Cost-Effective Recovery Strategies for Snake River Chinook Salmon: A Biological-Economic Synthesis

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Abstract: Formulation of recovery plans for endangered salmon populations in the Columbia River Basin of North America is a complex, controversial resource-management issue. To inform this issue, we constructed an integrated assessment model for analyzing biological-economic tradeoffs in recovery of Snake River spring/summer-run chinook salmon (*Oncorhynchus tshawytscha*). We merged three modeling frameworks: a salmon-passage model to predict migration and survival of smolts, an age-structured matrix model to predict long-term mean annual population growth rate of salmon stocks, and a cost-effectiveness analysis to determine the set of recovery strategies that are cost-minimizing solutions to achieving particular population growth rates. We applied the integrated model to assess six individual salmon recovery measures and 76 recovery strategies composed of one or more measures. To reflect uncertainty, results are derived conditional on two assumptions about the effectiveness of smolt transport around dams. We found that removal of an estuarine predator, the Caspian tern (*Sterna caspia*), and elimination of adult salmon harvest are recovery measures that markedly increase long-term population-growth rates regardless of transport effectiveness. Dam breaching significantly increases growth rates under the best available estimate of transport effectiveness. We also found that the recovery strategies in the cost-effective set depended on assumptions about transport effectiveness. Tern removal and harvest elimination are generally cost effective. At the best estimate of transport effectiveness, strategies that discontinue smolt transportation or breach dams are prevalent in the cost-effective set. In contrast, strategies that maximize transportation are prevalent in the cost-effective set if transport effectiveness is relatively high. More generally, the analysis eliminated 80-90 percent of the recovery strategies from the cost-effective set. Linking biology and economics through an integrated model thus provides a valuable tool for science-based policy and management.

Introduction

Researchers are advancing the integration of biology and economics for addressing conservation issues. Integrated approaches are being applied to study biodiversity conservation, terrestrial reserve site selection, establishment of marine protected areas, and many other topics. In particular, the ecological-economic framework for valuing ecosystem goods and services is a burgeoning field that promises new insights on the role of ecosystems in human economies (e.g., Daily & Ellison 2002; National Research Council 2005). Influential ecologists (e.g., Roughgarden 2001) and economists (e.g., Heal and Barbier 2006) argue persuasively that ecological-economic integration is an important research frontier and essential for better public policy.

Application of the U.S. Endangered Species Act (ESA) is a case in point. The ESA requires both biological and economic information for implementation. Biological evidence guides a decision to list a species as threatened or endangered, whereas economic costs may be used in designating critical habitat in a species-recovery plan (Brown & Shogren 1998). Typically, these two disciplinary approaches are not merged into an integrated framework for explicit assessment of tradeoffs between biological and economic metrics. Several studies, however, have developed such frameworks for analysis of recovery options for particular endangered species (e.g., Montgomery et al. 1994). Here, we construct an integrated assessment model to analyze alternative strategies for managing the wild Snake River spring/summer-run (SRSS) chinook salmon evolutionarily significant unit (ESU).

Snake River chinook salmon were listed as threatened under the ESA in 1992 (Federal Register 1992). A U.S. District Court recently ordered the National Marine Fisheries Service (NMFS) to prepare new biological opinions on recovery options in place of its 2004 Biological Opinion on the Lower Snake River and 2005 Biological Opinion on the Upper Snake River, to consider breaching the Lower Snake River dams, and to assess recovery options with a comprehensive analytical framework for the entire system (U.S. District Court 2005, 2006). Salmon recovery remains a scientifically complex, socially contentious resource-management issue (Barringer 2005).

Our integrated assessment addresses this issue by merging three modeling frameworks. First, we apply the Columbia River Salmon Passage (CRiSP) model to quantify the effects of in-river salmon recovery measures on second-year survival rates of juvenile salmon (Anderson et al. 2002). We use these results to adjust survival-rate parameters of the second model, an age-structured matrix population model. These matrices project the effect of changes in life-stage-specific survival-rate parameters on long-term annual population growth rates (Kareiva et al. 2000; McClure et al. 2003; Wilson 2003). By integrating CRiSP and matrix models, population growth rates become functions of particular recovery measures. Finally, we develop a cost-effectiveness analysis that merges matrix-model outputs with cost information on recovery measures. This analysis determines cost-effective recovery strategies, i.e., least-cost solutions to achieving fixed population growth rates. Unlike a benefit-cost analysis, a cost-effectiveness analysis avoids the challenge of estimating a monetary value that reflects the social benefit of salmon (Shogren et al. 1999). Instead, it takes recovery as a legal requirement and produces information on biological-economic tradeoffs to assist recovery decisions.

We organize the assessment around *recovery measures* and *recovery strategies*. Six commonly considered recovery measures are assessed: removing Caspian terns from the Columbia River estuary, eliminating human harvest, changing smolt transportation, reservoir drawdown, river flow augmentation, and dam breaching. We formed recovery *strategies* to represent alternative plans, where each strategy is composed of one or more recovery measures. One strategy approximates the status quo recovery plan and thus serves as the analytical baseline. Other strategies represent feasible changes to the baseline.

Our research makes two main contributions. First, we make a methodological contribution through the integration of biological and economic frameworks. The cost-effectiveness analysis creates a systematic way to assess tradeoffs between a biological metric (population growth rate) and an economic metric (cost). In particular, the analysis assessed the cost of marginal changes in growth rate—an important consideration given that, in a world of scarce resources, costs must be considered because "choices among species and between species and other programs must be made" (Shogren et al. 1999).

Second, our research produces insights on the biological and economic effectiveness of recovery measures and strategies for SRSS chinook. (1) Removing Caspian terns from the estuary and/or eliminating harvest of adult chinook can markedly increase long-term population-growth rates under two assumptions about the effectiveness of smolt transport. (2) The specific set of cost-effective strategies depends on assumptions about the effectiveness of smolt transport, as expressed by the delayed differential mortality rate. Tern removal and harvest elimination are generally cost effective, while at the best available estimate of transport effectiveness, cost-effective strategies include dam breaching, eliminating transportation, flow augmentation, and reservoir drawdown, in various combinations. (3) Cost-effectiveness analysis proves useful in evaluating numerous recovery strategies by eliminating over 80 percent of strategies from the cost-effective set.

Methods

Recovery Measures and Strategies

Our assessment includes six recovery measures that are options for improving survival conditions for SRSS chinook salmon. Table 1 reports the measures and their estimated annual costs; the costs are discussed later in this section. Four measures directly affect juvenile downstream migration through the hydrosystem, and are grouped into 19 "hydrosystem only" strategies. These are combined singly and jointly with measures for (1) Caspian tern removal and (2) harvest elimination, which affect other parts of the life cycle. Data were not available on either the biological effect or cost of recovery measures associated with hatcheries and tributary habitat.

Strategy A1, which replicates the status quo recovery plan, is the baseline; the other strategies are changes to this baseline, representing alternative recovery plans. Strategies A2-A19 are the other "hydrosystem only" strategies. Strategies B1-B19 are those 19 strategies combined with harvest elimination; strategies C1-C19 are the same 19 combined with tern removal; and strategies D1-D19 are the 19 hydrosystem strategies combined with both tern removal and harvest elimination. The cost of a recovery strategy is the sum of the costs of its recovery measures. Table 1 lists the seventy-six recovery strategies.

Biological Models

We applied the CRiSP model to simulate downstream passage of smolts and the age-structured population matrix model to analyze long-term population growth. We first describe the matrix model and then describe CRiSP.

Kareiva et al. (2000) constructed age-structured Leslie matrices to estimate the long-term mean annual population-growth rate, λ, of the seven index stocks of SRSS chinook salmon. Thus, λ is a metric to evaluate projected recovery outcomes. We re-created the matrices for these stocks and calculated λ values nearly identical to their results. The matrix elements and survival parameters for Minam River index stock are listed in Tables 2 and 3.

Our goal was to simulate outcomes of recovery measures that differ from those currently in place. We needed to estimate changes in one or more of the matrix parameters that would result from these measures. The measures most amenable to this approach were those affecting smolt survival during their downstream migration and in the Columbia River estuary, and adult survival during upstream migration. The second-year survival rate, s_2, is given by

$$s_2 = \left[z s_z + (1 - z) s_d \right] s_e , \tag{1}$$

where s_e is the estuarine and early-ocean survival rate, s_d is the in-river migration survival rate, z is the proportion of migrating smolts collected for transport to the Bonneville Dam tailrace, and s_z is their survival rate during transport. A recovery measure designed to improve downstream survival would change one or more of the bracketed parameters. Later, the bracketed terms in equation (1) are consolidated into a single variable, which we term "net downstream survival rate," or $s_{d\text{-}net}$.

We used the CRiSP model (Anderson et al. 2002) to simulate $s_{d\text{-}net}$. CRiSP reports survival rates through pools, dams, and reaches, as well as numbers of smolts collected and delivered to the Bonneville Dam tailrace. The combined survival rate below Bonneville Dam is identical to the net downstream survival rate discussed above. Multiplied by the s_e value, CRiSP output for $s_{d\text{-}net}$ yields s_2 and thus becomes input to the matrix.

We used CRiSP to reproduce the baseline $s_{d\text{-}net}$ value and to generate $s_{d\text{-}net}$ values for alternative strategies. From the literature on Columbia River hydrosystem operations, we configured CRiSP to mimic actual operations, including transporting 71-74% of all smolts, lowering reservoirs to minimum operating pools during migration, and providing 0.427 million acre-ft/yr of flow augmentation. For six of seven index stocks, our baseline λ was within ±0.003 of that reported in Kareiva et al. (2000), and the seventh, Marsh Creek, was within ±0.006. Thus, our CRiSP parameterization successfully replicated the baseline strategy.

Two adjustments were made to the baseline strategy to represent recent changes. The expansion of the Northern pikeminnow removal program has substantially decreased these salmon predators nearby the Snake and Columbia River dams; we reduced their density by 50% in CRiSP. Further reductions appear biologically infeasible even with higher effort (Radtke et al. 2004). We also incorporated the new standard of 0.487 million acre-feet of flow augmentation (NMFS 2005). These two changes raised the baseline λ's above those found in Kareiva et al. CRiSP specifications are available from the authors.

We next generated CRiSP outputs for each alternative recovery strategy. We used simulation results from four index stocks chosen to represent different tributaries: Imnaha River, Marsh Creek, Minam River, and Poverty Flat. Each stock was analyzed individually, but for space considerations and because absolute changes in results are similar across stocks, results are reported mainly for the Minam River index stock.

We entered the $s_{d\text{-}net}$ values produced by CRiSP into the matrix model. In addition, for those recovery strategies with harvest elimination, we adjusted adult mainstem harvest rates (h_{ms}) to 0, which changed the values for rates of adult salmon reaching spawning grounds (μ). For dam-breaching strategies, we increased adult upstream migration survival (s_{ms}) from its baseline of 0.794 to 0.913, following Kareiva et al. (2000). For strategies with Caspian tern removal, we increased the estuarine survival (s_e) rate from 0.017 to 0.018, using the same data and methods as Roby et al. (2003). Finally, we calculated the λ values for each of the 76 strategies (Table 1).

D Value and Extra Mortality. We expanded the analysis to account for two scientific uncertainties, delayed differential transportation mortality (*D* value) and latent mortality attributable to the hydrosystem (denoted here as "extra mortality"). The *D* value arises from juvenile-salmon transportation. Evidence indicates that s_e and ocean survival rates (s_3, s_4, and s_5) may be lower for transported than for untransported smolts. Although smolt survival during transport is about 98%, they may not do as well as in-river migrants in successive life stages. The *D* value is defined as the ratio of the rates of survival and return to spawning grounds of transported and untransported fish. If $D = 1.0$, the two groups are equal, whereas a $D = 0.5$ would mean that transported fish return at only half the rate of in-river migrants. This is important because the current program transports over 70% of migrating smolts, yet the *D* value remains uncertain (Wilson 2003). Williams et al. (2005) estimated the geometric mean *D* value for SRSS chinook at 0.553. We addressed the *D* value uncertainty by using two different values in the analysis: 0.553 and 1.0. Setting $D = 1.0$ bounds the analysis.

To configure the matrix model for different *D* values, we increased the s_e value as needed to make s_2 equal in the baseline across each *D*-value assumption (Wilson 2003). This held λ constant, but reallocated mortality to different life stages. We next adjusted CRiSP outputs for the 19 hydrosystem strategies to produce $s_{d\text{-}net}$ values based on different *D* assumptions. For each recovery strategy, the number of smolts delivered to the Bonneville tailrace was multiplied by the *D* value and added to the number of surviving in-river migrants. We then define s_{d-net} as

$$s_{d-net} = \left[z s_z D + (1-z) s_d \right]. \tag{2}$$

This expression for $s_{d\text{-}net}$ enters the following equation to replace equation (1) as input to the matrix model:

$$s_2 = \left[s_{d-net} \right] s_e . \tag{3}$$

Different λ's were generated from the matrix for each recovery strategy under each of the two *D*-value assumptions.

The second uncertainty, extra mortality, required other adjustments. Extra mortality is latent mortality from passing through the hydrosystem that is not manifested until a later life stage (Kareiva et al. 2000). This effect, distinct from *D* value, also impacts adults' upstream migration. Extra mortality implies that some mortality observed in the estuary or ocean is not caused by estuarine or oceanic conditions but comes from the reduced fitness of smolts caused by their downstream migration. Furthermore, adult migration is more difficult, and so some of the adult mortality observed in sub-basins must be reallocated to the mainstem. To examine extra mortality in breach strategies, we followed Kareiva et al. and increased adult mainstem survival and shifted part of the juvenile estuarine mortality to the downstream migration life stage, thereby increasing the s_e value. To assess assumptions about extra mortality, we took values from Kareiva et al., scaled them either to $D = 1.0$ or $D = 0.553$, modified the entries in the matrix model, re-ran the breach strategies in CRiSP, calculated new λ's, and compared cost and biological effectiveness, assuming a 3% extra mortality rate.

Cost-Effectiveness Analysis and Cost Estimates

A cost-effective salmon-recovery strategy is defined as the least-cost way to achieve a certain λ. By then varying λ parametrically over a range of values, the set of cost-effective recovery strategies is identified. This generated information on tradeoffs between λ and cost for strategies within the cost-effective set. Equally important, we also identified recovery strategies that are cost ineffective.

Formally, a cost-effective strategy for recovering a salmon stock is found by solving

$$\min_{i \in I} c_i \text{ subject to } \lambda_i \geq \lambda^0, \tag{4}$$

where $I = \{i \mid i = 1, ..., n\}$ is the index set of *n* recovery strategies, c_i is the cost of strategy *i* as derived from the sum of its individual recovery measures, λ_i is the mean annual population growth rate of strategy *i*, and λ^0 is a growth-rate constraint. The set of cost-effective strategies was found by repeatedly applying (4) as λ^0 was varied parametrically over the range of λ values for the *n* strategies.

The approach was applied as follows for each index stock and *D* value. Each recovery strategy is defined by a (λ , cost) pair. We sorted the 76 strategies in descending λ value and used the highest value of λ as the first cost-effective strategy in the set. When this λ is fixed as a growth-rate constraint, λ^0 , the first strategy is by definition the least-cost way of achieving that λ^0 . The second cost-effective strategy then was found by identifying the next strategy on the list that had *both* a lower λ value and a lower cost than the first strategy. Due to the sorting, lower strategies on the list have a lower λ, but they might have a higher cost. The "lower λ, higher cost" strategies were eliminated as inferior. This process was repeated until the entire list was exhausted. In conceptual terms, the value of λ for the second cost-effective strategy was fixed as a particular growth-rate constraint, λ^0 . The cost-minimization algorithm in (4) then found a cost-effective solution by sorting through the strategies to find the strategy that met λ^0 at least cost. We continued to re-set λ^0 and apply the algorithm in equation (4) recursively until the set of cost-effective strategies is found for a given stock and *D* value.

The baseline strategy provides several goods and services: hydropower, inland navigation, irrigation, recreation, and salmon recovery measures. Economic cost of the other recovery strategies is measured as a change from the baseline's costs and benefits. Cost estimates include direct costs (actual expenditures like the cost of breaching dams) and opportunity costs (the monetary value of foregone goods and services, such as lost hydropower generation after breaching). Costs are converted to 2003\$. A 3% discount rate is used when necessary.

Juvenile Salmon Transportation. In the baseline, smolts may be collected for transport at three Lower Snake River dams. Three transportation options are modeled: discontinuing transport, maximizing transport at the three dams, and adding transport at McNary Dam. To estimate the costs of these options, we start with an estimate for the transport program of \$2.5 million per year in 1995\$ (U.S. Department of Energy et al. 1995) and assume that these costs are divided equally among the four dams where transportation originally occurred (operations have since ceased at McNary Dam). This implies a cost per dam, including reinitiating transportation at McNary Dam, of \$0.75 million per year in 2003\$. The 2002 FEIS on Lower Snake River salmon migration (USACE 2002) does not update these costs.

Discontinuing transport at the three dams would reduce cost by \$2.25 million per year. In contrast, maximizing transport at these dams would involve transporting every smolt possible. We assume this increases costs by 15% (\$0.34 million per year) because of additional operating and/or fixed costs.

Maximizing transport has a second effect. Under the baseline, voluntary water spills are undertaken to bypass fish over spillways, thereby avoiding turbine-related hazards. Spill is unnecessary when transportation is maximized since all fish are diverted. This increases water available for hydropower production, with a corresponding estimated benefit of \$9.4 million (USACE 2002). Consequently, the net effect of maximizing transportation is not a cost; it is a benefit of \$9.06 million per year.

Spill is not a factor in strategies that incorporate dam breaching or reservoir drawdown. Consequently, the benefit of generating extra hydropower is not realized when maximizing transportation is combined with breaching or drawdown. The cost of maximizing transportation equals \$0.34 million per year in these cases.

Caspian Tern Removal. Augmenting the existing tern removal program involves reducing tern habitat in the Columbia River estuary and improving tern habitat at other locations (U.S. Fish and Wildlife Service 2005). This would reduce tern predation by 50% relative to the baseline program. The augmented program would require additional capital, annual operating, and sporadic monitoring costs. On an annualized basis, these respective costs are \$135,044; \$76,699; and \$12,811 per year, under the assumption that the habitat projects last for 25 years. We sum these costs and round to an estimate of \$225,000 per year.

Harvest Elimination. Eliminating mainstem harvest of wild adult SRSS chinook salmon would require a prohibition on fishing for wild and hatchery stocks. Given this prohibition, every adult SRSS chinook salmon has value. A recent commercial price for fish from the mainstem Columbia River

(USACE 2002) is $56 per fish. The 30-year average of wild and hatchery adult SRSS chinook salmon is an estimated 42,979 fish per year (Columbia Basin Research 2006). Our estimated cost of harvest elimination is $2.407 million per year.

Reservoir Drawdown. Drafting the four Lower Snake reservoirs to 35 feet below maximum pool for 4.5 months each year would be more costly than current drawdown practices. For the augmented drawdown, Huppert (1999) estimates a cost of $157 million/yr in 2003$. It would require replacement of the existing smolt bypass screens with collection systems for a lower river. We assumed these systems would be similar in cost to the submersible traveling screens that improved the original bypass screens. These were estimated at $1.985 million per year for three dams (Huppert et al. 1996). These revisions would be necessary at all four Lower Snake River dams, so the cost was increased by 33% to $3.37 million/yr and added to strategies that included the 35-foot drawdown. Newer cost estimates are unavailable because the 2002 FEIS on smolt migration did not assess the augmented drawdown.

Flow Augmentation. Augmenting spring flow with water from the Upper Snake River would reduce water for irrigated agriculture. The Bureau of Reclamation (BOR) is responsible for acquiring 487,000 acre-feet per year for flow augmentation (NMFS 2005). We estimate the cost of an additional 1 million acre-feet (maf) per year. This is measured as a net cost as it consists of two components: the cost of acquiring water and the benefit of generating hydropower with the additional flow at downstream dams. Based on actual acquisitions by BOR to meet an earlier target, water prices range from $10 to $51 per acre-foot (U.S. Department of the Interior 2003). These figures are adjusted by a factor of 2.5 to account for an upward sloping supply function of offered water (Aillery et al. 1999; U.S. Department of the Interior, 1999) and then converted to 2003$. We apply the mid-point of this range, or $76 per acre-foot, which is similar to previous estimates of the unit cost of water acquisition (Huppert et al. 1996).

Power production from flow augmentation has an estimated value of $30.34 per acre-foot when the average electricity price is 2 cents per kwh (Huppert et al. 1996). We adjust this number by an updated average electricity price, 2.4 cents per kwh (USACE 2002), and convert to 2003$. The estimated per-unit benefit of power from flow augmentation is thus $43 per acre-foot. The net unit cost of flow augmentation is the difference between water acquisition and power generation, or $33 per acre-foot. Acquiring 1 maf thus costs an estimated $33 million per year.

This estimate changes when flow augmentation is combined with either dam breaching or reservoir drawdown. The new flow would not generate hydropower at the Lower Snake River dams in these cases, but would continue to generate power at the dams along the Upper Snake River and Lower Columbia River. Using estimates of power production by region under flow augmentation (Huppert et al. 1996), the benefit of power decreases from $43 to $34 per acre-foot. With this adjustment, the unit cost of flow augmentation increases to $42 per acre-foot. Acquiring 1 maf costs $42 million per year at this rate.

Dam Breaching. Breaching the four Lower Snake River dams would require a direct capital cost, and it would generate opportunity costs from reductions in hydropower generation, irrigation water, commercial barging, and reservoir-based recreation. Benefits would accrue from avoided dam maintenance costs and increases in river-based recreation. Previous analysis estimates these costs and benefits (USACE 2002). The USACE analysis applied discount rates of 0%, 4.75%, and 6.875%. We interpolated to develop an estimate for a 3% rate. The cost of breaching the four dams is $191.525 million per year at this rate. Finally, breaching eliminates smolt transportation costs, and our calculations reflect this.

Results

Biological Analysis

We assess the effect of recovery measures and strategies on λ. According to convention, $\lambda > 1$ implies that the population is projected to increase, which means that the growth rate is given by $\lambda - 1$. A negative growth rate, or $\lambda < 1$, projects the population to go extinct. Our results on individual recovery measures are reported by *D* value for the Minam River index stock in Table 4. Results for other index stocks are similar in magnitude and are available from the authors. A key finding is that none of the recovery measures, singly or when combined into strategies, produce $\lambda > 1$, regardless of D value.

Caspian tern removal and harvest elimination are the only recovery measures that markedly increase λ regardless of D value. For the Minam River stock, tern removal increases λ relative to baseline by 1.16% when $D = 0.553$ and by 1.4% when $D = 1.0$; harvest elimination brings a 1.4% increase regardless of D value. Smaller gains (~0.33%) come from reservoir drawdown, regardless of D value.

The effectiveness of other measures depends on D value. Dam breaching has a substantial positive effect on λ when $D = 0.553$. Across four index stocks, λ increases by 0.075-0.1 (10.5%-11.5%) under this measure (Table 4). Yet, when smolt transportation is most effective at $D = 1.0$, the gain in λ from breaching shrinks to 0.32%. Maximizing transportation helps when D is high (1.95% increase), but hurts when D is low (-0.41%). Eliminating transportation has the reverse effect; λ increases by 3.15% with $D = 0.553$ and decreases by 7.14% when $D = 1.0$. The impacts of flow augmentation or adding McNary Dam transportation are very small (-0.4% to 0.26%), regardless of D value. Results for recovery strategies are discussed in the cost-effectiveness analysis.

Extra Mortality. We also analyzed the effect of extra mortality, which primarily affects recovery strategies that include dam breaching. With an extra mortality assumption of 3%, $\lambda > 1$ in every dam-breaching recovery strategy (A16-A19) for the Minam River stock; λ increases by 19-20% when $D = 0.553$ and by 24-25% when $D = 1.0$. Strategies B16-B19, C16-C19 and D16-D19 had similar percentage increases. For the other index stocks, similar percentage increases were realized, but lower initial λ values kept them from reaching $\lambda > 1$. A larger extra mortality effect is required to achieve this goal.

Cost-Effectiveness Analysis

Three general findings emerge from the cost-effectiveness analysis. First, cost-effectiveness analysis is a useful tool for eliminating ineffective recovery strategies. Of the 76 recovery strategies, 59 (78%) are eliminated as cost ineffective when $D = 0.553$ for the Minam River stock (Table 5). When $D = 1.0$, 68 (89%) are eliminated. Each eliminated strategy is dominated by a strategy that produces a given λ

value at a lower cost. Figure 1 illustrates the cost-effectiveness analysis for *D* = 0.553. The set of cost-effective strategies generates an envelope known as the cost-effectiveness frontier.

Second, although a robust set of cost-effective strategies exists for the Minam River stock, the strategies in the set differ markedly by *D* value. When *D* = 0.553, cost-effective recovery strategies span a wide range, but cluster into four distinct groups. At the cheaper and less biologically effective end are several strategies that counter-intuitively maximize smolt transportation (strategies A3, C3, C5, B3, D3, and D5). These produce small increases in λ (or a decrease, in A3), yet are cost effective for two reasons: their cost is actually negative (they produce more hydropower by avoiding spill), and they are combined in strategies with tern removal and/or harvest elimination. A second cluster involves strategies that discontinue smolt transportation (A2, B2, C2, and D2). These reach λ's over 0.9 at relatively low cost. A third cluster builds on strategy D2 (D2 = discontinue transportation, add tern removal, add harvest elimination) by adding either flow augmentation (D7) or reservoir drawdown (D10). These are relatively high-cost strategies. A fourth cluster involves dam-breaching strategies (A16, C16, B16, D16, and D18) at the high end on the biological and economic axes. The highest achievable λ with this *D* value is 0.988.

Clear differences occur with *D* = 1.0. Here, strategies that maximize smolt transportation (strategies A3, C3, C5, B3, D3, D5, and D11) produce higher λ's, while almost all other strategies are eliminated. The exception is strategy D17, which incorporates tern removal, harvest elimination, dam breaching, and transportation at McNary Dam. The highest achievable λ with *D* = 1.0 is 0.916.

Third, the cost-effectiveness analysis also provides information on the cost of marginal increases in λ (Table 6). For example, with *D* = 0.553, compare four sequential cost-effective strategies: D7, D10, A16, and C16. Reservoir drawdown replaces flow augmentation when moving from strategy D7 to D10. This increases λ by 0.005 (0.5%) at a cost of $127.3 million/yr. In contrast, strategy A16 involves only dam breaching; relative to the measures in D10, it increases λ by 0.044 (4.8%) at a cost of $28.5 million/yr. Finally, moving from A16 to C16 adds tern removal; this increases, λ by 0.011 (1.16%) at a cost of just $225,000/yr.

Figure 1 illustrates these marginal changes, with Δcost/Δλ equal to the slope of the cost-effectiveness frontier between two points. Graphically, relatively flat line segments represent relatively low-cost ways of increasing λ, such as moving from D10 to A16, or from A16 to D16. Relatively steep line segments represent the reverse, e.g., moving from D7 to D10. Numerically, values of Δcost/Δλ increase as the cost per unit of λ increases for adjacent strategies in the cost-effective set (Table 6). The analysis makes these tradeoffs transparent.

The cost-effective recovery strategies for the other index stocks are similar for a given *D* value, suggesting that the analysis offers general insight into management of SRSS chinook salmon.

Discussion

The integrated framework creates insights into options for recovering SRSS chinook salmon. We evaluated potential recovery measures with the population growth rate λ. By linking the matrix model results on λ with cost information on recovery measures, we produced a cost-effectiveness analysis of recovery strategies. The analysis of recovery strategies is especially informative for salmon management given that official and proposed recovery plans are composed of several measures. At the same time, the focus on recovery strategies pre-empts an extensive sensitivity analysis of individual recovery measures. That type of analysis can be found in Wilson (2003), who develops sensitivity, elasticity, and perturbation analyses using population projection matrices for SRSS chinook salmon.

Prior research shows that salmon population-growth rates are sensitive to increases in first-year and estuarine survival rates (Kareiva et al. 2000, Wilson 2003). Kareiva et al. highlight the need for “management actions that might produce the desired improvements” in these survival rates. Removing Caspian terns from the estuary is one such action as it markedly increases λ regardless of *D* value.

Breaching the four Lower Snake River dams is a second recovery measure with the potential to increase λ substantially. Its effectiveness, however, depends on assumptions about *D* value and extra mortality. Dam breaching markedly increases λ when *D* = 0.553, the best available estimate; this is consistent with previous results (Wilson 2003). When we assume 3% extra mortality, dam-breaching strategies produce λ gains of 20% or more and result in $\lambda > 1$ for the Minam River stock. Larger extra mortality effects (of 5-6%) are needed to raise all index stocks above that threshold, but the magnitude of extra mortality is uncertain.

Biological metrics other than λ are available. For example, the Interior Columbia Basin Technical Recovery Team (ICBTRT) used four population-level principles to assess ESA-listed salmonids: abundance, productivity, spatial structure, and diversity (ICBTRT 2005). The ICBTRT combines abundance (the number of spawners) and productivity (λ) into a single metric: the risk of extinction in a 100-year period. For our analysis, extinction risk would be too blunt, as the risk is 100% whenever $\lambda < 1$ for an extended period, and most of our analysis pertains to $\lambda < 1$. This is one argument for λ as a metric. A second argument is that λ is a transparent and direct product of the population matrices. Finally, there is widespread use by scientists of matrices for evaluating Columbia basin salmonids in the academic literature and in management applications.

The ICBTRT also evaluates populations' geographic distributions and their phenotypic and genetic diversity. We implicitly account for these by assessing the SRSS chinook salmon index stocks, which were intended to serve as proxies for the entire SRSS chinook ESU. Explicit metrics for spatial structure and diversity are beyond the scope of our analysis.

Two other qualifications are relevant for the biological analysis. One weakness of λ is that, as a long-run metric, it fails to account for short-term productivity changes or the population's dynamic path of adjustment to a new equilibrium condition. This may be most severe with dam breaching, which would take several years to implement. A second limitation is the use of deterministic matrices, which tend to increase λ relative to a stochastic model with environmental variability incorporated (Caswell 2001). Precautionary adjustments for stochasticity may be appropriate.

Cost-effectiveness analysis is useful in conservation planning, as it seeks to find the least-cost way to achieve a biological goal. We use the conceptual foundation of earlier work that applied cost-effectiveness analysis to protecting the endangered northern spotted owl (*Strix occidentalis caurina*)

(Montgomery et al. 1994). We apply the cost-minimization algorithm in equation (4) as a tool for identifying inferior strategies: for the Minam River index stock, 83.5% of strategies across the two *D* values are eliminated, leaving 25 cost-effective strategies.

The status quo strategy is not cost effective at the best available estimate, *D* = 0.553. It is dominated by one that adds Caspian tern removal and maximizes smolt transportation, which actually reduces cost while meeting or exceeding the baseline λ of 0.864 (Table 5). Strikingly, every individual recovery measure is represented among the cost-effective strategies for this *D* value. By definition, the strategy that maximizes λ (at 0.988) is cost effective; it combines breaching, tern removal, harvest elimination, and flow augmentation.

We assess the cost of marginal changes in λ as a way to compare strategies within the cost-effective set (Figure 1, Table 6). A policymaker can consider this type of marginal analysis for management purposes. Strategies that lie within the cost-effectiveness frontier may also be relevant. An "inferior" strategy can be assessed by comparing its (λ, cost) outcome to that of a cost-effective strategy. A policymaker might use this information to consider a strategy that is somewhat more expensive yet politically expedient.

Our study is similar to analyses by Paulsen & Wernstedt (1995) and Garber-Yonts & Rettig (1997), but applies a more recently constructed salmon-population model along with recent estimates of the *D* value and recovery costs. We also assess some measures (dam breaching, Caspian tern removal) that have not been studied with cost-effectiveness analysis.

Three general qualifications to the analysis remain. First, several recovery measures—such as dam breaching—would likely affect survival rates of other ESA-listed salmonid ESUs in the Columbia River basin. In economic terms, a single input would generate several outputs, creating a joint production problem. This raises a conceptual issue about the appropriate allocation of the costs of recovery measures and strategies. Guidelines exist for allocating costs of multi-output water projects in the context of benefit-cost analysis (U.S. Water Resources Council 1983), but not for cost-effectiveness analysis.

Should breaching costs simply be allocated equally among the four Snake River ESUs? Should costs be further allocated among each of the stocks comprising an ESU?

Another perspective on multiple ESUs relates to a recovery measure's biological effect on each ESU. One special case is when a measure's effect is equal across ESUs. In this case, our cost-effectiveness results would apply generally to the other ESUs. This is true even if the absolute results differ, but the relative effects remain the same. The cost-effectiveness rankings of strategies would not change. The issues associated with multiple ESUs are left to future research.

Second, in addition to assisting salmon, a recovery measure may produce other economic goods and services as a byproduct. For example, our analysis includes the costs of lost hydropower production in dam-breaching strategies. Breaching, however, would also produce a free-flowing Lower Snake River, from which economic benefits may be derived from new recreational opportunities or the aesthetic qualities of a natural river (Shogren et al. 1999). These benefits are distinct from breaching's salmon-recovery benefits. A complete cost-effectiveness analysis of salmon recovery would subtract the benefits of a free-flowing river from the costs of dam removal. Estimates of these benefits, however, exist only in a crude form for the Lower Snake River (USACE 2002). Research is needed on the benefits of prospective dam removal and river restoration for the Snake and other rivers.

Third, the analysis does not assess recovery measures associated with hatchery management or freshwater habitat restoration. Biological models are not available to estimate changes in survival rates at the relevant life stages for hatchery- or habitat-based measures.

In sum, this analysis eliminates 80-90% of recovery strategies from the cost-effective set for SRSS chinook salmon. It also makes transparent the tradeoff between biological benefit and economic cost of alternative strategies, all within the context of scientific uncertainty. Linking biology and economics thus provides a valuable tool for science-based policy and management.

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Table 1. Recovery measures and recovery strategies. The 19 hydrosystem-only strategies (A1-A19, with A1 being the status quo baseline) are formed from combinations of in-river recovery measures. These are merged singly and jointly with harvest elimination and Caspian tern removal to form 3 other sets of 19 strategies: B1-B19, C1-C19, and D1-D19. The cost of a recovery strategy is the sum of the costs of its individual recovery measures. The "AltCost" column reflects costs of flow augmentation and/or maximizing transportation operations when these measures are included in a strategy with dam breaching or reservoir drawdown. Breaching eliminates, and drawdown reduces, hydropower generation, which adds cost and/or reduces benefits of flow augmentation or maximizing transportation in these strategies.

Recovery Measure	Measure Code	Cost ($)	AltCost ($)
Baseline Hydrosystem Operations	base	$ -	
Breach Lower Snake River Dams	breach	$ 191,525,000	
Reservoir Drawdown	draw	$ 160,370,000	
Flow Augmentation	flow	$ 33,000,000	$ 42,000,000
Caspian Tern Removal	tern	$ 225,000	
Add McNary Dam Transportation	MCN tx	$ 862,500	
Maximize 3-dam Transportation Operations	max tx 3	$ (9,060,000)	$ 337,500
Discontinue Smolt Transportation	no tx	$ (2,250,000)	
Mainstem Harvest Elimination	harvest	$ 2,406,843	

Recovery Measure Code	Hydrosystem changes only	Harvest Elimination PLUS Hydrosystem	Tern Removal PLUS Hydrosystem	Harvest Elim., Tern Removal, PLUS Hydrosystem
base	A1	A1 + harvest = B1	A1 + tern = C1	A1 + harvest + tern = D1
no tx	A2	A2 + harvest = B2	A2 + tern = C2	A2 + harvest + tern = D2
max tx 3, no spill	A3	A3 + harvest = B3	A3 + tern = C3	A3 + harvest + tern = D3
MCN tx	A4	A4 + harvest = B4	A4 + tern = C4	A4 + harvest + tern = D4
MCN tx, max tx 3, no spill	A5	A5 + harvest = B5	A5 + tern = C5	A5 + harvest + tern = D5
flow	A6	A6 + harvest = B6	A6 + tern = C6	A6 + harvest + tern = D6
flow, no tx	A7	A7 + harvest = B7	A7 + tern = C7	A7 + harvest + tern = D7
flow, max tx 3, no spill	A8	A8 + harvest = B8	A8 + tern = C8	A8 + harvest + tern = D8
draw	A9	A9 + harvest = B9	A9 + tern = C9	A6 + harvest + tern = D9
draw, no tx	A10	A10 + harvest = B10	A10 + tern = C10	A10 + harvest + tern = D10
draw, max tx 3, no spill	A11	A11 + harvest = B11	A11 + tern = C11	A11 + harvest + tern = D11
draw, flow	A12	A12 + harvest = B12	A12 + tern = C12	A12 + harvest + tern = D12
draw, flow, no tx	A13	A13 + harvest = B13	A13 + tern = C13	A13 + harvest + tern = D13
draw, flow, max tx 3, no spill	A14	A14 + harvest = B14	A14 + tern = C14	A14 + harvest + tern = D14
draw, flow, max tx 3, no spill, MCN tx	A15	A15 + harvest = B15	A15 + tern = C15	A15 + harvest + tern = D15
breach	A16	A16 + harvest = B16	A16 + tern = C16	A16 + harvest + tern = D16
breach, MCN tx	A17	A17 + harvest = B17	A17 + tern = C17	A17 + harvest + tern = D17
breach, flow	A18	A18 + harvest = B18	A18 + tern = C18	A18 + harvest + tern = D18
breach, flow, MCN tx	A19	A19 + harvest = B19	A19 + tern = C19	A19 + harvest + tern = D19

Table 2. Structure of demographic matrices for female SRSS chinook salmon. s_x, probability of survival from age (x - 1) to age x; b_x, propensity to breed at age x; μ, survival during upstream migration; m_x, number of eggs per female spawner of age x. Parameter μ is defined as $\mu = (1- h_{ms}) s_{ms} (1- h_{sb}) s_{sb}$, where h_{ms} is the harvest rate in the mainstem of the Columbia River, s_{ms} is the survival rate of unharvested spawners from Bonneville Dam to their spawning basin, h_{sb} is the harvest rate in the subbasin, and s_{sb} is the survival rate of unharvested adults in the subbasin before spawning.

Matrix Elements						
		t				
		1	2	3	4	5
t + *1*	1	0	0	$\mu s_1 b_3 m_3/2$	$\mu s_1 b_4 m_4/2$	$\mu s_1 b_5 m_5/2$
	2	$s_2 = s_e s_{d\text{-}net}$	0	0	0	0
	3	0	s_3	0	0	0
	4	0	0	$s_4 (1 - b_3)$	0	0
	5	0	0	0	$s_5 (1 - b_4)$	0

Table 3. Survival parameters for baseline matrix for Minam River index stock of SRSS chinook salmon.

Parameter	Value
Net s_d	0.831
s_1	0.041
s_2	0.01413
s_3	0.8
s_4	0.8
s_5	0.8
s_e	0.017
b_3	0.009
b_4	0.42
b_5	1
m_3	3257
m_4	4095
m_5	5149
μ	0.670295
h_{ms}	0.062
s_{ms}	0.794
h_{sb}	0
s_{sb}	0.9
z	0
s_z	0.98
s_d	0.202
CRiSP s_d	0.831
CRiSP λ	0.864

Table 4. Results for individual recovery measures for the Minam River index stock. The Δ λ/$ is negative for some recovery measures with lower costs than the baseline strategy A1, implying a cost savings even while λ increases. This is because the baseline is not on the cost-effectiveness frontier (see also Figure 1).

Single-Measure Description	**Cost**	**D = 0.553**				**D = 1.0**			
		λ	Δ λ	% Δ λ	**Δ λ / $**	λ	Δ λ	% Δ λ	**Δ λ / $**
Baseline	$ -	0.864	0.000	0.00%	N/A	0.864	0.000	0.00%	N/A
Discontinue smolt transportation	$ (2.250)	0.891	0.027	3.15%	(0.0121)	0.802	(0.062)	-7.14%	0.03
Maximize 3-dam transportation	$ (9.060)	0.860	(0.004)	-0.41%	0.0004	0.880	0.017	1.95%	(0.00)
Add McNary Dam transportation	$ 0.863	0.863	(0.001)	-0.13%	(0.0013)	0.864	0.001	0.06%	0.00
Flow augmentation	$ 33.000	0.866	0.002	0.26%	0.0001	0.860	(0.003)	-0.40%	(0.00)
Reservoir drawdown	$ 160.370	0.867	0.003	0.34%	0.0000	0.866	0.003	0.32%	0.00
Breach Lower Snake River dams	$ 189.275	0.963	0.099	11.48%	0.0005	0.866	0.003	0.32%	0.00
Caspian tern removal	$ 0.225	0.874	0.010	1.16%	0.0444	0.874	0.011	1.25%	0.05
Mainstem harvest elimination	$ 2.407	0.876	0.012	1.40%	0.0050	0.876	0.012	1.40%	0.01

Table 5. Complete cost and λ results for the Minam River index stock with $D = 0.553$, in order of decreasing λ values. Cost-effective recovery strategies are highlighted in gray. The baseline strategy is highlighted in black.

Cost-Effectiveness Analysis: Minam River index stock, D = 0.553

Strategy #	Cost ($M)	λ
D18	**$ 233.907**	**0.988**
D16	**$ 191.907**	**0.988**
B18	$ 233.682	0.977
B16	**$ 191.682**	**0.976**
C18	$ 231.500	0.974
C16	**$ 189.500**	**0.974**
A18	$ 231.275	0.963
A16	**$ 189.275**	**0.963**
D19	$ 234.769	0.947
D17	$ 192.769	0.947
B19	$ 234.544	0.936
B17	$ 192.544	0.936
C19	$ 232.363	0.934
C17	$ 190.363	0.934
A19	$ 232.138	0.923
A17	$ 190.138	0.923
D13	$ 202.752	0.919
D10	**$ 160.752**	**0.919**
D7	**$ 33.382**	**0.914**
D2	**$ 0.382**	**0.914**
B13	$ 202.527	0.909
B10	$ 160.527	0.908
C13	$ 200.345	0.907
C10	$ 158.345	0.906
B7	$ 33.157	0.904
B2	**$ 0.157**	**0.903**
C7	$ 30.975	0.902
C2	**$ (2.025)**	**0.901**
A13	$ 200.120	0.896
A10	$ 158.120	0.896
A7	$ 30.750	0.891
A2	**$ (2.250)**	**0.891**
D12	$ 205.002	0.891
D9	$ 163.002	0.889
D6	$ 35.632	0.888
D1	$ 2.632	0.886
D4	$ 3.494	0.885
D15	$ 196.804	0.884
D11	$ 153.942	0.884
D14	$ 195.942	0.884
D5	**$ (5.566)**	**0.883**
D8	$ 26.572	0.882
D3	**$ (6.428)**	**0.882**
B12	$ 204.777	0.881
B9	$ 162.777	0.879
C12	$ 202.595	0.879
B6	$ 35.407	0.878
C9	$ 160.595	0.877
C6	$ 33.225	0.876
B1	$ 2.407	0.876
B4	$ 3.269	0.875
B15	$ 196.579	0.874
B11	$ 153.717	0.874
B14	$ 195.717	0.874
C1	$ 0.225	0.874
C4	$ 1.088	0.873
B5	$ (5.791)	0.872
B8	$ 26.347	0.872
C15	$ 194.398	0.872
B3	**$ (6.653)**	**0.872**
C11	$ 151.535	0.872
C14	$ 193.535	0.872
C5	**$ (7.973)**	**0.870**
C8	$ 24.165	0.870
C3	**$ (8.835)**	**0.870**
A12	$ 202.370	0.869
A9	$ 160.370	0.867
A6	$ 33.000	0.866
A1	**$ -**	**0.864**
A4	*$ 0.863*	*0.863*
A15	*$ 194.173*	*0.862*
A11	*$ 151.310*	*0.862*
A14	*$ 193.310*	*0.862*
A5	*$ (8.198)*	*0.860*
A8	*$ 23.940*	*0.860*
A3	***$ (9.060)***	***0.860***

Italics	indicate a reduction in lambda relative to baseline (strategy A1).
Black	highlights show the baseline strategy (A1), which is not cost-effective.
Gray	highlights indicate a cost-effective strategy: one which achieves a lambda gain at a lower cost than any other strategy.

Table 6. Cost-effective strategies and marginal analysis for recovery strategies with $D = 0.553$ for the Minam River index stock. Δcost and $\Delta\lambda$ are changes in annual cost and growth rate, respectively, of moving between cost-effective strategies. *Negl.* implies a negligible $\Delta\lambda$ (= 0 to three decimal places).

D = 0.553					
Strategy #	**λ**	**Cost (Million 2003$)**	**$\Delta\lambda$**	**Δ cost**	**Δ Cost / $\Delta\lambda$ (Million 2003$)**
A3	0.860	$ (9.060)	N/A	N/A	N/A
C3	0.870	$ (8.835)	0.010	$ 0.225	$ 22.63
C5	0.870	$ (7.973)	*Negl.*	$ 0.863	$ 2,765.09
B3	0.872	$ (6.653)	0.002	$ 1.319	$ 738.95
D3	0.882	$ (6.428)	0.010	$ 0.225	$ 22.30
D5	0.883	$ (5.566)	*Negl.*	$ 0.863	$ 2,724.80
A2	0.891	$ (2.250)	0.008	$ 3.316	$ 396.35
C2	0.901	$ (2.025)	0.010	$ 0.225	$ 21.81
B2	0.903	$ 0.157	0.002	$ 2.182	$ 1,002.32
D2	0.914	$ 0.382	0.010	$ 0.225	$ 21.49
D7	0.914	$ 33.382	*Negl.*	$ 33.000	$ 75,376.04
D10	0.919	$ 160.752	0.005	$ 127.370	$ 28,077.94
A16	0.963	$ 189.275	0.044	$ 28.523	$ 647.91
C16	0.974	$ 189.500	0.011	$ 0.225	$ 20.09
B16	0.976	$ 191.682	0.002	$ 2.182	$ 923.29
D16	0.988	$ 191.907	0.011	$ 0.225	$ 19.79
D18	0.988	$ 233.907	*Negl.*	$ 42.000	$ 475,221.86

Figure 1. Results of cost-effectiveness analysis. Gray diamonds represent the cost-effective set of recovery strategies. The line connecting them is the cost-effectiveness frontier. The baseline strategy and the other cost-ineffective strategies are illustrated to allow evaluation of all strategies.