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Christopher J. Costello for the degree of Master of Science in Agricultural and Resource Economics presented on July 9, 1996.

Title: The Value of Improved ENSO Forecasts: A Stochastic Bioeconomic Model Applied to the Pacific Northwest Coho Salmon Fishery.

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Richard M. Adams

The El Niño Southern Oscillation (ENSO) is the largest source of interannual variability in the global climate system. The capability to make predictions about ENSO is already in place and is likely to improve in coming years. Extreme phases of this phenomenon are associated with climatic effects that have economic consequences in sectors such as agriculture, energy demand, and fisheries. Fluctuations, and extreme interannual variability in stock sizes of U.S. Pacific fisheries, and specifically the coho salmon (*Oncorhynchus kisutch*) fishery, have been attributed, in part, to El Niño. Historically, the Pacific Northwest coho fishery is thought to have been severely impacted by ENSO, and strong El Niño events over the past 15 years are partly responsible for recent closures of both the commercial and recreational coho fisheries. Accurate predictions of future ENSO events, and associated variations in stock sizes are hypothesized to have value to society insofar as they are incorporated into management regimes. A bioeconomic model of coho salmon is developed with biological parameters stochastically determined by the ENSO phase. Uncertainty is modeled in a Bayesian information framework with the prior distribution of the ENSO phase updated by an annual forecast. The optimization criterion is maximizing the net present value of all future economic benefits by choosing optimal harvest rates, hatchery production, and hatchery releases. Economic benefits are measured as the sum of consumer surplus and producer quasi-rents in the commercial and recreational fisheries. Consumer surplus arising from existence values for wild spawning salmon is also included in this calculation. Naïve, improved, and perfect one-year forecasts are evaluated using nonlinear optimization and stochastic simulation. Results indicate that developing a perfect, one-year forecast of the ENSO phase is worth approximately $19 million over a 50 year planning horizon if it is incorporated into management of the coho fishery. This equates to an annual gain of approximately 2 percent of the annual value of the fishery. Results also suggest that optimal management when a perfect forecast is unavailable involves hedging with a conservative management strategy. Given the bioeconomic objective function defined in this analysis, "conservative" management involves low harvest, high escapement, and low hatchery releases as compared with a perfect forecast of strong ENSO conditions.

The Value of Improved ENSO Forecasts: A Stochastic Bioeconomic Model Applied to the Pacific Northwest Coho Salmon Fishery

by

Christopher J. Costello

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Christopher J. Costello, Author

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1. INTRODUCTION

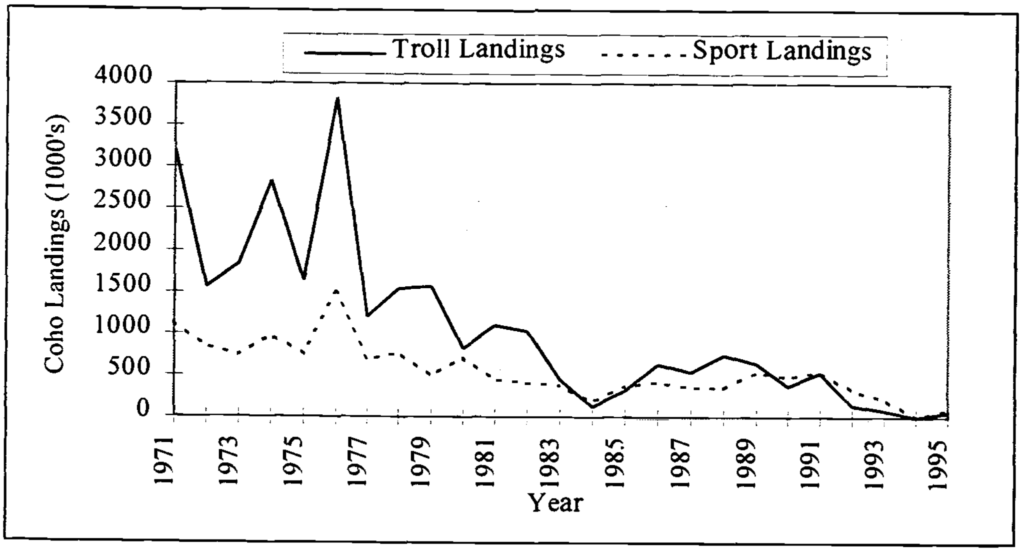
The El Niño Southern Oscillation (ENSO) is the largest source of interannual variability in the global climate system. Strong ENSO phases, El Niño events, are characterized by a reduction in intensity, or sometimes even a reversal of trade winds, resulting in a buildup of warm ocean water off Peru and Ecuador. During strong El Niño events, these effects extend into the northeastern Pacific Ocean, affecting biological and climatological functions in North America (Pearcy and Schoener, 1987, Barber and Chavez, 1983). Ocean and inland climate effects associated with El Niño have large economic consequences in sectors such as agriculture, energy, and fisheries. The ability to predict El Niño, the Pacific Ocean manifestation the El Niño Southern Oscillation, is already in place and forecast accuracy is likely to improve in coming years (Adams et al., 1995; Barber and Chavez, 1983).

ENSO forecasts have economic value insofar as they are incorporated into management strategies which mitigate the adverse effects described above. For example, with an accurate one-year forecast of El Niño, farmers may choose a crop mix that is less sensitive to weather, energy suppliers may hold more energy in reserves, and fisheries managers may initiate more conservative management strategies in anticipation of the event. Some of the potential benefits from accurate ENSO and other climate forecasts have been assessed (see Adams et al., 1995 for the value of ENSO forecasts; Mjelde and Frerich, 1987 for a comprehensive review of value of climate forecast studies).

Pelagic fish species are susceptible to the extreme interannual variability of ocean conditions which accompanies El Niño. For example, the collapse of the Peruvian anchovetta fishery in 1972 was attributed, in part, to El Niño. In North America, many Pacific salmon stocks have undergone precipitous decline since the late 1970's (Pacific Fishery Management Council, 1996). Although several factors have been implicated in this decline, the severe El Niño of 1982-1983 and subsequent weaker, but extended, El Niños are believed to have contributed (Johnson, 1988b). Extreme interannual variability in commercial fish stocks, attributable in part to El Niño, has resulted in reduction or temporary elimination of several fisheries, including the complete closure of the recreational and commercial coho salmon

(*Oncorhynchus kisutch*) fisheries off California, Oregon, and Washington in 1994 and closure of the commercial coho fishery off California and Oregon in 1995 (PFMC, 1996). A time series graph of commercial and recreational ocean harvest of coho salmon from 1971 through 1995 is depicted in Figure 1.1.

Figure 1.1 Historical landings of coho salmon in the OPI area.



Drastic reductions in fish stocks have clear economic consequences to recreational users, commercial fishers, and indirect users of the salmon resource. Improved ENSO forecasts may allow fishery managers to make more effective decisions and avoid drastic, short-term measures such as the recent coho fishery closures.

1.1 Problem Definition

El Niño is the Pacific Ocean component of a global climate system called the southern oscillation, which stretches between Indonesia and the Indian Ocean to the shores of East Africa (Bragg, 1991). The two phenomena are combined and called the El Niño Southern Oscillation (ENSO). This climatic, oceanographic phenomenon has been described as "a sort of seesawing balance between ocean and atmospheric currents that control weather across much of the globe" (Bragg, 1991). The southern oscillation index, which measures the difference in pressure between Easter Island and Darwin, Australia, is an indicator of the onset of an El Niño event. The coho salmon fishery on the west coast of North America was severely impacted in 1982-1983 by what some describe as the most severe El Niño event this century (Pearcy and Schoener, 1987).

In 1983, wild coho returns to Pacific Northwest streams were only 42 percent of the fishery management agency's preseason prediction (Johnson, 1988b; PFMC, 1995). Subsequent year returns indicated that mortality of all age classes was increased, fecundity (number of eggs per female) was reduced, and average weight of adults was reduced (Johnson, 1988b; Pearcy and Schoener, 1987; Barber and Chavez, 1983). As a result of this abrupt decline in coho stock abundance, harvests in both commercial and recreational ocean fisheries were greatly reduced. Annual harvest of coho salmon in the Pacific Fishery Management Council (PFMC) area (California, Oregon, and Washington) averaged 2.1 million fish in the 1970's, 620 thousand fish in the 1980's, and just 350 thousand fish in the 1990's (PFMC, 1996). Causes of this decline include several anthropogenic factors such as construction of dams, destruction of spawning and rearing habitat, high harvest rates, and hatchery introductions. However, oceanographic phenomena such as El Niño and longer-term, decadal shifts in ocean climate regimes, are believed to be equally responsible (NMFS, 1995; Hare and Francis, 1995; Beamish, 1993; Nickelson, 1985).

Prior to 1995, stock predictors used by the Pacific Fishery Management Council, the primary salmon management agency along the Pacific Coast, did not include ocean conditions as an explanatory variable. In 1995 and 1996 the predictor for wild coho returns included *current* ocean conditions, but no forecast of *future* ocean conditions was incorporated (PFMC, 1995). Because fishery managers must commit to various management actions before the season starts, and because management takes place in a dynamic setting where management in one year relies on predictions of uncertain conditions in future years, forecasts of ocean conditions are hypothesized to have value.

Economists have studied the value of improved weather forecasts for decades, with applications in raisin crop management and prices (Lave, 1963), forest management (Thompson, 1966), frost forecasting (Conklin et al., 1977; Baquet et al., 1976), irrigation (Glantz, 1982), acid deposition (Adams and Crocker, 1984), corn production (Mjelde et al., 1993), agriculture (Adams et al., 1995), and other economic activities (see Mjelde and Frerich, 1987 for a comprehensive review). Adams et al. (1995) estimated the value of improved and perfect ENSO forecasts to agriculture in the southeastern United States using models from meteorology, plant sciences and economics. They conclude that the net present value of perfect ENSO forecasts to agriculture is approximately $145 million.

To date, no systematic analysis has been conducted on the value of improved climate forecasts to an ocean fishery. One possible explanation for this is the dynamic nature of fisheries. Unlike agriculture, where crop decisions are assumed to be flexible enough to change the planting mix annually, decisions in fisheries must account for effects of current management on all future populations. A stochastic fisheries model of this type also assumes that a different ENSO phase can occur in every future year. Thus, all possible combinations of different ENSO phases must be evaluated to solve the problem. Introducing a dynamic biological production model into this stochastic information framework has not been attempted.

1.2 Objectives

Within the scope of this broadly defined problem, there are three primary objectives of this thesis. The first objective is to develop a framework for assessing the value of improved weather information using a dynamic biological population model with stochastic parameters. This methodology will be sufficiently general in format to apply to any dynamic modeling situation.

In the second objective, the valuation framework will be adapted to assess the value of improved forecasts as they are incorporated into the management of coho salmon off California, Oregon, and Washington. Assessed value of improved forecasts provides useful information to policy-makers who must decide whether to fund research on forecast development. As mentioned in the Introduction, the ability to forecast ENSO events is currently in place, although its accuracy is only slightly better than “guessing”. In this empirical analysis, the value of consecutive, improved and perfect, one-year forecasts will be assessed. The value of these forecasts will be measured against a base case, which is calculated using historical frequencies of ENSO events. The forecast time frame for all forecast accuracy levels will be one year. That is, every year, managers receive a forecast of the next year’s ENSO phase, which they then incorporate into current management.

The third objective of this thesis is to determine the extent to which hedging can mitigate the effects of El Niño in the coho fishery. Without a forecast, managers facing an uncertain future must somehow choose control variables such as harvest and hatchery releases. Optimal management includes accounting for the historical frequency of ENSO phases, and hedging accordingly. Optimal management strategies without a forecast are explored, and various management strategies are compared, each assuming different expected ENSO events in the absence of information. This preliminary, prototype study will provide a foundation from which further, more detailed analysis can be built.

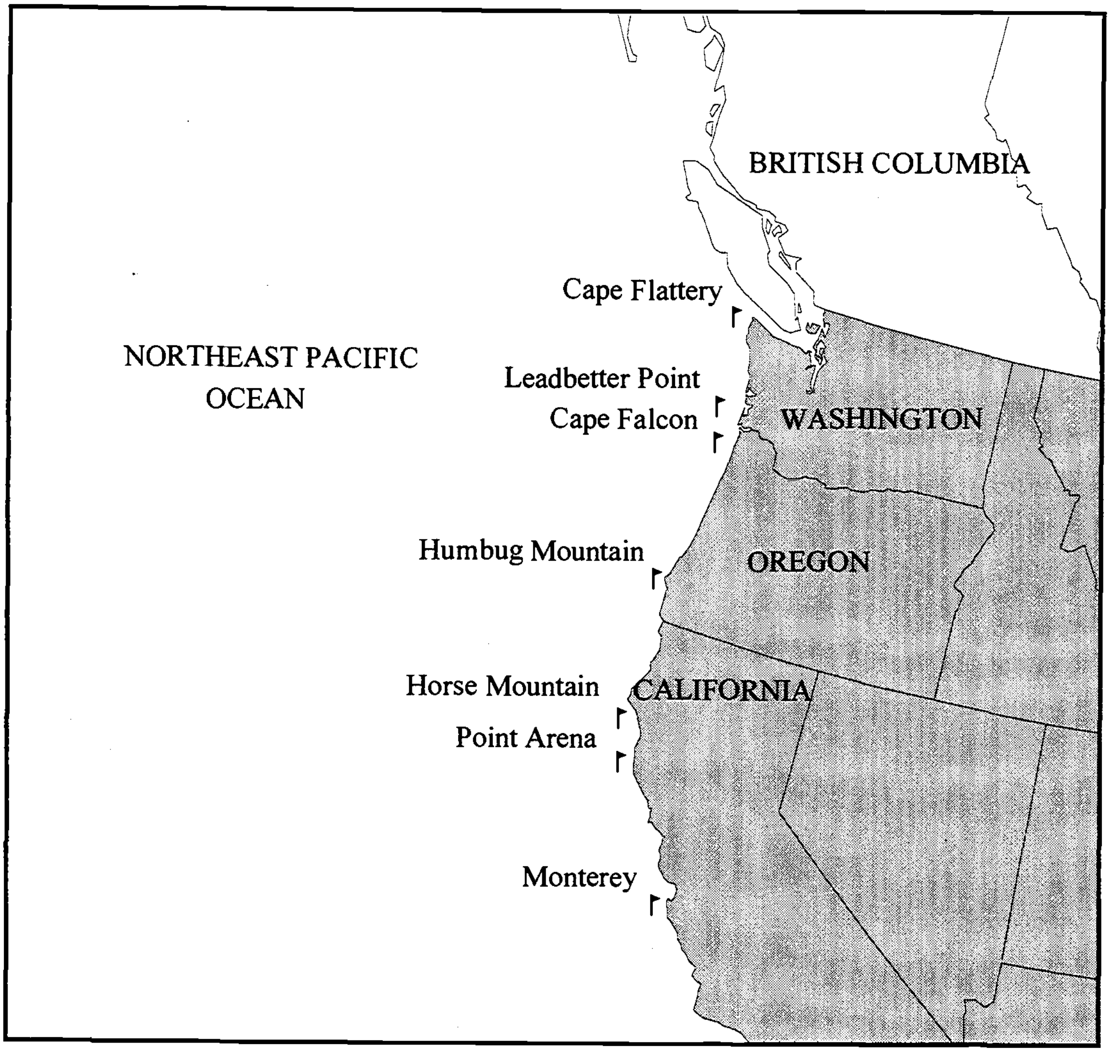
1.3 Study Area and Scope

The range of coho salmon in North America extends from Point Hope, Alaska, to Monterey Bay, California. In the Pacific Northwest, salmon stocks are managed by the Pacific Fishery Management Council and include stocks off California, Oregon, and Washington. Figure 1.2 shows the PFMC management area. Coho in this region are particularly susceptible to variability in ocean conditions because this is the southernmost range of the species (Oregon Department of Fish and Wildlife, 1995). Evidence suggests that ENSO does not negatively impact salmon stocks farther north. Alaska salmon abundance data, for example, demonstrates no appreciable correlation between coho abundance and El Niño (Pearcy and Schoener, 1987).

Although coho migrate throughout the Pacific Ocean, most stocks originating in the Pacific Fishery Management Council area remain near the coast of the United States. To simplify analysis, this assessment focuses on coho stocks managed by the PFMC which include all stocks, hatchery and wild, south of the United States-Canada border.

This analysis focuses only on coho salmon (*Oncorhynchus kisutch*). Several other species which may be affected by El Niño are not considered. For example, chinook salmon (*Oncorhynchus tshawytscha*), another important Pacific Salmon species, are omitted from this analysis due to uncertainty within the scientific community regarding El Niño's effect on this species. However, some evidence suggest a negative influence of particularly strong El Niño events on chinook salmon. The 1982-1983 ENSO event reduced the size of many of Oregon's chinook stocks to well below expected returns (Johnson, 1988b). Generally, during this devastating event, chinook stocks that reared in the ocean south of Vancouver Island had reduced productivity, while chinook that inhabited more northerly portions of the Pacific may not have been impacted at all (Johnson, 1988b; Pearcy and Schoener, 1987).

Figure 1.2 The Pacific Fishery Management Council area.



Chinook escapement to in-river fisheries, hatcheries, and coastal spawning grounds was reduced in 1983 compared with recent years (Johnson, 1988b), but there was no noticeable increase in pre-spawning mortality. Further evidence suggests that the 1983 El Niño did not interfere with the ability of chinook to spawn, and fecundity was apparently not affected (Johnson, 1988b).

The forthcoming model and solution procedure can be adapted to accommodate any species for which the state equations under various ENSO phases are assumed known.

Although all species are affected differently by the onset of El Niño, its manifestations both inland (e.g. effects on stream flow and spawning habitat) and in the ocean (anomalously warm temperatures) make El Niño events especially important to anadromous species. Specifically, the life-history of anadromous species such as coho salmon make them particularly susceptible to environmental stochasticity and, in general, more difficult to manage than strictly marine species. The historical distribution of coho salmon included several major drainages in the Pacific Northwest region. The major basin within the PFMC management area is the Columbia River system, which includes the Columbia and Snake rivers. Historically, the Columbia system supported large runs of coho salmon, but, following construction of hydropower generating dams in the Columbia and Snake systems, nearly all wild stocks have been extirpated. Wild populations of coho in Columbia Basin tributaries from the Deschutes River to Snake River tributaries became extinct between 1900 and the mid 1980's (ODFW, 1995). Other major drainages within the PFMC area include the Sacramento River where mining, logging, and agriculture have been implicated in the extirpation of nearly all wild coho stocks, and the Klamath-Trinity River system, where most coho are propagated in hatcheries, and natural production is minor (Brown et al., 1994).

1.4 Thesis Organization

This thesis consists of seven chapters. Chapter two provides a theoretical framework for the problem defined above. This involves a discussion of stochastic bioeconomic models, including a general biological production model with stochastic parameters and a model capable of measuring changes in economic welfare. The basic theory of stochastic dynamic programming is presented and the theoretical optimization solution is discussed, along with a description and discussion of the principle of certainty equivalence. Finally, the theoretical method for assessing the value of information in a stochastic, dynamic setting is presented.

Chapter three introduces the biological model of coho salmon production. The biological consequences of El Niño are presented, and the classic Ricker spawner-recruit model defined. Hatchery stocks are included in the model to more closely approximate current management, and the economic and biological ramifications of the wild-hatchery fish mixed-stock fishery are discussed. To conclude this chapter, current management of the coho fishery is discussed, including stock predictors currently employed by the Pacific Fishery Management Council.

The formal economic decision model is presented in chapter four. The objective function for each model is described and alternatives to economic efficiency are discussed. The "Benefits Transfer" approach, used to calculate various components of economic value, is described. Changes in the components of economic value, including producer and consumer surplus in both the commercial and recreational fisheries, and existence values to nonusers, arising from alternative management options, are presented.

A discussion of various decision criteria for each model is presented in chapter five. Five models, with increasing proximity to "optimal" management of the coho fishery are described. These include a case, defined as a naïve model, where the manager ignores the possibility of ENSO events. A constraint of certainty equivalence is placed on the second model, and is relaxed on the third. The final two models involve increasing one-year forecast accuracy to improved, and perfect, one-year forecast of the ENSO phase.

Results from the various models are discussed in chapter six, beginning with an estimation of the expected net present value under each information structure described above. The value of hedging and the value of improved ENSO forecasts is assessed. Procedures used to extrapolate the results to longer time horizons are discussed. Finally, results of sensitivity analyses, testing the "robustness" of the estimates of the value of information, are described.

In chapter seven, a summary and discussion of the findings is presented. Management implications of the analysis are reviewed, including a discussion of implications to hatchery management, harvest management, and allocation between commercial and recreational fisheries. The analysis concludes with a brief discussion of recommended future research in the area of stochastic bioeconomic modeling, with specific suggestions for assessing the value of improved ENSO forecasts to the coho fishery in the Pacific Northwest.

2. THEORETICAL BIOECONOMIC MODEL

Calculating the value of improved ENSO forecasts to the coho fishery requires the development and eventual combination of models and data from biology, climatology, and economics into a composite bioeconomic model. This chapter addresses the components of a bioeconomic framework for assessing the value of improved information in a dynamic, stochastic setting.

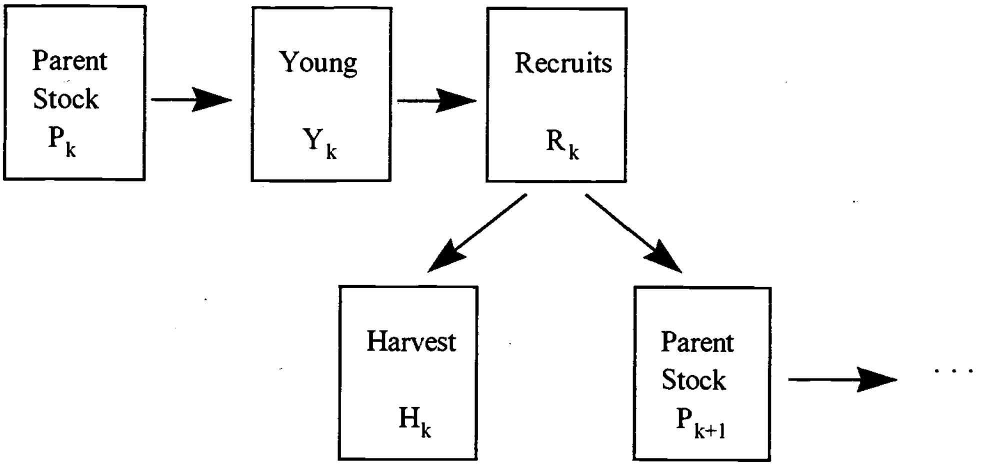
To describe the theoretical bioeconomic model, it is necessary to define the relationship between biological production and economic objectives. As Clark (1976) points out, most natural biological populations are subject to complex dynamic processes that cannot be encompassed by simple continuous-time models of biological production. This description follows the theoretical framework for modeling discrete-time “metered” biological populations presented by Clark (1976).

2.1 Biological Modeling

Metered biological models consist of two components; a first order difference equation $y_{k+1} = F(y_k)$ where the population at time $t = t_{k+1}$ is a function of the population in the previous time period $t = t_k$, and a function $F(y_k)$ which represents a general growth function which depends on some assumed biological processes of birth and mortality occurring between time periods (t_k, t_{k+1}). The dynamics of the entire life-cycle of the species is characterized by these components where the short-term dynamics are described by the difference equation above (Clark, 1976).

Following Clark (1976), the parent stock of the $k^{\underline{th}}$ generation (P_k) produces some number of young (Y_k), which ultimately provide recruits (R_k). Some proportion of the stock may be harvested (H_k), and those that “escape” the fishery become parent stock (P_{k+1}) of the next generation. These relationships are graphically represented in Figure 2.1.

Figure 2.1 Flow diagram of salmon growth and harvest.



In this analysis, P_{k+1} is referred to as the escapement. The theoretical biological model described in this section assumes that the harvest takes place immediately prior to spawning. This restrictive, and perhaps unrealistic assumption will be relaxed and modified in the empirical model of the coho fishery (Chapter 3). The general model implies that recruits in time $t = t_k$ are some known function of the parent stock that period: $R_k = F(P_k)$. The growth function F(P) is referred to as the spawner-recruit relationship. The dynamics of this general, simplistic model are characterized by:

$$P_{k+1} = R_k - H_k = F(P_k) - H_k \text{ or,}$$

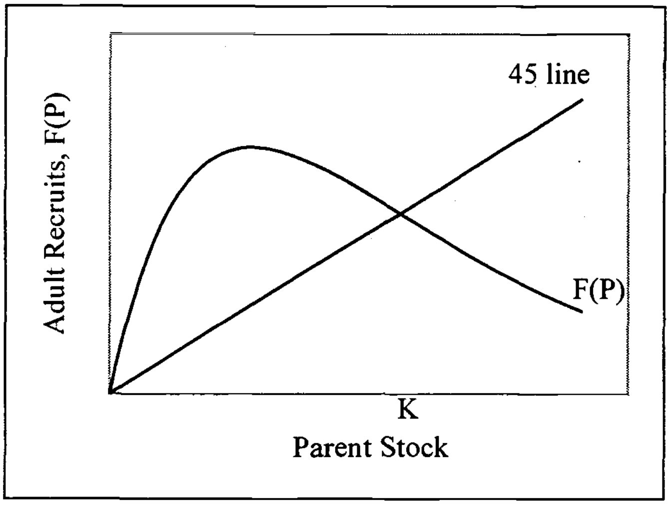
$$R_{k+1} = F(P_{k+1}) = F(R_k - H_k)$$

The dynamics of an unexploited (unharvested) population are calculated recursively by:

$$P_{k+1} = F(P_k)$$

One frequently-used form of growth (spawner-recruit) relationship is the “overcompensation” function depicted in Figure 2.2, where the spawner-recruit relationship is concave (not monotonically increasing, as in the case of “compensation” or “depensation” models). Functions of this general shape are often used to describe species of fish, such as salmon, which habitually cannibalize their eggs and larvae (Clark, 1976).

Figure 2.2 General non-linear stock-recruitment relationship with overcompensation.



The 45° line in Figure 2.2 represents all "steady-state" points where the number of adult recruits equals the parent stock from the previous time period. Equilibrium point P = K, where the population subject to growth F(P) is in steady-state, is characterized by F(K) = K. Following Clark (1976): Assume that F(P) is continuously differentiable. Let K be an equilibrium point such that F(K) = K. Then K is stable provided that:

$$-1 < F'(K) < 1$$

Conversely, K is unstable if $F'(K) > 1$ or if $F'(K) < -1$. For the purposes of this development, the point to note is that the overcompensation curve shown in Figure 2.2 is of the form $F(P) = Pe^{r(1-P)}$. This family of curves, called Ricker curves (Ricker, 1954), has been used extensively in Pacific salmon management (Clark, 1976).

Ricker (1958, 1954) assumes that the relative predation rate is proportional to the initial population of fry (L):

$$\frac{1}{N}\frac{dN}{dt} = -\kappa L, \ \ N(0) = L$$

where N(t) is the number of larval-stage fish alive at time, t.

In this case, both the fry population, L and the rate of predation are proportional to P. By assuming the larval population is proportional to the parent stock and the recruits are proportional to the young, and by solving the differential equation for N(T), Ricker (1954) obtains the following:

$$R = \alpha P e^{-\beta P}$$

which defines the family of Ricker curves. This generalized Ricker model assumes that the parent population P_k dies during spawning and is replaced the next time period by the subsequent cohort of recruits $R_k = P_{k+1} = F(P_k)$, an appropriate assumption for a semelparous population (one that reproduces only once before dying) such as coho salmon.

With the general spawner-recruit curve defined, it is appropriate to focus on the dynamics of each cohort between birth and spawning. The time interval (t_{k+1}, t_k) is the life-cycle length of the species in question, and, in the case of Pacific salmon, this interval varies from three to seven years. To further explore mortality and biological interactions, the model can be generalized to a multi-year life-cycle, equaling three years for coho salmon. Survival to the end of each of the θ years in the life-cycle may be expressed by a general function:

$$s_i(\theta_i, m_i)$$

where i indexes the life cycle year, s_i is a general survival function of the life-cycle year, and m_i represents natural mortality during year i. It is assumed that $s(\cdot)$ monotonically decreases through time.

At some specified point in the life-cycle of the species, the density of the stock may influence survival. This additional mortality term is usually expressed as a function which depends on the population of a particular cohort at the start of the density dependent phase, $d(\phi)$ with $0 \leq d(\phi) \leq 1$. Generally $d(\phi)$ is monotonically decreasing over all ϕ, reflecting the consistently negative effect of density dependence on survival. This function can be treated as an additional term, expressed as a proportion of the population of a particular age-class surviving the density-dependent phase of the life-cycle.

2.2 Economic Considerations

Interannual variability in biological, economic, and political factors translates into variable management decisions. More specifically, fluctuations in control variables such as harvest and hatchery releases have direct and indirect economic consequences. The model developed in this thesis focuses on the direct impact of management changes on economic efficiency. Assessing changes in net economic benefits accruing to fishers requires an understanding of both the commercial and recreational markets.

2.2.1 Net benefits to commercial fishers and charter operators

This section explores the theoretical estimation of changes in welfare accruing to commercial harvesters and charter operators. Thorough analysis of welfare changes in the commercial fishery includes a discussion of both consumer and producer components of the market. Perhaps the most obvious measure of welfare to commercial fishers is profit. Profit accruing to commercial harvesters and charter operators is the difference between total revenue and total cost:

$$\pi = TR - TC$$

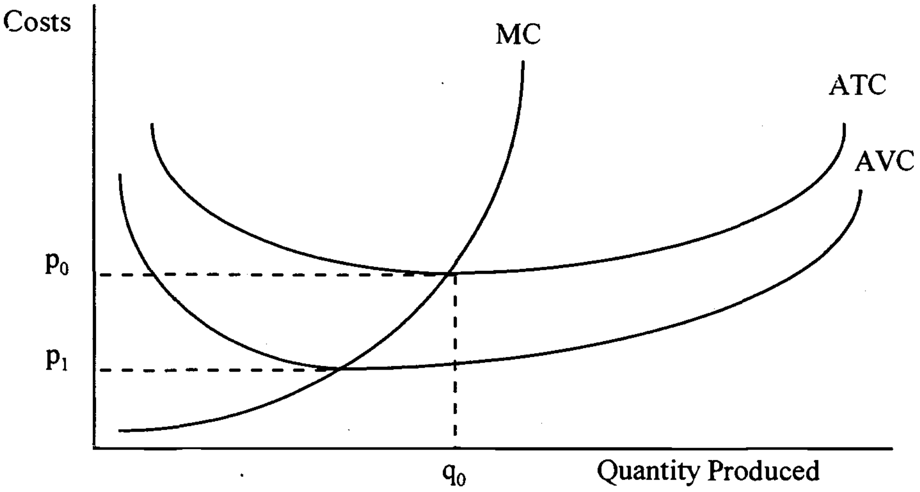
To determine the extent to which profit accurately measures welfare of producers, it must be compared with theoretically correct welfare measures: compensating and equivalent variation (Just et al., 1982). The compensating variation (CV) associated with a price increase is the sum of money that, when taken away from the producing firm, leaves it just as well off as if the price did not change (given that it is free to adjust production in either case). The equivalent variation (EV) associated with a price increase is the sum of money that, when given to the firm, leaves it just as well off without the price change as if the change occurred, again assuming freedom of adjustment. Therefore, the change in profit associated with a price change is an exact measure of both compensating and equivalent variation. However, in the case of a commercial fishery, welfare changes usually arise from changes in management which might, in the extreme, prevent fishers from producing in a given period.

In the short-run, it is assumed (by definition) that fixed inputs, such as boats, cannot be costlessly transferred to other activities. When a firm is faced with restrictive management which curtails production (harvest), it faces a loss associated with shutting down equal to total revenue minus total variable cost, called quasi-rent (QR) (Just et al., 1982).

$$QR = \pi + TFC = TR - TVC$$

This is called quasi-rent because it represents a temporary rent on the fixed factors of production which, unlike a resource rent, is not sustainable over the long-run (Just et al., 1982).

Figure 2.3 Generalized cost curves facing the firm.



The benefits to fishers from remaining in business, given by profit plus fixed costs, equals quasi-rent. Just et al. (1982) argue that because 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. The area above marginal cost (MC) and between p_0 and p_1 in Figure 2.3 is equal to producer surplus or quasi-rent. In the ocean recreational fishery, producer surplus accrues to charter boat operators. As in the commercial fishery, short-term profits may be interpreted as producer quasi-rents and are a relevant measure of producer welfare (Just et al., 1982).

Changes in supply of fish generally result in welfare changes to consumers as well. However, when suppliers from a localized region face a large, world market, they are likely to face a constant, exogenously given price. In this case, the net economic surplus consists only of producer surplus, as consumers are assumed to be unaffected by changes in supply from the region. However, in a detailed analysis of highly localized markets, where a premium may be paid for fresh product from that region, changes in price, and associated changes in consumer surplus, would likely be coincident with changes in harvest.

2.2.2 Net benefits to recreational fishers

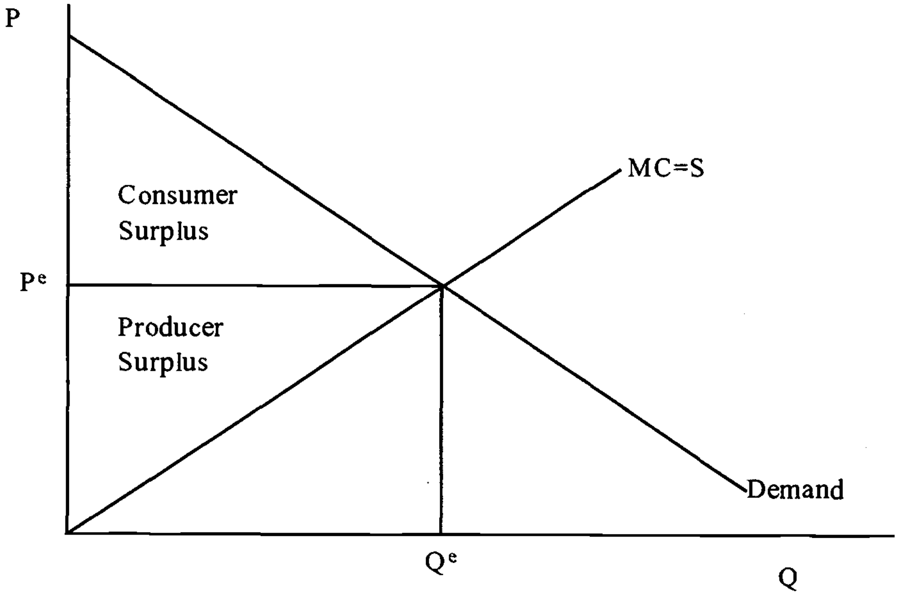
An assessment of changes in net benefits accruing to participants in the recreational fishery from altered management or stock abundance must contain a discussion of theoretically correct measures of welfare. Two measures with practical and theoretical appeal, particularly when applied to non-market valuation, are the compensating and equivalent surplus. The compensating surplus (CS) measures the compensating payment necessary to make an individual indifferent between an original situation and the opportunity to purchase a new quantity of a good whose price has changed (Freeman, 1993). Pragmatically, the compensating surplus measures the maximum willingness to pay for an improvement in an environmental amenity.

Equivalent surplus (ES) measures the change in income necessary to make an individual as well off as he would be with a new price set and his original consumption level. In empirical work, the compensating surplus measures the maximum required compensation to accept a decrement in an environmental amenity (Freeman, 1993).

Compensating variation (CV) and equivalent variation (EV), in the context of a consumer, share the same meaning as the previously discussed definitions for producers. Following Freeman (1993), CV may be interpreted as the maximum that the individual would be willing to pay for the opportunity to consume at a new price set. Freeman describes EV as the minimum lump sum payment the consumer requires to induce that person to voluntarily forgo the opportunity to purchase at a new price set.

One further welfare measure which is often employed in empirical work is Marshallian consumer surplus. Consumer surplus is measured as the area below the *ordinary* demand and above the price line. Figure 2.4 depicts the producer and consumer surplus.

Figure 2.4 Consumer and producer surplus.



Freeman (1993) indicates that although the Marshallian consumer surplus is intuitively attractive, it is not, in general, equal to either of the theoretically correct measures of welfare, CV or EV. However, Freeman points out that Marshallian consumer surplus does lie between CV and EV.

Willig (1976) offers a rigorous and intuitive explanation of the relationships between CV, EV, and Marshallian consumer surplus. Compensating and equivalent variation are derived directly from utility curves (as is the compensated demand curve) and Marshallian consumer surplus describes a graphical area, derived from an ordinary demand curve. Recall, the ordinary demand curve includes both income and substitution effects, while the compensated demand curve only includes substitution effects. For this reason, the differences between the three welfare measures depend on the income elasticity of demand for the good in question and consumer surplus as a percentage of income. Willig (1976) believes that for most realistic scenarios, the differences between the theoretically correct welfare measures discussed above and the empirically viable Marshallian consumer surplus appear to be trivial.

2.2.3 Obtaining a demand function

This section introduces the basic theoretical model, where the demand for a recreation site is derived from a generalized utility function. The individual is assumed to maximize his utility:

$$\max u(t, c, s, n)$$

where utility is a function of time spent at the recreation site (t), catch (c), other site quality characteristics (s), and a numeraire (n) capturing all other goods. This utility maximization problem is subject to time and budget constraints. Following Freeman (1993), suppose the number of visits to the recreation site and the quality of the site are compliments in the utility function. This implies that the number of visits to the site is an increasing function of the quality of the site. Employing this framework, and maximizing the originally defined utility function subject to time and budget constraints reflecting the opportunity cost of time, yields the individual's demand function for visits to the recreation site.

Recreational demand functions for catch or other aspects of the fishing experience can be estimated via non-market valuation techniques using direct methods, such as the contingent valuation method, or indirect methods, such as the travel cost method. Empirical implementation of the angler's choice problem generally involves estimating a demand function for visits to a particular fishing site, j (Loomis, 1988; McConnell, 1985):

$$T_j = f(p_j, c)$$

where trips to a site are a function of travel cost (p) to the site and catch (c). This simplistic model assumes that all site quality characteristics are captured in the catch variable. Once a demand schedule has been estimated, consumer surplus arising from changes in catch can be calculated (Loomis, 1988) and used to estimate changes in net benefits to recreational anglers arising from changes in stock abundance or fishery management.

In a recreational fishery, consumer surplus is a measure of the net benefits to anglers from participating in the recreational fishery and deriving satisfaction beyond what they must pay to participate. Economic surplus in the freshwater recreational fishery can be characterized by consumer surplus alone since no firm supplies the fishing experience, *per se*. 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 are assumed to specifically apply to use values of a fishery. In some settings, there may be a social goal of maintaining viable wild populations of fish. This introduces another important component of total economic value. Specifically, nonusers of the resource may derive satisfaction from simply knowing the wild salmon are sustained in viable, "healthy" populations. This passive-use, or existence value, can theoretically be captured via hypothetical or direct methods, where a demand function for wild spawning fish is measured from survey respondent data. Such functions provide a measure of welfare change associated with different levels of spawning populations. Costs of producing fish for all of the above cases must be considered, and should theoretically be subtracted from the net economic value assessment described above.

2.3 Role of Uncertainty: Stochastic Decision Making

To adequately approximate natural systems and assess the value of improved information, stochasticity must be incorporated into the decision model. Recall the general biological model which consists of a recruitment function, mortality functions, and a density dependent mortality function. To include environmental stochasticity, some subset of parameters must be treated as random rather than deterministic. This section first presents a brief overview of dynamic programming (DP) theory and the principle of optimality. It then addresses the modifications of the basic DP result necessary to incorporate stochasticity into the model.

The theory of dynamic programming (Bellman, 1957) provides the background necessary to obtain a solution to this problem. Dynamic programming is one of three heavily used approaches to solve the general control problem:

$$\text{maximize or minimize } V[u] = \sum_{\forall t \in T} F[t, y(t), u(t)]$$

$$y'(t) = f[t, y(t), u(t)]$$

$$y(0) = A$$

$$y(T) = Z \text{ ; } T, Z \text{ given}$$

Where $V(\cdot)$ is the objective, or value, function, t represents time, $y(\cdot)$ is a state equation, and $u(\cdot)$ is a control function. Unlike the solution procedure using optimal control theory or the calculus of variations, dynamic programming focuses on the optimal value of the functional V^*, rather than on the properties of the optimal state path $y^*(t)$ or the optimal control path $u^*(t)$ (Chiang, 1992). The principle of optimality, or Bellman equation, is of the following form:

$$\text{maximize} \sum_{t=0}^{T} NEV(u_t, y_t)\delta^t$$

$$\text{subject to } y_{t+1} = f(u_t, y_t);\ y_0 \text{ given}$$

where δ is the discount factor. If u_t^* is the optimal control path, and y_t^* is the optimal state path, the above can be written:

$$V_0(y_0) = \sum_{t=0}^{T} NEV(u_t^*, y_t^*)\delta^t$$

This "value function" represents the maximization of the objective function over all possible paths. The value from time t is expressed:

$$V_t(y_t) = \max \sum_{s=t}^{T} NEV(u_s, y_s)\delta^s$$

$$\text{subject to } y_{t+1} = f(u_t, y_t)$$

The Bellman equation allows this equation to be treated in two parts:

$$V_t(y_t) = \max NEV(u_t, y_t) + \delta \cdot V_{t+1}(y_{t+1})$$

This equation is solved by iteration, making use of the fact that the optimal path is optimal over all of its parts. In other words, an optimal policy function defines how to best proceed from any initial point, i, in order to attain V*(i) by selecting the optimal path leading from the initial point to the terminal point (Chiang, 1992). The rationale for using an iteration solution procedure is best understood by Bellman's principle of optimality which asserts that if the first step of an optimal solution path is eliminated, the remaining steps must define an optimal path in their own right (Bellman, 1957).

Uncertainty can enter a bioeconomic model such as this in several ways. Most notably in this application, uncertainty in the state equation, due to stochastic ENSO events affecting the growth of coho salmon, is likely to disrupt the basic deterministic model. That is, the state equation is likely to include a random error term (ε_t) and will take the general form:

$$y_{t+1} = f(u_t, y_t, \varepsilon_t)$$

Thus, the optimality equation becomes:

$$V_t(y_t) = \max \mathrm{NEV}(u_t, y_t) + \delta \cdot E[V_{t+1}(y_{t+1})]$$

where the expectation will, in general, depend on the stochastic components of the model. The only difference between the deterministic DP result and the stochastic DP result is the expectation operator on the value function.

2.4 Bayesian Decision Theory

The preceding sections of this chapter describe components of an assessment framework which, later in this thesis, are empirically estimated and applied to the Pacific Northwest coho salmon fishery. Implementation of this framework can provide two major functions. First, through utilization of dynamic programming, an optimal control path can be determined. Second, an estimate of the value of the coho fishery can be obtained. However, to transition this analysis into a value of information format requires the implementation of specific statistical techniques. Assessing the value of information implies a condition of uncertainty. Decision-making under uncertainty often relies on a subset of decision theory: Bayesian decision-making. Bayes' Theorem is employed to solve problems of this type. From the definition of conditional probability, for events A and E:

$$\Pr(E \cap A_i) = \Pr(A_i)\cdot\Pr(E \mid A_i) \quad \forall\, i = 1, \ldots, n; \text{ thus,}$$
$$\Pr(E) = \Pr(A_1)\cdot\Pr(E \mid A_1) + \Pr(A_2)\cdot\Pr(E \mid A_2) + \cdots + \Pr(A_n)\cdot\Pr(E \mid A_n)$$

That is, the probability of events E *and* A_i equals the probability of A_i multiplied by the probability of E given A_i. The conditional probability formula can be written as:

$$\Pr(A_i \mid E) = \frac{\Pr(E \cap A_i)}{\Pr(E)} = \frac{\Pr(A_i)\cdot\Pr(E|A_i)}{\Pr(E)} \quad \text{(Bayes' Theorem)}$$

This relatively simple result states that the probability of an event A_i given event E equals the probability of E and A_i divided by the probability of E.

To apply this theory to stochastic ENSO phases, let x represent the true phase in a given year and let z represent the forecast phase. Three possible ENSO phases considered in this analysis are: normal (N), weak (W), and strong (S). It should be noted that, in this exercise, ENSO events are modeled as independent events. Although serial correlation between events was not considered, this framework could easily be adapted to include such a structure. The posterior probability distribution of the true phase, x, given a forecast phase, z, is:

$$\Pr(x \mid z) = \frac{\Pr(z|x)\cdot\pi(x)}{\sum_{\forall x}\Pr(z|x)\cdot\pi(x)}$$

The prior probability $\pi(x)$ is the historical frequency of true ENSO phase, x. An appropriate measure of forecast accuracy is the likelihood function, $\Pr(z \mid x)$, or the probability of a particular phase forecast given the true phase. The likelihood function for each information structure contains 9 possible "true state"-"forecast state" combinations, and can be arranged in the following table with unit row sums:

		z		
		N	W	S
x	N	$\Pr(z_N \mid x_N)$	$\Pr(z_W \mid x_N)$	$\Pr(z_S \mid x_N)$
	W	$\Pr(z_N \mid x_W)$	$\Pr(z_W \mid x_W)$	$\Pr(z_S \mid x_W)$
	S	$\Pr(z_N \mid x_S)$	$\Pr(z_W \mid x_S)$	$\Pr(z_S \mid x_S)$

The likelihood and prior distributions are combined, according to Bayes' Theorem, to obtain the posterior distribution:

		x		
		N	W	S
z	N	$\Pr(x_N \mid z_N)$	$\Pr(x_W \mid z_N)$	$\Pr(x_S \mid z_N)$
	W	$\Pr(x_N \mid z_W)$	$\Pr(x_W \mid z_W)$	$\Pr(x_S \mid z_W)$
	S	$\Pr(x_N \mid z_S)$	$\Pr(x_W \mid z_S)$	$\Pr(x_S \mid z_S)$

Decisions where managers must commit to policy actions based on the current state of information are called terminal decisions (Winkler, 1972). If no sample information on El Niño is available or utilized, but the manager recognizes historical frequencies of occurrence, these decisions are based solely on the prior distribution. For example, suppose that the manager can obtain additional ENSO information before he commits to his terminal decision. The forecast need not be perfect, but assuming he is aware of its accuracy, this improved information might be valuable in reducing his uncertainty regarding the state of the world. By "updating" his prior information regarding the future ENSO phase via Bayes' Theorem, the accuracy or expected value of his terminal decision is increased.

An upper bound on the value of information is the value of perfect information, where the stochastic problem of decision-making under uncertainty becomes a deterministic problem of decision-making under certainty. In this application, the certainty model implies perfect knowledge of all future ENSO events. Based on real-world projections of ENSO forecast accuracy, this is an unrealistic case. The time-frame (forecast horizon) of the information assessed in this study is assumed to be one year. Thus, every problem explored in this analysis is a problem of decision-making in year t, where the manager is uncertain of the ENSO phase in years t+1, t+2, ..., T.

The value of information is clearly a relative assessment, which must be judged against a "base case" appropriate to the situation being analyzed. 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. Usually, the statistic of interest is the mean, or expected value, of information which is defined as the difference between the expected value of the objective function with and without the improved information:

$$E[VOI] = E[\sum_{\forall t} NPV(\cdot)\delta^{t}]_{\alpha} - E[\sum_{\forall t} NPV(\cdot)\delta^{t}]_{\beta}$$

where α and β represent different information structures, completely defined by their respective posterior distributions. In this case, β is the base case for comparison, and information structure α is assumed to be "better", that is, closer to the true distribution of stochastic events, than β. This simple difference will be utilized to assess the expected value of improvements in management of the coho resource resulting from improved ENSO forecasts.

The theoretical biological and economic models developed in this chapter are linked, incorporating empirical estimation of parameters, into a bioeconomic model of the coho salmon fishery. This model alone is not sufficient to obtain estimates of the value of improved information to fishery managers. Instead, it is employed in the estimation of the expected value of the fishery. Using Bayesian decision theory, different models, representing different levels of information accuracy, are assessed, providing a structure from which to calculate the value of information.

3. BIOLOGICAL MODEL OF COHO SALMON

To implement the theoretical bioeconomic decision model presented in Chapter 2, empirical estimates of the model parameters must be calculated. Elements of the biological model depend, in part, on the state equations of undisturbed populations of coho salmon. However, the contribution of the model presented in this thesis critically relies on estimation of the effect of the El Niño Southern Oscillation on coho salmon. This chapter explores the biological consequences of El Niño, focusing on its effects on coho salmon off California, Oregon, and Washington.

3.1 The El Niño Southern Oscillation

A significant amount of the data and analysis on the biological consequences of El Niño was motivated by the severe ENSO event of 1982-1983. Beginning in the winter of 1982 and lasting into the summer of 1983, extensive changes in water temperatures and upwelling patterns occurred off the coast of the Pacific Northwest (Bragg, 1991; Johnson, 1988b; Pearcy and Schoener, 1987; Pearcy et al., 1984). This anomalously warm water upset the normally cool sea surface temperatures (SST's), raised the sea level, deepened the surface mixed layer, and drove down the thermocline (Barber and Chavez, 1983). In the absence of El Niño, cool SST's, a shallow mixed layer, and a shallow thermocline normally support high productivity at all trophic levels. The increase in ocean temperature during an El Niño has substantial biological ramifications to many marine species. As primary productivity is decreased, the entire food web is disrupted, resulting in increased mortality of higher trophic level organisms.

The occurrence of extensive intrusions of warm equatorial water along the shores of South and North America significantly alter the marine biota off the Pacific Northwest. The abrupt changes in ocean conditions which accompanied the 1982-1983 event forced many species to greatly expand their normal range (Pearcy and Schoener, 1987), and resulted in heightened mortality for others (Barber and Chavez, 1983). Ocean temperatures off the coast of Oregon remained above historical averages for several consecutive months (Johnson, 1988b). The 1983 upwelling index was the lowest since measurements began in 1946 (Johnson, 1988b). Upwelling is a particularly important marine ecosystem function for pelagic fishes such as salmon because it transports cool, nutrient-rich water to the surface, supporting prey species upon which salmon feed.

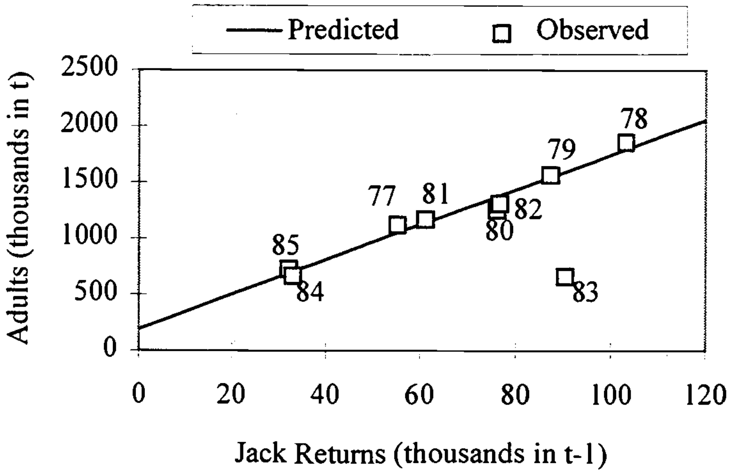
Time series data suggests that approximately seven strong ENSO events have occurred in the past 100 years (Diaz and Markgraf, 1992). This includes two events classified as "very strong"; 1925-1926 and 1982-1983. Other strong ENSO events this century occurred in 1899-1900, 1932, 1940-1941, 1957-1958, and 1972-1973. The length of an event may last anywhere from a few months to a few years. Johnson (1988b) reviewed historical catch statistics of Oregon salmon and concluded that the abundance and average size of coho were below normal during these events.

3.2 Effect of El Niño on Coho Salmon

An understanding of the coho salmon life-cycle is necessary to comprehend the impact the effects of environmental stochasticity. The coho is an anadromous species of salmon which rears for part of its life in the Pacific Ocean and spawns in rivers and streams in North America from Point Hope, Alaska, to Monterey Bay, California (ODFW, 1995). Adults of three years typically migrate to their natal streams from November through February where they often spend several months prior to spawning. Juveniles emerge the following spring and rear for 12 to 18 months in the stream before migrating to the ocean. Ocean migration patterns remain largely unknown, but initial ocean migration off Oregon appears to be to the north of their natal streams (ODFW, 1995). However, in their second summer, they appear to migrate south, and are found off the coasts of California and Oregon. After their second year, some adult males return to spawn precociously as "jacks".

Stock size prediction models play a critical role in the management of any natural resource. Prior to 1994, the Pacific Fishery Management Council (PFMC) predicted coho stock size for the following year as a function of jack returns. In 1983, the actual stock size (666,700) was only 42 percent of the preseason estimate based on the jack predictor (1,593,400), the worst prediction on record (PFMC, 1986). This suggested that the conditions associated with the severe El Niño of 1983 resulted in poor survival of coho in their last year of life. Figure 3.1 depicts the accuracy of the jack predictor between 1977 and 1985.

Figure 3.1 PFMC "jack" predictor of coho abundance, 1977-1985.



The same graph cannot be utilized for recent years due to updating of the prediction equation. The poor accuracy of the coho adult predictor in 1983 also suggested the need to alter the prediction model to incorporate anomalous ocean conditions such as El Niño. Jack returns the following year (1983) indicated that the smolts that entered the ocean in the spring of 1983 survived poorly (Johnson, 1988b). Lack of data prevents the assessment of El Niño's impact on survival of juveniles during their residency in fresh water. However, summer flows (and associated stream temperatures) are generally thought to be limiting factors in the rearing phase of the coho life-history. Evidence suggests that although precipitation is increased in the winter months in the Pacific Northwest during El Niño, the summer flows in rivers decrease, possibly reducing survival of fry rearing in freshwater (Sampson, 1995).

Other data suggest that the biological consequences of El Niño may extend beyond increased mortality. In 1983, average fecundity (eggs per female) was reduced at all Oregon public hatcheries, decreasing about 25 percent from historical averages (Johnson, 1988b; Pearcy and Schoener, 1987). The reduced fecundity during El Niño events is most likely a result of the markedly reduced adult body size recorded during the 1982-1983 ENSO event (Johnson, 1988b; Pearcy and Schoener, 1987). Finally, coho of a given length weighed significantly less than in previous years (Pearcy and Schoener, 1987).

The primary cause of increased mortality, decreased fecundity, and decreased average weight appears to be reduced prey. The cycling of nutrients within the marine ecosystem relies heavily on upwelling. Originally, oceanographers believed that upwelling ceased or weakened during El Niño (Barber and Chavez, 1983). However, oceanographers discovered that during El Niño, coastal upwelling continues but that the water entrained is warmer and poorer in nutrients (Barber and Chavez, 1983). This upwelling was apparently ineffective in distributing nutrients through the thick warm surface layer. As a result, primary productivity was low along the west coast during the summer of 1983. The reduction in nutrient transport likely causes primary production of organic material to decrease proportionally (Brodeur and Pearcy, 1992; Pearcy and Schoener, 1987; Nickelson, 1985; Pearcy et al., 1984).

Several caveats must be added here regarding this seemingly clear picture of the impact of El Niño on coho salmon. Although survival of smolts in the ocean during the 1982-1983 El Niño was strikingly low, growth rates of juvenile coho in the ocean were similar to other years (Pearcy and Schoener, 1987). Data analyzed by Pearcy and Brodeur (unpublished data, 1986) suggest that feeding conditions of juveniles that survived were not unusually poor.

Furthermore, the impact of El Niño is probably not uniform along the Pacific coast. During El Niño, anomalously warm water is present off the coast of the Pacific Northwest. However, even during strong events, coho off the coast of Washington and British Columbia may not be as susceptible to ocean changes, indicating that the impacts may vary along the coast (National Oceanic and Atmospheric Administration, 1995). This severe 1982-1983 event apparently had the effect of forcing many marine animals north, beyond their historical range (Brodeur and Pearcy, 1992; Pearcy and Schoener, 1987; Pearcy et al., 1984). No published evidence identifies this El Niño as having adversely impacted salmon survival or fitness in Alaska. In fact, the 1982-1983 event may have had a positive effect on Alaskan salmon. Historically large catches of salmon in Alaska between 1983 and 1985 coincide with above average sea temperatures (Pearcy and Schoener, 1987). This observation provides further support that the impacts of El Niño vary along the coast. However, this analysis focuses on effects within the PFMC management area where, during strong ENSO events, impacts on coho salmon are unambiguously negative.

3.3 Biological Component of the Assessment Framework

The biological effects of El Niño on coho salmon are incorporated into a larger bioeconomic decision model. The objective of the integrated model is to maximize the expected net present value of the coho fishery. The biological model of coho salmon with stochastic parameters, determined by ENSO phase, was developed by Sampson (1995). The El Niño Southern Oscillation may be broadly classified into three phases; El Niño- associated with anomalously warm water, normal, and El Viejo (or La Niña)- associated with anomalously cool water (Adams et al., 1995). There is no clear evidence that the manifestations of El Viejo effect coho differently than normal conditions. Thus, the biological model used in this application classifies ENSO events as normal (N), weak (W), and strong (S) with known historical probabilities, where N includes the El Viejo and normal phases. This section describes the essential elements of the Ricker spawner-recruit model modified to accommodate the stochastic biological manifestations of ENSO on coho salmon in the Pacific Northwest.

A discrete-time approach is employed, modeling coho survival to a given point, τ, in their life-cycle as an exponential function of time and natural mortality coefficients:

$$S_1 = \exp(-M_1 \cdot \tau)$$
$$S_2 = \exp(-M_2 \cdot (\tau - 12))$$
$$S_3 = \exp(-M_3 \cdot (\tau - 24)),$$

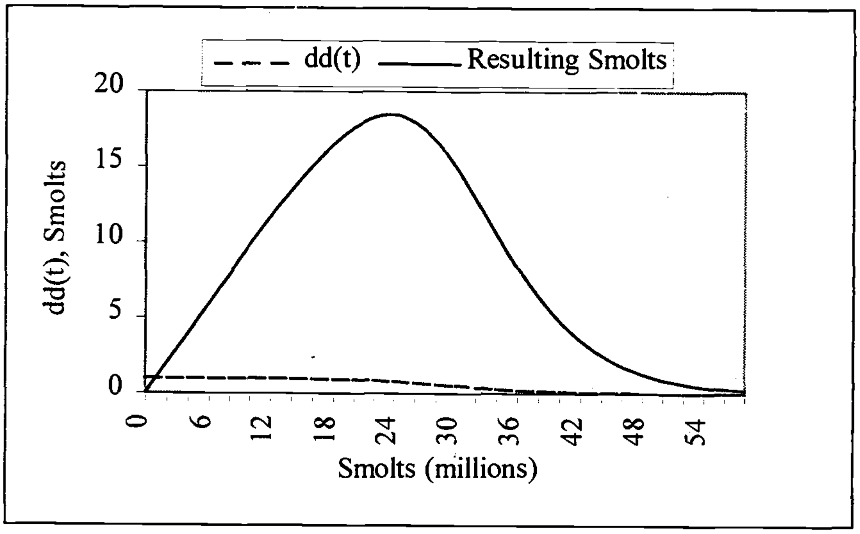
where S_i is the survival of coho in year i of their life-cycle, M_j is the natural mortality rate in year j, and τ is time in months.

One factor potentially limiting ocean survival of coho salmon is density dependent mortality. This hypothesis has been explored by Nickelson (1986), McGie (1984), McCarl and Rettig (1983), and others. Nickelson (1986) suggests that there is no evidence for density dependent survival for public hatchery, private hatchery, or wild coho salmon. However, when wild and hatchery stocks are combined in the marine environment during years with weak upwelling, density dependence may be a factor. Nickelson concludes that the apparent density dependence may be an artifact of the shift from wild fish with high survival rates to hatchery fish with low survival rates. Other researchers including McGie (1984) and McCarl and Rettig (1983) conclude that density dependence may play an important role in the survival of Pacific salmon. The model used here (Sampson, 1995) assumes that following smoltification, as the fish mature to a harvestable age, coho are subject to density dependent mortality according to the following relationship:

$$dd(t) = \frac{1}{1 + \exp(\gamma(smolts(t) - \delta))}$$

where dd(t) is the density dependent survival factor in year t. Gamma is a "steepness" parameter where larger γ concentrates the density dependent effect around a (specified) critical population level. The parameter δ symbolizes the critical number of smolts (in millions) at which survival is reduced to 50 percent as a result of the density dependent effects. Beyond a certain population of smolts (roughly 24 million), increases in smolts entering the ocean will actually reduce the effective (post-density dependent) salmon population. This greatly reduces the effectiveness of large infusions of hatchery fish into the system, and is depicted in Figure 3.2.

Figure 3.2 Density dependent mortality factor.



Wild fish that escape the fishery enter their natal streams and spawn. The effectiveness of this spawning is governed by the Ricker spawner-recruit model. The number of fry produced in a given year (t) is a nonlinear, concave function of the number of spawners the previous year with two exogenously determined shifters α and β, according to the following relationship:

$$fry(t+1) = \alpha \cdot spawn(t) \cdot \exp(-\beta \cdot spawn(t))$$

The parameter α represents the initial slope of the spawner-recruit function (a measure of the number of fry produced before any crowding can take place; a measure of fecundity), and is treated as a random variable determined by the ENSO phase. Beta is the inverse of the number of spawners (in millions) which maximizes the number of fry produced. Finally, average weight of adult fish, ω, (in pounds) affects biological functioning indirectly via its influence on fecundity. However, ω directly affects the economic decision model by influencing the ex-vessel revenue per fish (fishers are paid on a price per pound basis). Table 3.1 gives the values for each stochastic parameter under the three possible ENSO phases.

Table 3.1 Parameters of the biological model under various ENSO phases.

		Parameter							
		M_1	M_2	M_3	δ	γ	α	β	ω
ENSO Phase	Normal	0.25	0.15	0.1	30	0.2	6821	3.5587	5.49
	Weak	0.275	0.165	0.11	30	0.2	6253	3.5587	4.45
	Strong	0.3	0.18	0.12	30	0.2	5684	3.5587	3.8

Recall from the theory of dynamic programming that the entire optimization problem is characterized by an objective function, one or more constraints, and initial conditions. In this application, the initial conditions refer to the structure of the coho population at the beginning of the analysis. The theory of renewable resource harvesting suggests that over a long planning horizon, the initial population structure does not alter the steady-state population (if one exists), but, rather, it alters the approach path to that steady-state. That is, if the initial population structure is well below the steady-state, the optimal control in period one will likely be to greatly curtail, or even eliminate, harvest (commonly referred to as a "Bang-Bang" strategy). Therefore, the results of this analysis do not rely heavily on the initial population structure. For solution convenience, an initial population structure of near the steady-state was arbitrarily chosen as shown in Table 3.2.

Table 3.2 Initial population values for the biological model.

Age-Class (months)	Label of age-class	Initial Population (millions)
0	wild fry	611
18	wild smolts	9.97
30	wild adults	2.047
30	hatchery adults	2

3.4 Hatchery-Wild Fish Interactions

The interaction between, as well as any differential effects of El Niño on, hatchery and wild coho, remain, to a large extent, unknown. This section provides a brief history of hatchery production in the Pacific Northwest region and describes some important elements in the hatchery-wild fish debate. It concludes by describing the manner in which hatchery fish are incorporated into the bioeconomic model.

The original purpose of salmon hatchery operations on the west coast was to introduce salmon to rivers in the eastern United States (Nelson and Bolde, 1990). The first salmon hatchery in the Columbia Basin was built in 1887 on the Clackamas River. By that time, the impetus for artificial propagation had shifted from introduction to eastern streams to maintaining existing population levels (Nelson and Bolde, 1990). Prior to 1960 less than one million hatchery coho were produced in the Oregon Production Index (OPI) area (ocean fishery south of Leadbetter Point, Washington) on an annual basis. Large scale hatchery coho smolt production in the OPI area was initiated in the early 1960's to mitigate freshwater limitations to production (Nickelson, 1986). Releases peaked in 1981 when 60 million hatchery coho smolts were released into Oregon's rivers.

In the early days of hatchery production, a significant positive relationship between smolts released and adult production was observed (Pearcy, 1988). The relationship between releases and returns was less clear as production increased through the 1970's and early 1980's, but the population of wild coho has declined since the mid-1960's (Nickelson, 1986). The Oregon Department of Fish and Wildlife Coho Salmon Plan of 1982 identified high harvest rates by commercial and recreational fisheries, stimulated by the historically high releases of hatchery coho, as the primary cause of decline during this period (ODFW, 1982). This exemplifies the problem of the mixed-stock fishery where increased harvest rates on one prolific stock (hatchery) causes disproportionate hardship on another, generally un-targeted, stock (wild fish).

The uncertain impact of hatchery releases on wild stocks complicates the development of a biological model of this mixed-stock fishery. A further difficulty in model development is the possibility of different influences of El Niño on hatchery and wild fish. One major argument against hatchery production is based on the premise that hatchery-reared smolts are less fit than their wild counterparts. Thus, increased hatchery output, and subsequent cross-breeding between populations, reduces the fitness of the entire population. If true, this suggests that adverse ocean conditions might more severely impact hatchery fish. Nickelson (1986) concludes that hatchery coho might be more sensitive than wild coho to changes in upwelling-related factors. However, he recognizes that the limitations of the data in estimating wild smolts and adults may be responsible for this result (Nickelson, 1986).

In this analysis, the impact of El Niño is assumed to be identical for (post-release) hatchery and wild coho of all age classes (Sampson, 1995). Hatchery smolts are assumed to be released at age 18 months, the same time wild fish migrate to the ocean. Two major factors limit the production of hatchery smolts: density dependent mortality and the cost of hatchery production. Density dependence has already been discussed, and hatchery smolt production costs will be addressed in the description of the economic model. The biological model further assumes that hatchery and wild stocks uniformly mix, forming one indistinguishable stock once they enter the marine environment. (Uniform mixing may be mitigated, and possibly eliminated with careful development and implementation of terminal fisheries, where salmon are raised in net pens, released to the marine environment, and eventually harvested as they return to their natal estuaries.) Management becomes convoluted under the condition of perfectly mixed stocks. The following section discusses current management of coho salmon by the Pacific Fishery Management Council.

3.5 Management of the Coho Fishery

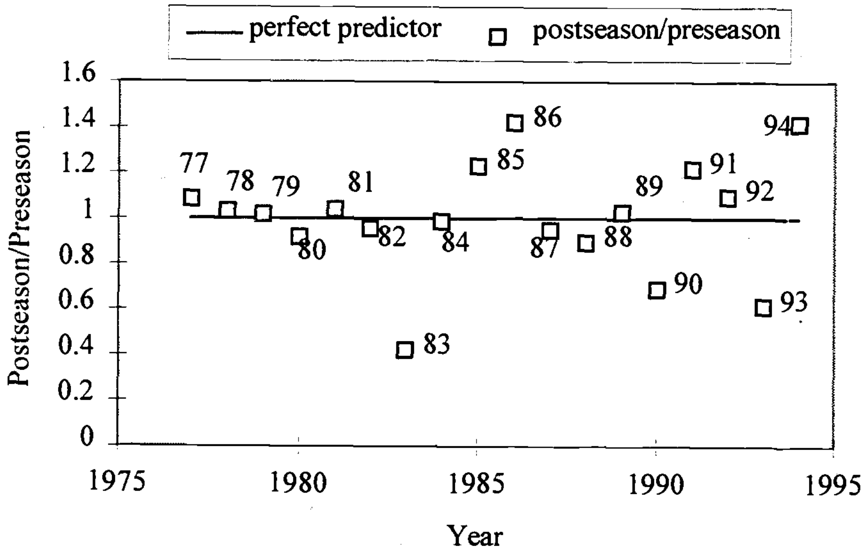
This section summarizes current management of the coho fishery in the Pacific Northwest. In includes a description of the harvest decision, various stock predictors, and the allocation decision between commercial and recreational fisheries. The harvest decision plays a critical role in the management of any fishery. Each spring, the PFMC determines the available ocean harvest of coho salmon for the upcoming (summer) season, which depends on the expected harvests by inside fisheries (harvest excluding the ocean catch) and PFMC spawning escapement goals (PFMC, 1996). Management of the coho fishery is broken into several jurisdictions. Coho are currently managed as one unit south of Cape Falcon, just south of the Oregon-Washington border (see Figure 1.2). North of Cape Falcon, the PFMC allocates harvest from a total allowable area harvest which is "maximized to the largest extent possible, but still consistent with treaty obligation, state fishery needs, and spawning escapement requirements" (PFMC, 1995).

The harvest decision currently revolves around the management practice of meeting constant escapement targets for wild fish. In 1995, the escapement goal for wild Oregon coastal coho was 42 naturally spawning adults per mile, or approximately 200,000 fish. Recent, unpublished studies by the PFMC indicate that the selection of "representative" streams from which to sample may have been grossly inaccurate. If true, estimates of stock abundance and even escapement targets were probably incorrect.

Several other stock components are included in management of the coho fishery. The population of each stock component is predicted annually using PFMC models, and the harvest decision is adjusted accordingly. Oregon Production Index hatchery (OPIH) stock are coho originating from public hatcheries in the OPI area. These fish are primarily raised in Columbia River facilities and net pens, although a smaller percentage are raised in Oregon and California coastal hatcheries. Since 1988, the OPIH stock size has been predicted by the PFMC using a linear regression model. The model predicts public hatchery stock with jack returns the previous year and a correction term for delayed smolt releases (smolts released at an older age) from Columbia River hatcheries. One measure of the accuracy of the prediction in any given year is the quotient of observed postseason stock size to preseason prediction of stock size. For hatchery coho, this quotient has ranged over the past decade from .453 in 1993 to 2.07 in 1994. Oregon Production Index hatchery fish have historically accounted for approximately 64 percent of the total Pacific Northwest adult coho salmon.

Oregon Coast Natural (OCN) stocks are naturally spawned (wild) coho within the OPI area. Oregon Coast Natural fish are divided into two components; those spawning in rivers, and those spawning in lakes. From 1988 to 1993, the Oregon Coast Natural river (OCNR) stock size was predicted using a modified Ricker spawner-recruit model (PFMC, 1995). However, concern that this model did not adequately incorporate environmental variability led to the development of a new model in 1994. The newly adopted model relates upwelling, sea surface temperature, and year to predict OCNR abundance. Surprisingly, this model does not include a variable for spawner escapement. It supposes that the population of wild coho spawning in rivers can be most accurately predicted using ocean conditions alone as explanatory variables without any information about previous spawner escapement. According to PFMC documents (1995) the newly adopted model predicted abundance better for 1995 than the previous model, and the quotient of postseason estimate to preseason prediction indicates a fairly accurate prediction for this newly adopted model. Inspecting past performance of prediction models for wild coho reveals that, in every year since 1986, the model used by the PFMC has over-predicted stock size (by as much as 250 percent in 1987). It has been suggested that, in come cases, agencies may underpredict coho abundance to avoid biased use of this information (Rettig, 1996 personal communication).

Figure 3.3 Coho stock abundance predictor performance, 1977-1993.



OCNR coho comprise roughly 23 percent of the total coho stocks in the Pacific Northwest. The Oregon Coast Natural lake (OCNL) component of the OCN index only comprise about one percent of the total stocks and will not be discussed in this analysis. In addition, there have not been any Oregon Coastal private hatchery (PRIH) coho smolts released since 1991 (PFMC, 1995). Comparison of stock predictors can be made between years using the quotient of observed postseason to predicted preseason abundance. Figure 3.3 represents these predictors, pooling all Oregon coho stocks for which predictions were available.

Coho north of the OPI area are classified as Washington Coastal and Puget Sound stocks. They are divided into seven primary adult natural coho stocks. A different model is employed to predict the abundance of each of these stocks. Initial abundance estimates for some Puget Sound and Washington coastal stocks prepared for pre-season planning assume an average ocean or pre-terminal area fishing impact rate (PFMC, 1995). The Salmon Technical Team then adjusts the forecasts of ocean escapement for each stock according to an approximate level of expected harvest and average stock distribution patterns by time and area (PFMC, 1995). The quotient of postseason abundance to preseason predictor using pooled data between stocks ranges from .47 in 1993 to 1.33 in 1988. The Washington coastal and Puget Sound stocks comprise about 12 percent of the total coho stocks in the Pacific Northwest.

After the total allowable harvest decision has been made, the PFMC must determine the allocation of the harvest between many user groups. This decision is assumed to be guided by some combination of biological, economic, social, and political objectives. Harvest must be allocated among broad management areas, between Indian and non-Indian harvesters, between troll and recreational fisheries, and among ports within broad management areas. Each of these allocation decisions plays an important role in the bioeconomic analysis of the fishery. This study focuses on the allocation between the two major users of the coho resource: the commercial and recreational fisheries. From an economic perspective, optimal management in every year involves allocating fish such that the marginal benefit is equal across uses. However, political and social realities inevitably contradict this decision rule.

The Pacific Fishery Management Council's management plans generally involve stable harvest in the recreational fishery and high variability in the commercial fishery (PFMC, 1996). The majority of the annual variation in available ocean harvest is usually absorbed in the troll fishery (PFMC, 1996). PFMC analysis of socioeconomic impacts suggests that the effects of reduced (and in many cases eliminated) harvest are distributed differently across specific geographic areas. For example, recent restrictions on coho fishing have had severe impacts on recreational fisheries in Washington and Oregon north of the Brookings Port area, where coho are the primary salmon species (PFMC, 1996). Similarly, the commercial fishery has been most severely impacted in northern areas where harvesters tend to rely more heavily on coho than chinook.

The PFMC regulates the commercial and recreational ocean fisheries with multiple management tools in an attempt to achieve the desired harvest levels and mitigate socioeconomic impacts. The commercial fishery is primarily managed by setting season lengths and minimum size limits for several management areas. The PFMC (1995) language reads, "The Council will make every effort to establish seasons and gear requirement which provide troll and recreational fleets a reasonable opportunity to catch the available harvest". Coho retention (harvesting coho salmon) was not permitted in the 1995 troll fishery south of Cape Falcon due to projected poor OPI area abundance from both natural and hatchery production (PFMC, 1996). The Oregon Production Index (an index used for predicting stock size) predicted 293,500 fish in 1995, an all-time low. Although targeting coho in the troll fishery was not permitted in 1995, the PFMC adopted a non-retention troll fishery with an expected hook-and-release mortality of 7,300 coho (PFMC, 1996).

The recreational coho fishery is primarily regulated with season length restrictions, bag limits, and minimum size limits. In 1995 some recreational angling was permitted in California and Washington, but no recreational fishery targeting coho was open in Oregon.

In order to proceed, several simplifying assumptions must be made to keep the decision problem tractable. This model assumes that the coho fishery is managed as single unit along the coast with one management agency. The management objectives are simplified into various economic components which are discussed in the next chapter. The management agency conducts stock assessments and can differentiate (in assessment, not in harvest) between hatchery and wild fish. As mentioned previously, wild and hatchery stocks mix in the ocean and targeting one or the other is impossible, i.e. harvest is proportionally the same on both stocks.

3.6 Optimal Control in Stochastic Fisheries

Optimal fisheries management under uncertainty has been explored by several researchers (Getz et al., 1987, Reed, 1979; Reed, 1978; Beddington and May, 1977; Walters, 1975; Reed, 1974; Jaquette, 1972). This literature primarily focuses on simplified stochastic models with well-behaved error structures and generally defined objective functions. Most of these models were developed before high-powered computer simulation was readily available, and therefore, were solved analytically for the steady-state. Reed (1978) formulates a stochastic harvesting model based on a discrete-time Markov population model. He concludes that the maximum rate of exploitation of an animal population subject to random variation decreases with the degree of environmental fluctuation. This maximum is always less than the deterministic maximum sustainable harvest rate. In a classic paper exploring the optimal escapement policy for a stochastic fishery, Reed (1979) again uses Markovian transitions between states with a multiplicative error term to capture environmental variability. He assumes demand is perfectly elastic and unit cost of harvesting is independent of harvest size but increases with decreases in population size. Reed concludes that under these seemingly realistic assumptions the optimal control path involves implementing a constant escapement policy. That is, in the absence of any information (e.g. without a forecast of future conditions), the optimal policy requires managing for a constant parent stock escaping the fishery. Of course, this model excludes several important components of the coho fishery such as hatchery and wild mixed-stocks, density dependence, and a complex economic surplus model including recreational, commercial, and existence values of salmon.

Getz et al. (1987) suggest that, provided the control policy is designed to maximize expected sustainable yield in a stochastic fishery, long-term yield is relatively unaffected by the policy in question. However, they also suggest that the socioeconomic ramification of different policies may be vastly different, indicating that if one is maximizing the expected net economic surplus in the fishery over time, different harvest policies may dramatically influence the results. This defines what they consider a fundamental complication in the management of stochastic fisheries: How to find an appropriate compromise between short-term stability of the fishery and long-term viability of the fish.

4. ECONOMIC MODEL OF THE COHO FISHERY

The primary objective of this study is to provide a framework for assessing the value of information in a dynamic, stochastic setting. This chapter begins by developing the key economic relationships necessary to assess economic welfare. These economic relationships are not estimated in this study; rather, they are derived from existing literature via a benefits transfer approach. In conjunction with the use of economic parameters borrowed from other studies, several basic statistical models are estimated using secondary data to aid in the modeling of various aspects of the coho fishery.

4.1 Purpose and Scope

The economic model developed in this section accounts for all significant welfare impacts of altered management resulting from ENSO predictions and occurrences, including harvest rates, hatchery releases, and average coho weight, manifested in both the commercial and recreational sectors. The commercial sector effects include reduced harvest in terms of both number and average weight of fish. In the extreme, a total closure of the commercial coho fishery may occur, as experienced in recent years. Within the recreational sector, the welfare of a number of participants including charter boat fishers, charter boat operators, private ocean fishers, and in-river fishers will be affected by changes in stock size and management. The economic model must be developed before the optimization over management alternatives can take place. This chapter describes the variables and general structure of the objective function of the optimization model. A detailed explanation of the benefits transfer approach, and calculation of each variable with citations for the source, is then provided.

4.2 Objective Function

The optimization criterion is to maximize the 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 stochastic biological parameters. Net present value is optimized over a set of management alternatives, reflecting combinations of harvest and hatchery smolt releases. The undiscounted net economic value, referred to henceforth as NEV, in any year, t, may be expressed as follows:

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

where:

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

The desired future stream of benefits, net present value (NPV), is obtained by summing the discounted net economic values over the desired planning horizon:

$$NPV=\sum_{t=0}^{T}\frac{NEV(t)}{(1+r)^t}$$

The expected net present value of the future stream of benefits will be maximized over the control variables; harvest, hatchery smolt production, and hatchery smolt releases.

4.3 Allocation Between Users

Calculating the welfare impacts of changes in allowable harvest critically depends on the allocation of the catch between various users of the resource. Some components of the allocation decision are not mandated by any regulatory body, while others are strictly determined by management agencies. The Pacific Fishery Management Council estimates the freshwater catch of coho salmon prior to allocating the ocean harvest. Although the correlation is not high, for the purposes of this analysis, the freshwater harvest is assumed to be a constant proportion of the ocean harvest. This proportion is estimated by the following regression, fit from PFMC (1996) and ODFW (1995) data from 1982 to 1994:

$$\text{freshH}(t) = .1319 * \text{saltH}(t), \quad R^2 = .24$$
$$(t = 4.79)$$

where freshH(t) and saltH(t) represent the freshwater (recreational) harvest and ocean (commercial and recreational) harvest of coho, respectively. The low R^2 statistic was as expected (in that much of the error was unexplained by the model), given that only one explanatory variable is included. The statistically significant t-statistic, and the fact that the freshwater harvest is a relatively small proportion of the total allowable harvest, deems this an acceptable function for the purposes of this analysis. Simple algebraic manipulation confirms the following results:

$$\text{freshH}(t) = .1165 * h(t)$$
$$\text{saltH}(t) = .8835 * h(t)$$

where h(t) is the total allowable harvest, both freshwater and marine, of coho salmon in year t.

Current management by the PFMC mandates that the allowable ocean harvest of coho salmon south of Cape Falcon be allocated between commercial and recreational sectors according to the schedule shown in Table 4.1. The allocation schedule distributes a greater percentage of salmon to the commercial fishery at high harvest levels than at low harvest levels, but the near linearity of the allocation schedule is seen in Figure 4.1. Commercial harvest (comH(t)), expressed as a linear function of total ocean harvest, describes the PFMC allocation schedule with a high level of explanatory power:

$$\text{comH}(t) = .7927 * \text{saltH}(t), \quad R^2 = .9839$$
$$(t = 82.07)$$

By the identity that commercial plus recreational harvest equals the total saltwater harvest, the ocean recreational allocation (recH(t)) is:

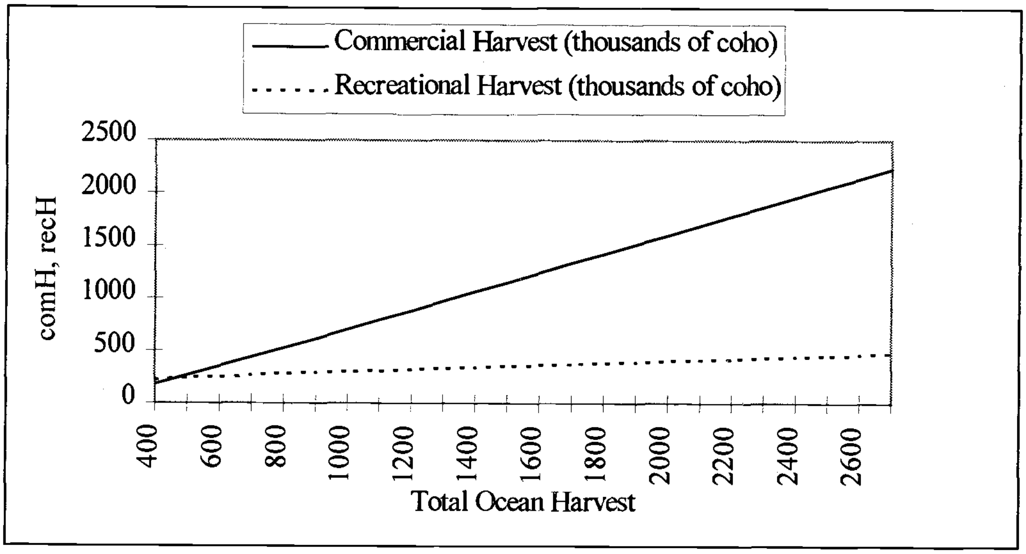
$$\text{recH}(t) = .2073 * \text{saltH}(t)$$

Table 4.1 Allocation of coho salmon between commercial and recreational harvesters.

Allowable Ocean Harvest (thousands)	Commercial Harvest (thousands of coho)	Recreational Harvest (thousands of coho)
400	176	224
500	262	238
600	348	252
700	434	266
800	520	280
900	610	290
1000	700	300
1100	790	310
1200	880	320
1300	970	330
1400	1060	340
1500	1150	350
1600	1240	360
1700	1330	370
1800	1420	380
1900	1510	390
2000	1600	400
2100	1690	410
2200	1780	420
2300	1870	430
2400	1960	440
2500	2050	450
2600	2140	460
2700	2230	470

The linear approximations above explain the PFMC allocation schedule with a high degree of accuracy. Incorporating allocation in the model as an endogenous variable (as would be the case if the schedule was used in the model rather than the linear regression), causes many pragmatic programming complications. Therefore, the linear regressions were used in the calculation of commercial and recreational percentages of harvest.

Figure 4.1 Allocation of coho salmon between commercial and recreational harvesters.



The economic impacts of changes in harvest also depend on the proportion of fish taken by ocean charter fishers (charH(t)) and ocean private fishers (privH(t)). Analysis of PFMC (1996) data from 1982 to 1994 yields the following regression results:

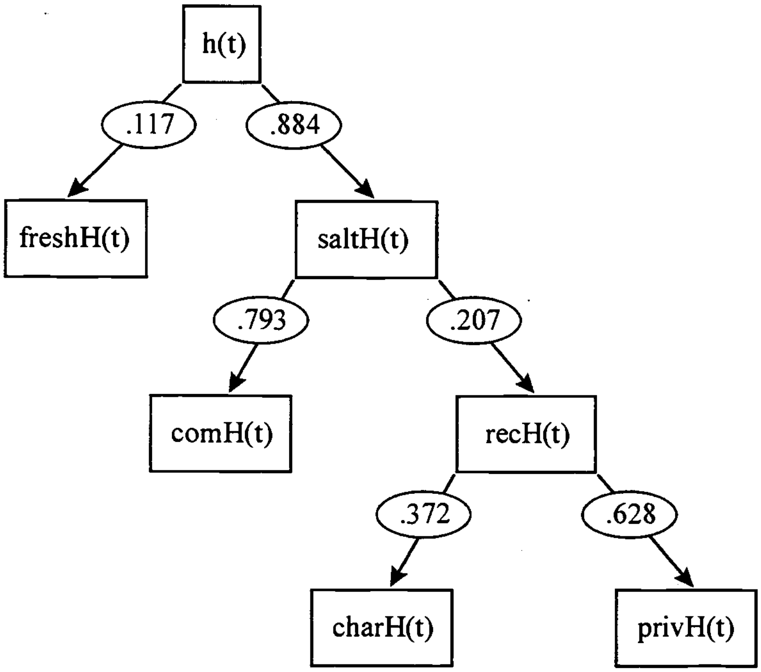
$$\text{charH}(t) = .372 \cdot \text{recH}(t), \quad R^2 = .896$$
$$(t = 27.78)$$

Since the entire ocean recreational harvest is consumed by charter and private fishers, the corresponding allocation to private fishers is:

$$\text{privH}(t) = .628 \cdot \text{recH}(t)$$

This indicates that approximately 63 percent of the total ocean recreational harvest is taken by fishers with private boats. The above allocations are represented in Figure 4.2.

Figure 4.2 Flow diagram of allocation of coho between various harvesters.



4.4 Benefits Transfer

Estimating parameters of the economic model from original data is beyond the scope of this analysis. Published, secondary data and analyses were used to obtain these estimates, and the benefits transfer approach was employed. Benefits transfer refers to the utilization of an existing valuation estimate from the original study site to an alternative setting (Berrens, 1993; Brookshire and Neill, 1992). Its low cost, few data requirements, and expedient analysis make this approach particularly attractive for use in prototypical analyses such as this. Considerable care must be taken by the researcher to avoid making gross errors in the transfer of benefits from the original research site to a different time or place. This section briefly discusses the benefits transfer approach, necessary cautions that must be taken for its implementation, and specific considerations when using this technique to value the coast-wide recreational coho fishery.

The most basic form of benefits transfer is a simple point estimate value transfer from one site to another (Berrens, 1993). Agencies which must aggregate between various sites (as in a coast-wide assessment of recreational fisheries) often employ average or representative value estimates (PFMC, 1996; ODFW, 1993). A more accurate approach involves transferring an entire benefits function. Loomis (1992) cites two primary reasons that estimating total recreational benefits using an existing demand curve is likely to yield more reliable estimates than transferring a per-day point estimate. First, total recreation benefits depend both on the value per trip and total site visitation. If a point estimate is used, it is likely that the "transferred" value per day estimates employed are inconsistent with estimates of the total use of the recreation site. Transferring the entire demand function, where values per day and total use were estimated from the same data set, presumably mitigates the bias from inconsistent assumptions. Second, estimates of recreational benefits are often a complex function of site quality characteristics, user characteristics, and spatial attributes of the site relative to the visitor's residence (Loomis, 1992). A properly estimated demand curve accounts for these effects. Simply using a point estimate or "average value" ignores these possibly influential variables.

Brookshire and Neill (1992) suggest benefits transfers can only be as good as the initial benefit estimates. They argue that the problems associated with non-market valuation in general are magnified in benefits transfer applications. Thus, extreme caution must be exercised in the selection of the appropriate study from which to transfer benefits. The error created in the transfer of benefit estimates from one site to another is a function of the uncertainty in the differences between demand functions for recreation at the two sites. McConnell (1992) stresses the need to use good judgment, relying on economic theory, empirical evidence, and research experience when employing a benefits transfer.

Time and budget constraints prevented the estimation of original benefit functions for this study, so the benefits transfer approach was used to explore the value of information assessment framework. The scope of this analysis requires selecting from demand estimates derived in numerous recreational locations. In addition, it was hypothesized that different recreational uses of coho salmon might imply different demand functions. That is, the demand, and resulting consumer surplus for freshwater, ocean-charter fishing, and ocean-private fishing are likely to be distinct. The recreational and existence value literature is sparse. Existence values are also the most problematic in terms of both conceptual and empirical viability. Most economists accept the plausibility of existence values as a component of total economic value, but may also seriously question the magnitude of such estimates. Thus, existence demand and valuation estimation is much different than the use-oriented recreational demand values.

The benefits transfer approach employed in this analysis begins with a literature review of valuation studies of salmon and steelhead in the Pacific Northwest. Based on the results of these valuation studies, the recreational coho fishery is decomposed 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 entire Pacific Northwest region. Estimates from the literature are also used to formulate a demand curve reflecting the existence value of wild coho salmon.

Although not "benefits transfer" *per se*, producer quasi-rents accruing to charter boat operators and commercial harvesters are estimated via a transfer of secondary cost and revenue data from the literature.

4.5 Variable Estimation

Each component of the economic model is estimated from existing data and published analyses. Numerous studies have analyzed the economic value of fisheries-based recreation (see Freeman, 1995 and Johnson, 1994 for reviews). However, few of these estimates address the value of Pacific Northwest salmon fisheries. An even smaller number of these investigations focus on coho salmon. Furthermore, the distinction between private and charter ocean recreational fisheries is not addressed in the literature. Most studies of benefits from recreational angling report "average" values, which, for reasons outlined earlier, provide little guidance in evaluating the changes in consumer surplus when fish population levels change. When "marginal" values are reported, reference values from which to infer a demand curve for additional fish are often excluded. A number of these studies also utilize the same data sets for their analyses, indicating that the apparent conformity in value estimates across studies may be deceiving. Consumer surplus estimates for use in this investigation are believed to represent an approximation of the body of literature on this subject. Although they are more heavily influenced by particular studies with characteristics similar to those in this policy setting, the estimates presented and utilized here certainly fall within a "reasonable" range, as defined by the available literature.

Lack of recent, well-researched analyses also complicates the calculation of producer quasi-rents in both the commercial and recreational fisheries. The few studies estimating costs of operating commercial fishing vessels and charter boats do not estimate curves, but rather obtain point estimates for one or two years. Point estimates do not provide the information necessary to calculate changes in economic surplus resulting from altered management.

However, the literature does provide suggestions for estimating fishers' costs when data are scarce.

4.6 Consumer Surplus from In-Stream Angling

The demand for freshwater salmon angling in the Pacific Northwest region, expressed either on a per fish or per trip basis, has been estimated by several researchers. Meyer et al. (1983) develop a travel cost model and estimate the consumer surplus attributable to the in-river recreational salmon fishery as a function of catch. One considerable contribution of this research is the estimated functional form of the model. They fail to reject the hypothesis that salmon anglers' consumer surplus is a linear homogeneous function of catch. The implication is that the demand curve for fish may be perfectly elastic, indicating that each fish is worth the same amount, regardless of the quantity of fish. If appropriate, this would greatly simplify the analysis. They obtain average (and marginal) value per fish of $77.64 expressed in 1977 dollars.

Loomis (1988) conducts a travel cost study assessing demand for salmon fishing in Oregon coastal rivers. His analysis uses 1977 Oregon Department of Fish and Wildlife data to obtain river-specific demand curves for trips as a function of distance and site quality characteristics. He estimates marginal values per fish between $7.48 and $14.85.

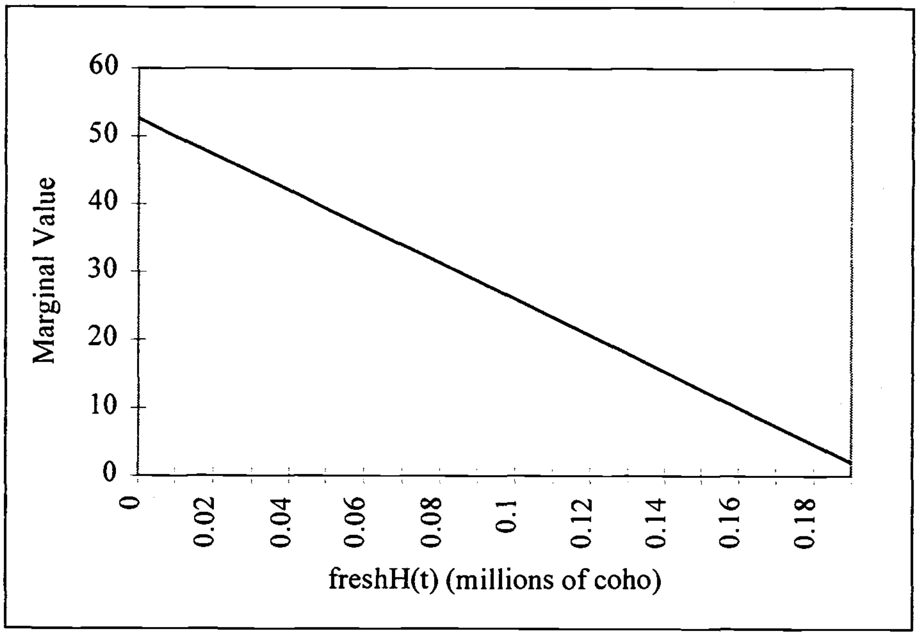
Olsen et al. (1991) use a contingent valuation survey to assess the value of doubling fish runs in the Columbia River system by the year 2000. Conducted in 1989, their analysis estimates the average and marginal values per trip and per fish for several locales for the fishing experience, including coastal rivers. They estimate an average net value per trip of $58.39, while the marginal (i.e. doubling of the catch) value per trip is estimated to be $23.55. On a per fish basis, these values translate to average and marginal values of $36.72 and $14.81, respectively.

Urrutia and Adams (1992) employ a travel cost model estimating trips as a function of distance, income, catch, and a dummy variable for location. Their analysis addresses both salmon and steelhead and reports marginal values per fish for several increments in the catch rate (using '85-'88 as the baseline). The marginal values, in 1989 dollars, range from between $35.30 per fish for a 25 percent increase in the catch rate, to $28.72 per fish for a doubling of the catch rate.

Johnson (1994) conducts a thorough review of previous valuation studies of salmon in the Pacific Northwest. She normalizes various studies to 1992 dollars and converts them to per day estimates. Her review of nine contingent valuation and travel cost studies cites a range of \$18.07 to \$60.36 per angler day for freshwater salmon angling.

The estimation of freshCS(t) in this analysis is estimated from the representative values presented above, but is based primarily on the results from Olsen et al. (1991). Adjusting their estimates of marginal values per fish to 1995 dollars yields an average net value per fish at 1988 catch levels of \$43.92 and marginal value per fish associated with a doubling of the catch of \$17.72. The next step in the procedure for developing an economic model which measures the economic impacts of changes in management is to translate these values into a demand curve for fish. A linear function estimates the demand curve for freshwater angling, as the data was inadequate for accurately estimating a more complex functional form.

Figure 4.3 Demand curve for in-stream salmon angling.



Using freshwater harvest of coho salmon from Columbia River tributaries and coastal streams, and noting that the freshwater harvest in 1988 was approximately 65,500 coho, the following linear schedule is fit:

$$MV/fish(t) = 52.64 - 266.53 \cdot freshH(t)$$

where MV/fish(t) is the marginal value per coho salmon harvested in the freshwater recreational fishery, and freshH(t) is the freshwater harvest in millions of coho salmon. The demand for in-stream recreational angling is represents in Figure 4.3. The associated consumer surplus (in millions of dollars) is obtained by integrating the marginal function between zero and the current catch level (in millions of fish), obtaining:

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

4.7 Consumer Surplus from Ocean Recreational Angling

Many of the studies addressing in-stream salmon angling also calculate consumer surplus in the ocean recreational fishery. None of these studies distinguish between private trips and charter trips, or, for the most part, between chinook and coho recreational angling. Meyer and Brown (1983) develop a travel cost study for ocean salmon fishing similar to that used to estimate consumer surplus in the freshwater fishery. They obtain an estimate of $58 per fish for ocean recreational salmon fishing.

Abdullah (1988) also uses the travel cost method to value Oregon ocean sport-caught salmon. He estimates consumer surplus between $13.10 and $37.20 per car trip in 1987 dollars. He calculates a marginal value of $23.46 and an average value of approximately $46 per coho salmon. Loomis (1988) estimates port-specific consumer surplus from ocean recreational salmon fishing in Oregon. His travel cost study yields marginal value per fish estimates of $21.43 to $64.61. Brown (1990) also takes the approach of estimating port-specific demand curves to estimate consumer surplus from coho fishing. The reported marginal values (in 1987 dollars) range between $10 and $36.80 per coho with a weighted average between ports of $23.20 per fish.

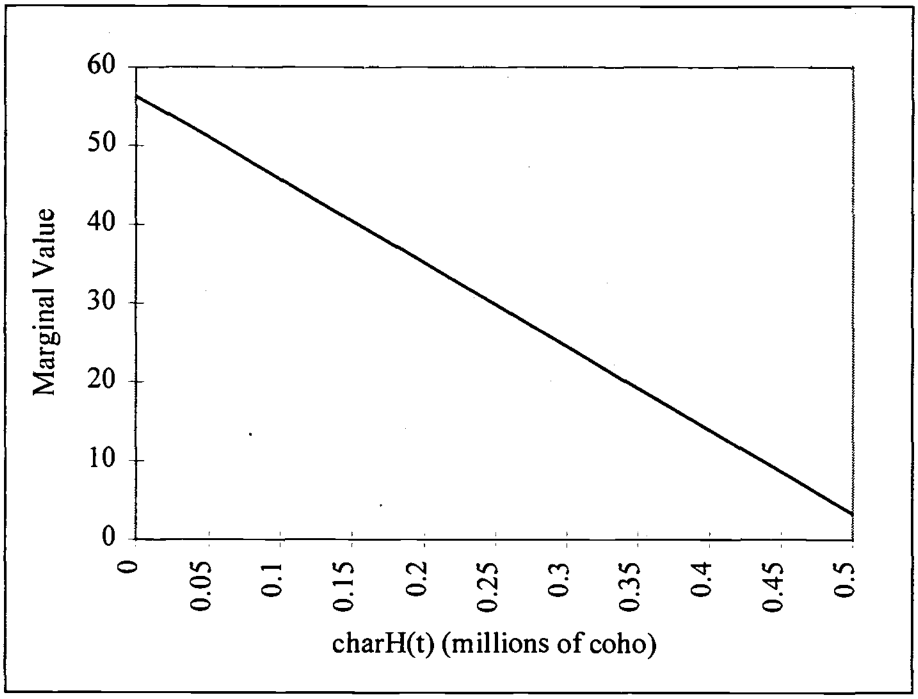
Olsen et al. (1991), in their CVM study, estimate values per trip and per fish for Washington and Oregon coastal salmon fishing. The CVM survey was implemented in 1989, and it is assumed for the purposes of this analysis that respondents used 1988 fish stocks as their baseline. Olsen et al. (1991) obtain average value estimates of $41.61 per fish and $89.47 per trip. A doubling of the salmon catch is expected to result in marginal values of $25.26 per fish and $54.31 per trip. Finally, Johnson (1994) calibrates the results of seven studies of ocean salmon fishing to 1992 dollars per angler day. She cites estimates between $27.68 and $76.15 per ocean salmon angling day.

The estimate of consumer surplus in the ocean recreational fishery for this analysis relies heavily on results from Olsen et al. (1991), but is consistent with the literature cited above. Inflating the estimates from Olsen et al. to 1995 dollars, an average net value per fish caught at 1988 catch levels was $49.77. The marginal value associated with a doubling of the 1988 catch rate was $30.22. Given that the charter harvest of coho salmon in 1988 of approximately 123,000 fish, the following linear demand function was estimated:

$$MV/fish(t) = 56.30 - 106 \cdot charH(t)$$

This demand schedule is graphed in Figure 4.4.

Figure 4.4 Demand curve for charter salmon angling.



Again, the associated consumer surplus (in millions of dollars) is the integral of the demand function up to the given harvest (in millions of fish):

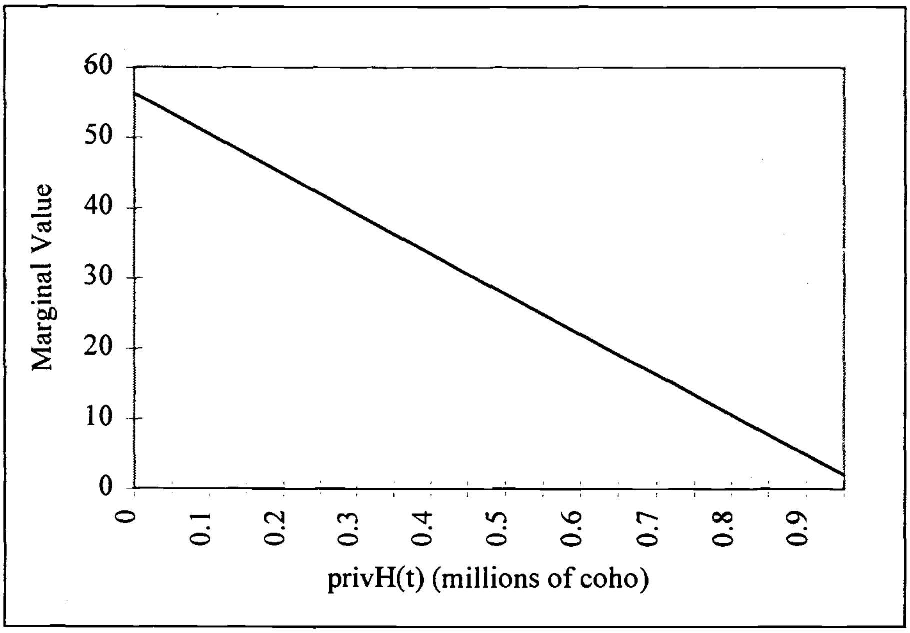
$$\text{charCS}(t) = 56.30\cdot\text{charH}(t) - 53\cdot[\text{charH}(t)]^2$$

The consumer surplus from private ocean recreational angling is estimated using the same average and marginal valuation estimate as the charter consumer surplus. The number of fish harvested in each year is different. Therefore the demand curves are different. The private harvest of coho in 1988 was approximately 228,000 fish, resulting in the following linear demand estimation:

$$\text{MV/fish}(t) = 56.29 - 57.11\cdot\text{privH}(t)$$

The demand for private harvest is represented in Figure 4.5.

Figure 4.5 Demand curve for ocean private salmon angling.



This implies a consumer surplus (in millions of dollars) as a function of private harvest (in millions of fish) of:

$$\text{privCS}(t) = 56.29 \cdot \text{privH}(t) - 28.56 \cdot [\text{privH}(t)]^2$$

This review and estimation of ocean and in-stream salmon angling consumer surplus estimates serves several purposes. First, it demonstrates the wide range of values imputed to recreational salmon fishing in the Pacific Northwest. It also shows that the marginal (or average) values per fish are likely to fall within a range of roughly \$10 to \$100 per fish, depending heavily on location, angler success rates, and a host of site quality characteristics. For those studies calculating marginal values over a range of catch rates, values show the expected diminishing marginal values consistent with consumer theory. Thus, within the neighborhood of "historical averages", one expects to realize marginal values within the approximate range defined above. The estimates chosen for this analysis are believed to sufficiently represent the literature on this subject.

4.8 Consumer Surplus from Existence of Coho Salmon

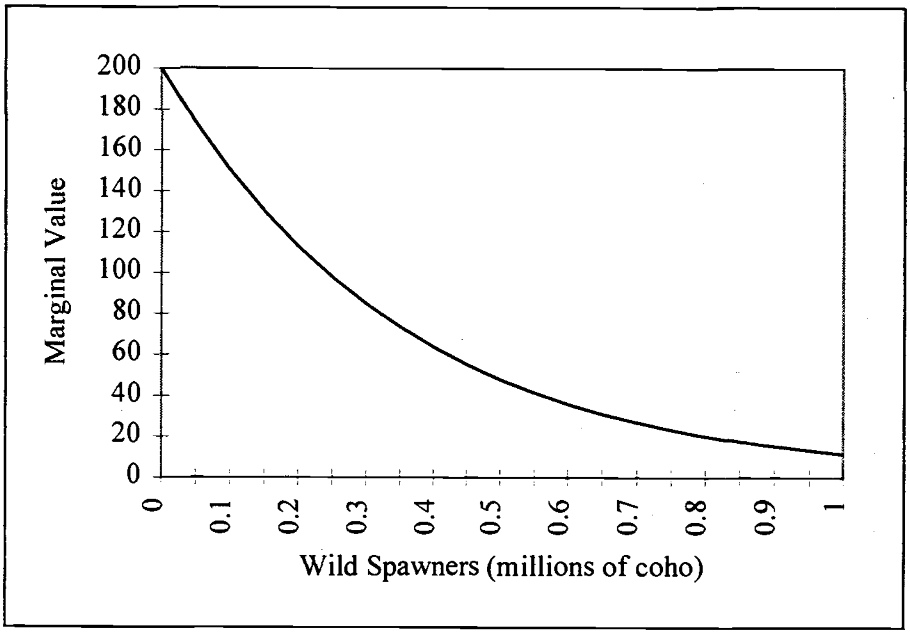
Current management of coho salmon along the Pacific coast (as presented in Chapter 3) includes managing the stock of wild fish according to a constant escapement policy. Wild fish provide several services which cannot easily be substituted by hatchery-raised fish. These services include enhancing biodiversity, adding nutrients to streams with decaying bodies, and providing an indicator of general aquatic ecosystem health. For these reasons, it is assumed that an existence value is associated with wild coho salmon. Legislation, and current public sentiment appear to confirm this hypothesis. Determining appropriate values reflecting the apparent social goal of viable wild coho stocks was complicated by the lack of literature estimating non-use, or existence values. Traditionally, the preferred method for estimating existence values is the contingent valuation method (CVM), because existence values cannot be inferred from observed behavior. Olsen et al. (1991) included existence value questions for non-users (i.e. Pacific Northwest residents who were not salmon anglers) in their CVM surveys. They estimate an existence value per spawner for a doubling of 1988 Columbia River salmon stocks of \$16.97. Adjusting this to 1995 dollars, one point on the existence value demand curve is obtained; 800,000 wild coho spawners have a marginal value of $20.29. An entire demand schedule is needed to assess the welfare impacts of changes in allowable catch.

In estimating a demand schedule, an exponential decay function is assumed to be the correct functional form. This form was chosen for several reasons. First, the functional form implies a finite value per fish as the population of wild coho approaches zero. This avoids needing to specify a maximum price for integration purposes, as is needed with a logarithmic form. The intercept (choke price) for this function has been arbitrarily set at $200 reflecting the assumed high marginal value for very low (e.g. endangered) coho populations. Furthermore, it seems likely that the true function is convex. That is, the rate of change of marginal values decreases with the number of wild spawners. The following demand curve for wild spawners is assumed:

$$\mathrm{MV/fish}(t) = 200\cdot\exp(-2.86\cdot\mathrm{spawn}(t))$$

This non-linear demand for wild fish is graphed in Figure 4.6.

Figure 4.6 Existence value of wild coho salmon.



It should be noted that when attempting to estimate original functions from primary data, one must determine an appropriate population over which to aggregate. That is, it is likely that inhabitants of the Pacific Northwest place a much higher value on the existence of wild fish than residents of, say, Nevada. The benefits transfer approach employed here borrows estimates which are in marginal value *per fish* terms, thereby evading the aggregation issue. Again, the consumer surplus (in millions of dollars) can be easily obtained by integrating the above function between zero and the number of spawners (in millions of fish):

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

4.9 Quasi-Rents to Charter Boat Operators

Modeling the quasi-rents accruing to charter boat operators requires an estimate of total revenue (TR) and total variable cost (TVC). The calculation of TR is a straightforward task. This analysis assumes an average charter fee of $45 per trip, based on the average cost of a charter trip in 1994. The calculation of trips is difficult to estimate from the data because of the interaction between coho and chinook recreational fisheries and the fact that PFMC (1996) data does not distinguish between coho and chinook charter fishing trips. This lack of disaggregation in the data is probably because charter boats do not generally target one species. However, because coho are the species of interest in this analysis, it is necessary to determine how changes in the coho catch affect charter trips. PFMC (1996) data was used to estimate a linear regression explaining total charter trips with chinook charter catch and coho charter catch from 1981 to 1995. The intercept was not statistically significant and the model was run without an intercept, yielding the following result:

$$\text{charter trips}(t) = .8349 \cdot \text{charter\_chinook} + .6887 \cdot \text{charter\_coho}, \quad R^2 = .994$$
$$(t = 13.59,\ 13.49,\ \text{respectively})$$

The statistically significant parameter estimates and the high R^2 statistic indicate a good fit of this model to the data. An increase in the charter catch of coho increases of 10 fish, coincides with approximately 7 more ocean charter fishing trips. The resulting estimate of total revenue to charter boat operators is:

$$TR(t) = 30.99 \cdot charH(t)$$

Radtke (1996) estimates an average of $14,260 in total variable costs per charter boat per year. Using PFMC (1996) data from 1987 to 1995, the number of operating charter boats (charter_boats(t)) is well predicted by the charter catch of chinook and coho by:

$$charter\_boats(t) = .00196 \cdot chinook\_catch + .001 \cdot coho\_catch, \quad R^2 = .972$$
$$(t = 6.81,\ 3.66,\ \text{respectively})$$

Using this regression, and the estimate of $14,260 in total variable costs per year, the following estimate of TVC as a function of harvest is obtained:

$$TVC(t) = 14.26 \cdot charH(t)$$

The quasi-rent to charter operators is estimated by the following:

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

4.10 Quasi-Rents to Commercial Harvesters

Determining the quasi-rents accruing to commercial fishers is a much more complex task. Literature specifically addressing quasi-rents in the coho fishery is particularly sparse, although some general guidelines for estimating the welfare impacts of changes in management have been established. Total revenue to commercial harvesters equals price per pound times the number of pounds landed. The real price per pound for coho salmon has decreased substantially since the late 1970's, from an average price per pound of $2.50 in the 1970's to $1.15 per pound in the 1990's (PFMC, 1996). This drop in coho prices follows an overall decline in world salmon prices due, primarily, to the rapid expansion in the supply of farmed fish. The economic model assumes a constant price per pound of $1 as recommended by Christopher Carter of the

Oregon Department of Fish and Wildlife (1996, personal communication), reflecting the price decrease coincident with the probable continued increase in farmed salmon worldwide. The following calculation of total revenue as a function of commercial harvest (comH(t)) and average weight ($\omega(t)$) is obtained:

$$TR(t) = 1 \cdot comH(t) \cdot \omega(t)$$

The model of total variable costs is handled with two separate components. Commercial harvesters face variable costs directly resulting from the level of effort. They also face costs which accrue every season they participate in the fishery, independent of the level of fishing intensity. Depending on the structure of the particular fishery, some aspects of this second component of costs may be classified as either fixed or variable. For the purposes of the economic model presented here, costs which are dependent, in any way, on fishing intensity, are classified as variable costs. Due to considerable uncertainty about costs, and non-uniformity between fishers, the literature generally does not attempt to estimate cost curves of the usual shape and functional form. Instead, in the case of salmon fisheries, variable costs (which depend on the effort level) are generally modeled as a percentage of total revenue (Kearney, 1993; Carter and Radtke, 1988; King and Flagg, 1984; Rettig and McCarl, 1984; Crutchfield et al., 1982; and Petry, 1979) .

Rettig and McCarl (1984) provide an insightful discussion of this issue by first noting that Pacific salmon fisheries can probably be characterized as somewhere between two polar bioeconomic cases. The first hypothetical case proposes that increased salmon populations could be harvested without any additional cost. After noting that, due to high overcapitalization (in fixed capital and labor), this scenario is possible, they conclude that it is unlikely. The second polar case presented by Rettig and McCarl (1984) is that the salmon market is an extreme case of a common-property resource. In this case, when short-term profits are made, additional entry results and profits are dissipated. According to their report, neither of these cases likely represents Pacific salmon fisheries. Following a thorough review of various estimates of variable costs as a percentage of total revenue, Rettig and McCarl (1984) estimate that net benefits to commercial fishers falls somewhere between 50 and 100 percent of gross benefits in the first year that the size of the available harvest expands. This is consistent with the literature on this complicated issue (Carter and Radtke, 1988; Smith, unpublished cited in Rettig and McCarl, 1984; King and Flagg, 1984; Petry, 1979). Due to considerable uncertainty on this issue, Rettig and McCarl (1984) recommend conducting sensitivity analyses of total variable costs between 50 and 90 percent of total revenues. This suggestion is adopted, and discussed later in this analysis.

Carter and Radtke (1988) model variable costs which depend directly on the level of effort as a percentage of total revenues and decompose them by category as shown in Table 4.2.

Table 4.2 Commercial fishers' variable costs as a percentage of total revenue.

Category	% of TR
repair work	4.1
gear replacement	6.8
fuel and lubricants	10.3
food and supplies	5.1
ice and bait	1.0
dues and fees	0.7
transportation	2.5
miscellaneous	2.5
crew shares	39.0
Total	72%

The following relationship predicting this component of costs is obtained:

$$TVC(t) = .72 \cdot comH(t) \cdot \omega(t)$$

In order to incorporate the seemingly significant welfare impacts of changes in fleet size during poor years, the additional cost component discussed above is included. Components of costs which could be avoided if the fisher decided, prior to the beginning of the season, that he would not participate in the fishery, should be included. Calculation of this element of costs, although somewhat smaller in magnitude than the costs which depend directly on effort, is very difficult. Several size classes of boats are utilized when fishing for salmon along the Pacific coast (King and Flagg, 1982; PFMC, 1996). It is necessary to divide vessel maintenance costs between the various uses, and it is likely that these vessels may pursue more than one species (e.g., albacore, halibut, and crab). King and Flagg (1982) identify four boat types that target salmon with percentages of revenues that come from salmon landings ranging form 29.5 percent to 94.8 percent. In order to proceed, it is assumed that 75 percent of the variable costs which accrue (regardless of effort) are attributable to the salmon fishery. Based on PFMC (1996) historical landings data, 44 percent of the salmon landed are coho salmon. If one coho is worth approximately one-fourth of a chinook (roughly half the weight and half the price per pound), it is assumed that coho contribute approximately 16.4 percent to total revenues of the average vessel targeting salmon. Multiplying the percentage of costs attributable to salmon fishing by the coho contribution to total revenues implies that 12.3 percent of the total variable costs of the type discussed in this section are attributable to coho fishing.

Table 4.3 depicts Carter and Radtke's (1988) estimates the costs of commercial salmon fishers not classified as variable costs.

Table 4.3 Additional annual costs to commercial fishers.

Cost Category	Cost ($)
insurance	480
moorage	720
licenses	360
miscellaneous	25
Total	$1,585

Inflating to 1995 dollars, these costs which accrue regardless of effort amount to approximately $1980 per boat. Multiplying by the percentage of costs attributable to the coho fishery (12.3 percent), an estimated $244 in variable costs of this type per vessel per year are attributable to the coho fishery.

Finally, the number of vessels must be estimated to complete the model of quasi-rents in the commercial coho fishery. Using PFMC (1995) data from 1978 to 1995, the following relationship of vessels participating in the ocean commercial salmon fishery is estimated as a function of commercial harvest of coho salmon:

$$\text{vessels}(t) = 1469 + 3018 \cdot \text{comH}(t), \quad R^2 = .86$$
$$(t = 9.92)$$

The model was run using both chinook and coho as explanatory variables, but the coefficient on chinook was not statistically significant. Thus, the costs which accrue regardless of fishing effort, but which can only be avoided if no fishing takes place, are modeled by:

$\text{Cost}(t) = 243.7 \cdot [1469 + 3018 \cdot \text{comH}(t)]$ or, in millions of dollars and millions of fish,

$$\text{Costs}(t) = .358 + .735 \cdot \text{comH}(t)$$

And the quasi-rents in the commercial fishery (in millions of dollars and millions of fish) as a function of commercial harvest (comH(t)) and average weight ($\omega(t)$) are:

$$\text{comQR}(t) = .28 \cdot \text{comH}(t) \cdot \omega(t) - [.358 + .735 \cdot \text{comH}(t)]$$

4.11 Hatchery Production Costs

The final component of the economic model, hatchery production costs, is estimated from Oregon Department of Fish and Wildlife (1996, unpublished data) budget data. These statistics indicate an average cost of $2.45 per pound of smolts produced. Although variability in smolt release size is an important biological and management issue, for the purposes of this analysis, a constant number of smolts per pound is assumed. Radtke (1996, personal communication) recommends using between 10 and 12 smolts per pound. Assuming 11 smolts per pound yields the following model of hatchery smolt costs as a function of hatchery smolt production (hsprod(t)):

$$\text{hsCOST}(t) = .22 \cdot \text{hsprod}(t)$$

The inclusion of hatchery production costs is justified in a net economic welfare analysis because all components of the economic model rely on hatchery production of smolts, which are funded by license fees and other taxes. In the simple supply and demand framework presented in chapter two, the hatchery production costs reflect the supply curve of fish in the system. The production of wild smolts involves opportunity costs of foregoing timber harvest and development which might influence the riparian ecosystem, negatively impacting spawning and rearing habitat of wild fish. While such costs of producing wild fish are relevant for thorough accounting of benefits and costs, estimating these opportunity costs are beyond the scope of this analysis and are not included.

4.12 Choice of Discount Rate

Implicit in any dynamic analysis is some notion of time-preference. The factor used to reflect the (generally assumed) impatience of society is the discount rate. In an analysis of resource extraction, higher discount rates have the effect of discriminating against the future by choosing higher resource extraction today, consequently leaving less for the future (or less for future growth in the renewable resource case). Freeman (1993) points out that, for rational individuals, the appropriate discount rate equals the relevant after-tax real rate of interest. Discount rates of between 1 and 5 percent are common for use in policy questions such as this, and in this analysis, a discount rate of 4 percent is assumed. Although this particular discount rate was chosen somewhat arbitrarily, the effects of choosing a slightly lower, or higher, rate are easily predicted. For example, choosing a lower discount rate implies that the future is relatively more valuable. This would shift consumption (harvest) away from the present, towards the future (in terms of growth). This shift would cause slight changes in optimal management under various forecast scenarios, but would not significantly change the model results. Choosing a slightly larger discount rate would have the exact opposite effect on management, but also is not likely to significantly alter results of this model. A thorough discussion of intergenerational equity, although interesting and relevant to any dynamic resource question, is not the focus of this thesis.

5. DECISION MODELS AND SOLUTION PROCEDURES

To achieve the stated objectives of this project, the net present value of the Pacific Northwest coho salmon fishery is assessed under five information structures reflecting ENSO predictions of varying accuracy. The first section of this chapter describes three models without El Niño forecasts, but with increasingly appropriate management based solely on the prior distribution of a particular phase occurrence. The second section discusses two models of updated forecast accuracy, improved and perfect one-year predictions. Regression models are fit to the generated data to evaluate the expected net present value over various planning horizons. This chapter provides a description of each of the five configurations of the decision model in ascending order of ENSO prediction accuracy, and their unique contribution to the eventual understanding of the value of improved ENSO forecasts in this fishery.

5.1 No-Forecast Models

Three "no-forecast" information structures are evaluated prior to the assessment of improved ENSO forecasts in the coho fishery. Complexity of current management, with different stocks being predicted and managed with different objectives, precludes the development of a perfectly descriptive model of current management. In this regard, the no-forecast models provide reference values from which to judge the value of information. Three models are presented without any ENSO forecast, each representing a different management strategy without a forecast of future conditions.

The "naïve" model assumes complete ignorance of future ENSO events and is the least accurate of the five models presented. In this model, managers assume that the El Niño Southern Oscillation phase in all future years will be normal. Like all other models described in this chapter, the true ENSO phase in any year is determined by the prior distribution. In every year t, the manager observes the true ENSO phase and resulting biological population structure from all previous years. Thus, the naïve model assumes that in each year t, the manager has perfect information regarding years up through t, but in his decision of the next year's harvest, he assumes normal ENSO conditions for all future years.

The solution to this model is relatively straightforward. In period 0, the manager knows the initial population structure, y_0, and he predicts normal ENSO conditions without recognizing the possibility of weak or strong phases. The dynamic optimization criterion is:

$$\max \text{NPV}(u, y, N)$$

where NPV is the net present value objective function (described in Chapter 4) which depends on the control variables (a vector, u), state variables (y), and expected ENSO phase in all future years (in this model, "normal" conditions, N, are always expected). This optimization provides the manager with the optimal control for year one. He commits to this control, u_1, and then the true phase for year 1, x_1, is realized. He observes the population structure (y_1, a vector depicting the population of each age-class) which results from the ENSO phase and control, and determines the optimal control (u_2) using the same procedure. This procedure is repeated over all possible true phase combinations for every year of the planning horizon, T. In other words, the net present values for 3^T combinations of true phases are assessed. The expected net present value of managing coho according to this strategy is determined by weighting each NPV(u, x) by the probability of occurrence of the particular sequence of true events, and summing over the weighted NPV terms. That is:

$$E[\text{NPV}] = \sum_{\forall j} \pi^j \cdot \text{NPV}(u^j, yj, xj)$$

where π^j is the probability of the particular sequence of true phases occurring, u^j is a unique (j) vector of control variables over the entire planning horizon, y^j is the vector of state variables, and x^j is the associated vector of true ENSO phases over the planning horizon. The probability of the unique string (j) of ENSO phases occurring, π^j, is calculated as:

$$\pi^j = \sum_{\forall i,t} \pi_{i,t}$$

where $\pi_{i,t}$ is the probability of ENSO phase i occurring in year t.

In the second no-forecast model, the manager is aware of all possible ENSO phases and their respective probabilities of occurrence. The following posterior (p(x | z)) distribution, the probability of phase, x, given forecast, z, as developed in Chapter 2, is used (Diaz and Markgraf, 1992).

	z_N	z_W	z_S
x_N	0.61	0.61	0.61
x_W	0.25	0.25	0.25
x_S	0.14	0.14	0.14

The assumption that the manager has perfect information regarding past and present events still holds, but when predicting future ENSO phases, the principle of certainty equivalence (C.E.) is assumed to hold, and management is based on the average (or expected) ENSO phase, a seemingly appropriate management strategy. The principle of certainty equivalence states that, under certain conditions of the objective function and error structure, if a solution to the maximization problem exists, the stochastic problem:

$$\max E[NPV(u, y, x)]$$

subject to starting values and other constraints, can be replaced by the certainty (deterministic) problem:

$$\max NPV[u, y, E[x]].$$

This theoretical result, developed by Theil (1954), implies that under specific conditions of the objective function, the solution to the stochastic optimization problem is equal to the solution to the deterministic problem where the objective function is optimized based on the expected value(s) of the stochastic parameter(s).

The objective function of the general model is of a fairly complex form and does not conform to the requirements necessary to satisfy certainty equivalence. For this reason, optimal management without a forecast does not necessarily follow the certainty equivalence management strategy defined in the C.E. model. The expected net present value using the certainty equivalence constraint is expected to be sub-optimal.

The third and final model without an improved forecast relaxes the assumption of certainty equivalence but assumes no further information or updating of the prior distribution. In the "hedge" model, the manager faces the same posterior distribution as in the previously defined, certainty equivalence model. Recognizing the true ENSO phases occur according to the prior distribution, but managing without a forecast of future events, the manager's objective is:

$$\max E[NPV(u, y, x)]$$

This stochastic dynamic programming objective is approximated by choosing vectors of controls (u) and "assumed states", $\tilde{x}$, which represent the optimal expected state of nature to maximize expected net present value, to satisfy:

$$\max NPV(u, y, \tilde{x})$$

subject to the same constraints. According to this heuristic solution method, the manager must not only decide what vector of control variables to apply, but he must assume an ENSO event for this management decision. If the certainty equivalence result holds, the optimal assumed ENSO event will equal the expected ENSO event. If the certainty equivalence result holds, the following relationships will be true:

$$E[x] = \tilde{x} \quad \text{and,}$$
$$E[NPV(u, y, \tilde{x})] = NPV(u, y, E[x])$$

As asserted earlier, the necessary conditions for certainty equivalence are violated in the objective function, and the following result is expected under these two no-forecast scenarios:

$$E[NPV(u, y, \tilde{x})] > NPV(u, y, E[x])$$

The value of the inequality is the expected value of relaxing the certainty equivalence constraint. The third model, without the assumption of certainty equivalence, may be interpreted as a hedge against the effects of El Niño. It represents the optimal management action that can be taken without an ENSO forecast, based on the historical frequencies (i.e. prior distribution) of El Niño occurrence.

5.2 Models of Improved Forecasts

Two models of improved ENSO forecasts are explored in this section. In each of these models, the manager is assumed to maximize the expected net present value of the coho fishery, and, when facing an uncertain future, hedge optimally to maximize the stated objective function (i.e. he need not assume that the certainty equivalence result holds). Improved and perfect one-year forecasts are presented. In each model, the forecast is available one year in advance, and it is received on an annual basis throughout the planning period.

The improved, one-year forecast assumes a posterior distribution with forecast accuracy improved from the no-forecast models, but with some uncertainty regarding the following year's ENSO phase. The values were arbitrarily chosen with each element midway between the prior and perfect predictors. In a probabilistic sense, this forecast predicts the following year's ENSO phase with half the accuracy of a perfect forecast (as compared with predictions based only on historical frequencies). This improved forecast is characterized by the following posterior distribution:

	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

The manager's problem and solution procedure are the same as in the no-forecast models, and he is assumed to have full knowledge of the posterior distribution and optimal hedging strategies without perfect information. Again, the objective is to maximize the expected net present value of the coho fishery by choosing control variables and an assumed state for each forecast and future year for which forecasts are not available. The improved forecast is available and incorporated into management annually. Therefore, E[NPV] can be interpreted as the expected net present value of the coho fishery using an El Niño forecast of improved accuracy (defined by the posterior distribution) on a consecutive, annual basis over the entire planning horizon.

Finally, the perfect, one-year forecast is evaluated. This final model is identical to the previously described, improved forecast model except for the posterior distribution of the forecast which contains ones as diagonal elements. In this "perfect" model it is assumed that in year t, the manager knows the ENSO phase for year t+1 with perfect certainty.

Table 5.1 Description of management decision models.

Model	Objective Function and Description of Information	Expected Performance ("<" worse, ">" better, "?"uncertain)
1. Naïve	max NPV[u, N]always expect Normal ENSO conditions, no forecast	? C.E. ≤ Hedge, Improved, Perfect
2. Certainty Equivalence	max NPV[u, E{state}] manage based on the average event, no forecast	? Naïve ≤ Hedge, Improved, Perfect
3. Hedge	max E[NPV(u, x)] relax certainty equivalence, no forecast	≥ Naïve, C.E. ≤ Improved, Perfect
4. Improved, one-year, consecutive	max E[NPV(u, x)] imperfect, consecutive, one-year forecasts	≥ Naïve, C.E., Hedge ≤ Perfect
5. Perfect, one-year, consecutive	max E[NPV(u, x)] perfect, consecutive, one-year forecasts	≥ Naïve, C.E. Hedge Improved

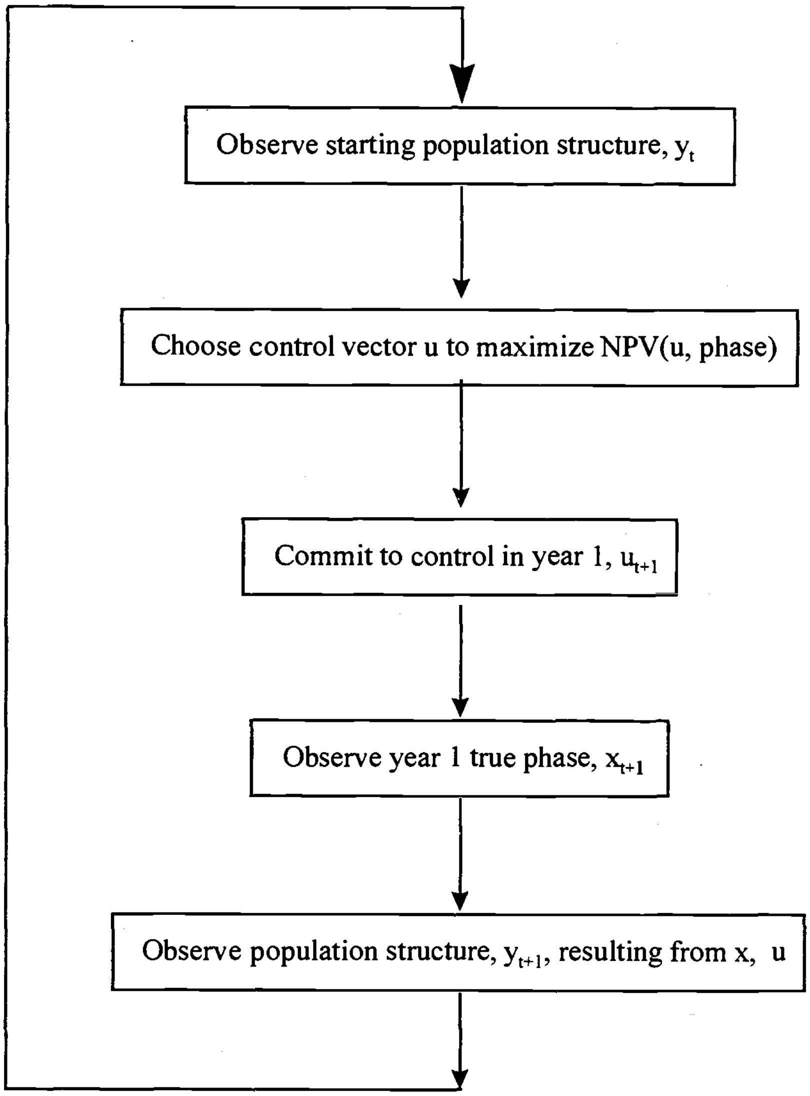
As in all other models, the manager is assumed to have perfect knowledge of the occurrence of previous ENSO events, and their manifestations on the population structure of coho. The posterior distribution for the "perfect" one-year forecast is:

$$\begin{array}{c|ccc} & z_N & z_W & z_S \\ \hline x_N & 1 & 0 & 0 \\ x_W & 0 & 1 & 0 \\ x_S & 0 & 0 & 1 \end{array}$$

The objective function is maximized using this information, again relaxing the condition of certainty equivalence for all years greater than t+1. The manager receives a perfect, one-year forecast of the ENSO phase in every year of the planning horizon. Thus, the expected net present value which results is the expected value of the coho fishery using perfect, consecutive, one-year forecasts over the entire planning horizon. The five models are described mathematically, and stylistically, in Table 5.1.

The decision-making framework is very similar for all five models described above.

Figure 5.1 Manager's generalized decision problem.



In the "naïve" model (model 1), the manager is ignorant of the possibility of weak or strong ENSO events, and manages accordingly. The "C. E." model (model 2) assumes the principle of certainty equivalence, and replaces the stochastic problem with a deterministic problem, always assuming the average (expected) ENSO event. In the absence of a forecast, the optimal management strategy is assessed in the "hedge" model (model 3) where the condition of certainty equivalence is relaxed. The next case (model 4) considers consecutive, "improved", one-year ENSO forecasts with a known posterior distribution. Finally, consecutive, "perfect", one-year forecasts are modeled (model 5). The solution framework for these models is pictorially represented in Figure 5.1. The solution framework in Figure 5.1 is executed for the models described above and, after incorporating the results into a simple statistical model, allows the calculation of the expected value of improved ENSO forecasts to the Pacific Northwest coho fishery.

5.3 Extrapolating to Longer Planning Horizons

The models of different management information presented in this chapter 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. Due to computational time constraints, a heuristic was employed to achieve this objective, enabling the evaluation of the expected value of the coho fishery over any planning horizon length. The models without improved information (naïve, certainty equivalence, and hedge) each require $3^T + 3^{T-1} + \cdots + 3 + 1$ optimization runs (where T is the length of the planning horizon). The model of improved information requires $3^{2T} + 3^{2T-1} + \cdots + 3$ optimization runs. The order of magnitude increase in CPU time to solve the "improved" model arises from the necessity to account for all prediction and true phase combinations. The perfect information model requires $3^T + 3^{T-1} + \cdots + 3$ simulations. Each simulation run requires approximately 3 seconds of mainframe computer time. Due to this enormous use of computational time, it was necessary to abbreviate the solution procedure and use another technique for extrapolating to the desired planning horizon.

The procedure for extrapolating to longer T begins by evaluating each model over 3, 4, …, and 8 year planning horizons. Then, regression analysis is used to estimate general trends of these values for each model. These trends are extrapolated to the general T-year planning horizon, and enable the assessment of the value of information over any planning horizon. As the planning horizon increases, the E[NPV] of each model should increase, but at a diminishing rate, due primarily to the effects of discounting.

The anticipated ranking of each model is depicted in Table 5.1. It is expected that the hedge, improved, and perfect models will maintain superiority over the naïve and certainty equivalence models regardless of the planning period. Furthermore, the hedge, improved, and perfect models are expected to maintain their originally predicted ranking in terms of E[NPV] regardless of the planning horizon length. However, there exists no *a priori* reason to suspect that either the certainty equivalence or naïve models is superior to the other. Results of the original model simulations and regression analysis are discussed, along with the estimation of the expected value of improved information, in the next chapter.

6. RESULTS

Previous chapters have described and interpreted the components of an assessment framework for valuing information. This framework is implemented to determine the value of ENSO forecasts when incorporated in the management of coho salmon in the Pacific Northwest. This chapter reports the results of that application and begins by presenting the magnitude of several control and state variables chosen by the optimization model. A comparison of the optimal values chosen by the model with historical values provides a means of assessing model validity. The focus then shifts to determining the value of information under the various information and management structures presented in Chapter 5. Results from three no-forecast models are presented and compared with optimization results from two models with improved information. Finally, several sensitivity analyses are conducted, providing some approximate bounds on the value of information.

6.1 Model Validation

Validation of model output is an important step in any modeling exercise. In the case of this thesis, values of control and state variables (such as harvest and population levels) chosen by the bioeconomic decision model must be realistic for the value of information estimation to be credible. Although the model developed here employs an objective function driven by economic factors, actual management of the coho fishery involves complex interaction between biological, economic, political, and sociological forces. For this reason, it is likely that the specific values of control and state variables chosen in this assessment will deviate from those arising from historical management practices. That is, because the model developed here utilizes optimization criteria which may deviate from current management, the optimal control path identified may also be different. However, the chosen values must be consistent with plausible biological and managerial realities. This section compares realizations of the generalized model with management of the coho fishery in recent history.

The complexity of model simulations, with different information structures, different planning horizons, and different ENSO events, necessitated the estimation of a "generalized" model, which is representative of the tens of thousands of models simulated in this thesis. The generalized model can be characterized simply as the model of "average" events, where, over a planning horizon of eight years, average ENSO conditions occur every year. Clearly, under different information structures, and different patterns of ENSO phases, management of the coho fishery would change, resulting in a different expected value of the fishery under each scenario. However, the stylized results reported here should approximate long-term historical averages.

The generalized model is solved under the optimization criterion of maximizing the net present value of the coho fishery. Four optimal control and state variables of interest are saved as output; harvest, proportion of the stock harvested, hatchery releases, and wild coho escapement. Models such as this typically achieve a steady state quickly, remain at that steady state until near the end of the planning horizon, and harvest (up to the zero profit level) near the end of the planning horizon. Values for year two are reported for two reasons. First, the year one values are likely to be influenced heavily by the starting conditions, and therefore are not likely to represent the steady state of the model. Second, as the end of the planning horizon is approached, model optimizations suggest a management policy of harvesting all adult fish (as their progeny will not reach a harvestable age prior to the end of the planning horizon). The values of year two realizations for the variables identified above, along with the historical averages from 1971-1993, are shown in Table 6.1.

In comparing the reported values with historical averages, it is important to note that the model presented here is a model of optimal management.

Table 6.1 Comparison of 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 smolt releases	7.93	42

As mentioned previously, optimal management in this context involves approaching a steady-state. Since 1993, the coho fishery has experienced a precipitous decline, and clearly is not at, or near, a steady-state. Thus, 1994 and 1995 are not appropriate years for comparison; instead, averages of these variables from 1971-1993 are chosen to represent historical means. As shown in Table 6.1, average harvest during this period is 1.75 million fish per year, comparable to the value of 1.86 million fish chosen by the bioeconomic model developed here.

The second control variable of interest is the percentage of adults harvested. This variable is particularly important because of the mixed-stock fishery issues discussed earlier. If harvest levels are commensurate with high numbers of hatchery fish released to the ocean, wild fish populations suffer because the proportion harvested is equal across wild and hatchery stocks. This typifies the problem of mixed stock fisheries. The 1971-1993 average exploitation rate of Oregon Production Index area (south of Leadbetter Point, Washington) coho was 62 percent. This is slightly more than the optimal exploitation rate chosen by the model of 54 percent, but the difference between the two is less than the variability in the historical data.

With regard to wild spawner escapement, the model optimal policy of 420,000 is consistent with the historical (1971-1993) escapement average in the Oregon Production Index area of 500,000 fish. This suggests that an escapement policy of roughly twice the current 200,000 wild spawner target may be appropriate.

Recently, some confusion has arisen as to the appropriateness of the particular index streams used by the Oregon Department of Fish and Wildlife to conduct stock assessments of wild coho salmon. The index streams used to represent all streams may be much more productive than average, thereby leading to consistent overestimates of stock size. The biological model (Sampson, 1995) used in this thesis was developed using individual stream data, thereby accounting for this potential miscalculation. Therefore, the numbers reported in this thesis reflect true numbers of spawners.

The higher escapement levels chosen by the model are likely a result of the existence value (marginal value of approximately $60 per fish) assigned to wild fish in the model. To test the effects of this existence value on escapement, an existence value of one-half the reported value is tested in the sensitivity analyses at the end of this chapter.

As reported earlier, hatchery releases increased through the 1960's and 1970's, reaching a peak in the mid-1980's. Recent evidence suggests that a large reduction in hatchery releases would improve the management of the fishery (National Research Council, 1996). The model solution indicates a hatchery release value of eight million coho smolts per year, substantially smaller than the 1971-1993 annual average of 42 million. Because of uncertainty with regard to hatchery-wild fish interactions and the effect of large numbers of hatchery fish on wild stocks, sensitivity analyses are conducted on density dependent parameters and reported subsequently.

Results of the validation process discussed here suggest that output from the model developed in this thesis is plausible in a long-term context.

6.2 Control and State Variables Under Various Information Structures

Although not a primary objective of this analysis, a comparison of control and state variable values resulting from the various model simulations can give important insights to management of the fishery. Because of the many model simulations performed in this analysis, selecting representative values to report is somewhat difficult. This section discusses specific results from selected model ENSO forecast/phase combinations. Year two values of four state and control variables are reported for both the naïve and C.E. models, under three different "state of the world" predictions; normal ENSO events in every year, weak events in every year, and strong ENSO phases every year over an eight year planning horizon. Because of its proximity to the C.E. model, the hedge model is not shown. Given that these no-forecast models use deterministic solution procedures, independent of the future ENSO phase, one would expect the controls (harvest, proportion harvest, and smolt releases), and corresponding optimal escapement levels (spawners) to be independent of the predicted event.

Control and state values from the models incorporating updated forecasts of El Niño are reported in the same manner. The values from the improved forecast model represent optimal control and state variables under three forecast scenarios; a forecast of normal conditions every year, a forecast of weak conditions every year, and a forecast of strong conditions every year. The perfect forecast values are also subsequently reported. Unlike the no-forecast models, optimal control and state variables in the improved and perfect forecast models will likely change under different predictions of El Niño, indicating that incorporating the ENSO forecast can improve management of the fishery. Table 6.2 shows the model output for four control and state variables (in millions of coho salmon) under each scenario described above. When managing in the no-forecast case, the optimal control and state variables are independent of the predicted state of nature, as expected. When a forecast of El Niño is incorporated into management, however, the optimal paths do rely on this forecast, thereby creating potential for a value of information. Analysis of results from the perfect model provides insights on how coho fishery managers might incorporate El Niño forecasts into their management plans. These results suggest that both future total harvest and future total proportion harvest will decrease when an El Niño is forecast. This is likely a result of the poor survival and growth in the first time period, leaving fewer fish in the ocean available for harvest.

Decline in the optimal values for the wild coho escapement state variable under different ENSO forecasts appears, at first, to be counterintuitive.

Table 6.2 Model output under different ENSO conditions.

Model	Variable	N forecast	W forecast	S forecast
Naïve	harvest	2.32	2.32	2.32
	proportion harvest	0.59	0.59	0.59
	wild escapement	0.44	0.44	0.44
	smolt releases	6.79	6.79	6.79
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
	smolt releases	7.86	7.86	7.86
Improved	harvest	2.16	1.88	1.63
	proportion harvest	0.58	0.55	0.52
	wild escapement	0.44	0.42	0.41
	smolt releases	7.45	7.94	9.58
Perfect	harvest	2.32	1.76	1.55
	proportion harvest	0.59	0.53	0.54
	wild escapement	0.44	0.42	0.33
	smolt releases	6.79	8.29	13.99

Apparently, when strong ENSO phases are accurately forecast for the future, fewer fish should be allowed to escape the fishery. The intuition behind this result is that if future growth of the progeny of these wild fish is know to be poor, then a more appropriate management strategy involves forgoing future existence values in favor of harvesting them today. In cases of imperfect forecasts, similar behavior is observed, but to a lesser degree, implying that "hedging" involves managing more closely to the "average" event when perfect forecasts are not available.

Smolt releases increase when future El Niño events are accurately forecast. The rationale behind this policy is that, despite the poor conditions in the wild, hatchery smolts are not susceptible to the effects of El Niño until they are released. On the other hand, wild fish are vulnerable for their entire life-cycle. Therefore, there is a shift from high wild production during non-El Niño years to high hatchery production when strong ENSO phases are forecast for the future (note, however, that even in the worst case, these numbers are well below current levels of hatchery releases).

One final observation of hatchery practices is in order. When a forecast is unavailable, the optimal release of hatchery smolts is much closer, relatively, to the release rate when normal conditions are forecast than to the release rate when strong conditions are forecast. In fact, this observation holds for all control variables, indicating that only when forecasts are highly accurate should managers use extreme measures such as those for a perfect forecast of strong conditions. In the no-forecast, or improved forecast case, the model indicates that more conservative management strategies will be welfare-maximizing.

6.3 Expected Net Present Value: No-Forecast Models

The validation process suggests that the assessment model provides reasonable estimates of key state and control variables. The net present value estimates for the no-forecast models are now discussed. Recall that the solution procedure for obtaining estimates of the expected net present value of the coho fishery involves evaluating each optimization model over multi-year planning horizons, and extrapolating to longer horizons using a regression model. Evaluation of E[NPV] for each model over planning horizons of length 3, 4, … , and 8 produces the predicted monotonic increase in E[NPV] with increases in the planning horizon. The ranking of models in terms of E[NPV] also conforms to the predicted order, where the expected net present value of the fishery using “naïve” information is less than E[NPV] using the certainty equivalence constraint. Interestingly, the “hedge” case is almost exactly equal to the certainty equivalence case, indicating that, without a forecast of future El Niño events, managing based on the average event may be appropriate. The implications of this result will be discussed in Chapter 7.

The prediction of diminishing marginal expected value with increases in the planning horizon is difficult to validate over short planning horizons such as those used in this analysis. The outcomes of each model do increase at roughly a linear rate over the 5 planning horizon lengths (3, … , and 8 years). There are several factors contributing to this result. First, due to the relatively low discount rate employed (4 percent), the eight year planning horizon is not of sufficient length to realize an appreciable influence of discounting. A second possible explanation, is that information and proper accounting for the possibility of future ENSO events does not play an important role for short planning horizons, i.e., it is possible that the increase in E[NPV] is small because there is very little value to improving management (hedging) over very short planning horizons. The expected net present value for each no-forecast model over T is presented in Table 6.3.

Table 6.3 Results for the no-forecast models.

	Planning Horizon, T					
Forecast	3	4	5	6	7	8
Naïve	109.68	178.69	242.92	304.20	361.30	416.81
C. E.	109.98	179.14	243.36	304.81	362.05	417.73
Hedge	109.99	179.15	243.36	304.81	362.05	417.73

Following the optimization of this model for planning horizons of length 3, 4, ..., and 8, regression models are fit to these data. The previously discussed theoretical rational of diminishing marginal expected net present value over T is imposed, and expected net present value is run against the natural logarithm of T, the planning horizon length. The following regression model, linear in parameters, is imposed on the information model results:

$$E[NPV] = \alpha + \beta \cdot \ln(T)$$

It is expected that for a planning horizon of length 0, the expected net present value will also be zero. Therefore, the intercept of the described regressions should technically be $-\infty$ because of the semi-log functional form ($\lim_{x \to 0} \{\ln(x)\} = -\infty$). Results of these regression runs are presented in Table 6.4.

Table 6.4 Regression parameters for extrapolating the no-forecast models to longer planning horizons.

Model	α	β	t-statistic	R^2
Naïve	-247.23	312.47	19.6	0.990
C.E.	-247.00	313.05	19.6	0.990
Hedge	-247.61	313.05	16.2	0.989

The high significance (t-statistics) and high level of error explanation (R^2) indicates that the semi-log functional form used to extrapolate to longer planning horizons is appropriate.

6.4 Expected Net Present Value: Improved Forecast Models

The procedure for determining the expected net present value of the coho fishery without a forecast of El Niño is also used to assess the two models with improved forecasts. The order of magnitude increase in CPU time for the "improved" model prevents running this model over all six values of T. Therefore, it is run for 3 and 4 year planning periods. As in the no-forecast models, both improved forecast models demonstrate the expected monotonic increase in expected value as the planning horizon increased. Furthermore, the "improved" model results are larger than all no-forecast models, but are less than those for the "perfect" one-year forecast model, as expected. Expected net present value results from both the improved and perfect models are shown in Table 6.5.

Table 6.5 Results for the improved-forecast models.

	Planning Horizon, T					
Forecast	3	4	5	6	7	8
Improved	110.02	179.52	-	-	-	-
Perfect	110.50	180.12	245.38	307.95	366.44	422.88

An expected diminishing marginal value of the fishery (due, primarily, to the effect of discounting) is assumed and the semi-log function is fit to the above results. However, because the improved model only has two data points, longer planning horizons are imputed by assuming that the intercept term is -247, as in the three models without a forecast. A regression model is fit to the "improved" data by constraining the regression to this intercept. The results of the improved-forecast models are presented in Table 6.6.

Table 6.6 Regression parameters for extrapolating improved-forecast models to longer planning horizons.

Model	α	β	t-statistic	R^2
Improved	-247.00	314.40	21.5	0.998
Perfect	-253.10	318.00	19.2	0.989

6.5 Base Case for Comparing Values of Information

Assessing the value of improvements in ENSO forecasts requires establishing an appropriate base case against which to compare changes in the net present value. The default base case in this analysis is the naïve information structure. The value of information relative to this admittedly simple decision model is evaluated by taking the difference between each improved forecast model and the naïve model over all planning horizons.

Complexity of current stock predictors and management of the coho fishery prevents precise modeling of ENSO information as currently employed in management of the coho fishery. However, as mentioned previously, managers of the coho fishery recently recognized the need to incorporate ocean conditions in their stock prediction models (PFMC, 1995). They do not, however, explicitly incorporate a forecast of those conditions. It is likely that fishery managers recognize the possibility of future ENSO phases and the associated biological and economic impacts discussed in this analysis. Therefore, the presumption that managers are naïve to the occurrence of El Niño is probably unrealistic.

The certainty equivalence model is employed to explore the effect of using a more realistic base model against which to judge the value of information. The certainty equivalence model is likely the one which most closely resembles current management of the coho fishery.

However, the apparently sub-optimal policy of managing for constant escapement when a forecast of future ENSO phases is available implies that the certainty equivalence model may overestimate the effectiveness of current management of the coho fishery, in which case the value of information figures, generated using the C.E. model as a base case, are understated. The recommended base case for the remainder of this analysis is the C.E. model, but, results using both the naïve and C.E. models as base models are reported in the next section.

6.6 Expected Value of Information

As outlined in Chapter 2, the value of information is defined as the difference between the expected value of the objective function with, and without the information. Two approaches could be employed to calculate the value of information in this manner. The first method involves taking the difference of the *estimated* expected net present value figures between the desired information structure and the base case, and fitting a regression to this differenced data. One potential problem with this approach is that any small errors from the originally estimated data could be amplified when the difference is taken, and the resulting data may not be explained as well by the semi-log functional form.

The second approach entails estimating the original expected net present value functions and taking the difference between the estimated curves as the value of information. Application reveals that the data generated by differencing according to the first approach does not fit the semi-log form very well. The second approach was chosen because of the suitable fit (significant t's, high R^2 values, as reported earlier) of the original regression equations. The value of information function follows the form:

$$E[VOI]_\gamma = \psi \cdot \ln(T)$$

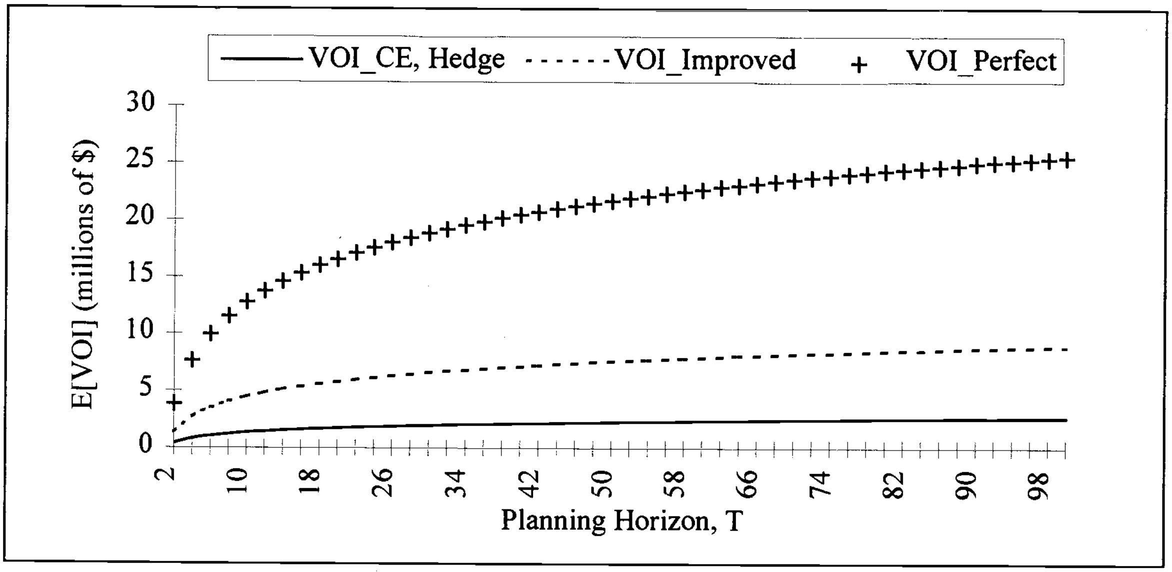
where γ is the information being valued and ψ is the difference in the β parameters of the originally estimated regressions. The objective of this regression analysis is to provide a model which enables the estimation of the value of information over long (e.g. 50 or 100 year) planning horizons. It is believed that the value of information is captured entirely in the slope terms of these regression equations. For this reason, the intercept terms were not used, as they have little economic interpretation. However, if included, the intercept term reduces the expected value of the fishery for each model. The resulting value of information is also reduced approximately 30 percent. The ψ parameters for all models, relative to the naïve model, are presented in Table 6.7.

Table 6.7 Parameters of the regression models, relative to the naïve case.

Model	ψ
C.E.	0.58
Hedge	0.58
Improved	1.93
Perfect	5.53

Estimates of the value of improved ENSO forecasts, relative to the naïve model, are obtained by inserting a time-horizon into the desired information model. Graphically, these values are shown in Figure 6.1.

Figure 6.1 Value of information relative to the naïve case.



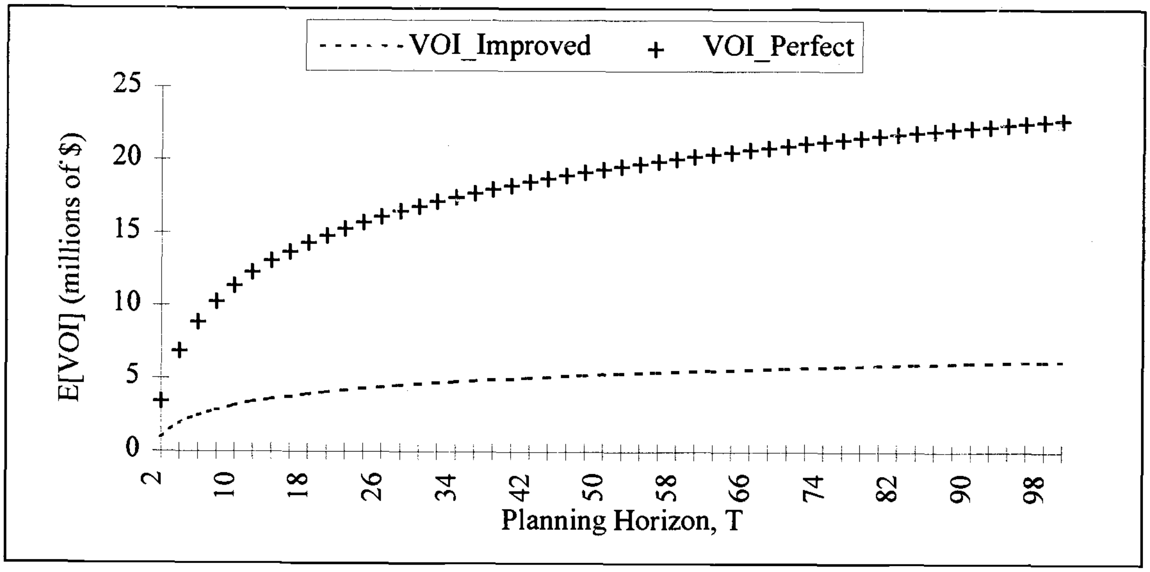
For the purposes of comparison, the parameters estimating the value of hedging, improved, and perfect information, relative to the certainty equivalence model, are presented in Table 6.8.

Table 6.8 Parameters of the regression models relative to the C.E. case.

Model	ψ
Hedge	0.00
Improved	1.35
Perfect	4.95

The associated value of information predictions over 2 through 100 year planning horizons are depicted in Figure 6.2.

Figure 6.2 Value of information relative to the C.E. case.



The value of information results are given numerically for 50 and 100 year planning horizons in Table 6.9.

Table 6.9 Expected value of information over 50 and 100 year planning horizons.

	E[VOI] relative to:						
	Naïve				Certainty Equivalent		
T	C.E.	Hedge	Improved	Perfect	Hedge	Improved	Perfect
50	2.29	2.29	7.57	21.65	0.00	5.28	19.36
100	2.69	2.69	8.91	25.49	0.00	6.22	22.80

Again, it is assumed that the C.E. model most closely approximates current management, and therefore is the most appropriate base model for comparison. Thus the values of improved and perfect forecasts are "best" represented by the $5.28 million and $19.36 million estimates for 50 year planning horizons, as reported in Table 6.9.

6.7 Sensitivity Analyses

The scope and complexity of the bioeconomic decision model developed here involved making many assumptions. Although the results are not meant to provide specific policy recommendations it is important to assess the stability of these results relative to the assumptions. In order to test some of the key assumptions made in the process of model development, several sensitivity analyses are conducted, and the results are compared against the originally reported results using the C.E. model described above. Five models, each incorporating a different assumption, are simulated for planning horizons of length 3, 4, 5, 6, and 7. Results of these model runs are fit to a semi-log functional form using the same procedure as outlined in Chapter 5.

The first sensitivity run, labeled "no dd", relaxes the assumption of density-dependent mortality on coho smolts. As discussed in Chapter 3, a review of the fisheries literature suggests that there is not complete agreement on this issue. One reason for including a density dependence parameter in the model is that it provides a check on excessive release of hatchery smolts. Essentially, it incorporates a tradeoff between reduced survival of the entire stock and the release of more smolts. In the absence of density dependence, the expected value of the coho fishery is expected to increase substantially, perhaps by more than the information value itself.

Suppose, as suggested in Chapter 3, wild fish are more resilient than hatchery fish and are not as susceptible to density effects in the ocean. The second sensitivity run, "hatchery dd" assumes that the density dependent effects are the same as the original model, but that only hatchery fish are subject to this mortality term. This change in model assumptions is expected to increase the net present value of the fishery, but, because density dependence is still imposed on hatchery fish, it will probably not increase the value by as much as the "no dd" scenario.

The next sensitivity analysis examines the role of the assigned existence value on wild coho spawners by halving the initial value. In fact, this analysis, labeled "low exist", assumes the same functional form of the existence value function as described in Chapter 4, but the exponential decay function begins at 100 instead of 200. Thus, the consumer surplus from existence value of wild fish is reduced to:

$$\text{existCS}(t) = 34.97\cdot[1-\exp(-2.86\cdot\text{spawn}(t))]$$

Because existence values are a significant component of the value of the coho fishery, as captured in the model objective function, this sharp decrease in marginal values will likely result in a significant decrease in the expected value of the fishery.

The fourth and fifth sensitivity analyses focus on the importance of the assumptions of costs in the commercial fishery. As discussed in Chapter 4, the standard procedure in fishery cost studies is to model variable cost in the commercial fishery as a percentage of total revenues. Rettig and McCarl (1984) recommend conducting sensitivity analyses of variable costs between 50 and 90 percent of total revenues. The fourth sensitivity model, "com 50%" assumes the same structure of costs as in the original model but that total variable costs accruing to commercial harvesters are equal to 50 percent of the total revenues. The fifth, and final, model, "com 90%", assumes variable costs are 90 percent of revenues. Clearly, as costs to commercial harvesters increase, the expected value of the fishery will decrease, and *vice versa.*

The α and β parameters of the following regression equation were estimated for each sensitivity model using the C.E. model and perfect one-year forecast model of El Niño according to the following regression model:

$$E[NPV] = \alpha + \beta \cdot \ln(T)$$

Results from each sensitivity analysis are depicted in Table 6.10.

Table 6.10 Parameters of various sensitivity models using C.E. and perfect information.

Sensitivity Model: C.E. Information	α	β	t	R^2
no dd	-279.91	368.33	16.75	0.99
hatchery dd	-239.42	314.07	17.86	0.99
low exist	-105.22	190.32	17.58	0.99
com 50%	-225.34	304.04	18.36	0.99
com 90%	-232.37	297.05	18.72	0.99
Sensitivity Model: Perfect Information	α	β	t	R^2
no dd	-286.37	373.69	16.08	0.99
hatchery dd	-241.27	315.89	17.74	0.99
low exist	-108.34	193.53	17.56	0.99
com 50%	-226.10	305.36	18.78	0.99
com 90%	-233.43	298.49	18.99	0.99

Two types of sensitivity analyses are explored to determine the sensitivity of the model to the various assumptions discussed above. First, the behavior of the expected net present value of the fishery is tested under the various assumptions outlined above. Second, the value of information itself is tested for sensitivity to these assumptions.

6.7.1 Sensitivity analysis I: Expected value of the fishery

Results of the first sensitivity analysis, assessing changes in expected net present value (in millions of dollars) under each sensitivity assumption over a 50 year planning horizon, are reported in Table 6.11. Results from the C.E. (base) model are presented to provide the reference from which to judge the effects of each altered assumption on the expected value of the fishery with perfect information. In order to provide a consistent means for comparison, the "base" model is solved for planning horizon lengths three through seven, and the sensitivity models are normalized for results to be consistent with the originally reported statistics.

Table 6.11 Expected value of changes in model assumptions over a 50 year planning horizon.

Model:	E[NPV]: T=50	Δ from CE_{base}
CE	977.66	-
Sensitivity:		
no dd	1219.06	241.40
hatchery dd	1038.69	61.03
low exist	671.28	-306.38
com 50%	1012.28	34.62
com 90%	976.18	-1.48

All results from this initial sensitivity analysis conform to the prior expectations discussed above. If, in fact, density dependence does not play a role in ocean survival of coho salmon, the model indicates that the expected value of the fishery would substantially increase. Similarly, if density dependence only influences hatchery fish, the value increases, but by less than it does in the no density dependence case. Given that existence values play an important role in the total economic value of the coho salmon fishery developed here, reducing the existence value results in a large decrease in the expected value of the fishery. Finally, the expected inverse relationship between harvesting costs and value are observed.

6.7.2 Sensitivity analysis II: Expected value of information

Under the various tests of model assumptions described above, the expected value of the objective function increases, and decreases, according to prior expectations. The expected value of information is now tested under the same set of altered assumptions. To conduct this analysis, each set of assumptions is tested by comparing the objective function values using the C.E.

management strategy and perfect information. Each new set of assumptions is run, for both C.E. and perfect models, over planning horizons of length 3, 4, 5, 6, and 7. The difference between the results of these models measures the value of information while operating under the new set of model assumptions.

Anticipating direction of changes in the expected value of the fishery (as in the previous section) is straightforward. However, it is more difficult to develop *a priori* expectation of changes in the value of information in any particular sensitivity analysis as compared with the originally defined model. Simply because the expected value of the *fishery* increases or decreases does not necessarily imply that the value of *information* will increase or decrease. Regressions were fit to the generated results of each sensitivity model using the same procedure as outlined in Chapter 5. Table 6.12 reports the expected value of information (in millions of dollars), under each scenario, and provides the originally estimated value of information as a reference point.

Table 6.12 Changes in expected value of information with changes in model assumptions.

Model	E[VOI] (millions)
Base	19.36
no dd	22.81
hatchery dd	7.73
low exist	13.67
com 50%	5.59
com 90%	6.16

These results indicate that when the assumption of density dependence is relaxed, the value of improving the ENSO forecast increases. On the other hand, if density dependence only acts on hatchery fish, the value is decreased. Similarly, if the marginal existence value decreases, the value of improving the forecast decreases. This may be partially explained by the fact that the value of the fishery also decreases. However as a percentage of the value of the fishery, the value of information does not significantly change. Finally, results indicate that the value of information (not to be confused with the expected value of the fishery) may be sensitive to assumptions about costs of commercial fishers. One might hypothesize that, if costs to commercial harvesters increased, the value of information will decrease. Intuitively, with very high costs, fishers make fewer profits regardless of forecast accuracy. The results from com 50% are the most perplexing of the sensitivity analyses. Intuition suggests that if costs to commercial harvesters decrease, the value of the fishery will increase. In fact, this is the case, as presented in the previous section. However, despite the increase in the value of the fishery, the value of information decreases. As mentioned previously, the dynamic, nonlinear nature of this problem creates difficulty in deriving intuitive explanations for these values.

The original bioeconomic assessment framework presented in this thesis was developed utilizing what were considered to be the most appropriate estimates of model parameters. Large changes in the objective function are expected to lead to substantial changes in estimates of the value of the fishery and the value of information. The results of these sensitivity analyses indicate that certain parameters, such as commercial quasi-rents and density dependence, are sensitive to large changes in the objective function, as expected. Results from the base model indicate a value of developing a perfect, one-year forecast of the ENSO phase of approximately $19.4 million. This equates to an annual value of approximately $900,000; about two percent of the annual value of the fishery. Sensitivity analyses indicate that under large, but plausible, changes in the objective function, this value probably lies between $6 million and $23 million.

Before turning to a discussion of the implications of this research in Chapter 7, one final point must be made. The model developed in this thesis can be quite easily modified to explore questions concerning altered growth functions or parameters, or even different species. Although not an objective of this analysis, modifications would also allow the assessment of changes in allocation between users. Some general conclusions on this issue are discussed in Chapter 7, but a thorough analysis of allocation issues was not undertaken here.

7. CONCLUSION

The precipitous decline in Pacific salmon stocks over the past two decades has motivated increased interest in the factors limiting salmon growth and survival. The explanation for the roughly ten-fold decrease in coho abundance over this period has focused primarily on two factors: in-stream impediments to the completion of the salmon's anadromous life-cycle, and overfishing. Recently, the focus of research has shifted to address the possibility of limiting ocean conditions. In this regard, two major phenomena are believed to act in possible synergism: shifts in ocean productivity on a decadal scale, and interannual variability of the ocean climate system-ENSO. El Niño, the Pacific Ocean component of the El Niño Southern Oscillation, manifests itself as an anomalous warming of the eastern Pacific Ocean for a period of a few months to several consecutive years, and has historically occurred with moderate to extreme intensity roughly every four years.

Strong ENSO events affect coho salmon stocks by severely reducing primary productivity and the transport of nutrients through the water column. The sharp reduction in nutrients available to coho during El Niño years results in increased mortality, decreased average weight, and, subsequently, reduced fecundity. Strong El Niño events also affect the weather patterns of the Pacific Northwest. In Oregon, rainfall generally increases in the winter during El Niño conditions, but decreases in the summer, resulting in reduced streamflow during the critical juvenile rearing period of the life-cycle. Thus, the effects of El Niño likely extend inland, possibly increasing mortality of wild smolts rearing in coastal rivers.

The oceanic and climatic effects of strong El Niño events have economic consequences for sectors such as agriculture and fisheries. Although it constitutes a relatively small portion of the world salmon fishery, the coho fishery of the Pacific Northwest has historically supported a substantial local commercial and recreational fishery. Furthermore, wild coho salmon represent an indication of ecosystem health to the inhabitants of the Pacific Northwest. Management of coho stocks involves a delicate balance between allocation and conservation in an attempt to best meet the goals of society.

Management of any fishery resource requires predictions of future stock sizes. The 1982-1983 El Niño event, possibly the strongest this century, resulted in actual returns of coho salmon which were only 42 percent of preseason predictions - the least accurate PFMC prediction on record. A recent, long-lived El Niño is thought to have contributed to current low population levels of coho, which resulted in the closure of commercial and ocean recreational coho salmon fishing in 1994 and 1995 (PFMC, 1996). Predictions of El Niño are hypothesized to have value insofar as they are incorporated into management plans, reducing the need for drastic, short-term measures such as the 1994 and 1995 closures of the commercial and recreational fisheries.

7.1 Summary

The overall objective of this thesis was to develop a general modeling 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 valuing improved (more accurate) consecutive, one-year ENSO forecasts in the coho fishery. In the absence of a forecast, managers must commit to management under uncertainty of future conditions. A second specific objective was to determine the extent to which hedging (optimal management without a forecast) can mitigate the adverse effects of El Niño. The Pacific Fishery Management Council area, from central California to the U.S.-Canada border provided an appropriate study area for this analysis for two reasons. First, since this area is at the southern end of the coho range, the fish are believed to be particularly susceptible to ocean variability. In addition, coho salmon of this region represent an important component of the Pacific Northwest commercial and recreational fisheries.

The approach for meeting the stated objectives of this analysis involved developing an economic decision model that allows for the effects of uncertainty. This model included what were deemed the most relevant components of economic surplus in the coho fishery. Conception of the model had, as its underlying theme, the need to estimate changes in economic surplus resulting from altered interannual management of the coho fishery. Time and budget constraints mandated the use of the benefits transfer approach to valuing the fishery. Specifically, results from published literature were used to develop economic relationships for use in the economic decision model. Based on such estimation from previous studies, in conjunction with data from various management agencies, demand estimates for charter ocean recreational, private ocean recreational, and in-stream recreational angling were developed for use in the economic model. The social goal of maintaining viable stocks of wild salmon was incorporated using an existence value demand curve for wild fish. Finally, producer quasi-rents accruing to commercial fishers and charter boat operators, less hatchery production costs, were estimated.

The economic model was then integrated with a stochastic biological model of coho salmon production. Specifically, to create the assessment framework, a nonlinear spawner-recruit curve (Ricker model) was employed along with stochastic mortality, fecundity, and average weight variables. The interaction between hatchery and wild fish remains, to a large extent, unknown. In this model, hatchery production is limited by a density dependent ocean mortality term which reduces survival of fish in the ocean as population density increases. The full stochastic bioeconomic assessment model was employed to map out optimal management, and associated expected net present value of the coho fishery, under five models of varying forecast accuracy. Each of the five models was chosen to represent a plausible information structure available to fishery managers. The first, "naïve", model assumes normal ENSO conditions for all years in the future. The "certainty equivalence" model incorporates the possibility of weak and strong El Niño events according to their historical frequencies, but manages based on the expected or average event. The third no-forecast model is the "hedge" model which recognizes the prior distribution of ENSO phases and manages optimally given this information. Finally, the "improved" and "perfect" models assume updating of the prior distribution based on consecutive, one-year forecasts of ENSO events. The output for each model included the expected net present value of the coho fishery resulting from managing with the associated information structure. Placing a value on forecast improvements involved taking the difference between the forecast in question and an appropriate "base case" for comparison. Both the "naïve" and "C.E." models are used as plausible base cases.

Computational limitations prevented the evaluation of these models for infinite planning horizons, but a heuristic approach is used to closely approximate the true values. The procedure involved running each model for planning horizons of length 3, 4, … , and 8 years and obtaining exact measures of the expected net present value of the coho fishery under each model. Using these points to predict longer planning horizons involved fitting a regression linear in the natural log of the planning horizon. This functional form is rationalized by the fact that discounting is of this general form, and future benefits of the coho fishery were discounted to reflect time-impatience. In this manner, the expected value of information for planning horizons of any length, T, may be assessed.

Results of the net present value of the coho fishery over planning horizons of any length T indicate there is significant value from improving the ENSO forecast. Using the certainty equivalence model as the base case for comparison, improving the one-year ENSO forecast to an accuracy level of approximately halfway between no forecast, and a perfect one-year forecast, is worth approximately $5.3 million over a 50 year planning horizon. This is roughly equal to $247,000 annually.

The value of a perfect one-year ENSO forecast is approximately $19.4 million over a 50 year planning horizon. Annualizing this sum indicates that a perfect, one-year forecast is worth approximately $900,000 per year. This is equal to roughly 2-3 percent of the annual value of the coho fishery, as predicted by this model. Although the assessment framework giving rise to these values reflects what is deemed the most appropriate bioeconomic model of the coho fishery, various sensitivity analyses were conducted, testing the robustness of the expected value of the fishery and value of information estimates. Results from these runs indicate that the range in value of the perfect one-year forecast is likely between $6 million and $24 million.

Results from the originally defined bioeconomic assessment framework indicate that the "hedge" model, as introduced in Chapter 6, provides very little improvement in the expected value of the coho fishery over the "certainty equivalence" model. Although the conditions for certainty equivalence do not strictly hold for this complex model, the results of the two are very close. This result implies that, in the absence of a forecast, managing based on the expected (average) El Niño event is an appropriate management practice.

7.2 Management Implications

To assess accurately the value of improved forecasts, the decision-making framework had to include plausible components. If the components of the model closely approximate reality, and the solution procedure is theoretically correct, the model can be manipulated to obtain answers to particular questions of interest. Specifically, in the face of a forecast of El Niño, questions such as, "how much should we harvest", "how many smolts should we produce and release?", and "how should we allocate between commercial and recreational sectors?" can be answered with small modifications to the base model. While such questions were not the primary focus of this project and were not thoroughly explored, some incidental findings provide insight on these issues. Specifically, some interesting, and perhaps counterintuitive, results were observed through analysis of the model results.

When a strong El Niño is accurately forecast for the future, the optimal strategy involves maintaining harvest rates of near no-El Niño levels, subsequently leaving a smaller stock of fish in the ocean than when normal conditions are forecast. Essentially, the harvest decision can be characterized by a simple tradeoff 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, wild spawner escapement, is reported to compare optimal management under different ENSO forecasts. Results from the original bioeconomic assessment framework indicate that when a strong El Niño is accurately forecast, the optimal escapement level decreases. Again, this result arises from the manager's continuous tradeoff between harvest for today and growth for tomorrow. When future conditions are known to be poor, the optimal strategy more strongly favors harvest today. The Pacific Fishery Management Council currently manages for a constant escapement of wild coho salmon of 200,000 fish. Results from the original framework indicate that, under the relatively high existence value of wild fish used here, and due to the ramifications of mixed hatchery and wild stocks, the optimal escapement levels should be much larger- around 400,000 fish, and should not remain constant- especially when an accurate forecast of future conditions is available. Although the optimal level of 400,000 is much larger than current constant escapement goals, such a level is commensurate with historical averages, as discussed in Chapter 6.

When the manager faces a problem of decision-making under uncertainty, that is, if the one-year forecast is imperfect or unavailable, he must choose the best "hedge" to mitigate the effects of possible future El Niño events. The greater the level of uncertainty, the stronger the burden to devise a hedging strategy. No general statement can be applied to all modeling situations regarding the optimal hedging strategy in cases of uncertain harvesting. The best strategy relies entirely on the forms of the objective function and error structure. In this example, however, as uncertainty increases, the optimal hedge is to manage based on the expected, or average, ENSO event. That is, when uncertain about the future ENSO phase (i.e. when an accurate forecast is unavailable), the optimal policy is to manage as if a very mild El Niño will occur in every future year.

These results provide some insights into the immensely complicated management of the coho fishery. In particular, results suggest that managing based on the average event is nearly optimal, making management under uncertainty concerning ENSO phases (without a forecast) much less convoluted. The specifics of this simplification are laid out in detail in Chapter 2, but essentially, the stochastic decision problem can be replaced by a deterministic decision problem, thereby reducing the complexity of the manager's problem.

With regard to hatchery operations, results from the bioeconomic assessment framework indicate that a reduction in hatchery smolt releases from current levels would increase the economic surplus from the coho fishery. This phenomenon arises as a result of three factors. First, at $0.22 per smolt, hatchery fish are fairly expensive to produce. Second, density dependent effects begin to take effect at around 15 to 20 million smolts. As smolts are added to the system, marginal productivity, or marginal contribution to total coho production, decreases. The third reason the assessment framework indicates a strategy of reducing smolt output is based on the mixed-stock fishery argument. Because fishers catch the same percentage of hatchery and wild fish, increased hatchery production leads to increased harvest of hatchery and wild fish. For this reason, with the addition of the existence value term for wild fish, the optimal number of hatchery releases is decreased. The model indicates an equilibrium smolt release level of approximately 8 million, as compared with recent smolt release levels of 30 to 40 million (PFMC, 1995). As reported and discussed in Chapter 6, when a strong El Niño 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, hedging implies managing more closely to the "no-El Niño" case, resulting in moderate to low hatchery releases.

As mentioned in Chapter 6, an analysis of the efficiency of current allocation could be performed with modifications to the assessment framework. However, some basic conclusions can be drawn from results generated by the model simulations. The allocation decision in the Pacific Northwest is particularly complicated due to the multiple users of the salmon resource. Theoretically, the optimal allocation of coho in any given year is that which yields equal marginal benefits across all users. Although not analyzed for specific values, the results of the economic model indicate that the allocation should be adjusted to more heavily favor the recreational fishery and wild coho salmon. The commercial coho fishery generates significant revenues in years of good production, but costs are sufficiently high in average years that the quasi-rents accruing to the fishers is usually quite small. However, other considerations typically enter such allocation decisions. For example, fishing as a way of life apparently has significant benefit to people. Furthermore, because this was an economic welfare analysis, it excluded secondary impacts on communities and "downstream" beneficiaries such as processors and distributors. Such notions of equity, fairness, and way-of-life are usually considered by management agencies responsible for the fishery.

7.3 Recommended Future Research

Valuing improved information in dynamic, stochastic fisheries is a promising research area. Much of the literature on stochastic dynamic control problems was developed in the 1970's and 1980's, but only the simplest analytical problems were solved. The recent increase in computational capability has allowed more realistic, nonlinear problems to be solved using computer simulation, and will likely continue to enhance this capability.

Value of information analyses will likely play a critical role in future research as agencies determine where to allocate research and development funding for large-scale projects. With specific regard to fishery issues, analyses such as this can provide insight into the complex task of managing anadromous stocks. The results reported here show a potential increase in value of improving the one-year ENSO forecast for the coho fishery. It must be reiterated, however, that the forecast has no value if it is not incorporated into management. The results of this analysis suggest that when information on future stock size is lacking, managers should 1) err on the side of harvesting too few fish, and escaping too many wild spawners, and 2) release fewer hatchery smolts in the present, especially if one believes that there is an existence value associated with wild fish. Future research in this setting should focus on more detailed models of the coho fishery, collecting primary data wherever possible. Refinements in the model will allow more specific analysis of optimal management with an ENSO forecast, but will probably not significantly change the estimates of the value of information.

Longer-term ENSO forecasts are currently being considered by NOAA and other agencies, and will likely improve management for fisheries with multi-year life-cycles, such as salmon. Theoretically, a schedule of increments in forecast quality can be mapped against the associated expected value. This would provide agencies with a continuous function from which to derive the optimal expenditures on forecast research and development. Finally, forecasts of the large, decadal shifts in ocean climate regimes would likely be useful to fishery managers. Lack of data on the frequency and forces behind these large shifts in climate regime would probably be the major limiting factor in developing an economic assessment framework such as the one developed here.

In conclusion, the preliminary assessment presented here indicates that there is still a lack of knowledge in both the theoretical development and the pragmatic implementation of value of information projects. As computer capabilities and our understanding of environmental stochasticity increase, the ability to conduct analyses which explicitly include more of the complexities of decision making under uncertainty will improve, providing resource managers with additional information. As this thesis has demonstrated, improved information on future ENSO events appears to have value.

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APPENDIX

Table 1 Ocean recreational salmon catch statistics (PFMC, 1996).

	Charter					Private		
Year	Trips ($x10^3$)	Chinook catch ($x10^3$)	Coho catch ($x10^3$)	Charter Boats	% active based on CA	Trips ($x10^3$)	Chinook catch ($x10^3$)	Coho catch ($x10^3$)
1981	288.7	129.2	248.0	-	-	381.2	68.4	200.3
1982	255.1	185.5	176.4	-	-	360.9	98.8	232.0
1983	221.8	90.3	162.8	-	-	340.3	46.8	223.1
1984	115.7	78.1	66.6	-	-	241.0	41.8	163.9
1985	201.4	133.9	160.6	-	-	354.8	119.6	206.2
1986	188.2	104.0	175.2	-	-	303.9	81.7	238.1
1987	219.6	163.8	126.1	683.0	0.64	405.8	128.7	220.3
1988	196.6	127.6	123.1	760.0	0.57	366.0	101.1	228.2
1989	226.7	120.4	187.2	780.0	0.49	309.0	117.7	325.4
1990	198.7	100.0	162.7	603.0	0.58	459.3	96.1	294.2
1991	153.2	46.8	162.6	624.0	0.42	346.7	60.4	357.6
1992	115.9	56.9	95.7	566.0	0.35	272.4	47.6	212.7
1993	119.6	72.7	73.2	540.0	0.52	244.7	56.5	131.0
1994	74.2	99.6	0.0	507.0	0.59	142.6	89.6	0.5
1995	174.5	182.3	30.1	529.0	0.57	286.8	221.8	46.2

Table 2 Freshwater and ocean catch of coho salmon in the Pacific Northwest (ODFW, 1996; PFMC, 1996).

Year	freshH ($x10^3$)	recH ($x10^3$)	private harvest ($x10^3$)	charter harvest ($x10^3$)
1982	30.017	408.4	232	176.4
1983	9.353	385.9	223.1	162.8
1984	49.798	230.5	163.9	66.6
1985	26.593	366.8	206.2	160.6
1986	72.354	413.3	238.1	175.2
1987	27.379	346.4	220.3	126.1
1988	65.499	351.3	228.2	123.1
1989	48.17	512.6	325.4	187.2
1990	18.556	456.9	294.2	162.7
1991	168.554	520.2	357.6	162.6
1992	38.588	307.5	212.7	94.8
1993	22.429	204.2	131	73.2
1994	5.433	0.5	0.5	0

Table 3 Ocean troll and sport landings of coho salmon in the Pacific Northwest (PFMC, 1996).

Year	Total Council Area (thousands of coho)		
	Troll Landings	Sport Landings	Total
1971	3196	1126	4322
1972	1558	835	2393
1973	1835	736	2571
1974	2831	978	3809
1975	1635	752	2387
1976	3826	1501	5327
1977	1201	684	1885
1978	1538	770	2308
1979	1566	492	2058
1980	822	709	1531
1981	1107	449	1556
1982	1036	408	1444
1983	450	383	833
1984	128	182	310
1985	313	366	679
1986	636	413	1049
1987	536	352	888
1988	747	351	1098
1989	643	536	1179
1990	373	478	851
1991	525	536	1061
1992	144	322	466
1993	77	214	291
1994	0	0	0
1995	57	81	138