable cost (TVC). PFMC data were used to estimate total charter trips, average charter fees, and charter fleet size with chinook charter catch and coho charter catch. See Costello for a detailed description of econometric analysis and results. Using these estimates, and the estimate of $14,260 in total variable costs per boat per year (Carter and Radtke), yields the following estimate of quasi-rents to charter boat operators:

$$(15) \quad charQR(t) = 16.73 \cdot charH(t)$$

where $charH(t)$ is charter harvest (in millions) of coho salmon in year t.

Quasi-rents to commercial harvesters. Determining quasi-rents accruing to commercial fishers is a more complex task. Real price per pound for coho salmon has decreased substantially since the late 1970s, from an average price per pound of $2.50 in the 1970s to $1.15 per pound in the 1990s (PFMC). We assume a constant price per pound of $1, reflecting the price decrease coincident with the probable continued increase in farmed salmon worldwide.

Commercial harvesters face variable costs tied to effort. They also face costs that are independent of the level of fishing intensity. In the case of salmon fisheries, variable costs are generally modeled as a percentage of total revenue (Carter and Radtke, King and Flagg, Rettig and McCarl, others). Carter and Radtke estimate that variable costs are approximately 72% of revenues. Components of costs that depend on fleet size should be included.[7] Historical data are used to estimate maintenance costs, vessel size, and fleet size changes in response to altered harvest levels. These important components are incorporated into the variable cost calculation, as the bracketed term in equation (16), resulting in the following estimation of commercial fishery quasi rents [$comQR(t)$]:

[7] It is assumed that these costs could be avoided if the fisher decided, prior to the beginning of the season, that he or she would not participate in the fishery.

$$(16) \quad comQR(t) = 0.28 \cdot comH(t) \cdot \omega(t) - [0.358 + 0.735 \cdot comH(t)]$$

where $comH(t)$ is commercial harvest (in millions) and $((t)$ is average weight (in pounds) of coho salmon.

Hatchery production costs. Hatchery production costs are estimated from unpublished Oregon Department of Fish and Wildlife (ODF&W) budget data. Using the ODF&W estimate of $2.45 per pound of young coho produced, and assuming eleven fish per pound, the following hatchery production cost relationship is estimated:

$$(17) \quad hsCOST(t) = 0.22 \cdot hsprod(t)$$

where $hsprod(t)$ is hatchery production (in millions) of coho salmon in year t. All components of the economic model rely on hatchery production, which are funded by license fees and other taxes.[8]

Decision models and solution procedures. The net present value of the Pacific Northwest coho salmon fishery is assessed under seven models that reflect El Niño predictions of varying accuracy and time frame. A comparison of values across the seven models requires information summarized by the posterior distribution of each forecast. Improving the forecast "time frame" refers to lengthening the period of advance notice of an event.

The first three models represent possible management strategies that do not depend upon obtaining signals of the likelihood of future El Niño phases. The first model ("naïve") assumes that managers of the coho fishery are ignorant of the possibility and effects of El Niño on coho salmon stocks and manage based on the anticipation of normal conditions.[9] The second model ("certainty equivalence") assumes that fishery managers know the prior distribution of events and manage based on the expected, or average, event. In the third model ("hedge"), managers are assumed to maximize the expected net present value of the coho fishery.

Four models with enhanced information are evaluated and compared to the three previously described models. The first of these models assumes a likelihood function halfway between a perfect, one-year forecast and no forecast at all ("improved one-year"). The posterior distribution for the improved one-year model is as follows:

	Z_N	Z_W	Z_S
X_N	0.805	0.125	0.07
X_W	0.305	0.625	0.07
X_S	0.305	0.125	0.57

For example, if the true state is normal, the probability of getting a forecast of "normal" is 80.5% instead of 61% as in the case with only historical frequencies. The "perfect one-year" model assumes perfect, consecutive El Niño forecasts one year in advance. Future years (more than one year from the planning date) are assumed to follow the prior distribution of events. The "perfect two-year" model assumes perfect, consecutive two-year information. Finally, the "perfect T-year" model assumes that the El Niño phase for every year in the future is known with probability one. Although it is unlikely that El Niño (or any meteorological event) will ever be predicted with perfect accuracy, the seven forecast scenarios investigated here span the range of possible prediction accuracy levels. Results thus provide instructive insight into management under varying forecast abilities. The models and their associated objective functions are depicted in table 2.

The seven models are solved using the General Algebraic Modeling System (GAMS) software package and the Minos-5 nonlinear programming algorithm. Ideally, the models would be evaluated over an infinite planning horizon. Because of computational time constraints, it was necessary to abbreviate the solution procedure.[10]

Because the value of improved information is the difference in the expected value of

[8] Production of wild fish involves opportunity costs of foregoing timber harvest and other development that might influence the riparian ecosystem, negatively impacting spawning and rearing habitat of wild fish. While such costs of producing wild fish are relevant for a thorough accounting of benefits and costs, estimating these opportunity costs are beyond the scope of this analysis.

[9] Evidence from 1982–83 suggests that managers did not anticipate the strong El Niño event, or manage in an attempt to mitigate the potentially devastating effects of a strong event.

[10] The six models without improved information each require $3^T + 3^{T-1} + \ldots + 3$ numerical approximations and are evaluated over an eight-year planning period. The model of improved information requires an order of magnitude more runs and is evaluated over a four-year horizon. Annualized NPV and VOI estimates are calculated from results of these simulations using a discount rate of 4%.

Table 2. Description of Management Decision Models

Model	Objective Function and Description of Information
1. Naïve	max *NPV*[*u*, *N*], always expect normal ENSO conditions, no forecast
2. Certainty Equivalence	max *NPV*[*u*, E{*state*}], manage based on the average event, no forecast
3. Hedge	max E[*NPV*(*u*, *x*)], relax certainty equivalence, no forecast
4. Improved, one-year	max E[*NPV*(*u*, *x*)], imperfect, consecutive, one-year forecasts
5. 1-yr, perfect one-year	max E[*NPV*(*u*, *x*)], perfect, consecutive, one-year forecasts
6. 2-yr, perfect two-year	max E[*NPV*(*u*, *x*)], perfect, consecutive two-year forecasts
7. T-yr, perfect T-year	max E[*NPV*(*u*, *x*)], perfect, consecutive T-year forecasts

the fishery under two forecast/management scenarios, the parameters must be judged relative to a base case. The base case chosen for this analysis is the naïve model. This assumes that managers ignore El Niño forecasts; to the extent that managers incorporate some ocean-climate data, the value of information results presented below may be overestimated.

Results

The various decision models (El Niño phases) and sensitivity analyses generate a large number of model solutions, each with a corresponding set of values for variables of policy or management interest. This discussion of results distills the key findings and features of these model solutions, starting first with an assessment of how well model outputs compare with historical levels of important management variables.

Comparing Historical Averages with Optimal Values

Four optimal control and state variables are important in comparing model output with historical management: harvest, proportion of the stock harvested, hatchery releases, and wild coho escapement.[11] Values of each variable identified above, along with historical averages from 1971–1993, are shown in table 3. While the optimal values are not expected to correspond to historical averages (which reflect less than optimal management), the naïve model is closest to current management; it is used here to assess the reasonableness of the modeled output. The first three variables investigated (harvest, proportion harvest, and wild escapement) under the naïve model are similar to historical averages. However, a major difference occurs with respect to optimal hatchery releases. In this model, increased hatchery releases have three effects on the fishery. First, hatchery fish are costly to produce. Second, producing more smolts (up to a point) results in more fish to harvest when they mature. Finally, more hatchery fish translates into higher density dependent mortality, resulting in lower wild fish stocks. Here, the optimal solution under the naïve assumption shows releases of approximately one-fifth the 1971–93 annual average (of 42 million). This finding is consistent with recent evidence suggesting that a large reduction in hatchery releases would improve the management of the fishery (National Research Council). Overall, these comparisons suggest that output from the model is plausible in a long-term context.[12]

A brief discussion of the relative contribution of each measure of welfare to the total value of the fishery aids in understanding which components are driving model results. Our results indicate that commercial harvesters account for approximately 1% of total surplus, recreational users capture about 33%, and passive-use values account for about 66% of total surplus. The low contribution of commercial rents to total value is consistent with findings that entry of operators into a fishery, and their reluctance to exit, drives profits to near zero, except in very high yield years. Conversely, the large contribution of passive-use value is consistent with the current emphasis on wild stock enhancement by fisheries managers. As an example of strong public preference for wild stocks of salmon, the Bon-

[11] Reported statistics are year-two values for a "generalized" model simulation where average El Niño conditions occur every year.

[12] Sensitivity analyses suggest that the values of information are robust to fairly large changes in model parameters and assumptions. Value of information was found to increase without the assumption of density dependence and to decrease with lower existence values and lower commercial harvesting costs.

Table 3. Comparison of Naïve Model Values with Historical Averages

Variable	Model Value (millions)	Historical Average (millions)
Harvest	1.86	1.75
Proportion harvest	0.54	0.62
Wild escapement	0.42	0.50
Hatchery releases	7.93	42.00

neville Power Administration spends approximately $400 million per year on salmon enhancement in the Columbia system alone.

Value of Information

Model results are evaluated relative to the naïve case and the value of information is reported on an annual basis in table 4. Specifically, the numbers reported in the table are the difference between the value of the objective function of the naïve model and the value of the objective function under alternative planning horizons and information assumptions. The value of the Certainty Equivalence and Hedge models exceeds that of the naïve or base case, suggesting that even minimal information on El Niño events may have value if used by management agencies.

A one-year perfect forecast is much more valuable than a one-year improved forecast ($902,000 vs. $435,000 annually). Because an imperfect forecast may not change escapement targets significantly relative to no forecast, losses associated with suboptimal decisions may be large. These results are different from those in other settings (e.g., Adams et al. 1995 for agriculture) where improved forecasts were nearly as valuable as perfect forecasts. We should emphasize that the values estimated here (for any information case) are a small percentage of the objective function values. For example, the annual value of a perfect forecast is 1.5% of the objective function total for the naïve case.

Finally, lengthening the forecast horizon has only a small effect on the value of the forecast; that is, a perfect forecast available two or more years in advance is not significantly more valuable than the one-year forecast. For example, a perfect forecast two years in advance is only worth $46,000 more than the perfect one-year forecast on an annual basis. The reason for this small additional value is that the majority of the value of information results from setting the appropriate escapement target, which can be accomplished with a one-year forecast.

Table 4. Annualized Expected Net Present Value and Value of Information

Model	E[*NPV*]	E[*VOI*]
Naïve	61.908	0.000
C.E.	62.045	0.137
Hedge	62.045	0.137
Improved	62.343	0.435
1-year perfect	62.810	0.902
2-year perfect	62.856	0.948
T-year perfect	62.908	1.000

Note: E[*NPV*] is the objective function value (in millions). E[*VOI*] is the change in objective function value (in millions) from the base (naïve) model.

Management Implications

A comparison of control and state variables under different strategies provides insights into management of the fishery. Representative output (in millions) from the certainty equivalence and one-year perfect forecast models are presented in table 5.

In the certainty equivalence case, management of the fishery reflects an expectation of average El Niño conditions that is independent of the true phase. When a perfect one-year forecast of El Niño is incorporated into management, optimal management changes and the forecast has value. For example, results indicate that when a strong El Niño is accurately forecast, the optimal strategy involves maintaining harvest rates (proportion harvested) at near non-El Niño levels, subsequently leaving a smaller stock of fish in the ocean than when normal conditions are forecast. This is a simple trade-off between harvest today and growth for the future; when expected future growth declines (when an El Niño is accurately forecast), immediate harvest is more heavily weighted, and the optimal strategy is to leave fewer fish in the ocean, favoring short-term gains over future growth.

Another variable of interest is wild coho escapement. The Pacific Fishery Management Council currently manages for a constant escapement of 200,000 wild coho salmon. Our results indicate that optimal escapement should be much higher—approximately 400,000 wild coho—and should not remain constant, especially when an accurate forecast

Table 5. Model Output (Millions) under Different ENSO Conditions

Model	Variable	Normal Forecast	Weak Forecast	Strong Forecast
C.E.	Harvest	2.01	2.01	2.01
	Proportion harvest	0.56	0.56	0.56
	Wild escapement	0.43	0.43	0.43
	Hatchery releases	7.86	7.86	7.86
1-yr perfect	Harvest	2.32	1.76	1.55
	Proportion harvest	0.59	0.53	0.54
	Wild escapement	0.44	0.42	0.33
	Hatchery releases	6.79	8.29	13.99

of future conditions is available. For example, when a strong El Niño is accurately forecast, wild escapement should decrease to below non-El Niño levels. However, optimal escapement remains, under any El Niño condition, above the current coho fishery escapement goal of 200,000. This decrease (to less than 400,000) in wild escapement in the face of an El Niño event arises from two factors. First, with strong El Niño events in the future, low yield is expected from each adult, and present harvest becomes relatively more attractive. Second, although the model includes passive-use value, it does not include an extinction risk. Incorporating such a risk would increase the cost of reducing wild populations and would likely increase optimal escapement when strong events are forecast. When faced with uncertainty concerning El Niño phases, fishery managers must mitigate the effects of possible future El Niño events. The greater the level of uncertainty, the stronger the burden to devise a hedging strategy. In this analysis, as uncertainty increases, the optimal policy is to manage based on the expected, or average, El Niño event (i.e., when an accurate forecast is unavailable, the optimal policy is to manage as if a very mild El Niño event will occur in every future year).

Results also indicate that a reduction in hatchery releases (from current levels) would increase the economic surplus from the coho fishery. This arises as a result of three factors. First, at $0.22 per fish, hatchery fish are expensive to produce. Second, density-dependent effects begin to take effect at around 15 to 20 million young. As more young are added to the system, the marginal contribution to total coho production decreases. The third reason is related to the mixed-stock fishery. Because fishers catch the same percentage of hatchery and wild fish, increased hatchery production leads to increased harvest of hatchery and wild fish. With the addition of the passive-use value term for wild fish, the optimal number of hatchery releases is decreased. The model indicates an equilibrium production level of approximately 8 million young fish, as compared with release levels over the last few decades of 30 to 40 million (PFMC). When a strong El Niño event is accurately forecast, optimal releases of hatchery fish increase substantially. However, as in the case of all control variables in this model, when forecasts are imperfect, optimal management is closer to the "no El Niño" case, resulting in moderate to low hatchery releases.

Conclusions

The overall purpose of this analysis was to develop a general framework for determining the value of improved ocean/climate forecasts to a marine fishery in a stochastic, dynamic setting. A specific objective was to apply the model to value improved consecutive El Niño forecasts in the coho fishery. A second specific objective was to determine the extent to which optimal management without a forecast can mitigate the adverse effects of El Niño.

The resulting numerical estimates of value of El Niño forecasts are intended only to be comparative ordinal measures of different information states, not measures of the economic efficiency of specific management policies. The results of this analysis indicate that improving short-term El Niño forecast accuracy and lengthening forecast time frame have value in a stochastic dynamic setting such as the coho fishery, although the net gains from even a perfect forecast are small relative to the model objective function value. Because management decisions made today affect biology, economic values, and management in the future, information regarding future ocean conditions has the potential to improve current decisions. This is particularly relevant in the case of the escapement of wild coho salmon, where optimal levels from all of the models developed here are much higher than current management goals.

In the case of this fishery, larger gains can be made from increasing the twelve- to eighteen-month forecast accuracy than from lengthening the time frame of the forecast. By comparing results from the one-year perfect and two-year perfect forecasts with the theoretically optimal T-year perfect forecasts, it is clear that only small potential gains exist beyond a one-year forecast.

Value of information analyses such as this can play a role in directing future research, as agencies determine where to allocate research and development funding for large-scale projects. Such studies can provide insight into the complex task of managing fishery resources, many of which are at or near historical lows. Future research in this setting should focus on more detailed models of the coho or similar salmonid fishery, particularly with respect to the influence of large, decadal shifts in ocean climate regimes. At present, lack of data on the frequency and forces behind these large shifts in climate regimes limits the application of economic assessments such as the one developed here.

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